

STRESS CHRONOLOGIES AND PERIODICITIES IN A MASS BURIAL,  
CHARTERHOUSE WARREN FARM SHAFT, UNITED KINGDOM:  
MICROSTRUCTURAL RECONSTRUCTION OF ENVIRONMENTAL  
INTERACTIONS AT THE PRECIPICE OF VIOLENT DEATH

by

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Stress Chronologies and Periodicities in a Mass Burial, Charterhouse Warren Farm Shaft,  
United Kingdom: Microstructural Reconstruction of Environmental Interactions at the  
Precipice of Violent Death

A thesis submitted in partial fulfillment of the requirements for the degree of Master of  
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## **DEDICATION**

This thesis is dedicated to the Charterhouse Warren Farm Shaft individuals. No matter how much respect was given to these remains, consent is absent for analysis of these individuals. This story is for the Charterhouse Warren Farm Shaft individuals and we tell it as respectfully as possible under the circumstance.

## ACKNOWLEDGEMENTS

Firstly, I would like to thank the individuals who remains are the focus of this study. Thank you for teaching us about your lives, although you could not consent to telling the world your story. Secondly, thank you to Dr. Rick Schulting for the invaluable access to the CWFS assemblage, and the helpful insight in the revision and crafting of this thesis. The sincerest thank you to Drs. Dan Temple, Haagen Klaus, and Anne Schiller for all the encouragement, reassurance, and time dedicated to mentorship. You are inspirations! A most gracious thank you to Dr. Shannon McFarlin and Dr. Paul Sandberg assistance with training and access to lab equipment at the George Washington Hard Tissue Laboratory that were necessary for this thesis. I would also like to thank my friends and family through their tireless support. Lastly, this project would not have been completed without all the beautiful people I have met in Virginia. Thank you.

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## LIST OF ABBREVIATIONS

|  |       |
|--|-------|
| Charterhouse Warren Farm Shaft .....             | CWFS  |
| Early Bronze Age.....                            | EBA   |
| Developmental Origins of Health and Disease..... | DOHaD |
| Osteon Population Density .....                  | OPD   |
| Hypothalamic-Pituitary-Adrenal.....              | HPA   |
| Beaker People Project.....                       | BPP   |
| Beakers and Bodies Project .....                 | BBP   |
| Minimum Number of Individuals .....              | MNI   |
| First Molar .....                                | M1    |
| Second Molar .....                               | M2    |
| Third Molar.....                                 | M3    |
| Dentin-Enamel-Junction .....                     | DEJ   |
| Linear Enamel Hypoplasia.....                    | LEH   |
| Accentuated Lines.....                           | AL    |
| Neonatal Line.....                               | NNL   |
| Crown Formation Time.....                        | CFT   |
| United Kingdom.....                              | UK    |

## **ABSTRACT**

**STRESS CHRONOLOGIES AND PERIODICITIES IN A MASS BURIAL,  
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George Mason University, 2020

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This study examines the chronology and periodicity of stress of the Charterhouse Warren Farm Shaft (CWFS) individuals, dated to the Early Bronze Age (EBA, ca. 2200-2000 cal BC), Mendip Somerset, England. Previous studies suggested that these individuals were victims of violent deaths, defleshing, and conceivably cannibalism before internment within a deep natural fissure instead of the normative practice of burial under an EBA round barrow. Histological methods were used to identify the presence and estimate the chronology of accentuated lines (AL) in 10 permanent first, second, and third molars and canines sampled from five individuals ( $n = 5$ ). Accentuated lines were identified as large, dark striae of Retzius that were visible over 75 percent of the dental plane between the dentin-enamel-junction and tooth surface. Chronology and periodicity of the accentuated line was estimated based along enamel prism distance from the

neonatal line and other known chronologies. Defect timing ranged between 53-3,292 days (0.1-9.0 years). Chronologies expressed an interquartile range of 245-1,339 days (0.7-3.7 years) and a median of 999 days (2.7 years). Periodicity resulted in an interquartile range of 52-145 days (1.7-4.8 months) and an average of 100 days (3.3 months). AL were present in infancy, prior to weaning off breastmilk, and into the juvenile period, therefore metabolic stress was experienced throughout development. The introduction of complementary foods correlated to metabolic stress in a single individual, which indicates complementary foods failed to buffer from environmental stressors. Cyclical trends in AL depicted possible environmental impacts of seasonal shortages. Systemic seasonal impacts possibly impacted resource procurement and provide context to the subsequent violent deaths of the CWFS individuals.

## **CHAPTER 1: HISTOLOGY IN ANTHROPOLOGY**

The human body is composed of remarkably intricate structures, which are a product of both deep evolutionary forces and cultural realities. Within these intricate structures are hidden stories of metabolic stress, including trauma and disease. In anthropology, the use of histological methods is critical in identifying intricate structures unseen in initial observation by the naked eye. In following with Sherwood Washburn's (1951) call for a profound understanding of human physiology, bioarchaeological research explores relationships between evolution, culture, and microanatomy. Current bioarchaeological and clinical literature recognizes that normal microanatomy and physiology is needed to comprehend abnormalities in micro-tissues, and the correlation to cultural contexts.

Histology, or the study of soft and hard tissue microstructures, provides a broader assessment of normal and abnormal human conditions. Histological studies apply scanning electrons, polarized light, compound light, and bright field microscopes to investigate these tissue structures. Soft tissue histology may aid in the differential diagnosis of mummified tissues (Grove et al., 2015). For example, the preservation in soft tissue may aid in differential diagnosis of a hematoma in mummified remains. By collaborating with 3D imaging and radiographic analysis, a histological analysis may provide evidence of iron deposits from red blood cells in a hematoma (Sokiranski et al.,

2011). However, for this thesis, only hard tissue histology will be addressed. Hard tissue histology examines the tissues such as calcium carbonate structures in bone and calcium phosphate prisms of enamel. As the most commonly preserved human tissues are bones and teeth, the preservation allows for biological anthropologists to reconstruct life histories of the deceased due to the developmental record.

Within the Developmental Origins of Health and Disease (DOHaD) paradigm, the theory of developmental plasticity refers to the distribution of metabolic output during growth with later life consequences (Gilman, 2005; Baterson et al., 2004). Skeletal and dental tissues maintain plasticity with microstructures that are influenced at the cellular level by the external environment (Ragsdale and Lehmer, 2012). The formation of the microstructures in dental and skeletal tissues depends on resources available during development, and the preservation of these tissues record the lived experiences of the individual. Plasticity differs in enamel and bone because enamel never remodels. Therefore, histology reconstructs an individual's early life history in the finite structures of dentition and the recently constructed lamellar bone before death. Although disadvantages in histology include destructive methods and long preparation times, histological applications are beneficial in anthropology by formulating precise and holistic results.

### ***Application of Histology***

Histology is used in bioarchaeology, forensic anthropology, and paleoanthropology to estimate age-at-death. Based on the degree of remodeling in bone

structures, an accurate age estimate may be considered. Osteons, or the microscopic structure for vascular tissue in compact lamellar bone, are present when bone tissue remodels. Cross-sectioning of long bones allows for analysis of the internal structure of bone, where the density and osteon count may be analyzed. As humans age, the density of an internal bone matrix begins to thin, along with a different rate of turnover in bone remodeling (Ortner, 1975; Stout and Gehlert, 1980). Osteon population density (OPD) is used by histopathologists to estimate age-at-death (Goliath et al., 2016). Similarly, in dental anthropology, thin sections of structures in both anterior and posterior dentition accurately provide age-at-death estimations until full dental maturity (Mahoney, 2008).

The histological analysis of lesions aids differential diagnosis of pathological conditions. Microscopy provides evidence for differential diagnosis in trauma assessment (i.e., sharp force trauma) (Crowder et al., 2013; Lynn et al., 2009). Disease prognosis (i.e., anemia, scurvy, rickets, syphilis, gallstones, and osteomalacia), and other metabolic stress represented in skeletal and dental remains may be reinforced by a histological approach (Schultz, 2001; Von Hunnius et al., 2006; Biehler-Gomez et al., 2019; van der Merwe et al., 2018; Schultz et al. 2007; Dirks et al., 2002). In biological anthropology, histological analysis can be used to reconstruct timing of incremental microstructures in enamel, identify stress events, then establish a timeline for isotopic estimations of weaning and age-at-breastfeeding cessation (Humphrey et al., 2008b; Garland et al., 2018; Dirks et al., 2010; Temple, 2016). In paleopathology, these histological applications aid the macro-morphological or geochemical inquiries of differential diagnosis of abnormal microstructures, while also providing a holistic approach to

reconstructing life histories (Von Hunnius, et al, 2006; Humphrey et al., 2008a; Sandberg et al., 2014; Garland et al., 2018).

In the investigation of life histories, histology may aid in the investigation of functional morphology. Functional morphology refers to the relationship between anatomical structures, diversity of anatomical structures across organisms, and associated behaviors. Therefore, applications of functional morphology apply to life history theory because of insight into behavioral and reproductive strategies, phylogenies, and physiological constraints. For example, the functional morphology of plants may explain evolutionary histories of terrestrial plants based on root types (Dong et al., 2015; Ma et al., 2018; Pohl et al., 2011). Histology aids the investigating the functional morphology of the vascular tissue in roots, which distinguishes the taxa between seeded and seedless plants and provide the evolutionary history of terrestrial plants as roots adapted traits to withstand harsher seasonal climates (Dong et al., 2015; Ma et al., 2018; Pohl et al., 2011). Additionally, functional morphology of vertebrate animals may explore the performance and relationship between structural traits such as the upper gastrointestinal tract in the digestive system (Rodrigues-Sartori et al., 2015; Iwasaki, 2002). Here histology aids in the identification of cellular tissues in the esophageal and lingual structures for traits that impact feeding strategies (Rodrigues-Sartori et al., 2015; Iwasaki, 2002). Both evolutionary and ecological functional morphologies may impact life histories. Similar to these biology studies, the anthropological applications of histology may be used to investigate primate evolution (Schwartz et al., 2002).

Other life history strategies may be comprehended through histological approaches. Ontogeny, observed microscopically, may aid in the identification of taxa by maturation rates, which are indicators of distinct life history strategies. Tracking of osteon remodeling, and the presence of secondary osteons, reconstructs maturation rates for early life development. In skeletal tissues of extinct and living species reconstructing phylogenies is made possible by the categorizing of length and speed of developmental stages (Padian and Lamm, 2013; Veitschegger et al., 2018). Similar to skeletal tissues, dental tissues aid in the reconstruction of life history frameworks. Crown formation times, identified by histology, produce chronological maturation rates. In the example of hominins, crown formation times differ between some hominid species (Bromage and Dean, 1985; Beynon et al., 1998). The timing of tooth formation timing differs in slow or faster development, where *Australopithecus* illustrated a faster development than humans (Dean et al., 2001; Smith, 1994). Later *Homo erectus* exhibited slower tooth formation times than australopiths, while still faster than humans (Dean et al., 2001). Lastly, there remains a controversy whether or not Neanderthals matured faster than human development (Guatelli-Steinberg et al., 2005; Smith et al., 2010; Macchiarelli et al., 2006). The uncertainties in the Neanderthal ontogeny, and the association with humans, comes from tooth formation times recorded in different dentition locations (Macchiarelli et al., 2006; Dean et al., 2001; Guatelli-Steinberg et al., 2005). While all these examples of the application to histology benefit anthropology, evolution, and life history studies, this thesis focuses on the application of histology to human dentition and stress responses to the lived environment.

### ***Theory of Metabolic Stress***

Evaluation of stress and disease in human populations relies on the prevalence of abnormal growth of skeletal and dental lesions. The methods of early bioarchaeology were founded on processual archaeology and cultural ecology, which helped to contextualize the last ten thousand years of human history. These studies explored differences in stress and disease associated with major adaptive transitions using comparisons of lesion prevalence and average size in skeletal structures (Larsen, 2015). However, the Osteological Paradox highlights biased conclusions in these early studies of bioarchaeology because of hidden heterogeneity and selective mortality (Wood et al., 1992). Hidden heterogeneity infers that the sampled individuals are heterogeneous in death susceptibility. Therefore, skeletal lesions may be inaccurate in the portrayal of stress as vulnerability to death may be dependent on other factors (Wood et al., 1992). Selective mortality implies that at time-of-death the conditions for vulnerability to death increased due to association with an underlying condition. Due to these factors, presence of lesions may be absent at time-of-death due to the individual succumbing to death where hard tissues are unaffected by cause-of-death or before the condition could manifest lesions observable in the skeletal or dental records. As a result, lesion prevalence may provide a biased perspective on the experience of stress and disease in the past.

Recent studies employ epidemiological methods in bioarchaeology that address selective mortality and hidden heterogeneity (DeWitte and Stojanowski, 2015). For example, studies of metabolic stress in skeletal populations were introduced by Goodman

et al. (1984a; 1988). However, more recently, Temple and Goodman (2014) critiqued bioarchaeological studies for under-theorization of the health concept and the reliance on a paradigm that emphasized lesion prevalence and population means. In addition, the critique advocated a paradigm shift towards further integration of life history theory to clarify the previously ambiguous definition of health in bioarchaeology.

Current bioarchaeology recognizes the body as partly a reflection of material culture. As a material culture entity, the skeletal and dental body is a product of the lived environment, and active in both the natural ecosystem and as an agent of culture (Sofaer, 2006). The relationship between culture and nature is not a dichotomy, but rather symbiotic and interactive, where both entities produce the human experience (Sofaer, 2006). When the lived experience includes adversities, adaptive plasticity is a strategy sometimes used by the body to overcome metabolic stress events by investing energy in short term survival (Bateson et al., 2004). Correspondingly, the hypothalamic-pituitary-adrenal (HPA) axis provides hormonal responses for nutrient distribution when early development is subject to adverse circumstances (Worthman and Kuzara, 2005). Temple (2019) applied these concepts to bioarchaeology suggesting that certain skeletal and dental indicators of early life adversity could recognize adaptive plasticity in the past. Since the presence of these indicators represents survived adversities and surviving early life adversity is energetically costly, the skeleton may allow for investigation of morbidity and mortality at later stages of development (Temple, 2019). Bioarchaeological research is the contextual study of human skeletal remains, and therefore, has the excellent opportunity to explore the diverse environments and sociocultural contexts that

produce increased metabolic stress and impact longevity (Armstrong et al., 2009; Gowland, 2015; Agarwal, 2016; Temple, 2019). Bioarchaeologists utilize the dental record, due to the ideal preserved and uninterrupted record of development, to reconstruct early life stress events and the correlated mortality at later stages of development.

### ***Histology and Tooth Maturation***

Before enamel formation, the initial structure of teeth begins at the cellular level. Within both the mandible and maxilla, the initial structures of tooth development in stages are termed the epithelial thickening, bud stages, cap stages, and bell stages (Nanci, 2017). The thickening of the primary epithelial band allows for the dental placode to form, which will establish the structures for later enamel formation (Nanci, 2017). From the oral epithelium structure develops the dental placode into the bud stage. In the bud stage, the epithelial bud cells multiply as a condensation of cells. As these cells increase in density, the transition to the cap stage allows for the determination of tooth types from the germ cells. The cap stage includes the enamel organ, which is the cap shape structure composed of the enamel organ, dental papilla, and surrounding dental follicle. The primary enamel knot in cap stages forms between the enamel organ and the oral epithelium and is the vital structure that will signal the morphology of cusps. In the subsequent bell stage, the primary enamel knot has disappeared through apoptosis, and secondary enamel knots form to differentiate cusps. The late bell stage is critical because this structure develops the initial ameloblasts. Ameloblasts cells are necessary for the

creation of the matured enamel matrix, and possibly record developmental stress, studied by bioarchaeologists.

Enamel formation, or amelogenesis, begins with ameloblast cells releasing the initial enamel matrix, and ends with the matured ameloblasts leaving mineral crystalized prism structures, also termed enamel rods (Boyde, 1989; Nanci, 2017). During amelogenesis, the phases of enamel formation begin with a secretory phase and end with a maturation phase (Nanci, 2017). The matured structures of enamel bundle together as hydroxyapatite prisms that lengthen from the dentin-enamel-junction (DEJ) to the outer surface (Boyde, 1989; Berkovitz et al., 2017). Maturation of enamel happens through calcium and phosphate ions reinforcing the enamel crystallites (Berkovitz et al., 2017). The final enamel structure lacks water and living cells, and therefore this calcium phosphate structure lacks the ability to remodel. Once matured, teeth represent a permanent window into early development and a model for exploring life histories.

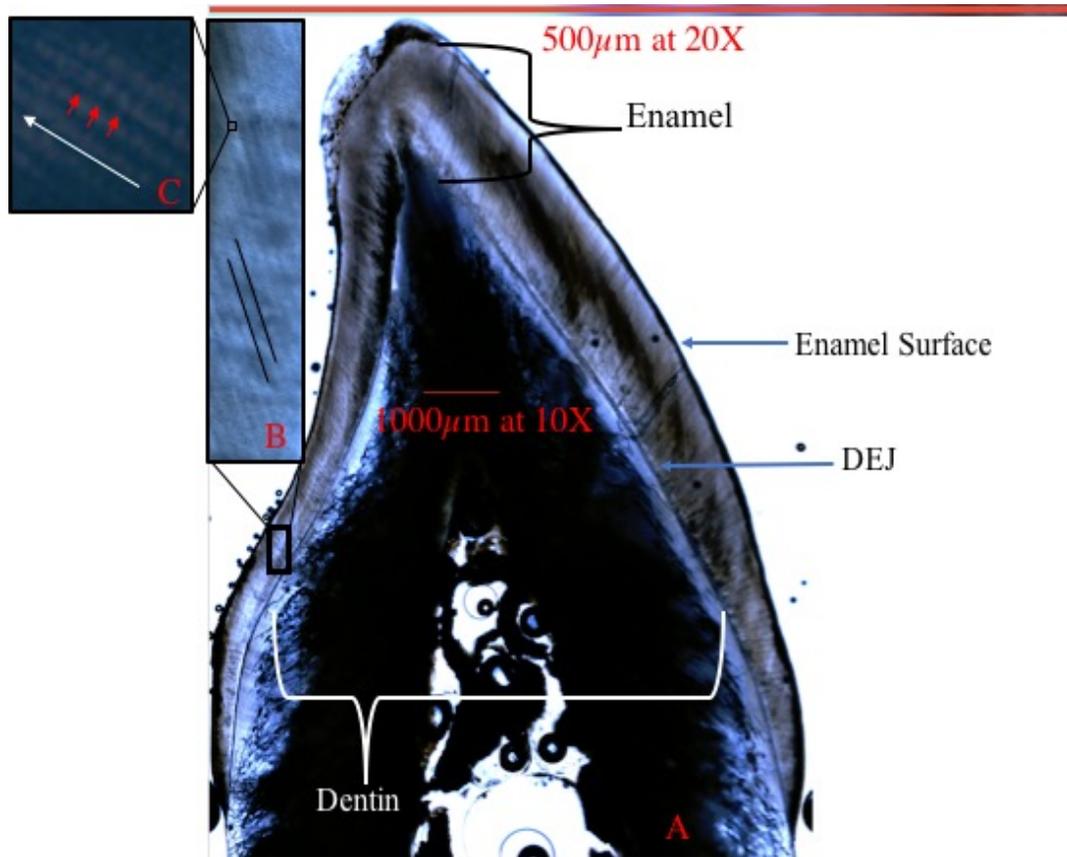
The overall morphology of tooth development is categorized macroscopically as the tooth progresses through the stages of crown initiation, crown completion, eruption, and apex closure (Hillson, 2014). Similar to external enamel, internal microstructures develop at uniform rates. Internal microstructures are formed in structures representative of long period and short period growth patterns. The internal enamel microstructures are comprised of cross-striations, enamel prisms, and striae of Retzius, which are visible under polarized light (see Figure 1). At the shortest period of traceable growth increments, cross-striations represent 24-hour intervals (Boyde, 1989; Smith and Tafforeau, 2008; Antoine et al., 2009). Cross-striations are folds of matured enamel

matrix observed along the longitudinal axis of each enamel prism (Nanci, 2017; Antoine et al., 2009). The incremental formation of enamel happens over repetitive increments of a 24-hour cycle and therefore is represent a circadian rhythm (Hastings et al., 1999). The hypothalamus is known to control mammalian biorhythms, and the hypothalamus production of melatonin is believed to control the circadian rhythm (Mirmiran et al., 1992; Ansari et al., 2009; Serón-Ferré et al., 2011, 2017). The cyclical formation of enamel additionally includes the more complex structures of striae of Retzius, which include a longer infradian biorhythm.

The near weekly biorhythm, between six to 12 days, in humans manifest as striae of Retzius lines, which appear as darkened lines running across the enamel prisms (Boyde, 1989; Reid and Ferrell, 2006; FitzGerald, 1998). The long-term growth intervals are present as band-like structures radiating around the tooth from the DEJ to the surface (see Figure 1). As the tooth structure curves, the striae bend to fit and stretch towards the enamel surface. At the surface of the tooth, the striae of Retzius manifest as perikymata (Hillson, 2014; Berkovitz et al., 2017). These microstructural growth increments provide a structure for precise measurements of growth intervals.

Striae of Retzius are not uniform throughout the tooth and vary by cuspal and lateral enamel location. At the cuspal margin, the lines surround the dentin tip and extend to the enamel surface. In the cervical portion, the striae stretch to the occlusal surface from the DEJ (Hillson, 2014). Formation of striae of Retzius falls within a week to 12 days, and the documentation of irregular striae represent metabolic stress between these days of enamel maturation (Berkovitz et al., 2017). Therefore, striae of Retzius may

identify irregular growth structures, or defects, caused by metabolic stress in the application of life history.



**Figure 1: Internal enamel microstructures observed in a canine thin section seen under polarized light. A represents the entire cuspal and lateral enamel taken at 10X. B represents the striae of Retzius with one onlined between the black lines taken at 20X. C shows incremental cross-striations indicated by red arrows and enamel prisms by a white arrow taken at 20X. The top red line represents 500µm at 20X while the smaller red bar within the dentin of image A represents 1000µm at 10X. Photo: Individual CWFS 27\_C. Image by E. Smith.**

Perikymata are the external enamel structures present along the surface of the tooth. Normal perikymata develop in wave-like structures, and the regularity of formation produces traceable chronologies. Within the crown, perikymata are spaced 50µm at the

cervical third, 70 $\mu$ m at the intermediate third, and 100 $\mu$ m at the occlusal third (Hillson and Bond, 1997). Formation standards of human perikymata were calculated from counting and measuring perikymata spacing and comparing with cross-sectional periodicity within striae (Reid and Dean, 2006).

Disturbances of growth along the enamel surface is termed enamel hypoplasia (Goodman and Rose, 1990). Enamel hypoplasia may form in furrow-form defects, plane-form defects, and pit-form defects, and furrow-types (Hillson and Bond, 1997). Early studies acknowledged that nutrition and infection caused enamel hypoplasia by impeding secretion by ameloblasts (Goodman and Rose, 1990). Currently, etiologies for enamel hypoplasia and accentuated striae include fever, infection, disease, malnutrition, diarrhea, congenital defects, and trauma (Goodman and Rose, 1991; Suckling, 1980; Suckling et al., 1986; Wolbach and Howe, 1933; May et al., 1993). Although these etiologies result in abnormal amelogenesis, the nonspecific stress indicators remain indistinct to the particular cause (Cares Henriquez and Oxenham, 2017; FitzGerald et al., 2006).

Bioarchaeology recognizes enamel hypoplasia as an indicator of metabolic stress. Linear enamel hypoplasia, or LEH, is commonly interpreted as a furrow-form defect covering the circumference of the tooth in a band. These furrow-form defects occur because of the function of ameloblast cells is hindered, and the disturbance of the enamel matrix secretion produces an irregular formation in perikymata (Hillson, 2014). These irregularities are identifiable due to the enamel matrix reduction for an interval outside of the standard rhythmic formation of perikymata (Hillson and Bond, 1997). As stated previously, these irregular formations may be correlated to illnesses and malnutrition, and

bioarchaeologists may infer association with a metabolic stress event (Hillson, 2014; Goodman and Rose, 1990; Temple, 2019). Therefore, bioarchaeology uses the prevalence of defects to reconstruct life histories of industrial, agricultural, and hunter-gatherer samples. For example, in urban populations of medieval Europe, increased access to nutritious resources outweighed the expense of living in more diseased locations and therefore drove down the frequency of LEH (Baten et al., 2019; Bereczki et al., 2019; Miskiewicz, 2015; Meinzer et al., 2019). Furthermore, the stress experience in transitioning to agriculture is highly variable between populations. In the transition from hunter-gatherer practices to wet rice agriculture in regions of Japan and Thailand, agriculture was noted to stabilize resource scarcity and reduce LEH frequency (Temple, 2010; Temple and Larsen, 2013; Pietrusewsky and Douglas, 2002), while other samples from the Dickenson Mounds of Illinois expressed a significant increase in stress after the transition to maize agriculture (Goodman et al., 1980; Goodman, 1989; Goodman et al., 1984b; Lallo and Rose, 1979). Lastly, in populations from the Jomon of Japan along with the Tigara from Point Hope Alaska, the comparison in prevalence of LEH indicated variation in infection and diet between the two populations (Temple et al., 2013). These studies used the prevalence of linear enamel hypoplasia to provide insight into different stress experiences in an array of socioecological settings.

Macroscopic investigation of LEH prevalence may be used to recognize variations in human stress experiences. Firstly, chronology of macroscopic LEH provides insight into the relationship between developmental milestones and metabolic stress. For example, the weaning process is a developmental milestone that may be reconstructed

due to the prevalence of linear enamel hypoplasias in early life chronologies (Moggi-Cecchi et al., 1994; Wood, 1996; Lanphear; 1990; Lilli, 1996). These chronologies outline the environmental availability or inability to access resources during the earliest years of development. Secondly, the periodicity of macroscopic LEH might illustrate metabolic stress in the ecological context. For instance, the periodicity of LEH in great apes was correlated to semi-annual rainy seasons in Africa, which were associated with increased levels of disease and malnutrition (Skinner, 1986; Skinner and Hopwood, 2004). These studies suggest the periodicity of stress events are representative of local ecological variation due to seasonality.

While these studies of macroscopic defects mentioned in the previous paragraph provide a foundation for the studies of linear enamel hypoplasia and stress experiences, identifying the presence of LEH by macroscopic methods fails to identify all LEH accurately. Microscopic methods find greater frequencies of individuals with LEH than macroscopic methods (Guatelli-Steinberg et al., 2003; King et al., 2005; Hassett, 2012; Temple et al., 2013). Macroscopic studies of LEH chronology and periodicity are additionally problematic. Striae of Retzius geometry is more acute in the occlusal third of tooth enamel, meaning that LEH in these regions is shallow and less well defined in the perikymata along the surface (Hillson and Bond, 1997; Guatelli-Steinberg et al., 2012). As a result, macroscopic methods may omit early forming LEH.

In an attempt to accurately define the presence of LEH and correct for problems associated with striae of Retzius geometry, microscopic studies of the enamel surface have been employed. These studies define LEH using objective definitions of accentuated

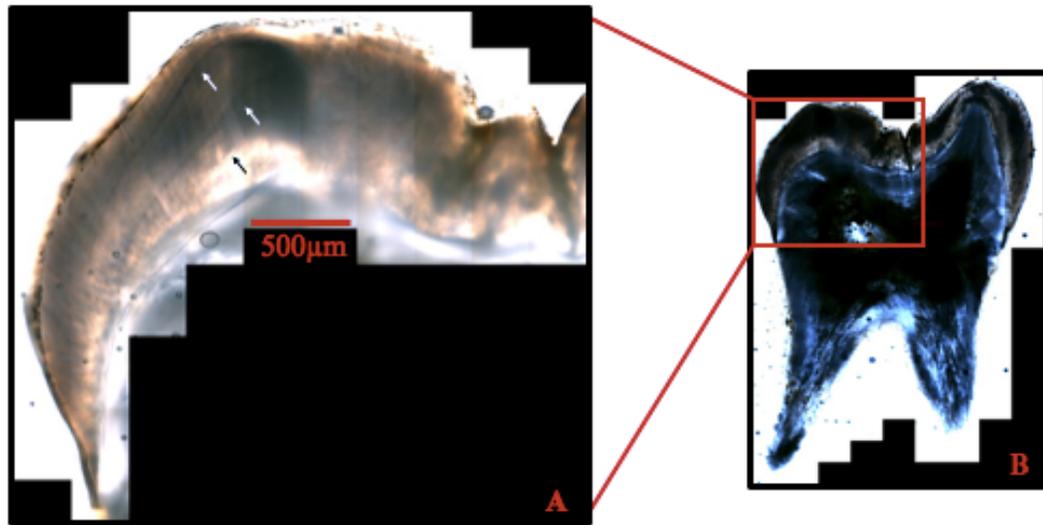
perikymata (Hillson and Jones, 1989; Hillson, 1992; King et al., 2002; Temple et al., 2012) as well as defining accentuated perikymata using z-scores or line fitting methods (Hassett, 2012, 2014; Bocaege and Hillson, 2016). These studies identify stress chronology and periodicity using perikymata counts (King et al., 2005; Temple 2014, 2016), and in some cases, match LEH to isotopic records to infer relationships between stress and infant feeding behavior (Temple, 2016, 2018, 2019; Sandberg et al., 2014; Humphrey et al., 2008b). In addition, questions surrounding adaptive plasticity, constraint, and the Osteological Paradox have been explored by microscopic analysis of LEH. For example, greater mortality risk is found among individuals with earlier forming LEH (King et al., 2005; Temple, 2014). Furthermore, the percentage of enamel disrupted by LEH is also associated with environment and survivorship in medieval London (King et al., 2005). These studies demonstrate that the use of incremental microstructures of enamel provide a method to reconstruct the relationships between stress chronologies, periodicities, and questions of infant feeding behavior, seasonal disruptions, and ultimately, mortality.

The problem with microscopic investigations of external enamel structures is that the approach relies on several assumptions. First, the work incorporates a generalized model of crown initiation and cuspal enamel formation times that were derived from select populations (e.g., Reid et al., 1998). Second, the work relies on modal periodicities derived from modern human perikymata (i.e., Reid and Dean, 2000, 2006; Reid and Ferrell, 2006), rather than identifying perikymata periodicities within each individual. Third, the work focuses on anterior teeth, which precludes the identification of growth

defects at earlier stages of the life cycle recorded in the first molar. As such, studies of LEH using the microscopic enamel surface represent an improvement over macroscopic methods, but still relies on a series of invalidated assumptions.

The internal surfaces of teeth provide more accurate and precise methods to identify growth disturbances, estimate the timing and periodicity of these events, and provide a contextual orientation for stress at the earliest stages of the life cycle.

Accentuated lines (AL) appear in enamel as darkened, enlarged striae that run between the DEJ and tooth surface parallel to striae of Retzius (see Figure 2). AL have been identified as "pathological striae" and differentiated from regular striae of Retzius for more than 50 years (Gustafson and Gustafson, 1967; Rose, 1977, 1979; Rose et al., 1978). The most common AL is the neonatal line (NNL), which forms at and after the time of birth, and is suggested to infer the stress event of birth (see Figure 2; Antione et al., 2009). Evidence for additional growth disruption, as ALs, may be assessed in reference to the NNL for precise chronologies (Hillson, 2014).



**Figure 2: Internal microstructures observed in a first molar thin section seen under polarized light. A represents the entire M1 taken at 10X. B represents the enamel at 20X. White arrows point to accentuated lines, while the black arrow points to the neonatal line. The red line in image A represents 500µm at 20X. Individual CWFS32\_M1. Image by E. Smith.**

Questions surrounding the deeper physiological etiology of ALs such as how timing impacts striae development have been explored, though no general consensus has been achieved (Fitzgerald and Saunders, 2005). Studies of primates with known life histories confirmed that ALs form in response to stress events. Chronology of AL formation in a gorilla was estimated by measuring cross-striation periodicity, which was achieved from estimating the timing between the AL and NNL (Schwartz et al., 2006). The results were consistent with hospital records documenting illness, injury, and psycho-social stress in the animal. A similar study was performed on a gorilla with a known age of capture (McGrath et al., 2019). The work found evidence of ALs that corresponded to the young age at which the animal was captured and sold to a zoo. Another study explored AL in two baboons of known age from the Awash National Park

in Ethiopia (Dirks et al., 2002). AL in these animals corresponded to periods of documented drought in the climatological record. These studies demonstrate that ALs are associated with stress events in the life history of primates and that the chronology of these events is possible to reconstruct using counts and measurements of enamel cross-striations.

Comparisons of AL chronology and weaning has been explored in baboons using microscopic and isotopic methods (Dirks et al., 2010). The work found elevated numbers of AL in one baboon during a period coinciding with a reduction in suckling, and in another case during the period associated with the cessation of breastfeeding. In a case study from St. Catherine's Island, increased frequencies of AL formation is found with the introduction of maize-based weaning products (Garland et al., 2018). These studies demonstrate that high levels of precision in reconstructing stress surrounding infant feeding behavior may be achieved when internal microstructures of enamel are combined with stable isotope analysis.

Questions surrounding life history trade-offs may also be explored using the chronology of AL and mortality. For example, individuals experiencing earlier forming AL in deciduous teeth were at an increased mortality risk than those individuals with later forming defects (Garland et al., 2016; Lorentz et al., 2019). Similarly, American Indians from the period of early Spanish colonization on St. Catherine's Island had elevated risks of mortality and future defect formation when ALs were identified at earlier stages of the life cycle (Garland, 2020). These internal microstructure results support findings of

earlier studies focused on relationships between mortality and early forming enamel defects using external microstructures (King et al., 2005; Temple, 2014).

Seasonal resource shortages are recorded in the periodicity of stress events. Times of drought, rainy seasons, or other climatic fluctuations play a role in the availability of resources (Macho, 2008). Identification of seasonal shortages in stress periodicities is important because reproductive characteristics and normal physiological function may be threatened during resource shortages (Martin et al., 2008). Repetitive intervals of AL may indicate seasonal fluctuations that affected resource availability or other selective pressures such as predation (Macho et al., 2003). These AL periodicities may identify extended periods of seasonality manifesting as seven month intervals, while shorter three to four month intervals reflect shorter seasonality (Macho et al., 2003). For example, the effect of rainfall seasonality on baboons was accompanied by AL events associated with life history events such as pregnancy, menarche, and childbirth (Dirks et al., 2002). In addition to these life history events, environmental factors such as drought and rainy seasons, and therefore resource scarcity, were suspect to cause AL events (Dirks et al., 2002). These conclusions were inferred due to the AL periodicity correlating to the semiannual rainy seasons and droughts from climatological records. Recording the rate of daily enamel secretion provides accurate data within an error margin of a week, therefore the periodicities recovered from internal enamel microstructures may accurately indicate seasonal fluctuations.

### ***Current Case Study***

Charterhouse Warren Farm Shaft (CWFS) will be analyzed with histological methods. As part of a larger project to reevaluate the individual life histories of those interned in the shaft, this histological analysis will accompany separate studies reevaluating the osteological remains. The thin sections of select dentition allow for reconstructing early life histories, including possible events of metabolic stress. As many of these individuals were subadults at time-of-death, the dentition may have recorded metabolic stress close to the time-of-death. This evidence will provide further understanding of the individuals' lived environment and cultural contexts. Previous analysis at the site of CWFS by Everton (1974) and Levitan et al. (1988) noted the individuals were placed in a natural shaft in a disarticulated state, with gnaw marks present on some bones. Modern reinvestigations noted the traumas on the skeletal material were from human modification from more than disarticulation practices, and the gnaw marks may have human origins (personal communication Schulting). The remains of 40 or more individuals were deposited in the shaft, probably as a single event or over a relatively brief period (personal communication Schulting). This reanalysis allows for a rediscovery of the possible metabolic stress endured by the CWFS individuals.

This current investigation looks at the internal microstructures of canines, first molars, second molars, and a third molar in a total of five individuals ( $n = 5$ ) and ten teeth. The internal enamel structures investigated include cross-striations and striae of Retzius. If present, periodicity and chronology of AL will be recorded. If preservation allows, then cross-striations measurements will produce ages-at-defect. For later analysis,

casts will be taken for external defects, including linear enamel hypoplasia. Analysis of the present stress chronologies will provide a window into the metabolic stress experienced by these individuals. In the individuals that perished with dental tissues forming around time-of-death, the cultural and environmental context preceding death may be further hypothesized.

While previous studies by Everton (1974) and Levitan et al. (1988) produced initial investigations of CWFS, this is the first published study to reanalyze the remains from a bioarchaeological perspective. Due to the nonnormative burial of the CWFS and prevalence of violence at time-of-death, this study questions how these individuals lived. This study seeks to investigate the prevalence, chronology, and periodicity of developmental stressors in the CWFS dentition. These nonspecific stress indicators may provide a differential diagnosis for metabolic stress. In investigating the cause of potential metabolic stress, both social and natural environmental stressors are investigated during the Early Bronze Age (EBA). The EBA in Britain experienced a shift in mortuary practice and the Beaker culture package diffusion (Barrett, 1988; Needham, 2005). Additionally, climate change during the EBA was recorded in continental Europe, raising the possibility of climatically-induced stress on the subsistence economy, although the impact in Britain is uncertain (Bond et al. 1997; Roland et al., 2013). If ALs are present, then chronologies and periodicities will aid in comprehending the socioecological factors impacting the CWFS individuals prior to violent death.

## CHAPTER 2: PREHISTORIC BRITAIN

### *Early Bronze Age Landscape in Britain*

Prehistoric Britain transitioned from foraging to farming in the Neolithic era (4000-2500 BC). Techniques for different subsistence strategies evolved in conjunction with societal changes. The British Neolithic developed monumental forms of architecture still seen today as Stonehenge, Skara Brae, and the Ring of Brodgar, to name a few. While the Neolithic was estimated to have around 50,000 individuals throughout Britain and Ireland, the Early Bronze Age (EBA) (2500-1950 BC) experienced a population growth to around 100,000 individuals (Roberts and Cox, 2003). While agriculture and sedentism were prevalent in the Early Neolithic (4000–3400 BC), the EBA was suggested to be more pastoral (Stevens and Fuller, 2012). Thus, biocultural adaptations to agriculture were not a linear development. Therefore, exploring mortuary practices, foodways, paleopathology, material cultural, and paleodemography, is critical in answering questions in the environmental and political climates in EBA Britain, including culture and warfare.

An ideal setting to study cultural practices and violence during EBA Britain is the site of the Charterhouse Warren Farm Shaft (CWFS) in England. The region of England, in the Mendip Hills, holds burials from the Late Upper Paleolithic to the Romano-British period, allowing for a full range study of funerary practices associated with the Bell

Beaker culture (2500-1800 BC), or Beaker culture for short. The Mendip Hills additionally holds the debated history at the Upper Paleolithic site of Gough's Cave (Bello et al., 2011, 2017). The CWFS site of EBA Britain joins additional sites in continental Europe that display violent episodes coinciding with warfare and potential evidence of cannibalism (Cáceres et al., 2007; Saladié and Rodríguez-Hidalgo, 2017; Santana et al., 2019; Villa et al., 1986). Concerning episodes of violence in prehistoric Mendip, the critical question emerges: were acts of cannibalism reflections of mortuary ritual, the rise of warfare, or some other form of violence entirely?

## **Foodways**

EBA Britain's agricultural foodways were the consequence of the continental European transformation from hunter-gatherers of the Early Neolithic to agriculturalists (Rowley-Conway, 2011). While hunter-gatherers still existed, domestication of cereals became prominent after the introduction to Britain around 4000 BC (Stevens and Fuller, 2015). Throughout the Neolithic and into the Bronze Age, cereal production rose and fell in relation to human population surges and reductions (Stevens and Fuller, 2015). The origins of British agriculture spread ultimately spread from southeastern Europe and the Near East, with more immediate origins from western France, and by 3500 BC the primary cereal in Scotland was barley (Parker Pearson, 2005; McLaren, 2000; Stevens and Fuller, 2015). Clear evidence around 4000 BC confirmed farming in the British Isles (Schulting, 2008; Parker Pearson, 2005). Early farming strategies varied by context in prehistoric Britain (Schulting, 2008).

The foodways in Britain from the Mesolithic, Neolithic, and EBA changed in a nonlinear process of intensification. Early Neolithic may have seen more intensive arable farming than the EBA, which was more extensive and potentially more focused on pastoralism (Stevens and Fuller, 2012, 2015). However, controversy remains as to the level of pastoralism practiced, and as contextual statements are argued for instead of general statements (Bishop, 2015). Controversies extend to the amount of domestication in the foodways of the Neolithic and EBA, and some cases included small amounts of hunted-game still incorporated in the diet (Schulting, 2008). The central sources in faunal exploitation were mainly of sheep/goat, pig, and cattle. Coastal resources were consumed at the lowest frequency, while cattle were consumed most frequently across samples (Jay and Richards, 2019). These traditions began with Neolithic farmers eating wheat and barley as the staple carbohydrates, while protein and fats came from animal meat, dairy, and blood (Parker Pearson, 2005; Schulting, 2008). Carbon and nitrogen isotopes found similar diets between 2500-1500 BC from present day England and Scotland (Jay and Richards, 2019). Furthermore, carbon and nitrogen isotopic data found possible gender-specific diets or possibly a continuously higher mobility rate in males (Jay and Richards, 2019). Lastly, while strontium and oxygen are more often used for mobility studies, dietary isotopes presented evidence for possible mobility patterns and distinctive diets during childhood compared to adulthood (Jay and Richards, 2019). These results were shown from a comparative analysis of dentition and skeletal isotopes, where dentition reconstructed childhood diet, and the skeleton reflected diet near time-at-death.

### *Early Bronze Age Beaker Traditions*

The discourse of prehistoric Britain bioarchaeology shares similar typological roots to the initial research of American physical anthropology. This typological approach told a story of invaders to Britain in an argument heavily rooted in colonial language. Initial osteological research of the Beaker people sought to label the groups as continental European versus individuals who were indigenous to Neolithic Britain as racial types. Similar to Morton's *Crania Americana* (1839), that claimed crania shape categorization of races, the works of Morant (1926), Thurnam (1864), and Abercromby (1912) used cranial measurements and artifacts to claim distinctly different races between the indigenous groups of Britain and continental Europeans. By the latter half of the twentieth century, scientists such as Brodie (1994) suggested that cranial deformation, culture, gene flow over time, and environment played a role in the differing cranial measurements between prehistoric Britain's populations, therefore discounting the argument for racial typologies. Most recently, the work of Olalde et al. (2018) found DNA evidence to support the Beaker people origin in continental Europe.

Recent investigation into the origins of Beaker culture in Britain further discouraged racial typologies emphasized by the early twentieth century scientists claiming that the Beaker people invaded and colonized Britain. Reinvestigations through skeletal tissue, dental tissues, and artifacts the Beaker People Project (BPP) and Beakers and Bodies Project (BBP) sought to comprehend the Beaker culture origin in Britain. The main component of BPP was the investigation of carbon, nitrogen, strontium, sulfur, and oxygen isotopes (Jay and Richards, 2019; Montgomery et al., 2019; Jay et al., 2019;

Pellegrini et al., 2019; Evans et al., 2012; Parker Pearson et al., 2016). By synthesizing data from both the dentition and skeletal tissues, isotopic reconstruction was possible for both the early life and adulthood. However, isotopic variation may not accurately indicate migrants, because of regional geological similarities or cultural practice enhancing oxygen levels in water (Pellegrini et al., 2019; Parker Pearson et al., 2016).

The interdisciplinary investigation BPP found that the British Beaker populations were mobile (Montgomery et al., 2019; Jay et al., 2019; Pellegrini et al., 2019; Parker Pearson et al., 2016). Similar to the continental European Beaker populations the British Beaker populations mobility covered small distances, and in the EBA over half the sampled individuals from Britain and Ireland exhibited some degree of mobility (Price, 2004; Montgomery et al., 2019; Jay et al., 2019; Parker Person et al., 2019). Specifically, in the EBA Britain, some individuals were possibly mobile around the Yorkshire region, where early life was spent in regions outside of the burial location in the Chalklands, and some adults buried in the Peak District preserved strontium isotopes suggesting possible early developmental origins in mainland Europe (Montgomery et al., 2019). These findings are uncertain with ongoing debate over the interpretations (Pouncett, 2020). Inversely, the DNA evidence informs that the genetic ancestry was predominantly continental European in population replacement (Olalde et al., 2018). Therefore, large-scale replacement and intermarriage continually spread the advantageous Beaker traditions and technology, which encouraged endurance of the culture throughout Bronze Age Britain (Olalde et al., 2018; Parker Pearson et al., 2019; Needham, 2007).

In addition to the isotopic analysis, artifacts provide insight into the traditions of the Beaker people in Britain. The Beaker culture was named from a type of grave good in the shape of a rounded beaker, which was used for funerary or food vessels. The Beaker culture in Britain is described as a ‘package’ emanating from mainland Europe which included different types of beaker pottery, gold, bronze, gendered mortuary treatment, different weaponry, fire starting kits, and sponge finger stones (Teather and Chamberlain, 2016; Needham, 1988, 2002, 2005). The Beaker pottery found in Britain is believed to originate from the Rhine region of Europe (Needham, 2005). Prior to the widespread use of Beaker pottery, the pottery prevalent in Neolithic Britain was variable, and sometimes made of a bone and clay composition in Groove Ware (Jones et al., 2019). Through chemical and microbotanical analysis of Britain funerary beakers, some beakers were believed to contain wheat ales or meads based on the herb and floral content (Rojo-Guerra et al., 2006). These alcoholic drinks placed in funerary contexts were hypothesized to aid the individual in the afterlife (Parker Pearson et al., 2019). Lipid presence additionally suggested dairy in some pots (Mukherjee and Evershed, 2007).

Further EBA traditions of hunting or violence were represented in weaponry grave goods included spearheads, axes, daggers, halberds, wristguards, and other tools used to sharpen these implements (Needham, 1988). Wristguards from Beaker burials were a funerary symbol that represented a tool, sometimes leather commonly used to protect archers’ arms while shooting (Ryan et al., 2018). Weaponry grave goods, such as these, were associated with male graves (Needham, 2010; Treherne, 1995). The male gendered Beaker burials included items such as these and battle axes, normally a single

disposition, indicating the idealized staging of male character in death (Treherne, 1995). These artifacts collective in a warrior ideal in the mortuary practice were absent in the Early Neolithic and significant during the Beaker period, while an argument for the violence necessitating an elite warrior class in EBA Britain is unclear (Schulting, 2013).

Besides bronze, other metals and mineraloids present as grave goods, such as gold and jet, give insight into the economic systems of the Beaker population in Britain. Presence of jet and jet-like materials was previously common in the Middle Neolithic (Gibson, 2019). Jet artifacts reemerged in the EBA as bead and button artifacts, while other buttons that preserved were also made from chalk and amber (Harding and Healy, 2007). Gold artifacts were present at jewelry such as earrings, beads, necklaces, armbands, hair accessories, and more (Harding and Healy, 2007; Sheridan, 2015). Precious items such as these may be traced due to artistic variations for evidence of trade between Britain, Ireland, and continental Europe (Sheridan, 2015). The presence of these rarer materials may have implied these individual burials under round barrows were possibly of high socioeconomic status (Teather and Chamberlain, 2016; Jones, 2008). The increase in the Beaker people utilizing precious materials illuminates the growing economy and mortuary practice transitions of the Bronze Age.

### **Mortuary Analysis**

Bioarchaeology increasingly recognizes the value of mortuary contexts which often represent the social perception of the mourners. Grave goods and mortuary

treatment are reflective of the mourners' perspective of the deceased (Parker Pearson, 1982; Barrett, 1990; Sofaer, 2006). Not only is the perception of burial reflective of social ideals, but the time and labor expended on the mortuary practice are additionally reflective of social memory. The mourners' relationship with the deceased plays a role in the mortuary treatment, where sometimes higher-status individuals display symbols of higher social status. Preservation also plays a part in the investigation of the elite burials, which tend to preserve better than the lower status burials (Knüsel and Smith, 2014). The many hours of labor leading to the deposition event may conclude with additional rituals such as feasts, sacrifice, and gatherings (Barrett, 1990). Additionally, the perception of labor in place for these mortuary monuments was seen as a veneration to the ancestors (Barrett, 1990; Mullin, 2001).

The mortuary treatment of individuals from the Late Neolithic and EBA involved the construction and use of large-scale mortuary monuments. The earliest mortuary monuments in Britain were long barrows and chambered tombs, with examples dating to ca. 3700 BC and the earlier at Coldrum, Kent (ca. 3900 BC) (Bayliss and Whittle, 2007; Wysocki et al., 2013). From this point, the prehistory of burials in Britain followed a nonlinear sequence of long barrows, round mounds, and finally, cremation burials. For example, cremation was prevalent during the Bronze Age around 1650 cal. BC, however cremation was previously prevalent during the Late Neolithic, such as the example at Stonehenge (Appleby, 2013; Barrett, 1990; Willis et al., 2016). Long barrows were prevalent in the Early Neolithic and the internal assemblages comprised of multiple disarticulated individuals organized by either element or age, and limited grave goods,

which differed from the EBA round mounds that consisted of single graves, mortuary goods, and cremations (Jones, 2008; Barrett, 1990). During the EBA, the round barrow was the most common burial monument, especially in southern England, however irregular and trapezoid monuments also occurred (Mullin, 2001; Barrett, 1990; Parker Pearson, 2005). The earliest round burial mound dates to around 2000 BC (Barrett, 1990). Inhumations were common during the EBA, with a slow switch to predominantly cremation towards the end of the period and into the MBA (Appleby, 2013). From the normative and non-normative burials, further insight into the prehistory of Britain may be drawn.

The important distinction of the single inhumations in the EBA was the transition away from the multiple burials of many disarticulated bodies, thus emphasis was on the singular person. Therefore, some archaeologists argue the transition symbolizes a political adjustment to highlight the elite few, specifically perception of ancestral rights transitioned from burying multiple individuals by elements for construction of an accumulated ancestral spirit to the importance of ancestral spirit persisting in selected individuals (Shennan, 1982; Jones, 2008). However, instance of multiple burials, disarticulated assemblages, and cremations also occurred in EBA Britain (Lucas, 1996; Petersen, 1972; Mizoguchi, 1993). Disarticulated assemblages sometimes included the process of excarnation, or defleshing via natural taphonomic processes and may be aided by human modification. Possible presence of excarnation was identified in an EBA to Middle Bronze Age burial in Scotland, where the majority of individuals within the cemetery were cremated, and a single cranial fragment depicted perimortem cut marks

that may have been evidence of defleshing prior to cremation (Cressey and Sheridan, 2003). Additional evidence for disarticulation in EBA burials was recognized in the Boscombe Bowmen graves where disarticulated individuals appeared between 2400 to 2310 BC (Barclay and Marshall, 2011). These different mortuary practices reflect diverse social performances.

Beyond inhumations, the common practices of social memory in the Bronze Age included the reuse of persistent landscapes (Lucas, 1996). The Mound of the Hostages at Tara in Ireland was a single megalithic passage tomb used during the Middle Neolithic. Then after a period of discontinued mortuary use, the site was again used for burials in the EBA (1900 cal. BC) (Quinn, 2015). During both periods, the burial goods suggested possible elite interments (Quinn, 2015). The question remains: why would individuals reuse a site with previous burial deposits? The re-use of Neolithic megalithic tombs in the EBA occurred across Ireland as a broader set of practices (Schulting et al., 2012). The case of Tara was highly visible on the landscape with a built tomb, while the use of in mortuary practices caves may differ in interpretations.

Mortuary practices had dualistic relationships between the natural and built landscapes (Mullin, 2001; Barnatt and Edmonds, 2002). Bronze Age barrow builders built funerary landscapes to mirror natural mounds and hills. By shaping the land with human-made features, the mourners preserved the impact of decedent lives in a tribute that became part of the natural and spiritual world, similar to an organic feature (Mullin, 2001). The human-made monument represented a connection with the human ancestors and, therefore, an association with ritualized belief and behavior (Mullin, 2001). By

placing burials in the mounds, the deceased entered the dualistic relationship of the organic and spiritual worlds (Barnatt and Edmonds, 2002). The inorganic geographic landscape also influenced Bronze Age barrow builders. Landscapes with Neolithic architecture, such as henges, attracted round barrows, and other burial monuments as a part of the dualistic relationship between the built and natural burial monuments, such as the persistent burial monument of Tara in Ireland (Mullin, 2001; Quinn, 2015). Furthermore, natural landscapes influence burial practices with the use of caves or shafts topographies, as depicted at CWFS.

In the construction of burial monuments and other mortuary practices, social memory played an essential role. Living descendants employ social memory for active participation of the dead in the living culture (Jones, 2008). Evidence for kinship ties and burials of the ancestors is proven from DNA analysis suggesting familial groups were buried within the same mortuary grounds and between sites during the EBA (Sheridan, 2008). Memory was active by mourners preserving tradition and social relationships in barrows (Mullin, 2001). The built architecture of a burial monument preserved the memory, stories, influence, and culture of the ancestral lives (Mullin, 2001). By building a monument into the landscape, the human ancestors were respected, remembered, and part of social memory (Mullin, 2001). In the EBA emphasized funerary rites for specific individuals reflect the remembrance placed on the individual rather than the communal ancestors (Barrett, 1988).

Veneration of the ancestors and social memory included the mourners in tributes through physical acts of moving and reorientation of the dead. This act instilled

remembrance in the living and consequently gave the ancestors an active spirit and agency (Mullin, 2001; Jones, 2008). For example, from the Neolithic, long barrows included both disarticulated and articulated individuals, while the chambered tombs included disarticulated individuals. The long barrows were normally inaccessible while the chambered tombs had open access for the living to enter. The access allowed for mourner accessibility to the dead, which influenced the social memory (Jones, 2008). While the enclosed burial preserved the memory of the deceased at time-of-death, these burial monuments invoked social memory of the ancestors in either fixed remembrance or transformative through later processing. Therefore, the single burials of the Bronze Age were chosen within round barrow cemeteries as a representation of status, placing memory and importance of these elite few.

### ***Early Bronze Age Violence in Britain***

Violence is the deliberate action intended to inflict injury or death. The archaeological record documents violence through attacks on sites, the presence of weaponry, and paleopathological evidence involving perimortem and antemortem trauma. Bioarchaeology relies on context for evidence of violence expressed as antemortem and perimortem trauma as healed violent experiences, and perimortem trauma happens as possible cause-of-death and funerary practices (Knüsel and Smith, 2014). Bioarchaeologists recognize mass graves as a burial of mass casualties from a relative time, which are placed next to one another or in a disorganized pit (Haglund et

al., 2001). Furthermore, mass graves may be produced by violent episodes rendering multiple individuals simultaneously dead (Skinner, 1987).

Warfare entails large-scale, structured violence and aggression backed by political sponsorship (Monks and Osgood, 2000; Knüsel and Smith, 2014). War is organized. Violence becomes warfare when two or more political entities sponsor the events. Feuds fail to classify as warfare because warfare relies on the motive of harming nonspecific individuals of a group while feuds target individuals and relations (Fry, 2007). Due to the impact of violence, defense becomes a strategy to counter violence. Defense mechanisms to warfare may be in the form of material culture such as shields or protective architecture. Rationales for warfare mainly ensue through resource protection and procurement, but may also arise in social relations, which include the exchange of these resources.

Resource scarcity, derived from climate change persistently overwhelming sociopolitical systems, may result in violence (Harrod and Martin, 2014; Salehyan, 2008; Ember and Ember, 1992). In the example of Central California, conflict identified as warfare occurred on occasion between 3000 BC and 1700 AD, which included dismemberment and trophy-taking. The argument by Andrushko et al. (2010) explained that the episodic violence was reliant on the population density, while other discourses proclaimed violence dependent on climatic changes, such as drought (Walker, 2001; Allen et al., 2016). However, violence is not environmentally deterministic. The work of Bartelink et al. (2019) countered that drastic climatic shifts were not the sole cause of violence. The prehistoric populations in Northern California practiced flexibility in the

diet, and therefore climatic changes may not always have consequent violent encounters. However, the social relations of migrants with differing traditions and behaviors may account for violence in this context (Bartelink et al., 2019). The complementary work of Harrod and Martin (2014) found that populations with greater socioecological flexibility had reduced violence during drought in the prehistoric American Southwest. Bartelink et al. (2019) along with Harrod and Martin (2014) support the synopsis of Hegmon et al. (2008), that similarly reported accounts of resilience theory, where populations that did not experience drastic transformation (i.e., had greater flexibility to challenges) also did not experience elevated violence.

Similarly, the level of active violence speaks to the culture, lived environment, and political ecology of the earlier British inhabitants. From the Mesolithic (around 9000 BC) and extending into the EBA, Britain experienced periods of violence in geographically isolated outbreaks (Schulting and Fibiger, 2012). The Neolithic violent episodes across Europe, which were intermittent, were evident from cranial fractures delivered by weapons such as stone maces (Knüsel and Smith, 2014; Schulting and Fibiger, 2012; Smith, 2013). The skeletal record of Neolithic Britain expressed violence present in 5-10% of individuals (Schulting and Wysocki, 2005; Smith, 2013). Furthermore, the inclusion of weaponry as cultural goods promoted the argument for the social acceptance of violence and defense tactics (Schulting and Fibiger, 2012). Additionally, the presence of defensive architecture coinciding with evidence for attacks, such as littering of arrowheads and fires, further implied that the experienced violence was of a scale beyond feuding (Mercer et al., 2008; Mercer, 1999). The case of

Hambleton Hill may be one of the defense strategies of the Neolithic in the form of a hill fort, that the scale of the causewayed enclosures suggested some evidence for warfare (Osgood, 2000; Mercer, 1985). Evidence of timber burning, arrowheads, and osteological confirmation expressed that the Neolithic occupation of the hillfort experienced episodic violent attacks (Mercer, 1985; Bayliss et al., 2008). The violent outbursts at Hambleton Hill coincide with evidence of increased episodic violence in Neolithic Britain around ca. 3700-3500 BC, which may have resulted from environmental or economic grounds (Bayliss et al., 2008). Therefore, warfare is suggested to have begun in some fashion during Neolithic Britain, while less skeletal indicators of violent trauma during the EBA possibly infer lower levels of warfare (Smith, 2013; Schulting, 2013).

Compared to Early Neolithic, the Early Bronze Age in Britain provided relatively limited evidence for violence. Both Neolithic and EBA Britain had weaponry, such as the bow and arrow combination. However, the EBA arrowheads were very finely made, with barbed and tanged edges rendering extraction difficult (Cressey and Sheridan, 2013). Other EBA weaponry included copper/bronze daggers, hafted stone axes, and wooden clubs, halberds, and spearheads (Needham, 1988; Schulting et al., 2013). The use of weapons like axes and clubs were more likely used in hand to hand combat because of the effectiveness (Schulting et al. 2013). In Britain, the Middle and Late Bronze Age saw more evidence for weapon hoards, placed as offerings into bogs, lakes, and rivers, that may suggest a higher necessity of weapons and warfare compared to the EBA (Needham, 1988; Mörtz, 2018).

An example of warfare in the EBA was the site of Tollense Valley in modern Germany (Brinker et al., 2014). These individuals died during a single violent event that scattered human remains along a riverside. Perimortem wounds on the individuals suggest that the individuals participated in hand-to-hand combat and injury by long-range weaponry (Brinker et al., 2014). Isotopic evidence suggests the presence of both local people and outsiders (Price et al., 2019). This example of deaths by armed conflict provides evidence for potential warfare on continental Europe, during the EBA.

### ***Cannibalism.***

Cannibalism appears to be a rare human behavior throughout British prehistory. However, the presence of cannibalism in Britain may be compared to overall trends in human violence, mortuary practice, and anthropophagy. Human cannibalism is defined as an individual consuming human tissue, including auto-cannibalism. Many other species participate in cannibalism, and although humans will hunt other humans, rarely is the victim consumed as food. Types of cannibalism include ritualistic, revenge, gustatory, and survival cannibalism, and may be further classified as either exocannibalism, endocannibalism, and self-cannibalism (Flinn et al., 1976).

Exocannibalism refers to the process of consuming individuals from outside of the group, which may happen in settings of warfare. Endocannibalism refers to the consumption of flesh from individuals within the same social group, which may include kin. Gastronomic cannibalism stems from the lack of subsistence resources, which results in either exocannibalism or endocannibalism. When describing the motivation for

ingesting human flesh as gastronomic or caloric, White (1992) argued that all forms of cannibalism are caloric because human tissue is ingested.

Historical accounts of cannibalism and modern controversies shaped the study of cannibalism. Previous anthropological accounts, those such as Arens (1979), attempted to understand cannibalism while still alienating the practice as enigmatic. These approaches bear remnants of European colonialism where justification of exploiting marginalized peoples partly came through a narrative of “savages” who engaged in cannibalism. An example is the accounts from Columbus describing cannibalism in the New World to justify Spanish exploitation of indigenous peoples (Keegan, 2015). Furthermore, cannibalism is fetishized and sensationalized by anthropologists failing to consider interpretations other than cannibalism. For example, defleshing practices may be attributed to mortuary practice and not consumption (Martin, 2016). Historically, cannibalism was placed on the linear scale of civilizations, where cannibalism was practiced in societies of ‘limited’ development. Cannibalism was tied to societies of lesser hierarchical scale because consumption of human flesh was perceived as an early developmental phase of society in the linear approach (Arens, 1979). Since cannibalism was socially taboo, and specifically used to promote industrial capitalist societies, cannibalism was further classed as an early societal stage.

Presently, bioarchaeology considers multiple skeletal indicators for cannibalism. Postmortem modification to human remains such as cut marks, marrow extraction, burning from probable cooking, and discarding with faunal remains are all indicators of probable cannibalism (Villa et al., 1986). This evidence was meant to classify human

remains as similar disposal to that of other vertebrates into middens. Further diagnosis recognizes cooking as pot polish or burning, and anvil damage, and butchery patterns in cut marks, spiral fractures, crushing vertebra, or greenstick fractures as intentional opening of marrow cavities (Turner and Morris, 1970; Turner, 1983; Turner and Turner, 1992). The problem with identifying cannibalism in prehistoric contexts is the lack of specific differential diagnosis for cannibalism (Martin, 2016).

Controversy has long followed the topic of cannibalism (Martin, 2016). Violence creates fractures, disarticulations, and cut marks without the intent to cannibalize. Violence generates chaotic events that display many of the same skeletal indicators similar to the deliberate defleshing in cannibalistic behavior. Although violent injury normally appears around the body in less patterned behaviors. Bodily mutilations are common in executions, massacres, and warfare, consequently the misinterpretation of burning or dismemberment is common. Other ritualistic mortuary practices or defleshing and disarticulation may form similar diagnostics traits in the skeleton. Therefore, the identification of cannibalism is difficult and sometimes impossible without definite differential diagnosis.

An example of a controversial case of cannibalism involved the debate over the mass grave victims at Herxheim, Germany (Orschiedt and Noel Haidle, 2012). These Linear Pottery Culture individuals from the Early Neolithic provided an example of a discussion surrounding an MNI of 450 possible cannibalism victims (Orschiedt and Noel Haidle, 2012; Boulestin et al., 2009). Since some of the skeletal material was absent, the likelihood of the assemblage being a secondary burial was high (Orschiedt and Noel

Haidle, 2012). While the individuals exhibit some gnawing, burning, defleshing, and disarticulation, some of this evidence may relate to ritualized mortuary processing of dead bodies or ritualized cannibalism (Orschiedt and Noel Haidle, 2012; Boulestin et al., 2009). Additionally, the perimortem cranial fractures may have been attributed to practices intended for creating a skull cap and not brain extraction for consumption (Orschiedt and Noel Haidle, 2012). The heating of the remains does not exhibit lengthy periods of cooking but only heating, and differentially diagnosed for the gnaw marks were debated as human or another mammal in origin (Orschiedt and Noel Haidle, 2012). However, exposure of marrow cavities and processing similar to faunal butchery patterns provide evidence for cannibalism (Boulestin et al., 2009). Today, the Herxheim individuals remain central in the animated debate on whether a unique form of mortuary practice or cannibalism occurred.

In cases of near definite evidence for differential diagnosis of cannibalism comes from the further investigation of the prehistoric Anasazi site at Cowboy Wash, Colorado, originally investigated by Turner and Turner (1999). To bolster the argument for cannibalism, which was previously stated due to osteological evidence of butchery marks, disarticulation, and possible cooking of seven individuals, a biochemical investigation sought to determine the composition of a human coprolite found at the site. The site was abandoned and burnt, with the coprolite found within the ashes of a hearth. The coprolite was examined for myoglobin, which is a protein found in the tissues of human connective tissues of the skeleton and muscle (Marlar et al., 2000). These tissues would only enter the digestive system if ingested. Additional evidence was sought from

the butchery implements and sherds of cookware found at the site, which all contained evidence for human tissues associated with butchery and consumption behaviors (Marlar et al., 2000). The addition of biochemical reconstruction of the cooking, butchery, and consumption practices at the Cowboy Wash site allows for near definite differential diagnosis of cannibalism and is an important example for scientific collaboration in the diagnosis of cannibalism.

### **Upper Paleolithic Cannibalism in Mendip, England**

The most well-documented example of probable cannibalism in southern England is Gough's Cave. Dated to the Upper Paleolithic (12,700 BC), the cave assemblage is associated with the Magdalenian culture based on artifact typologies. Human processing was evident in the appendicular skeletal remains (Bello et al., 2011, 2015). Similar to CWFS, Gough's Cave is in Somerset, England. The cave lies in a region close to Cheddar Gorge (Bello et al., 2015). The artifacts included butchered faunal remains, antlers, ivory, flint, and amber. The environmental context for this period in the Mendip Hills was still within the Lateglacial Interstadial period (Bello et al., 2015). Hunted fauna associated with this climate included arctic fox and ptarmigan (Bello et al., 2015). The diet was associated with hunting tundra and forested landscapes, with the site having a prevalence of aurochs, horse, and deer (Stevens et al., 2010; Richards et al., 2000).

The human remains excavated from Gough's Cave associated with probable cannibalism were deposits of fragmentary appendicular bone and neurocranium (Bello et al., 2015). With a minimum number of (MNI) of six individuals, the archaeologists

hypothesized the remains were from three adults and three preadults. The neurocranium fragments had evidence of human postmortem processing to produce skull modifications as likely skull-cups. In addition to the cut marks and fragmentation, eight fragmentary remains displayed human gnaw marks. The processing of the remains prior to burial was suggested as evidence for cannibalism. However, there was a debate about the type of activity as either endocannibalism or exocannibalism. Due to the small group number and internment method, cannibalism was suggested, in this case, to be a part of Magdalenian normative burial practice. Further taphonomic and other methods of inquiry were required to understand if cannibalism took place for gastronomic or ritualistic motives.

### ***Possible Cannibalism at Charterhouse Warren Farm Shaft***

Within the Mendip Hills of Somerset, England, Charterhouse Warren Farm Shaft (CWFS) has been dated to the EBA, with the human remains recovered from the entrance shaft dating to 2200-2000 cal BC (Levitan et al., 1988; Schulting personal communication). Considering the background given about the EBA and the materials discussed in the subsequent chapter, the CWFS individuals were members of the EBA Britain and likely participants in the Beaker culture. As described above, the EBA in Somerset practiced pastoralism with a change in mortuary practice when compared to the Neolithic era.

The normative EBA burial in Britain consisted of round barrows. However, the burial of CWFS falls under a non-normative burial practice for the time as the individuals were deposited within a shaft (Levitan et al., 1988). The normative round barrow burial

monuments were built landscapes, however this site used a naturally forming shaft. The CWFS grave goods were customary for the Beaker culture in the instance of single or double burial, but nonnormative for over forty individuals. The burial of this large group of individuals aligns with patterns of a mass grave, which additionally indicate violence. Lastly, the evidence of postmortem processing and disarticulated condition of human remains furthers the argument for a nonnormative burial.

Evidence for violence and systematic processing of the human remains at CWFS further demonstrates the uniqueness of the site. EBA Britain has limited accounts of violence in the bioarchaeological record (Thorpe, 2019). However, the osteological reevaluation of the CWFS individuals suggested violence. The CWFS individuals were originally believed to have canid gnawing marks, but reanalysis question whether the gnaw marks were from human teeth (Levitan et al., 1988; Schulting personal communication). Reanalysis of the human remains found several other modifications as evidence of treatment before the secondary burial. Postmortem manipulations of the remains included spiral fractures of long bones, cut marks from stone tools throughout skeletal elements, mineral staining, and gnaw marks, while cranial fractures were evidence for perimortem trauma and probably cause of death (see Figures 3-9). These modifications are characteristic of gastronomic processing, cranial trauma, beheading, and scalping (Schulting personal communication).



**Figure 3: Spiral fracture on humerus.**  
(Image courtesy of R. Schulting; image by I. Cartwright)



**Figure 4: Mineral staining and abnormal breakage on distal femora.**  
(Image courtesy of R. Schulting; image by I. Cartwright)



**Figure 5: Cut marks on cervical vertebra.**  
(Image courtesy of R. Schulting; image by I. Cartwright)



**Figure 6: Cut marks on posterior mandible.**  
(Image courtesy of R. Schulting; image by I. Cartwright)



**Figure 7: Cranial blunt force trauma.**  
(Image courtesy of R. Schulting; image by I. Cartwright)



**Figure 8: Cut marks across left frontal bone with mineral staining.**  
The right frontal bone, not shown in this photo, exhibited blunt force trauma.  
(Image courtesy of R. Schulting; image by I. Cartwright)



**Figure 9: Possible gnaw marks on metatarsal bones.**  
(Image courtesy of R. Schulting, taken by I. Cartwright)

The conditions surrounding burial, perimortem, and postmortem treatment of the remains at CWFS may be consistent with violent death and possible cannibalism. The goal of this study is to use internal structures of enamel to reconstruct the early life environment in individuals who experienced violent death at CWFS. The objective is to understand if this environment was characterized by resource dearth, or alternately, reduced frequencies of growth disruption. The climatic context for EBA continental Europe included the ‘4.2ka event’ (Bond et al. 1997), which coincided with the disposal of human remains at CWFS. However, the impact in Britain remains debated (Roland et al., 2013). This study seeks to investigate possible stress events correlated to climatic and social causes of potential adverse conditions prior to violent death.

## CHAPTER 3: MATERIALS, METHODS, AND ETHICAL CONSIDERATIONS

### *Charterhouse Warren Farm Shaft Background*

The site of Charterhouse Warren Farm Shaft (CWFS) is located in the Mendip Hills of Somerset, England (see Figure 10). This region is famous for carboniferous limestone geology which, through erosion, created hollow deposits for caves and depressions that were used for prehistoric inhumations (Lewis, 2000). The caves and shafts which cover the Mendip region are made of sedimentary rocks highly susceptible to water erosion. The porous nature of the bedrock, or karst landscape, creates hollow underground passageways for water drainage throughout Mendip (Lewis, 2000).



Figure 10: Charterhouse Warren Farm Shaft in Somerset, UK (Google Earth, 2020)

Located in the Velvet Bottom region of Mendip, the CWFS naturally extends around 22m deep into the limestone (Levitan et al., 1988). The archaeological and geological excavations examine the entrance shaft, of 22m, in four horizons (Levitan et al., 1988). While the cave system includes adjacent passage of chambers, which extend roughly 45m deep that contained Late Neolithic faunal remains and an Iron Age human bone, will not be addressed in this thesis. Only the entrance shaft will be described. Within the entrance shaft, the deposits of material culture and human remains were separated into four horizons. Previous investigations found that the depositional event was either single or multiple deposit events relatively close in time (personal communication Schulting. Faunal remains in Horizon 1 were dated to 1610-1440 BC, while the human remains from Horizons 2 and 4 were dated to 2200-2000 cal BC.

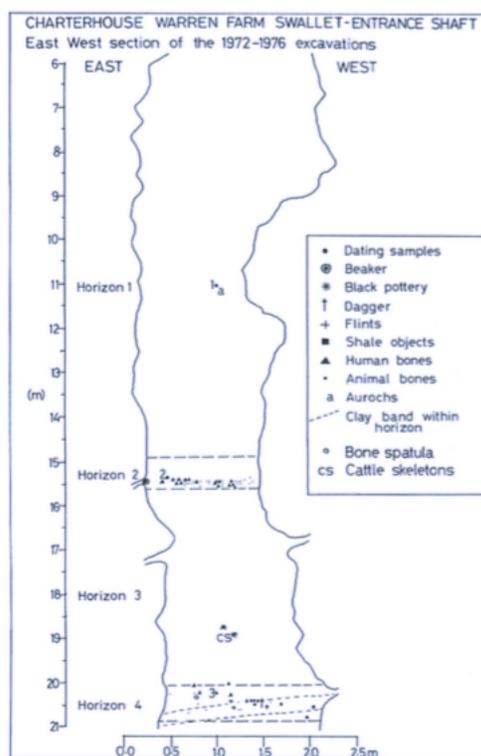


Figure 11: Horizons 1-4 and contents from the Entrance Shaft. (Levitan et al., 1988)

As depicted in Figure 11, Horizon 1 includes boulders and butchered aurochs remains from meters -6 to -14.9 (Levitan et al., 1988). Horizon 2, the focus of this thesis and sometimes termed the Beaker Layer, is located between -14.9 and -15.6 meters. The Beaker Layer is named for a single intact beaker placed along the shaft wall with a comingled human bone assemblage (see Figure 12). The human remains from Horizon 2 have been dated to ca. 2200-2000 cal BC (Schulting personal communication). Horizon 3 is located between -15.6 and -20.05 meters and includes some faunal bones, pottery, and stones (Levitan et al., 1988). Lastly, Horizon 4 extended to a depth of -20.05 to -20.79 meters and included human remains buried with artifacts.



**Figure 12: Decorated beaker from Horizon 2. (Levitan et al., 1988)**

Horizon 1 encompassed aurochs remains with human modifications, such as cut marks (Levitan et al., 1988). The aurochs remains in Horizon 1 are important because this type of Bovidae megafauna is known to decline around the Bronze Age. Dated to 1610–1440 BC, these aurochs are the latest dated in Britain. The presence of these animal remains in Somerset during the Early Bronze Age aids in the documentation of the aurochs extinction timeline.

Horizon 2, or the Beaker Layer, included a minimum number of 43 individuals, including males, females, and subadults (Schulting personal communication). The individuals date to ca. 2200-2000 cal BC, and provide evidence for violent death and possible cannibalism. The beaker placed with the individuals was intact and positioned on a natural protuberance at the shaft edge (Lewis, 2000). The unbroken preservation of the beaker indicates deliberate placement and lowering of into the shaft. This type of

beaker artifact was common in Britain during the Beaker period. Faunal remains were additionally recovered from this horizon. Horizon 3 provided more faunal remains and pottery sherds.

Horizon 4 contained additional artifacts, and few neonatal human remains possibly all from the same individual, with no evidence of cuts or processing. The stone artifacts deposited in Horizon 4 include a flint dagger, sponge finger stones, flint scrapers, and quartzite hammerstones (Levitan et al., 1988). Sponge finger stones were tools conceivably used for hide production, and the five from CWFS are currently the most recovered from a single site (Harding and Healy, 2007; Parker Pearson et al., 2019; Lewis, 2011). Manufactured items included a small pottery vessel, bone pin, and bone spatula, while natural items throughout the entrance shaft were non-local boulders (Levitan et al., 1988). The presence of non-local boulders in the entrance shaft furthered the argument for deliberate placement of grave goods (Lewis, 2000).

### **The Skeletal Sample**

All skeletal and dental material was retrieved from the CWFS during separate excavations sporadically between 1972-1986 (Everton, 1974; Everton, 1975; Everton and Everton, 1977; Levitan et al., 1988; Lewis, 2000). Mendip locals discovered the entrance shaft in 1968 as the top of the entrance shaft notably drained the region when the land substantially flooded (Everton, 1974; Levitan et al., 1988). The University of Bristol, UK and the associated Spelaeological Society undertook multiple excavations of the shaft.

While initial inquiries included geological research, the artifacts and remains recovered from the CWFS were also included in the 1972-1986 excavations.

The initial archaeological studies on the CWFS focused on material culture and geology. This thesis project is a part of a larger bioarchaeological and osteoarchaeological reassessment of the bone assemblage. When the individuals were first excavated, the first notations on the individuals stated that assemblage had evidence for disarticulation prior to placement within the shaft (Everton, 1974). Later investigation identified cut marks and potential butchery patterns (Levitan et al., 1988). The present and collaborative investigations seek to reconstruct individual life histories through analysis of diet, geochemical origin, low temperature heating patterns, carbon dating, and metabolic stress. The goal of these inquiries is to provide further insight into the lived experiences of these individuals prior to violent death.

### ***Materials***

The entire skeletal assemblage of CWFS has a minimum number of individual (MNI) of approximately 43 adult males, adult females, and subadults (Schulting personal communication). All individuals included in this study were recovered from the same shaft in a comingled state and vary in age-at-death from a range of eight to 15 years (see Table 1, see appendix Table 5 for detailed table). The teeth incorporated in this study were selected because of limited wear and acceptable preservation for histological methods.

**Table 1: CWFS Age-At-Death in Years**

| <b>Catalogue Number</b>                 | <b>CWFS 5423</b>  | <b>CWFS 1233</b> | <b>CWFS 10311</b> | <b>CWFS 6642</b> | <b>CWFS 3631</b> |
|---|-------------------|------------------|-------------------|------------------|------------------|
| <b>Sample Number &amp; Tooth Type/s</b> | CW16_M1_<br>M2_M3 | CW19_M1_<br>M2   | CW33_M1_<br>M2    | CW32_M1_<br>C    | CW27_C           |
| <b>Age at Death (Years)</b>             | 15.0              | 12.0             | 9.0               | 8.0              | 10.0             |
| <b>Range (years)</b>                    | ±3.0              | ±3.0             | ±3.0              | ±2.0             | ±2.5             |

The original sampling of CWFS teeth for this analysis included 17 teeth from 11 individuals, however only ten teeth from five individuals yielded successful thin sections due to appearance of the dentin horn and preservation. First molars were sampled in the greatest number because of optimal conditions for reconstructive microdevelopmental chronology. The first molar begins forming prenatally and complete around the age of three years (Mahoney 2008; Hillson, 2014); therefore, first molar teeth retain a neonatal line as a record of birth. The neonatal line is a baseline for chronological estimates for additional accentuated lines (ALs). Other teeth sampled included permanent canines, second molars, and a single third molar to reconstruct stress events happening at later stages of ontogeny. Table 2 provides the total number of individuals yield by each tooth type. For a full list of teeth for each individual, please see Appendix Table 5.

**Table 2: CWFS Tooth Samples Present by Tooth Type**

| <b>Tooth Type</b> | <b>Number of Individuals</b> |
|-------------------|------------------------------|
| M1                | 4                            |
| M2                | 3                            |
| M3                | 1                            |
| Canine            | 2                            |

## ***Methods***

### **Thin-Sectioning Teeth**

All teeth, besides the two canines, were sliced along the mesio-distal plane. Firstly, epoxy resin of two part Buehler™ EpoThin and one part Buehler™ EpoHardener was required to embed the canines and pre-sliced molars for enhanced structural integrity during thin sectioning. Once the release agent was dry, the pre-sliced molars were placed buccal-lingual plane down on a pre-hardened resin level. The two canines were suspended and stabilized in resin with aluminum wire. Thin sectioning of teeth produced 300-600µm thick cuts along the mesio-distal plane for molars and the labial-lingual plane for the canines. The ideal wafer captures the dentin horns within the optimal thin section plane. These wafers were thin sectioned by a Buehler™ IsoMet, diamond wafering blade.

Once thin sections were made and mounted onto microscope slides with the dentin horn plane facing down, the thin sections were ground and polished. The 300-600µm thick wafers required thinning to approximately 200-500µm for clarity under the microscope. Specimen were ground using a Buehler™ EcoMet 30 polisher with

Buehler™ [P320] and [P1200] CarbiMet™ grit papers to reduce sections till striae of Retzius were visible under the microscope. An ultra-sonic bath was necessary for sonicating excess particles between changing grit papers and polishing stages. Once at desirable thickness, slides were polished with Buehler™ aluminum oxide powder and white felt pads.

### **Microscopy and Imaging**

Microscope slides were imaged at the Hard Tissue Laboratory of George Washington University. Images were captured with a Zeiss Axio Manager AZ with MicroBrightfield microscope and processed with MBF Bioscience™ Stereo Investigator System imaging software. Due to the fragile nature and poor preservation of the archaeological samples, polarized light and brightfield light were used for optimal detection of microstructures. To analyze presence of defects and chronology of tooth development, each thin section was imaged multiple times in collages. An initial image was taken at 10X, and then multiple images were captured on specific cusps at 20X. This magnification allows for optimal viewing of striae of Retzius, cross striations, and accentuated lines (ALs). After the photographic montage of the entire section was complete, additional images were captured of the cuspal and lateral enamel sections. For the anterior dentition, individual images were taken of the labial and lingual enamel sections, while the molars had individual images taken for the cuspal and imbricational enamel. All images were saved as TIF files to be edited in Adobe Photoshop™ and

analyzed in ImageJ. Image montages of both anterior and posterior dentition are found in Appendix Figures 1-22.

### **Microstructure Measurements**

An accentuated line (AL) is a pronounced and distorted line parallel to striae of Retzius that represents enamel growth disruption. To classify a defect as an AL, at least 75% of the thick abnormal prism structure must be observable with the line running in the same location within both cuspal and imbricational enamel. In brightfield and polarized light microscopy, the AL lines may present as pronounced lines. The intensity of the defect may categorize microscopic defects, however this study made no distinctions between ALs. For the CWFS individuals, ALs were detected at unfocused 5X and 10X magnifications during the grinding and polishing process. Once detected in an unfocused image the AL was marked for calculation under focused 20X magnification. As previously stated in Chapter 1, the neonatal line (NNL) is an AL representative of the disruption of enamel formation during the birthing event. The NNL is present within interuterine forming teeth and may be identified as the first AL formed or AL closest to the DEJ (Hillson, 2014). For this study, the only interuterine forming teeth, and therefore the only teeth possible of containing a NNL were the first molars. Similar to other AL, all NNLs were identified at the thickest stages of grinding at either unfocused 5X and 10X magnifications. All first AL closest to the DEJ were classified as NNLs.

Daily secretion rate (DSR) was calculated by measuring the distance across well-defined cross striations and dividing the measurement by five. An average DSR was

taken by replicating this process throughout the enamel six times. Once the DSR was calculated, the chronology for an AL may be calculated by measuring the location of an AL relative to the NNL or other known chronological points. For teeth without NNLs, such as the second molar, third molar, and permanent canine, the chronology was estimated based on the Reid et al. (1998) standards for cuspal enamel formation times, then applied to the distance between the AL and DEJ. Presence and chronology of ALs were recorded (see Table 3). For first molars, the chronology of an AL was dependent on the distance of the AL from the NNL (Hillson, 2014; Lorentz et al., 2019). Periodicity refers to time between stress events recorded as ALs. Periodicity was calculated by measuring the distance between successive ALs, then dividing that distance by the DSR for the individual. Periodicity is calculated in days, but also listed parenthetically as years throughout this thesis.

**Table 3: CWFS Number of AL Present**

| <b>Catalogue Number</b> | <b>Sample Number &amp; Tooth Type/s</b>               | <b>Number of AL</b> |
|-------------------------|---|---------------------|
| CWFS 5423               | CW16_ M <sub>1</sub> _ M <sub>2</sub> _M <sub>3</sub> | 10                  |
| CWFS 1233               | CW19_ M <sub>1</sub> _ M <sub>2</sub>                 | 8                   |
| CWFS 10311              | CW33_ M <sub>1</sub> _M <sub>2</sub>                  | 6                   |
| CWFS 6642               | CW32_ M <sub>1</sub> _C                               | 4                   |
| CWFS 3631               | CW27_C  | 3                   |

## **Ethical Histology**

Analysis of human dentition under a microscope requires either thin-sectioning of the tooth or producing cast replicas. The thin-sectioning of teeth allows researchers to analyze the cross-section plane within the tooth, while the tooth cast is used to analyze the outer enamel surface. Thin-sectioning of teeth falls into the classification of destructive methods, along with DNA extraction, isotopic analysis, and radiation from CT scanning. Similar to the clinical field, the use of human remains and tissues in anthropology brings forward the sensitive question of ethical research (Lambert, 2012). Bioethics includes the following questions; “(1) Does the application of the method address an anthropological question? (2) Are there nondestructive methods that can be used to achieve the results?” (Lambert, 2012, 27). Biological anthropologists must justify destroying human remains for the worth of scientific knowledge, consequence of losing archaeological material for future studies, possibility of offending descendants, and probability of yielding viable results. Acquiring microanatomy data by destructive analysis sacrifices irreplaceable data for future studies of more advanced, accurate, and precise methods.

The ethical application of histology in anthropology depends on destructive methods incorporated with nondestructive methods. Biological anthropologists and bioarchaeologists Alonso-Llamazares et al. (2018), Biehler-Gomez et al. (2019), Grove et al. (2015), Primeau et al. (2015), Sokiranski et al. (2011), Schultz et al. (2007), Von Hunnius et al. (2006), van Der Merwe et al. (2018) suggested the practice of histology is ethical in the application of multidisciplinary methods. In many cases, histology provides

comprehensive evidence towards differential diagnosis, age-at-death, and stress chronologies, and becomes especially powerful when integrated with stable isotope analysis and radiocarbon dating. Histology is justified when the results are a part of a holistic dataset where the study will benefit living cultures.

In the case of CWFS, the ethical integrity of destructive remains is upheld because of the wealth of information given. Prior to thin sectioning, the sampled teeth were sliced for the other half of the tooth to be used for isotopic and DNA destructive analysis, therefore limited numbers of teeth were sampled. In comparison to histology with casts, the information gained from thin sectioning provided more accurate estimations for defect chronologies. Additionally, the chronologies built by thin sectioning incorporate both anterior and posterior dentition, which allows for a more complete reconstructed chronology. Lastly, high resin casts were taken to preserve the exterior tooth morphology.

## CHAPTER 4: RESULTS

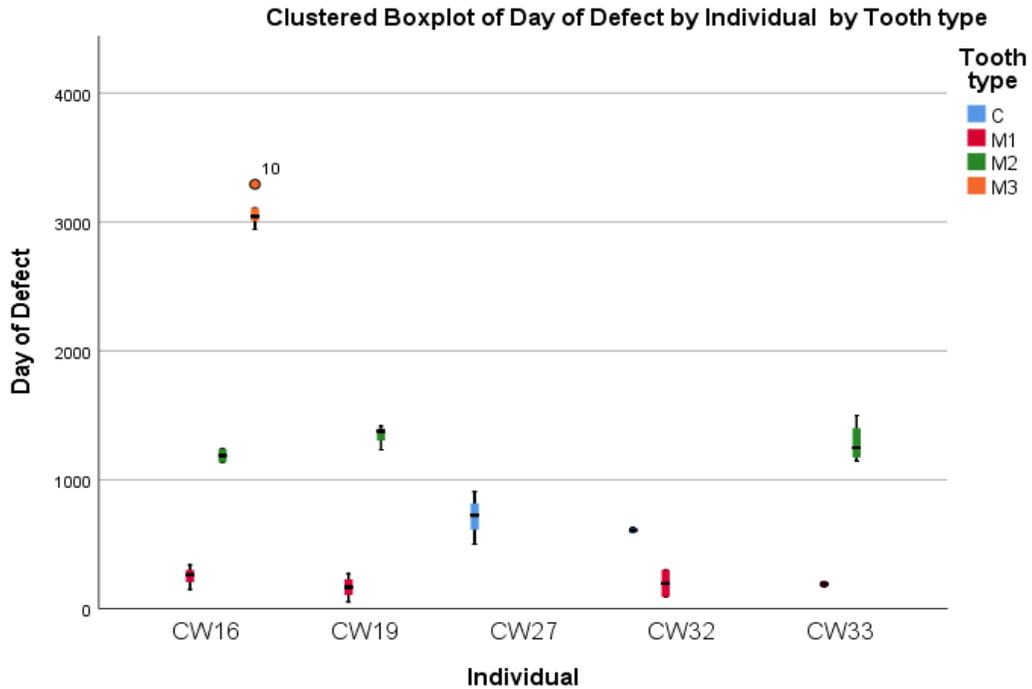
### *Daily Secretion Rates*

Due to the preservation of the molars, only the cuspal enamel yielded enamel daily secretion rates (DSRs). While the imbricational and cuspal enamel in the canines yielded DSRs. For this study, the overall DSR averages ranged between 3.40-4.16 $\mu$ m. The DSR for the Charthouse Warren Farm Shaft (CWFS) individuals fall within known rates of European sample populations, 2.50-4.50 $\mu$ m (Aris et al., 2020; see Appendix Table 4).

### *Chronology*

Table 4: CWFS AL Chronology in Days and Years

| Overall AL Chronology |      |       |
|-----------------------|------|-------|
|                       | Days | Years |
| Mean                  | 1092 | 3.0   |
| Min                   | 53   | 0.1   |
| Max                   | 3292 | 9.0   |
| Q1                    | 245  | 0.7   |
| Q3                    | 1339 | 3.7   |
| Inter Quartile        | 1094 | 3.0   |
| Median                | 999  | 2.7   |



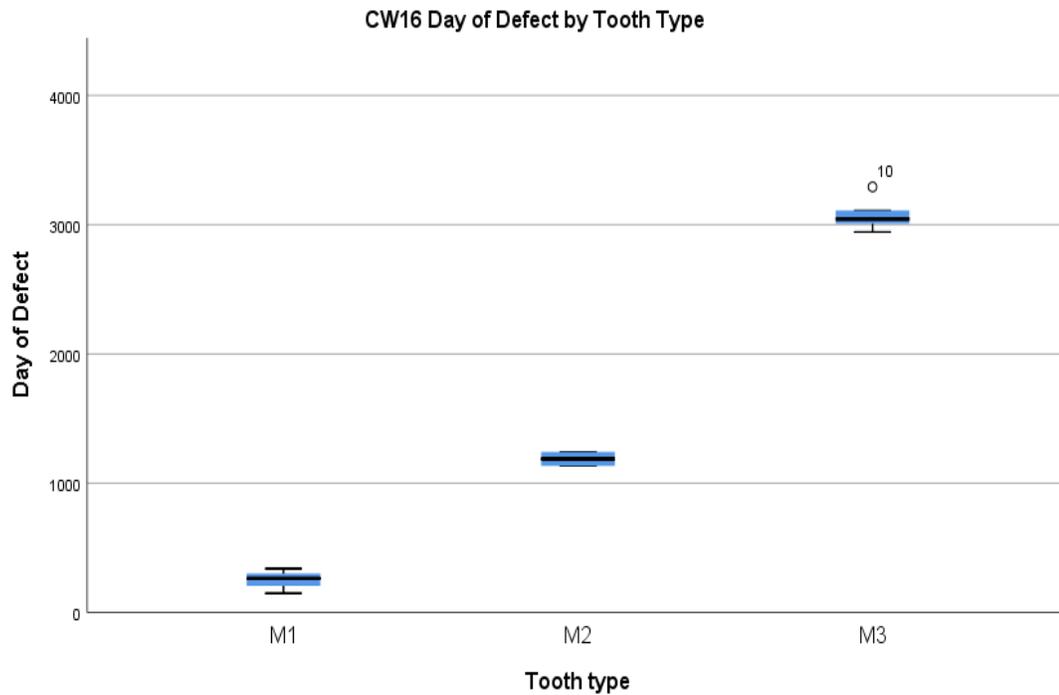
**Figure 13: CWFS AL Chronology in Days by Tooth Type and Individual**

Figure 13 is a boxplot of all AL chronology in days by tooth type for all CWFS individuals. The total number of AL observed in this sample is 31. The average number of AL per individual was six. For the entire sample, average-age-at-AL formation is 1,092 days (3.0 years) and AL range between 53-3,292 days (0.1-9.0 years). The total interquartile range is 245-1,339 days (0.7-3.7 years) with a median of 999 days (2.7 years). Table 4 provides the data for Figure 13, see Appendix Table 1 for larger data chart.

Figure 13 additionally describes AL by tooth type. The total number of AL observed in the first molars is 12, and AL range between 53-338 days (0.1-0.9 years). The first molars average-age-at-AL formation is 190 days (0.5 years), and the AL

interquartile range is 107-265 days (0.2-0.7 years). The first molar is trimodal with AL at 0.3, 0.6, and 0.7 years (see Appendix Figure 23). The total number of AL observed in the second molars is nine, and AL range between 1,133-1,498 days (3.1-4.1 years). The second molars average-age-at-AL formation is 1,283 days (3.5 years), and AL interquartile range is 1,198-1,377 days (3.2-3.7 years). The second molar is bimodal with AL at 3.1 and 3.4 years (see Appendix Figure 24). The total number of AL observed in the canines is five, and AL range between 773-1,180 days (2.1-3.2 years). The canines average-age-at-AL formation is 929 days (2.5 years), and AL interquartile range is 825-999 days (2.2-2.7 years). No mode was recorded in the canine (see Appendix Figure 25). The total number of AL observed in the third molar is five, and AL range between 2,943-3,292 days (8.1-9.0 years). The third molar average-age-at-AL formation is 3,079 days (8.4 years), and AL interquartile range is 3,007-3,109 days (8.2-8.5 years).

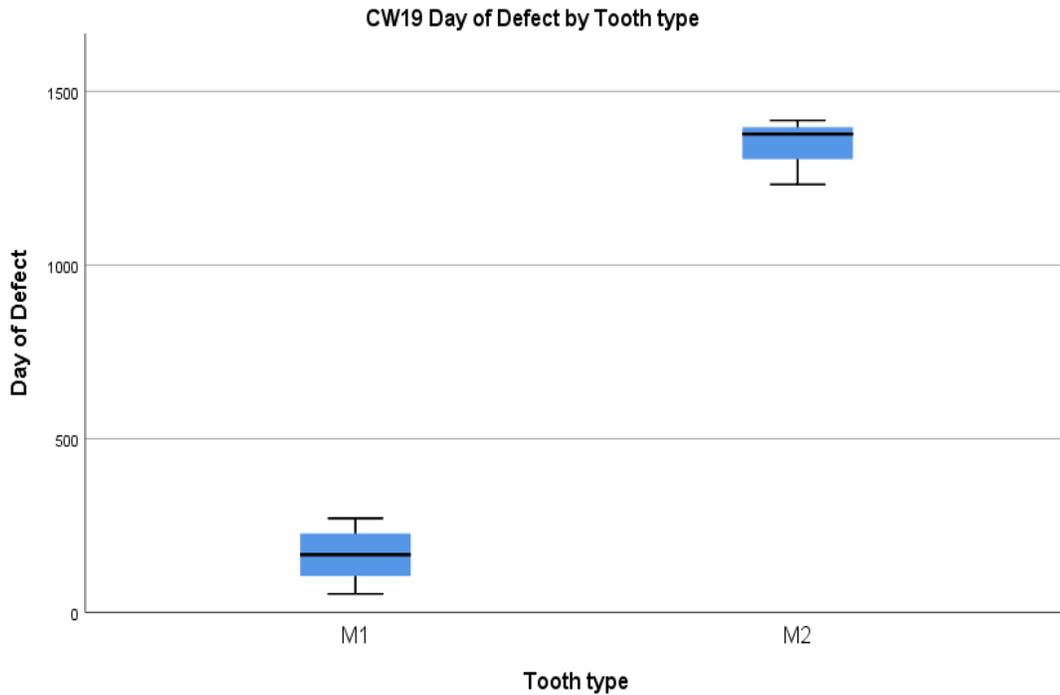
## Individual CW16



**Figure 14: CW16 AL Chronology in Days by Tooth Type**

Figure 14 shows the chronologies for 10 AL events in the first, second, and third molars of individual CW16. The chronologies range between 149-3,292 days (0.4-9.0 years). The five chronologies for the third molar range between 2,943-3,292 days (8.1-9.0 years). The second molar has two ALs occurring at 1,133 and 1,242 days (3.1 and 3.4 years). The first molar has three ALs between 149-338 days (0.4-0.9 years).

## Individual CW19



**Figure 15: CW19 AL Chronology in Days by Tooth Type**

Figure 15 depicts the chronologies for eight AL events in the first and second molars of individual CW19. The chronologies range between 53-1,416 days (0.1–3.9 years). The second molar has three defects ranging between 1,232-1,416 days (3.4-3.9 years). The first molar has five defects ranging between 53-271 days (0.1-0.7 years).

## Individual CW27

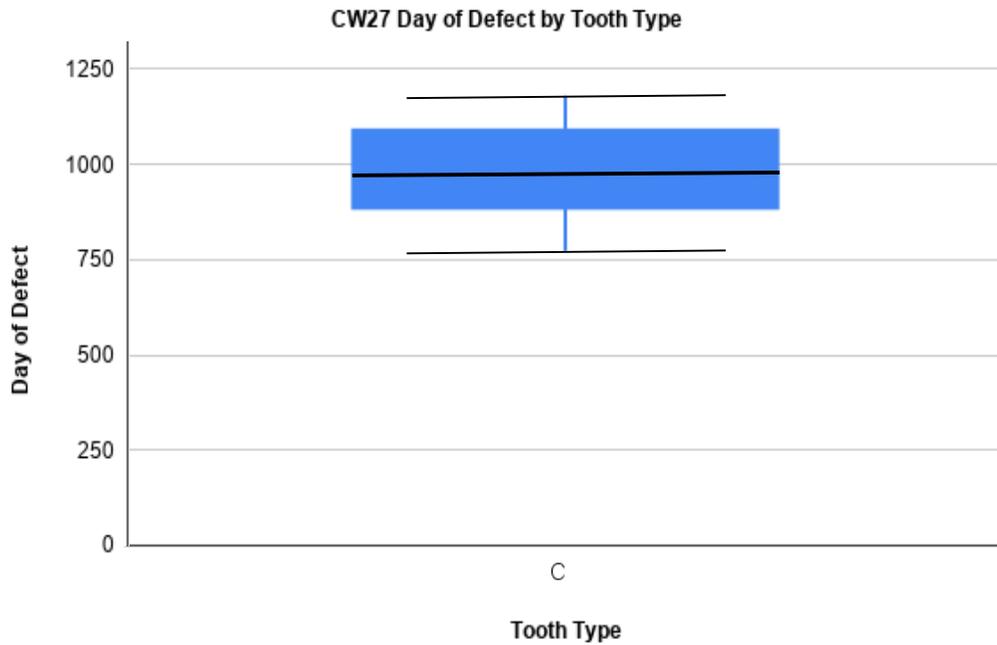


Figure 16: CW27 AL Chronology in Days by Tooth Type

Figure 16 displays the chronologies for three AL events in the canine of individual CW27. The chronologies range between 773-1,180 days (2.1-3.2 years). The median in the canine is 999 days (2.7 years), which is also the median for the entire CWFS sample.

## Individual CW32

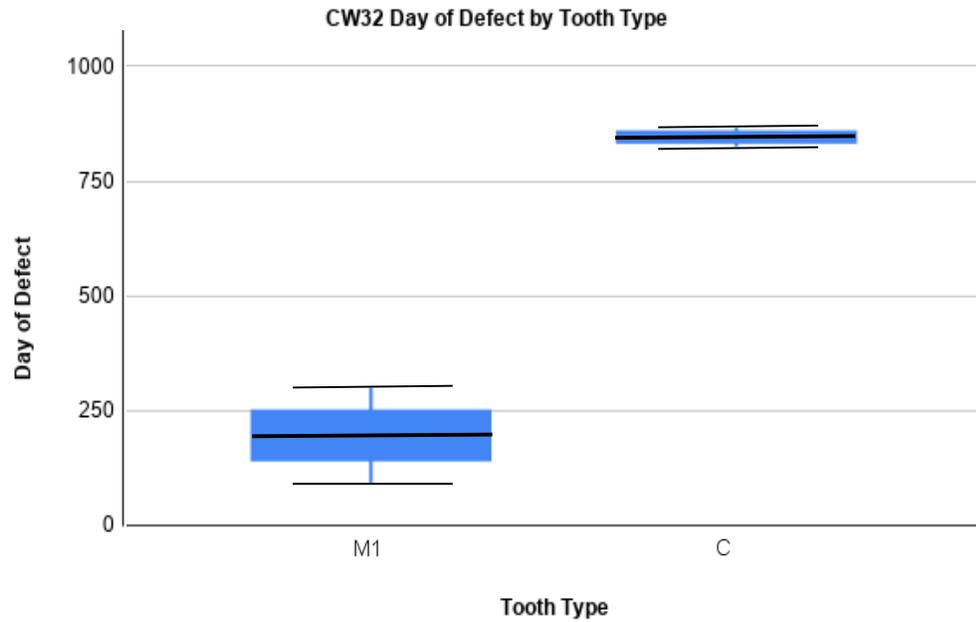
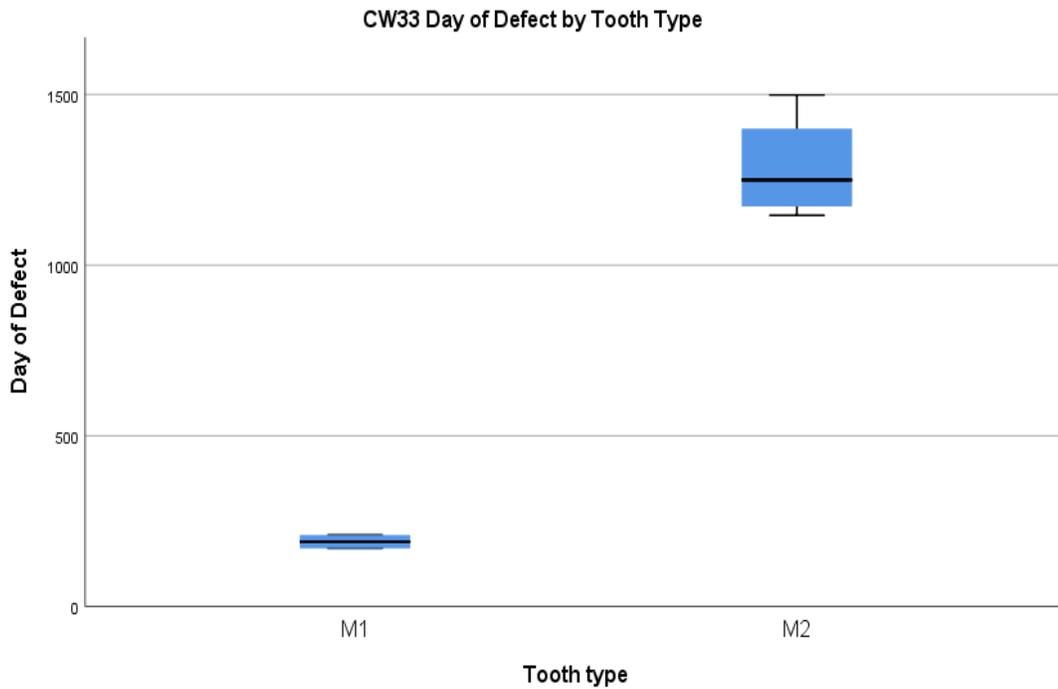


Figure 17: CW32 AL Chronology in Days by Tooth Type

Figure 17 shows the chronologies for four AL events in the canine and first molar of individual CW32. The chronologies range between 91-867 days (0.2-2.4 years). The canine has two defects occurring at 825 and 867 days (2.3 and 2.4 years). The first molar has two defects occurring at 91 and 301 days (0.2 and 0.8 years).

## Individual CW33



**Figure 18: CW33 AL Chronology in Days by Tooth Type**

Figure 18 illustrates the chronologies for six ALs in the first and second molars of individual CW33. Chronologies range from 107-1,498 days (0.3-4.1 years). The second molar has four defects between 1,146-1,498 days (3.1-4.1 years). The first molar has two defects from 107 and 209 days (0.3 and 0.6 years).

## Periodicity

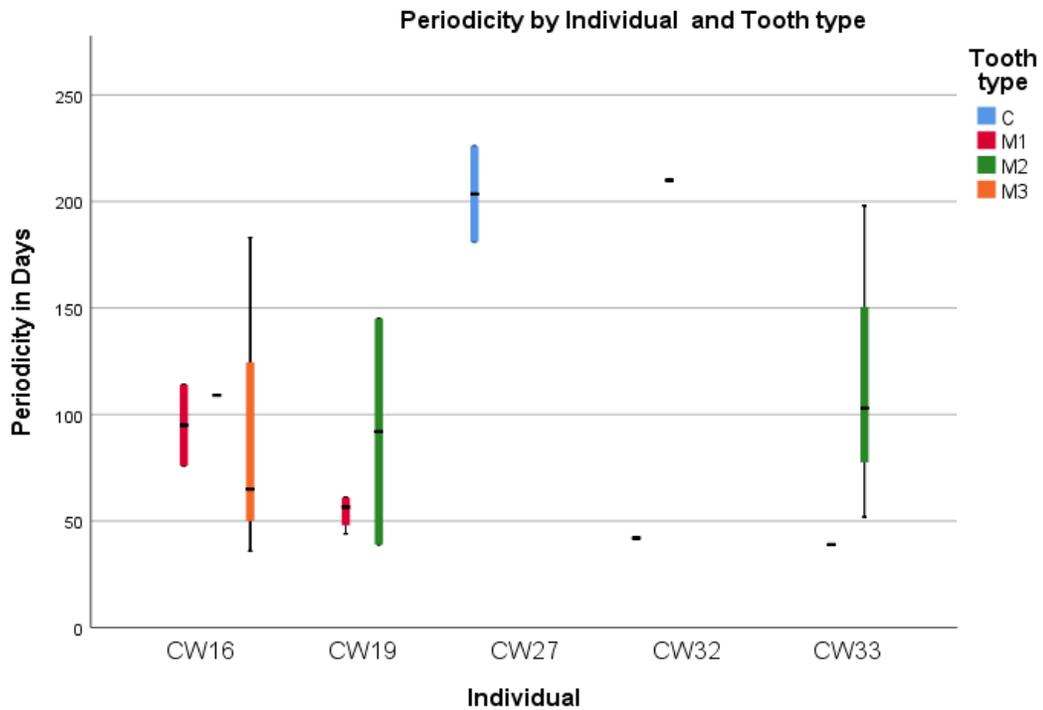


Figure 19: CWFS AL Periodicity in Days by Tooth Type and Individual

Figure 19 is a boxplot of periodicity in days between AL in the CWFS individuals. Range of periodicities falls between 36 and 226 days (1.2 and 7.5 months). The interquartile range is 52-145 days (1.7-4.8 months), with a median of 66 days (2.2 months). The average interval between AL events is 100 days (3.3 months). All individuals besides CW19 have periodicities around 200 days (6.6 months) or below. All individuals except CW27 have periodicities under 50 days (1.6 months). For Figure 19,

Table 5 provides data for periodicity by defect and individual, and see Appendix Table 2 for the more in-depth table.

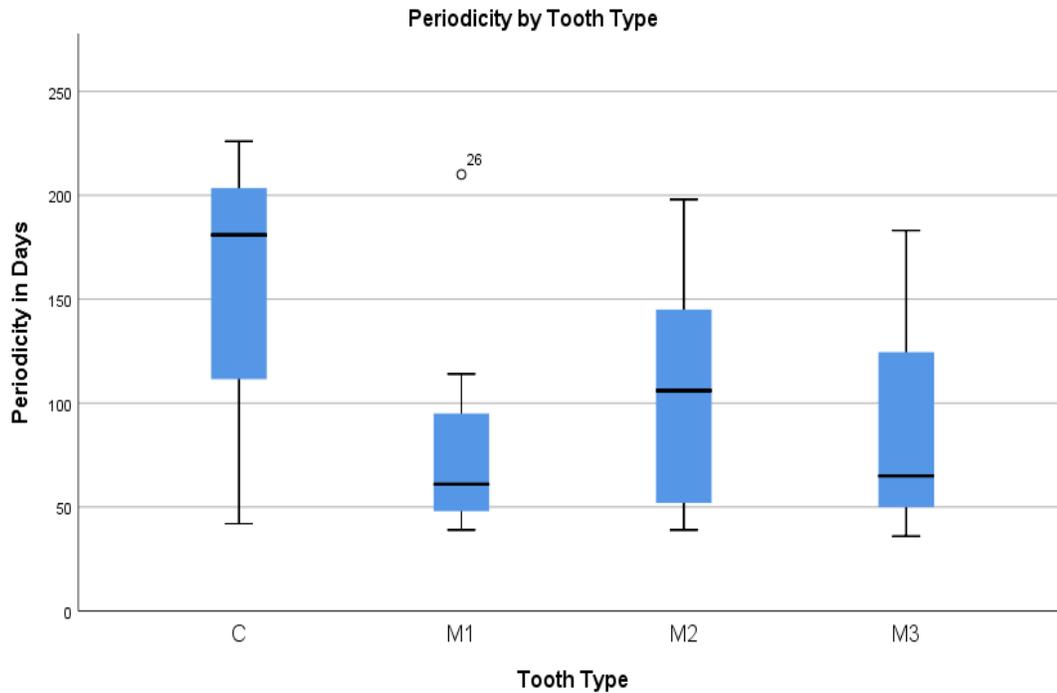


Figure 20: CWFS Periodicity in Days by Tooth Type

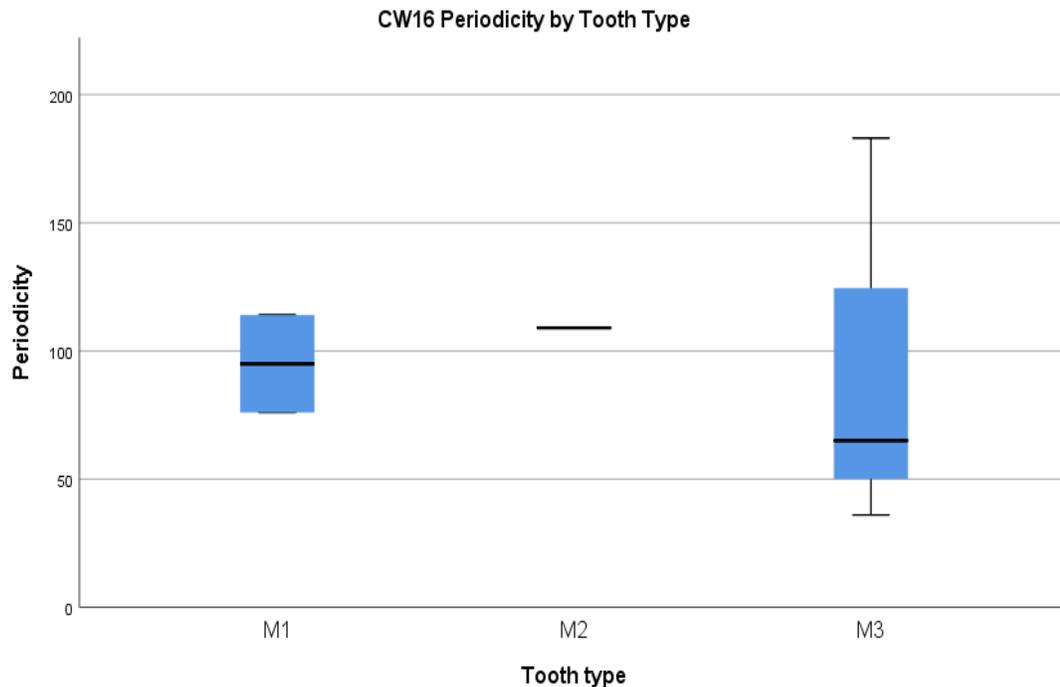
Figure 20 is a boxplot of periodicity between AL by tooth types for all CWFS individuals. The periodicities for all tooth types ranges between 36-226 days (1.2-7.5 months). The canine interquartile range is 112-204 days (3.7-6.8 months), with a median of 181 days (6.0 months). The first molar interquartile range is 50-86 days (1.6-2.8 months), with a median of 61 days (2.0 months). The second molar interquartile range is 65-136 days (2.1-4.5 months), with a median of 106 days (3.5 months). The third molar interquartile range is 57-95 days (1.9-3.1 months), with a median of 65 days (2.1

months). For Figure 20, Appendix Table 3 provides the periodicity data by tooth type for all individuals.

**Table 5: CWFS Periodicity in Days and Months**

| <b>Overall AL Periodicity</b> |             |               |
|-------------------------------|-------------|---------------|
|                               | <b>Days</b> | <b>Months</b> |
| Mean                          | 100         | 3.3           |
| Max                           | 226         | 7.5           |
| Min                           | 36          | 1.2           |
| Q1                            | 52          | 1.7           |
| Q3                            | 145         | 4.8           |
| Inter Quartile                | 93          | 3.1           |
| Median                        | 66          | 2.2           |

## Individual CW16



**Figure 21: CW16 Periodicity in Days by Tooth Type**

Figure 21 depicts the periodicities between AL in the first, second, and third molars of individual CW16. The total number of AL is three in the first molar, two in the second molar, and five in the third molar. The first molar periodicities range from 114 and 76 days (3.8 and 2.5 months). The second molar periodicity is 108 days (3.6 months). The third molar periodicities range between 183 and 36 days (6.1 and 1.2 months). The overall interquartile range of periodicities for individual CW16 is 65-111 days (2.1-3.7 months), with a median of 76 days (2.5 months).

## Individual CW19

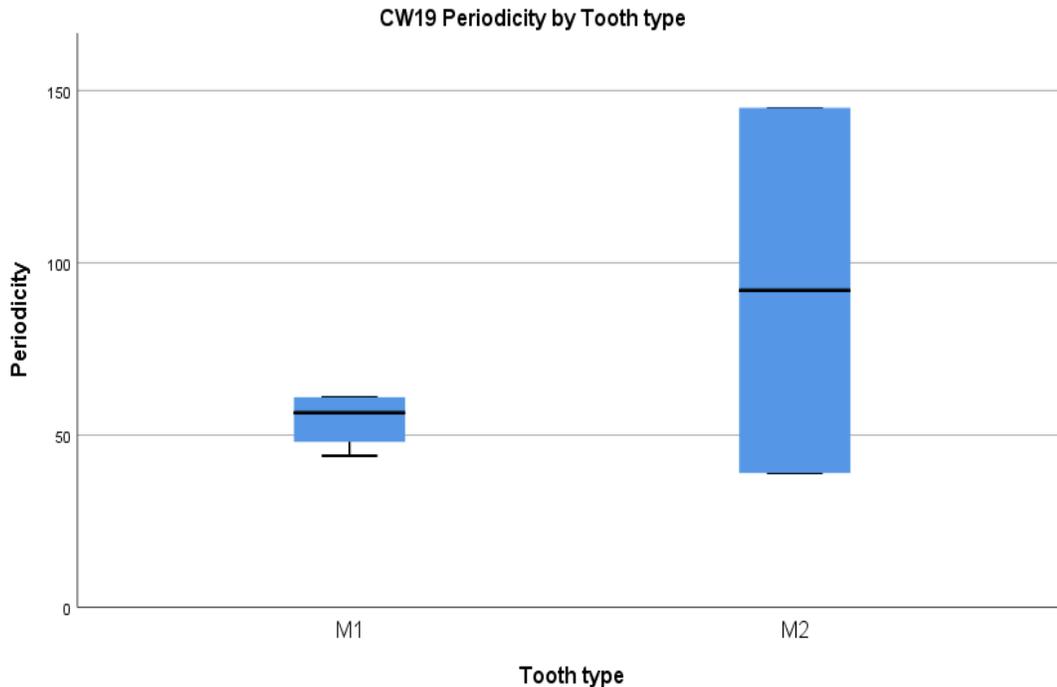
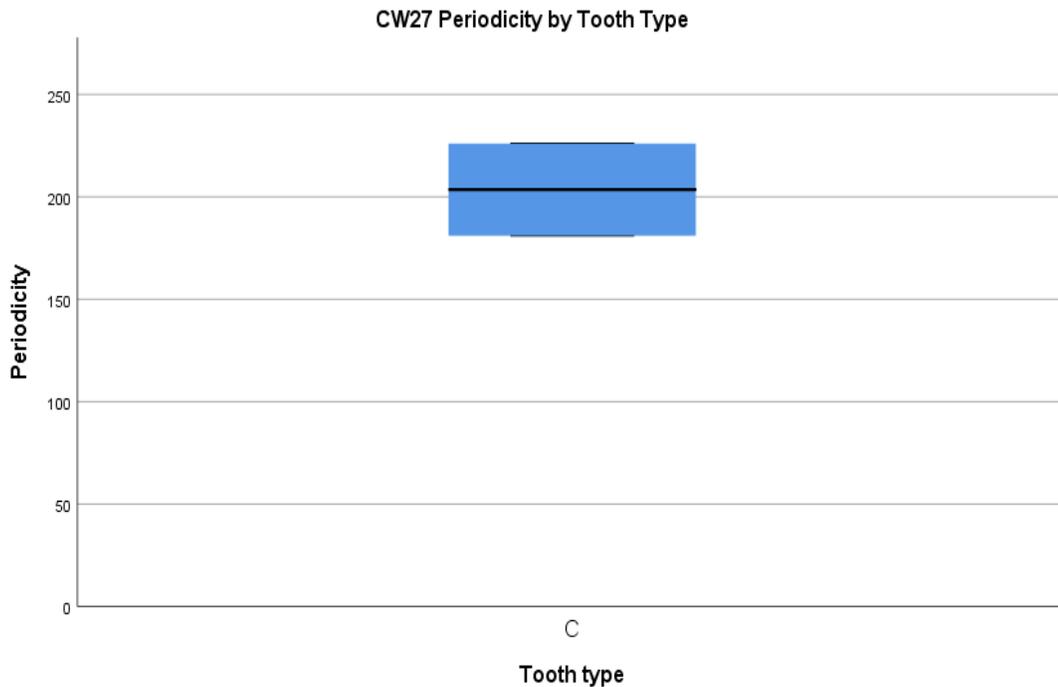


Figure 22: CW19 Periodicity in Days by Tooth Type

Figure 22 shows the periodicities between AL for the first and second molars of individual CW19. The total number of AL is five in the first molar and three in the second molar. The first molar periodicities range from 44 to 61 days (1.4 to 2.0 months). The second molar periodicities range from 39 and 145 days (1.3 and 4.8 months). The overall interquartile range for periodicities of individual CW19 is 46-61 days (1.5-2.0 months), with a median of 57 days (1.9 months).

## Individual CW27



**Figure 23: CW27 Periodicity in Days by Tooth Type**

Figure 23 illustrates the periodicities between AL in the canine of individual CW27. The total number of AL is three in the canine. The canine periodicities range from 181-226 days (6.0-7.5 months). The overall interquartile range for periodicities of individual CW27 is 192-215 days (6.4-7.1 months), with a median of 204 days (6.8 months).

## Individual CW32

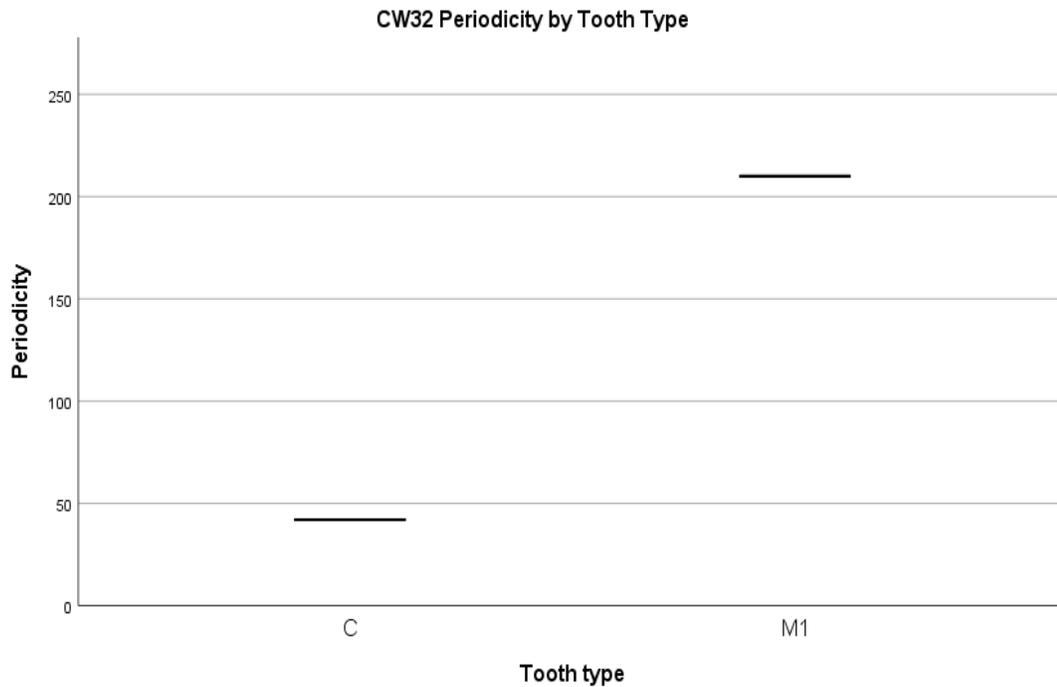


Figure 24: CW32 Periodicity in Days by Tooth Type

Figure 24 shows the periodicities between AL for first molar and canine in individual CW32. The total number of AL is two in the first molar and two in canine. The first molar periodicity is 210 days (7.0 months), while the canine periodicity is 42 days (1.4 months). The overall interquartile range for periodicities of individual CW32 is 84-168 days (2.8-5.6 months), with a median of 126 days (4.2 months).

## Individual CW33

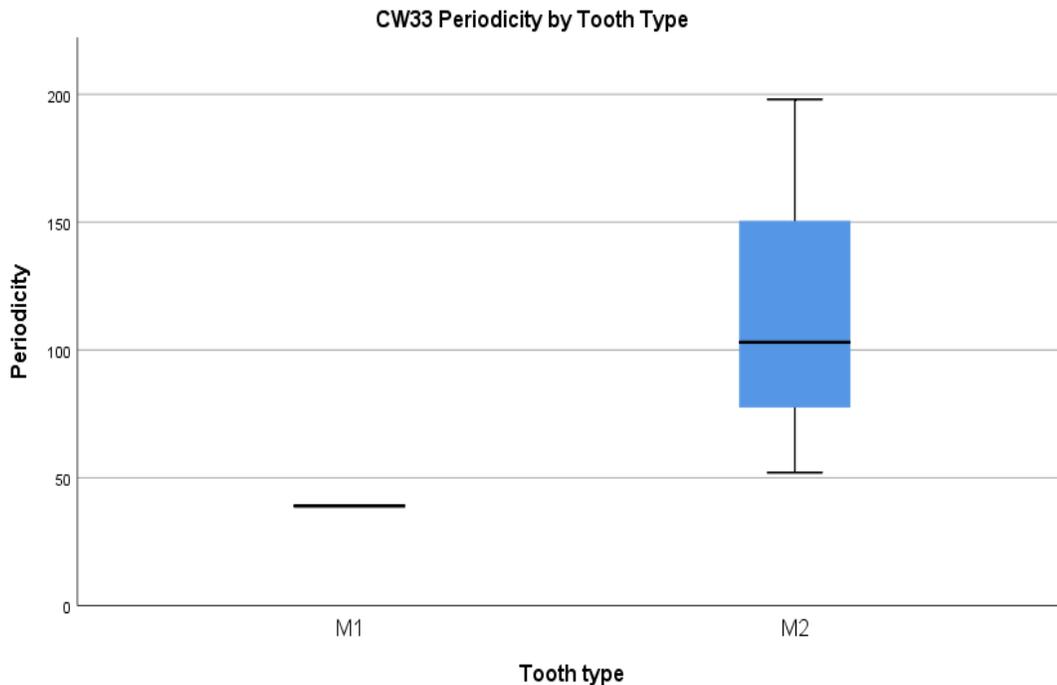


Figure 25: CW33 Periodicity in Days by Tooth Type

Figure 25 demonstrates the periodicities between AL for the first and second molars in individual CW33. The total number of AL is two in the first molar and four in the second molar. The first molar range for periodicity is 39 days (1.3 months). The second molar periodicities range between 52 and 198 days (1.7 and 6.6 months). The overall interquartile range for periodicities in individual CW19 is 49-127 days (1.6-4.2 months), with a median of 78 days (2.6 months).

## CHAPTER 5: DISCUSSION

### *Chronology*

This study first sought to determine presence or absence of accentuated lines (ALs) in the Charterhouse Warren Farm Shaft (CWFS) individuals. Due to the CWFS individuals falling victim to violent deaths and possible cannibalism, the initial hypothesis was AL would be found in enamel forming around time-of-death, indicating survival of environmental stressors prior to death. In the 10 CWFS teeth sampled, 31 AL were present. Four out of the five individuals sampled had teeth forming at the time of death. These individuals ranged in age between 8-15 ( $\pm 3.0$ ) years. Individual CW16 was 15.0 ( $\pm 3.0$ ) years of age, and the latest recorded AL in this individual was 9.0 years. Individual CW32 was 8.0 ( $\pm 2.0$ ) years of age, and the latest AL was recorded at 2.4 years of age. Individual CW33 was 9.0 ( $\pm 3.0$ ) years of age, and the latest forming AL was found at 4.1 years of age. Finally, individual CW27 was 10.0 ( $\pm 2.5$ ) years of age, with the latest recorded AL at 3.2 years of age. The nearest point between age at death and AL formation was 4.9 ( $\pm 3.0$ ) years, a considerable amount of time prior to death. However, it is important to point out that AL was not observed in later forming enamel in this individual due to taphonomic constraints that obscured the visibility of imbricational enamel. In this sense, the capacity to observe AL near to the time of death was challenged. In the entire sample, AL ranged from 53-3292 days (0.1-9.0 years), with an

average of 1092 days (3.0 years). This wide range provides evidence that AL was present across the developmental environment. Such results suggest that even if stressful events were concentrated in the environment immediately prior to death, then these experiences represent a continuation of early life adversity as opposed to a unique condition surrounding the pre-event environment.

In hypothesizing the CWFS human remains from Horizon 2 represent a single deposition event, then these individuals may have lived at the same time, and experienced similar stressors at the same time. A possible timeline of AL occurrences leading to the pre-death event was made (see Appendix Figure 26). AL chronology trends were found at 11.9, 6.8, and 5.7 years prior to death. AL was observed 11.9 years prior to death in the second molar of individual CW16 and the first molar of individual CW19. AL was observed 6.8 years prior to death in the canine of individual CW27 and the third molar of individual CW16. AL was observed 5.7 years prior to death in the second molar of individual CW33 and the canine of individual CW32. Since concurrent AL trends were found in different tooth types, metabolic stress happened simultaneously in individuals at different developmental ages, suggesting environmental stressors were severe during these times. This provides evidence for chronic environmental stressors impacting more than one individual concurrently in multiple years prior to the violent death event.

The earliest recorded ALs were in the first year of life in individuals CW33, CW32, CW16, and CW19. First molar teeth were unavailable for individual CW27, and therefore, not possible to identify AL in the first year of life in this instance. In all four individuals where AL was present in the first year of life, each individual had more than

one defect during this time. Twelve total ALs were in first molars, and 50 percent of these defects occurred during the first six months of life. These four individuals had consistent age-at-first defect, with four defects ranging between 0.1-0.4 years. Out of the 12 ALs the average age-at-formation was 190 days (0.5 years). These results are consistent with a substantial stress burden in the early life environment of these individuals prior to the experience of violent death.

Modern humans practice an infant feeding behavior of exclusive breastfeeding in the first six months of life prior to the introduction of complementary foods (Sellen, 2006). Studies demonstrate that the nutritional quality of breastmilk is buffered from environmental stressors experienced by mothers (Pond, 1977; Quinn et al., 2012; Brown et al., 1986). Introduction to complementary foods increases risk for pathogens and malnutrition. Weaning behaviors may be recorded in isotopes. Elevated numbers of defects were associated with the cessation of breastfeeding in previous studies that combine intra-tooth isotope analysis and histological evaluations of stress (Dirks et al., 2010; Sandberg et al., 2014; Garland et al., 2018). This histological investigation of the CWFS individuals may be bolstered by the incorporation of isotopic data.

**Table 6: Weaning start and end dates alongside age-at-death.  
Highlighted blue individuals are included in this thesis. (courtesy of Schulting)**

| <b>Cat. no</b> | <b>Sample no.</b> | <b>Age</b>                   | <b>Wean start</b> | <b>Wean end</b> | <b>Range <math>\delta^{15}\text{N}</math></b> |
|----------------|-------------------|------------------------------|-------------------|-----------------|---|
| CWFS805        | CW21              | 7±2                          |                   |                 |   |
| CWFS806        | CW22              | yng adult                    | <0.75             | 1.25            | >0.6  |
| CWFS1233       | CW19              | 12±3 no clear nursing signal |                   |                 |   |
| CWFS4611       | CW12              | yng adult                    | 0.5               | 0.83            | 1.61/2.83                                     |
| CWFS5423       | CW16              | 15±3                         | 0.9               | 1.5             | 1.82  |
| CWFS6642       | CW32              | 8±2                          | 1.25              | 1.75            | 0.73/1.37                                     |
| CWFS10311      | CW33              | 9±3                          | 1.25              | 1.75            | 2.35  |
| CWFS4861       | NA                | 10±2.5                       | 0.21              | 1.07            | 1.34/3.02                                     |
| CWFS5157       | NA                | 4±1                          | 0.75              | 1.75            | 3.32  |
|                |                   |                              |                   |                 |   |
|                |                   | <b>mean</b>                  | <b>0.77</b>       | <b>1.41</b>     |   |
|                |                   | <b>SD</b>                    | <b>0.40</b>       | <b>0.37</b>     |   |

Weaning chronologies were estimated using nitrogen isotope analysis for four individuals included in this study. The average start and end of weaning ages ranged between 0.7-1.4 years (Schulting personal communication). Individual CW19 had inconclusive weaning chronology estimations, therefore investigation of relationships between present intra-tooth isotope and AL records were unachievable. However, it is worth mentioning that individual CW19 expressed five ALs within the first year and the earliest recorded AL in the CWFS sample at 0.1 years. Individuals CW33 and CW32 began and completed the weaning process between 1.2-1.7 years, but the enamel from these years of growth were unavailable for this histological study due to preservation. The isotopic findings for individual CW16 indicate the onset of weaning at 0.9 years, which correlated to the enamel growth in the first molar. Individual CW16 had an AL at

0.9 years, which may represent the onset of weaning and introduction of complementary foods. The cessation of breastfeeding for CW16, recorded at 1.5 years, was unobservable in this histological investigation, consequently limiting the analysis of AL association.

Other studies in LEH (Sandberg et al., 2014; Garland et al., 2018; Temple, 2018, 2020) and AL (Dirks et al., 2010) combined histological and isotopic methods to find associations between metabolic stress events during weaning landmarks. Defects increased in frequency during the introduction of complementary foods (Dirks et al., 2010; Sandberg et al., 2014; Garland et al., 2018; Temple, 2018, 2020). Additional correlations between defects and isotopic levels indicated metabolic stress after the cessation breastfeeding (Dirks et al., 2010; Garland et al., 2018; Temple, 2018, 2020).

Similarly, individual CW16 showed a correlation between AL and introduction of complementary foods at 0.9 years. The total interquartile range for AL in all sampled dentition was 245-1339 days (0.7-3.7 years), which encompassed the average onset of weaning and introduction of complementary at 0.7 years and breastfeeding cessation at 1.4 years (see Table 6). This suggests a correlation between heightened AL frequency in the CWFS individuals during the incorporation of complementary foods. However, poor preservation in the imbricational enamel of the sampled first molars limits this study because histological findings were unavailable for comparison with the intra-tooth isotopic profiles associated with breastfeeding. Therefore, concluding remarks on similarities between this thesis and previous works on complementary feeding and metabolic stress are limited. Further work without restrictions in the first molar

imbricational enamel may indicate the relationship between the supplementary diets during weaning and metabolic stress in the CWFS individuals.

Comparable to the works of Dirks et al. (2010), Garland et al. (2018), and Temple (2018), the CWFS individuals suffered metabolic stress after the cessation of breastfeeding. Individuals CW16, CW33, and CW32 experienced AL after weaning completion. This provides evidence, like previous studies, that suggest metabolic stress was frequent without breastmilk buffering environmental stressors. However, in the CWFS individuals, 50 percent of AL in the first molars happened within the first six months of life prior to the age of weaning initiation at 0.7 years. Individuals CW16, CW33, and CW32 experienced two AL events prior to the initiation of complementary foods at ages 0.4 and 0.7 years in individual CW16, 0.3 and 0.6 years in individual CW33, and 0.2 and 0.8 years in individual CW32. Therefore, the metabolic stress of the CWFS individuals impacted development while breastfeeding, which indicated that the nutritional quality of the breastmilk failed to buffer environmental stressors.

Other studies proposed environmental impacts overwhelmed breastmilk buffering. For example, studies of infant feeding behavior and AL in baboons from the Awash National Park in Ethiopia found evidence for stress events around the cessation of breastfeeding and after introduction of food from independent foraging during periods of drought (Dirks et al., 2002). Additionally, Sandberg et al. (2014) critically found that extended breastfeeding ages may have hindered longevity. Trends in mortality rates medieval Nubian sample indicated that individuals with earlier cessation of breastfeeding had increased longevity when compared to individuals of lengthened breastfeeding.

Findings of enamel defects suggested heightened metabolic stress from initiation to cessation of breastfeeding (Sandberg et al., 2014), however the CWFS individuals differed in expressing defects before and following the weaning process. Sandberg et al. (2014) suggested breastmilk was insufficient as the sole nutrient source for the infants, therefore earlier weaning onto nutritious gruels may have benefitted survival. In this instance breastmilk failed to buffer environmental stressors. Breastmilk is part of a deep interconnected relationship between mothers and infants (Gowland and Halcrow, 2020). Disruption of the nutritional quality of breastmilk is rare in clinical settings, even in cases of severe malnutrition (Rakicioğlu et al., 2006; Torgersen et al., 2010; Quinn et al., 2012). Breastfeeding is, however, highly energetically demanding (Sellen, 2007). Stress experienced during this time may, therefore, be associated with maternal stress impacting the frequency and duration of breastfeeding episodes, or alternately, bouts of infectious disease. Therefore, the expression of AL in the CWFS individuals prior to the onset of weaning may be indicative of severe environmental stressors.

In the CWFS individuals, elevated numbers of AL during the first year of life was consistent with environmental stress models affecting the initial developmental years. Survivor models may not be applied to this sample. However, AL found in the early life environment is associated with increased mortality risk. For example, analysis of the Lambayeque Valley, Peru, during Spanish Colonial periods (1533-1760 AD) the presence of AL within 4.0-5.0 months was associated with earlier mortality than those individuals with AL absent. Pre-weaning stress was probably due to resource imbalance from Spanish oppression (Garland et al., 2016). An additional example from Shahr-i Sokhta,

Iran (3200-1800 BC) found a correlation to prenatal AL and reduced longevity (Lorentz et al., 2019). Here AL prenatal and postnatal frequencies were correlated to the imbalance of resources, possibly due to Bronze Age ecological shifts and the increase of the hierarchical stratification (Lorentz et al., 2019). Lastly, in Georgia at the Mission Santa Catalina de Guale on St. Catherine's Island (1605–1680 AD), presence of AL during the first year of life correlated to earlier deaths and resulted from resource imbalance through sociopolitical inequalities of Spanish missionization in Georgia (Garland, 2020). Most similar to the CWFS study showing age-at first defect at 0.1 years and higher frequencies at 0.3 and 0.6-0.7 years, Garland et al. (2016) had the age-at-first defect at 0.1 years and expressed high frequencies during 0.3-0.4 years and 0.6-0.8 years. All three studies showed AL during development associated dependence on the mother's nutrients during prenatal or breastfeeding infancy development. Again, while survivor models may not be applied to the CWFS individuals, the findings reflect similar results from previous studies that suggest breastfeeding behaviors, prior to the inclusion of complementary foods, may not provide full protection against environmental stressors. The identification of ALs in the early life of the CWFS individuals suggest survival of substantial environmental stressors prior to violent death.

Instances of violence may be the consequence of environmental factors. Previous studies suggested rising violence in response to environmental dearth in prehistoric California, where reduced stature and increased frequencies of chronic infection were reported (Broughton et al., 2010; Lambert, 1993; Lambert and Walker, 1991). However, large-scale violent events associated with periods of resource stress were most

pronounced when drastic transformation was observed (Bartelink et al., 2019). In the prehistoric San Francisco Bay Area, California, socioecological systems and corresponding behaviors led to imbalanced resources when Meganos populations migrated from the inland California Delta. Social pressures from a more hierarchical society than the previous social system may have increased resource scarcity. Therefore, migrants may have influenced violence increased in the prehistoric Bay Area (Bartelink et al., 2019). Applying a resource-stress model for the CWFS individuals may indicate similar sociopolitical and socioecological impacts on metabolic stress and violent deaths, such as the work of Bartelink et al. (2019). The CWFS site was from the Beaker period, which was associated with migrant populations from continental Europe that eventually resulted in population replacement (Olalde et al., 2018). While the violence at CWFS is unlikely to come from sociopolitical alternations between ‘migrants’ or ‘locals,’ there is a remote possibility. Alternative studies will conclude this possibility with DNA results (personal communication Schulting).

### ***Periodicity***

Overall, the CFWS individuals expressed recurrent patterns of AL in the earliest to the latest forming dentition. The average AL periodicity for all five individuals was 100 days (3.3 months). AL interquartile ranges were 50-86 days (1.7-2.9 months) in the first molar, 65-136 days (2.2-4.5 months) in the second molar, 112-204 days (3.7-6.8 months) in the canine, and 57-95 days (1.9-3.2 months) in the third molar. These interquartile ranges emphasize the average AL periodicity of 100 days (3.3 months), by

falling around three to six months. With the average interval between AL around three and five months, the CWFS individuals were likely experiencing metabolic stress correlated to seasonal cycles of resource shortages. In Europe, during the Early Bronze Age, the '4.2ka event' experienced climate change, however evidence remains inconclusive of the impact in Britain. (Bond et al., 2001; Roland et al., 2013).

Previous studies indicate seasonal shortages of resources as a probable cause of AL. An investigation of baboons from Awash National Park Hybrid Zone, Ethiopia found AL periodicities coinciding with droughts (Dirks et al., 2002). Similarly, in Allia Bay, Kenya where *Australopithecus anamensis* remains have been dated to about 3.9 million years (Ma), AL in contemporaneous mammals indicated seasonal resource scarcity (Macho et al., 2003). The climate that *Australopithecus anamensis* engaged with in Allia Bay included forests, bushlands, and grasslands, and the AL periodicities in grazing mammals identified rainy season 7.5 and 4.5 month intervals, which this hominid likely experienced (Macho et al., 2003). An additional study concluded that seasonal resource scarcity was associated with AL in *Theropithecus oswaldi* remains from 1.89-0.7 Ma in Kenya (Macho et al., 1996). In these extinct mammals, the recorded AL periodicities trended in intervals of 132-138 days (4.4-4.6 months) or 90-102 days (3.0-3.4), which were interpreted as seasonal fluctuations in resource availability in bi-annual rainy seasons or a heightened drought in the dry season of Kenya (Macho et al., 1996). All of these studies expressed AL periodicity reflective of ecological fluctuations resulting in the selective pressure of resource scarcity (Macho, 2008). Seasonal changes and climatic shifts, such as droughts or rainy seasons, from climatological reports or paleoclimate

research were matched to the AL defects for confirmation. Due to the AL events of CWFS individuals occurring at a mean interval of 3.3 averages, similar to the precocities in Macho et al. (1996; 2003) and Dirks et al. (2002) studies, seasonality may have impacted resource availability resulting in metabolic stress. The interquartile range of the AL periodicity was from 1.7-4.8 months, which indicated that some seasons experienced more severe metabolic stress, and therefore more severe resource scarcity than other seasons. Further evidence for possible chronic seasonal shortages may be found in correspondence with paleoclimatic data related to CWFS.

Paleoclimatologists researched the Early Bronze Age landscape in Britain. Beginning in the early Neolithic, human-driven deforestation became prevalent, and the continuance of grassland landscapes by inhibited succession of shrubs and trees was possibly due to the presence of grazing herbivores (Robinson, 2014). However, woodland succession by the Late Neolithic and Early Bronze Age may have correlated to arable agriculture decline (Robinson, 2014). Additional to the human factors, climate factors influenced the EBA landscape. The northern Atlantic is known to experience climatic shifts around ever 1500 years, including an event affecting Europe around 2200 BC (Bond et al., 1997). This event has been termed the ‘4.2 ka event,’ and is suggested to stem from the 1500 year cycles from solar output (Roland et al., 2013; Bond et al., 2001). However, the effect of this event in prehistoric Britain and Ireland is undetermined (Roland et al., 2013). Studies using bog surface wetness to report climatic shifts from 2300-2000 BC reported higher moisture levels compared to decreased moisture levels from 2000-1800 BC (Brown, 2008; Hughes et al., 2000). Additionally, the water table in

Britain supposedly dropped drastically around 2200-2000 BC (Brown, 2008; Charman et al., 2006). However, these studies represent instances of regional influences during the 4.2ka event, therefore present evidence remains insufficient for assumptions on the impact of this event for the entire EBA Britain (Roland et al., 2014).

Evidence for climatic shifts during the EBA in Europe provides similar evidence to the works of Macho et al. (1996; 2003) and Dirks et al. (2002), however further evidence of human agency mitigating these fluctuations may be found. Compared to the Early Neolithic and Middle Bronze Age of abundant arable agriculture with population growth, social hierarchies, and intensive landscape modification, the inhabitation of Britain during the EBA were likely pastoral, with possibly slight elevated levels of agriculture practiced during the Beaker period (Fyfe, 2012; MacFarlane et al., 2014; Stevens and Fuller, 2012). This was evident by levels of cereals compared to wild plants, such as hazelnuts, and succession of woodlands (Stevens and Fuller, 2012). The prehistoric procurement of food allows for human ingenuity against food shortages with subsistence patterns such as pastoralism, which allows for productivity in climates unfavorable to agriculture (Bradley, 1997). However, pastoralism may fall victim to climate change, therefore seasonal shortages, by herd health susceptible to environmental factors or disease. Furthermore, the possible agriculture during the Beaker period may have minimized food insecurities through crop cultivation aiding in the diet supplementation of the herd and individuals. However, climatic shifts play a role in the availability of plant cultivation. Crop yield is limited to plant susceptibility in extended droughts, cold or hot climates, harsh rainy seasons, and more during periods of fall

vernalization and spring reproduction in wheat and barley (Stevens and Fuller, 2015). Additionally, seasonal food insecurity may exacerbate metabolic stress by increasing susceptibility to infections (Macho et al., 2003). In the case of the pastoral communities of the EBA in Britain, the chronic resource shortages may have contributed to malnutrition and infection. Therefore, the evidence in this thesis proposes possible trends of seasonal shortages that possibly resulted from the '4.2ka event' possibly affecting Somerset, England, during the Beaker period. This conceivably disturbed the subsistence economy, where the socioecological repose resulted in prolonged resource unavailability and subsequent violence.

Resource scarcity may provoke violence. Revisiting the example of California prehistory, ample documentation of violence in the form of cranial trauma and projectile point trauma were matched with episodes of climatic events (Walker, 1989; Lambert and Walker, 1991). In the southern California Channel Islands, during the transition from the Early Middle (1400 BC-300 AD) and Late Middle (300-1150 AD) periods, resource scarcity was correlated to increases in nonspecific metabolic stress and violence intensification (Lambert and Walker, 1991). Evidence from dendrochronology and ocean temperature signified these periods experienced droughts (Lambert and Walker, 1991). Therefore, this socioecological pressure was suggested to accompany social pressures due to resource scarcity with subsequent violence. In the case of CWFS, metabolic stress depicted in AL reflected periodicities of seasonal stress. This thesis proposes that, similar to violence at the prehistoric Channel Islands, the CWFS individuals experienced violence possibly related to socioecological repose to climate change, which chronically

inhabited resource procurement. However, climatic shifts did not inhibit human creativity for adaptation in times of resource scarcity.

The CWFS individuals draw on another similarity to the prehistoric southern California natives, where not only climatic factors impacted resource scarcity but also human behavior. In the prehistoric Channel Islands, population growth, increased complexity of chiefdoms, and shift in subsistence economies further imbalanced resource procurements with consequences such as skeletal injuries, reduced stature, and metabolic stress in the form of periostitis (Walker; 1989; Lambert, 1993; Arnold; 1992). Here both metabolic stress and violence were indicators of this population's response to resource scarcity from climatic and human behaviors. Similarly, this thesis found a correlation between metabolic stress in the CWFS individuals and possible seasonal episodes of resource scarcity in EBA Britain.

This metabolic stress indicates that, like prehistoric southern California natives, the CWFS individuals were possibly impacted by socioecological factors hindering stable procurement of resources. Shift in mortuary practices emphasizing the individual instead of the communal ancestor highlights possible social shifts in EBA Britain (Barret, 1988, 1990; Mullin, 2001; Jones, 2008). The shift to individual burials was accompanied by some cases of violence in the EBA, however the Middle and Late Bronze Ages experienced increased hierarchical social systems and warfare (Evans, 1984; Needham et al., 2017; O'Flaherty, 2007; Schulting, 2013). In spite of this, violence was present at the CWFS site. Besides cranial fractures, a further indicator of violence was the nonnormative burial at the CWFS. With an MNI of 43, this burial was more similar to a

mass grave than the EBA Britain normative singular burial under a round mound. Mass graves may indicate violence (Haglund et al., 2001; Skinner, 1987; Brinker et al., 2014; Orschiedt and Noel Haidle, 2012). In addition, the CWFS individuals were not only victims of violent death, such as perimortem cranial trauma, but possible victim to cannibalism. Postmortem indicators of dismemberment and defleshing included spiral fractures, cut marks, and gnaw marks were all characteristic of possible cannibalism. Cannibalism may also be indicative of severe resource scarcity and coincide with violence (Flinn et al., 1976; White, 1992; Billman et al., 2000). However, the consequence of violent death may be dependent on a mosaic of causes that includes climate change. Violence and climate change are part of a relationship of more variables, where the subsistence economy and sociopolitical factors feed the relationship between violence and chronic climatic influences (Harrod and Martin, 2014). Therefore, the evidence of metabolic stress in the CWFS individuals indicated multiple factors resulting in violence.

### ***Periodicity by Tooth Type***

The first, second, and third molars and canine develop during different years. Therefore, analyzing AL by tooth type allows for a chronology of periodicities. The chronology of human development is broken into stages of infancy, childhood, juvenility, and adolescence (Bogin, 1999). Developmental milestones take place during these stages, such as first menarche in females during adolescence or the initiation of the weaning process near the end of infancy. In other studies, ALs were found in primates to

correspond to these developmental milestones. Recorded dates of weaning ages and first menarche in female baboons corresponded with AL (Dirks et al., 2002). Furthermore, the developmental milestones of sexual maturity in the adolescence baboons indicated more frequent AL periodicities, which suggested that the environmental stressors, including the social environment of the troop, were experienced readily during sexual maturity (Dirks et al., 2002). Similarly, analysis of periodicity by tooth type indicated the CWFS individuals experienced AL in association with developmental milestones.

Tooth type means for AL periodicities were 82 days (2.7 months) in the first molar, 108 days (3.6 months) in the second molar, 150 days (5.0 months) in the canine, and 87 days (2.9 months) in the third molar. The interquartile range for the tooth types included 1.7-2.9 months in the first molar, 2.2-4.5 months in the second molar, 3.7-6.8 months in the canine, and 1.9-3.2 months in the third molar. Similar to the work of Macho et al. (2003), the average interval between metabolic stress events between three and five month averages and ranges may represent resource scarcity affected by seasonal resource shortages. The trends indicated by these averages were more frequent occurrence of AL reflected in the first molar, and only a week difference in the average between the first and third molar. Enamel growth in the first molar is reflective of the infancy period, while the third molar forms enamel during the juvenile period of human life history. Therefore, metabolic stress had shorter periodicities during the years of development associated with total dependence on caregivers and breastmilk, then again when independence increased. The environmental stressors for the CWFS individuals were not completely buffered by breastmilk. Furthermore, the canines reflected the

longest periodicity average between ALs, which signify enamel growth during childhood. The second to the longest average in periodicities was found in the second molars, which also develop in childhood. The change from infancy to childhood is the period in development when cessation of breastfeeding normally occurs, and there is increased independence from the mothers as complementary foods become compulsory.

In other studies, these trends were associated with rainy or arid seasons significantly impacting resource procurement (Macho et al., 2003; Dirks et al., 2002). Macho et al. (2003) proposed that longer trends of seasonality were found in cycles of seven months, while Macho et al. (2003) and Franz-Odenaal et al. (2003) found shorter seasonal shortage trends between three and four months. In the CWFS individuals, the average periodicities in the first and third molars were both just under three months, which correlated to shorter periods of seasonal influencing metabolic stress. Differently, the average periodicities in the canines averaged at five months, reflective of longer seasonal cycles influencing metabolic stress. While the second molars average just over three months which again reflects shorter periods of seasonality influencing metabolic stress. These variations in severe metabolic stress between tooth type indicate that the social and physical buffering of chronic resource scarcity were less effective in both infancy and juvenile periods when compared to childhood.

Again, a survivor model may not be investigated, but previous studies showed that high frequencies of metabolic stress in the initial developmental periods equate to early mortality (Garland, 2020). Similarly, AL trends in the CWFS individuals with the shortest periodicities in the first years of development hold the shortest intervals.

However, the molar reflective of the juvenile period also indicated shortened intervals between AL. The juvenile period marks a developmental stage of further independence from the caregivers, where the individual has the capacity to forage for themselves, and approaches the adolescent growth curve before puberty (Bogin, 1999). This greater independence may have influenced the shorter intervals between metabolic stress events. The AL from the earliest developmental stages speaks to the harshness environmental stressors experienced by the CWFS. Questions are raised regarding why breastmilk was unable to buffer the environmental stressors, and what occurred during the juvenile period that these individuals were, again, more susceptible to environmental stressors? Further studies may investigate questions on complementary feeding behaviors, relationships between individuals, regional origin of these individuals, and more to provide a fuller picture to the metabolic stress experienced at CWFS prior to violent deaths. Social and violent responses to cultural and ecological pressures were present at time-of-death, and throughout development because environmental constraints were most recurrent and impactful at infant and juvenile periods.

## CHAPTER 6: CONCLUSIONS

This thesis aimed to contextualize the life histories of the Charterhouse Warren Farm Shaft (CWFS) individuals prior to violent death. Application of histological methods reconstructed early life histories of five individuals from CWFS. Since enamel is a finite structure, the developmental years are preserved for life history reconstructions. Thin sectioning of dentition allowed for more precise measurements of the intricate structures of enamel prisms when compared to macroscopic enamel observations. Analysis of presence, chronologies, and periodicities of accentuated lines (AL) in the enamel allowed for observation of lived metabolic stress experiences. This study importantly provided contextualization of the CWFS life histories from infant to juvenile development periods during the Early Bronze Age (EBA) in Britain.

The CWFS individuals were dated to 2200-2000 cal BC from a 20m natural shaft in Mendip, England. This period in southern England was associated with the Beaker culture, and the CWFS individuals were interred with a beaker artifact reflective of normative burial practice. However, the CWFS mortuary practice were nonnormative since the mass burial was within a deep natural feature instead of the normative practice of burial under an EBA round barrow (Barrett, 1990; Mullin, 2001; Parker Pearson, 2005). Additional nonnormative factors in this deposition of human remains as a mass burial included the presence of cranial trauma in the CWFS individuals indicated violent

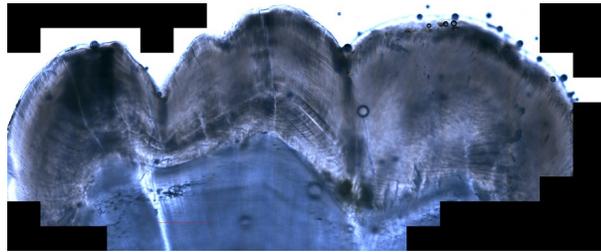
death. Although violence was experienced at CWFS, violence in the form of warfare, in EBA Britain, was less evident when compared to the Early eolithic and Middle/Late Bronze Age (Schulting, 2013). Furthermore, defleshing and disarticulation patterns indicated possible cannibalism at CWFS. Cannibalism was rare in prehistoric Britain, with the most documentation at the Magdalenian site of Gough's Cave from the Upper Paleolithic (12,700 BC) (Bello et al., 2015; Stevens et al., 2010). Thousands of years later, the CWFS occurrence of possible cannibalism was indicated by perimortem modifications as spiral fractures to the appendicular skeleton, cut marks, defleshing, and gnaw marks. Both violence and possible cannibalism at the CWFS site may indicate resource scarcity.

The application of thin section histology identified chronology and periodicity of AL to contextualize this violence and possible cannibalism. Four first molars, four second molars, one third molar, and two canines were thin sectioned and captured microscopically under polarized and brightfield lights. AL measurements were taken along the enamel prism between AL, neonatal line (NNL), and dentin-enamel-junction (DEJ). AL chronologies indicated a high frequency of metabolic stress within the first six months of life. These earliest defects reflected stress during a period of reliance on breastmilk, and since breastmilk is known to buffer stressors, these findings indicated survival of severe environmental stressors. AL periodicities indicated cyclical reoccurrences of metabolic stress in averages of three and five months. Other studies of cyclical defects, such as these, indicated seasonal correlations (Dirks et al., 2002; Macho et al., 2003, 1996; Macho, 2008). Means of AL periodicities between three and five

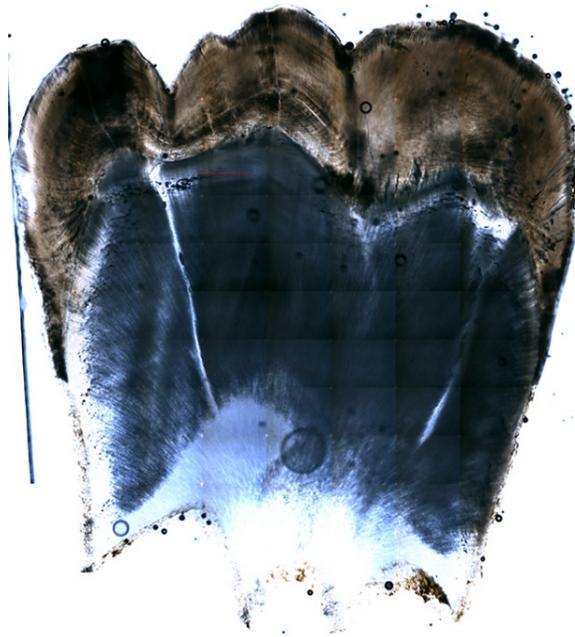
months implied the possibility of chronic seasonal shortages of resources experienced by the CWFS individuals. While the '4.2ka event' is well documented in continental Europe, the influence of this event throughout Britain is still undetermined, and contextual climatic shifts are documented (Roland et al., 2013; Brown, 2008; Charman et al., 2006; Hughes et al., 2000). EBA Britain experienced arable agriculture decline and increased pastoralism during this time (Stevens and Fuller, 2012). Since the AL periodicities indicated seasonal shortages, the '4.2ka event' may have impacted the subsistence economy of EBA England. Consequently, severe seasonal resource scarcity may have impacted lactating mothers and the CWFS individuals throughout development, with spikes in susceptibility during infant and juvenile periods. This thesis proposes that chronic seasonal resource scarcity may have contributed to the violent deaths and subsequent cannibalism at CWFS.

This study importantly contextualized the life histories leading up to the violent deaths at CWFS. Secondly, these employed methods significantly advocated for use of histology, specifically thin section analysis of internal enamel structures. Contextual documentation in this thesis of possible cannibalism at CWFS is critical because cannibalism was rare in prehistoric Britain. Future directions will aim to further document this violent event with external dental defects, DNA, and more isotopic profiles.

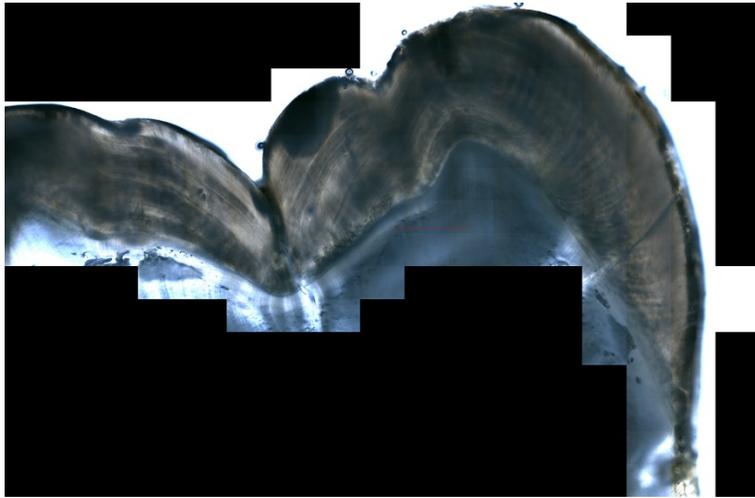
## APPENDIX



Appendix Figure 1: Individual CW16\_M3 at 20X enamel only.



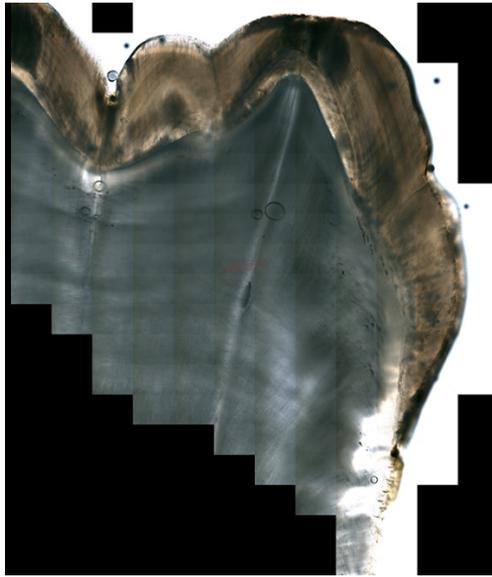
Appendix Figure 2: Individual CW16\_M3 at 10X entire montage.



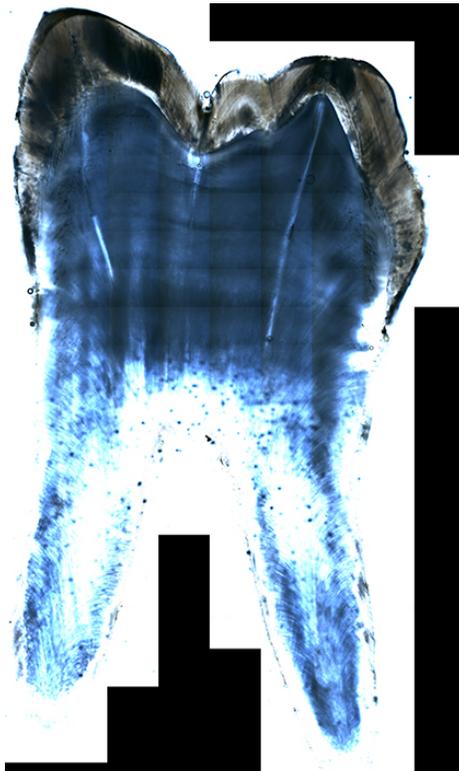
**Appendix Figure 3: Individual CW16\_M2 at 20X enamel only.**



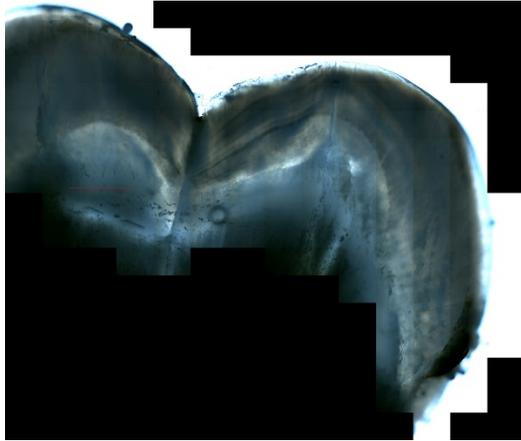
**Appendix Figure 4: Individual CW16\_M2 at 10X entire montage.**



Appendix Figure 5: Individual CW16\_M1 at 20X enamel only.



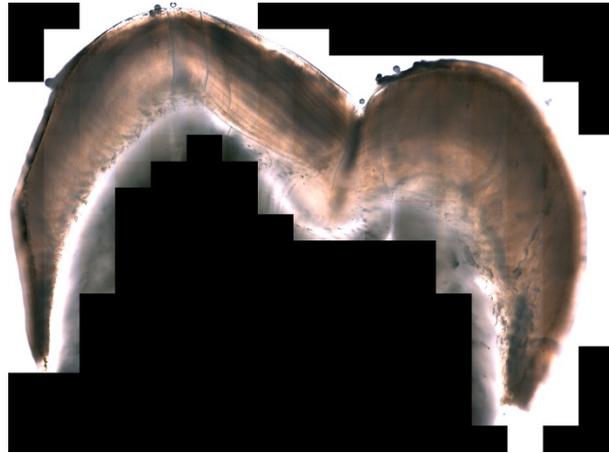
Appendix Figure 6: Individual CW16\_M1 at 10X entire montage.



Appendix Figure 7: Individual CW19\_M1 at 20X enamel only.



Appendix Figure 8: Individual CW19\_M1 at 10X entire montage.



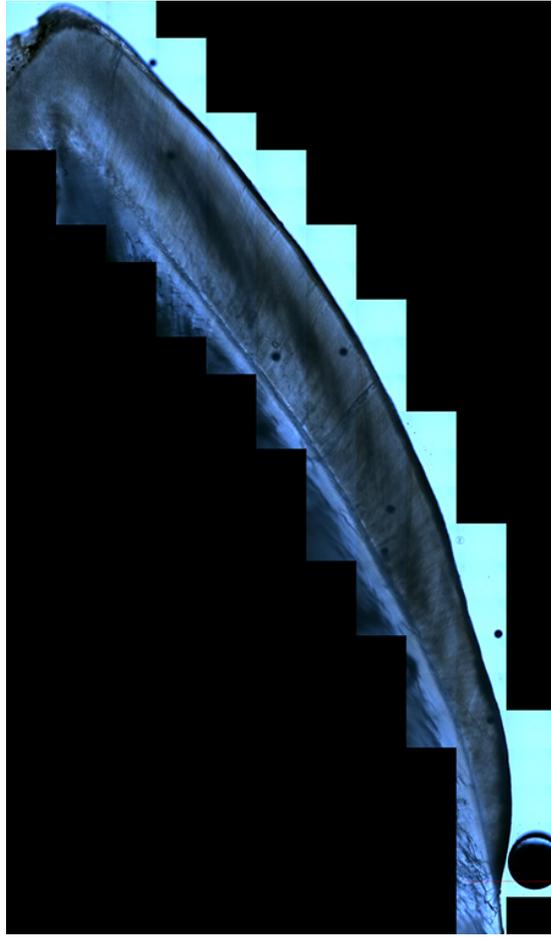
Appendix Figure 9: Individual CW19\_M2 at 20X enamel only.



Appendix Figure 10: Individual CW19\_M2 at 10X entire montage.



Appendix Figure 11: Individual CW27\_C at 10X entire montage.



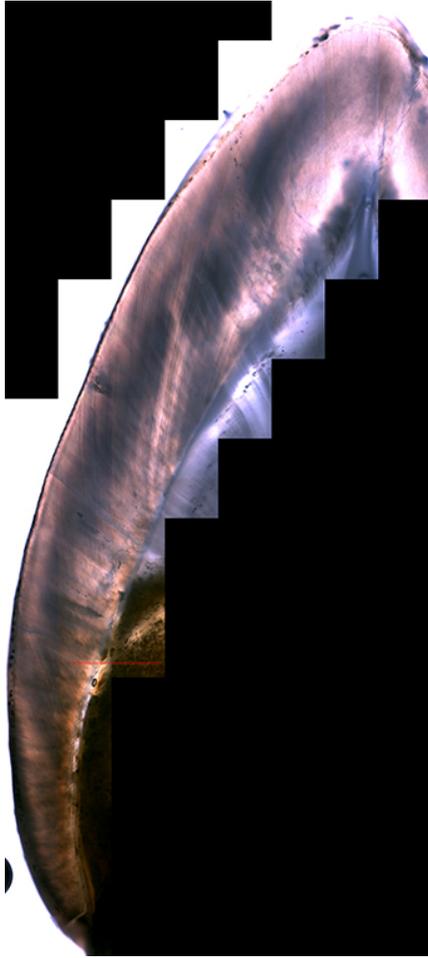
**Appendix Figure 12: Individual CW27\_C at 20X labial side of cusp only.**



Appendix Figure 13: Individual CW27\_C at 20X lingual side of cusp only.



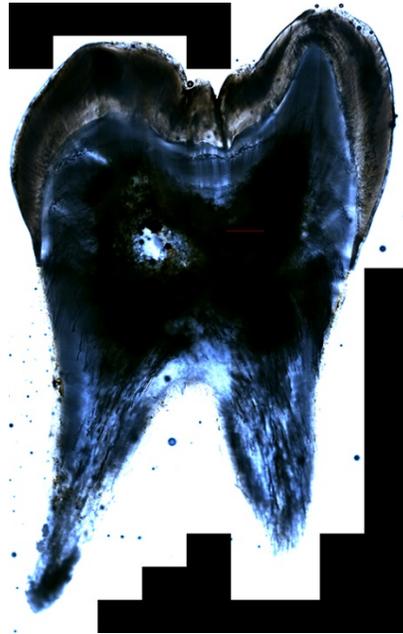
Appendix Figure 14: Individual CW32\_C at 10X entire montage.



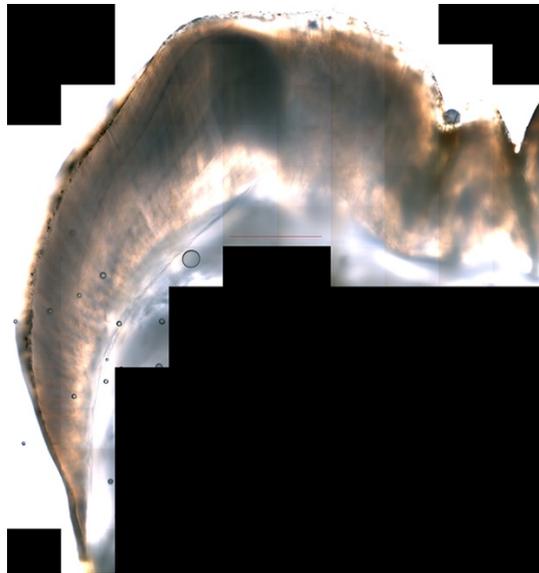
**Appendix Figure 15: Individual CW32\_C at 20X labial side of cusp only.**



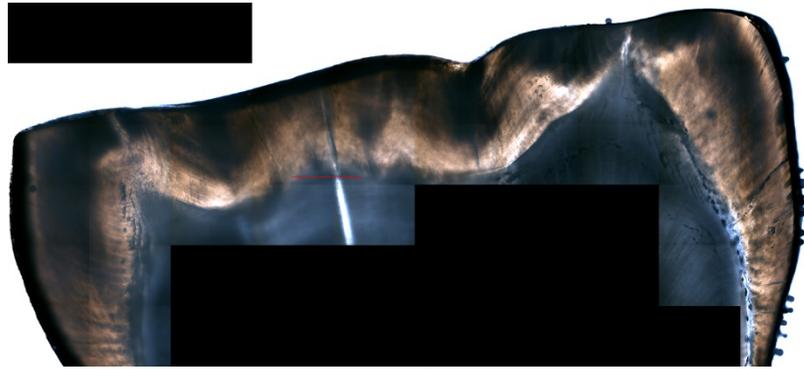
Appendix Figure 16: Individual CW32\_C at 20X lingual side of cusp only.



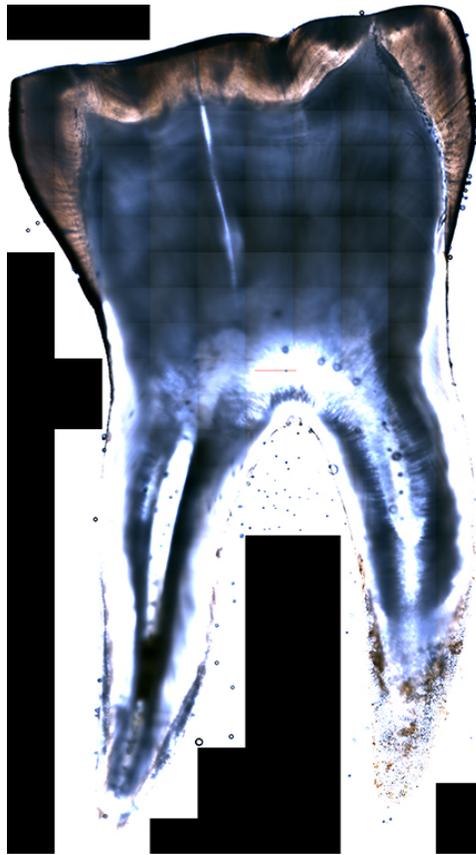
Appendix Figure 17: Individual CW32\_M1 at 10X entire montage.



Appendix Figure 18: Individual CW32\_M1 at 20X enamel only.



Appendix Figure 19: Individual CW33\_M1 at 20X enamel only.



Appendix Figure 20: Individual CW33\_M1 at 10X entire montage.



Appendix Figure 21: Individual CW33\_M2 at 10X entire montage.



Appendix Figure 22: Individual CW33\_M2 at 20X entire montage.

**Appendix Table 1: CWFS AL Chronology in Days**

| Each Individual AL Chronology by Days |               |            |            |           |           |
|---------------------------------------|---------------|------------|------------|-----------|-----------|
| Catalogue No.                         | CWFS 5423     | CWFS 1233  | CWFS 10311 | CWFS 6642 | CWFS 3631 |
| Tooth Type/s                          | CW16_M1_M2_M3 | CW19_M1_M2 | CW33_M1_M2 | CW32_M1_C | CW27_C    |
| Mean                                  | 1852          | 606        | 910        | 521       | 984       |
| Min                                   | 149           | 53         | 107        | 91        | 773       |
| Max                                   | 3292          | 1416       | 1498       | 867       | 1180      |
| Q1                                    | 537           | 151        | 443        | 249       | 886       |
| Q3                                    | 3034          | 1268       | 1275       | 836       | 1090      |
| Inter Quartile                        | 2497          | 1118       | 832        | 587       | 204       |
| Median                                | 2093          | 249        | 1172       | 563       | 999       |

**Appendix Table 2: CWFS AL Periodicity in Days by Individual**

| Each Individual Periodicity by Days |               |            |            |           |           |
|-------------------------------------|---------------|------------|------------|-----------|-----------|
| Catalogue Number                    | CWFS 5423     | CWFS 1233  | CWFS 10311 | CWFS 6642 | CWFS 3631 |
| Tooth Type/s                        | CW16_M1_M2_M3 | CW19_M1_M2 | CW33_M1_M2 | CW32_M1_C | CW27_C    |
| Mean                                | 92            | 67         | 98         | 126       | 204       |
| Max                                 | 183           | 145        | 198        | 210       | 226       |
| Min                                 | 36            | 39         | 39         | 42        | 181       |
| Q1                                  | 65            | 46         | 49         | 84        | 192       |
| Q3                                  | 111           | 61         | 127        | 168       | 215       |
| Inter Quartile                      | 46            | 15         | 78         | 84        | 23        |
| Median                              | 76            | 57         | 78         | 126       | 204       |

**Appendix Table 3: CWFS Periodicity in Days by Tooth Type**

| Periodicity by Tooth Type |     |     |     |     |
|---------------------------|-----|-----|-----|-----|
| Tooth Type                | M1  | M2  | C   | M3  |
| Mean                      | 82  | 108 | 150 | 87  |
| Max                       | 210 | 198 | 226 | 183 |
| Min                       | 39  | 39  | 42  | 36  |
| Q1                        | 50  | 65  | 112 | 57  |
| Q3                        | 86  | 136 | 204 | 95  |
| Inter Quartile            | 36  | 71  | 92  | 38  |
| Median                    | 61  | 106 | 181 | 65  |

**Appendix Table 4: CWFS Daily Secretion Rates (DSR) in  $\mu\text{m}$  and Tooth Types Highlighted by Colors**

| Catalogue No.              | Sample No.        | DSR 1 | DSR 2 | DSR   | DSR 4 | DSR 5 | DSR 6 | DSR   | SD DSR | Average DSR Cuspal/Lateral | min   | max   |
|----------------------------|-------------------|-------|-------|-------|-------|-------|-------|-------|--------|----------------------------|-------|-------|
| Internal Cuspal CWFS 3631  | CW2 7_C_ Tooth 13 | 4.656 | 4.028 | 3.957 | 3.462 | 3.639 | 3.148 | 3.815 | 0.524  | 3.844                      | 3.148 | 4.656 |
| Middle Cuspal CWFS 3631    | CW2 7_C_ Tooth 13 | 3.992 | 3.447 | 3.022 | 3.091 | 4.191 | 3.992 | 3.622 | 0.504  |                            | 3.022 | 4.191 |
| External Cuspal CWFS 3631  | CW2 7_C_ Tooth 13 | 3.071 | 3.692 | 4.243 | 4.532 | 4.741 | 4.283 | 4.094 | 0.613  |                            | 3.071 | 4.741 |
| Internal Lateral CWFS 3631 | CW2 7_C_ Tooth 13 | 2.756 | 3.085 | 3.005 | 3.335 | 2.990 | 3.710 | 3.147 | 0.333  | 3.615                      | 2.756 | 3.710 |
| Middle Lateral CWFS 3631   | CW2 7_C_ Tooth 13 | 4.093 | 3.828 | 3.406 | 3.356 | 3.657 | 3.322 | 3.610 | 0.307  |                            | 3.322 | 4.093 |
| External Lateral CWFS 3631 | CW2 7_C_ Tooth 13 | 3.724 | 4.223 | 4.333 | 3.757 | 4.198 | 4.292 | 4.088 | 0.274  |                            | 3.724 | 4.333 |
| Internal CWFS 5423         | CW1 6_M1          | 4.636 | 4.204 | 3.655 | 4.480 | 3.871 | 3.559 | 4.067 | 0.443  | 3.620                      | 3.559 | 4.636 |
| Middle CWFS 5423           | CW1 6_M1          | 3.881 | 4.442 | 3.024 | 4.601 | 3.202 | 3.500 | 3.775 | 0.649  |                            | 3.024 | 4.601 |
| External CWFS 5423         | CW1 6_M1          | 2.560 | 2.941 | 3.000 | 3.343 | 2.950 | 3.314 | 3.018 | 0.288  |                            | 2.560 | 3.343 |

|                           |             |           |           |           |           |           |           |           |           |           |               |           |
|---------------------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------------|-----------|
| Internal<br>CWFS<br>5423  | CW1<br>6_M2 | 4.2<br>00 | 3.4<br>75 | 3.5<br>12 | 3.5<br>39 | 4.4<br>21 | 3.9<br>10 | 3.8<br>43 | 0.4<br>01 | 3.55<br>7 | 3.<br>47<br>5 | 4.4<br>21 |
| Middle<br>CWFS<br>5423    | CW1<br>6_M2 | 3.4<br>90 | 3.1<br>62 | 4.0<br>02 | 3.4<br>39 | 3.4<br>95 | 3.2<br>55 | 3.4<br>74 | 0.2<br>92 |           | 3.<br>16<br>2 | 4.0<br>02 |
| External<br>CWFS<br>5423  | CW1<br>6_M2 | 3.8<br>42 | 3.5<br>20 | 3.7<br>53 | 3.0<br>00 | 3.5<br>70 | 2.4<br>35 | 3.3<br>53 | 0.5<br>37 |           | 2.<br>43<br>5 | 3.8<br>42 |
| Internal<br>CWFS<br>5423  | CW1<br>6_M3 | 4.7<br>96 | 4.1<br>40 | 4.4<br>27 | 3.9<br>88 | 4.4<br>46 | 4.2<br>04 | 4.3<br>34 | 0.2<br>86 | 3.80<br>2 | 3.<br>98<br>8 | 4.7<br>96 |
| Middle<br>CWFS<br>5423    | CW1<br>6_M3 | 4.1<br>27 | 4.0<br>14 | 3.0<br>97 | 3.0<br>46 | 3.7<br>36 | 4.7<br>03 | 3.7<br>87 | 0.6<br>38 |           | 3.<br>04<br>6 | 4.7<br>03 |
| External<br>CWFS<br>5423  | CW1<br>6_M3 | 3.2<br>50 | 3.2<br>59 | 3.1<br>07 | 3.3<br>74 | 3.1<br>37 | 3.5<br>86 | 3.2<br>86 | 0.1<br>75 |           | 3.<br>10<br>7 | 3.5<br>86 |
| Internal<br>CWFS<br>1233  | CW1<br>9_M1 | 3.3<br>39 | 3.4<br>68 | 4.0<br>56 | 4.3<br>28 | 4.5<br>71 | 4.0<br>28 | 3.9<br>65 | 0.4<br>80 | 3.83<br>9 | 3.<br>33<br>9 | 4.5<br>71 |
| Middle<br>CWFS<br>1233    | CW1<br>9_M1 | 3.6<br>67 | 3.8<br>86 | 4.7<br>19 | 3.5<br>01 | 3.5<br>61 | 4.0<br>38 | 3.8<br>95 | 0.4<br>51 |           | 3.<br>50<br>1 | 4.7<br>19 |
| External<br>CWFS<br>1233  | CW1<br>9_M1 | 3.7<br>38 | 3.7<br>88 | 3.5<br>57 | 3.9<br>30 | 3.6<br>51 | 3.2<br>73 | 3.6<br>56 | 0.2<br>26 |           | 3.<br>27<br>3 | 3.9<br>30 |
| Internal<br>CWFS<br>1233  | CW1<br>9_M2 | 3.5<br>89 | 4.3<br>12 | 4.4<br>57 | 4.1<br>48 | 3.9<br>17 | 5.2<br>76 | 4.2<br>83 | 0.5<br>75 | 3.63<br>3 | 3.<br>58<br>9 | 5.2<br>76 |
| Middle<br>CWFS<br>1233    | CW1<br>9_M2 | 3.3<br>63 | 3.6<br>46 | 3.3<br>45 | 3.9<br>73 | 3.5<br>97 | 3.1<br>56 | 3.5<br>13 | 0.2<br>88 |           | 3.<br>15<br>6 | 3.9<br>73 |
| External<br>CWFS<br>1233  | CW1<br>9_M2 | 2.8<br>48 | 3.1<br>48 | 2.9<br>96 | 3.1<br>97 | 3.1<br>01 | 3.3<br>22 | 3.1<br>02 | 0.1<br>64 |           | 2.<br>84<br>8 | 3.3<br>22 |
| Internal<br>CWFS<br>10311 | CW3<br>3_M1 | 3.0<br>44 | 4.3<br>27 | 5.1<br>56 | 4.3<br>49 | 4.9<br>20 | 5.2<br>65 | 4.5<br>10 | 0.8<br>20 | 4.16<br>8 | 3.<br>04<br>4 | 5.2<br>65 |
| Middle<br>CWFS<br>10311   | CW3<br>3_M1 | 3.8<br>20 | 3.7<br>87 | 4.1<br>38 | 3.5<br>45 | 3.5<br>35 | 4.1<br>24 | 3.8<br>25 | 0.2<br>65 |           | 3.<br>53<br>5 | 4.1<br>38 |

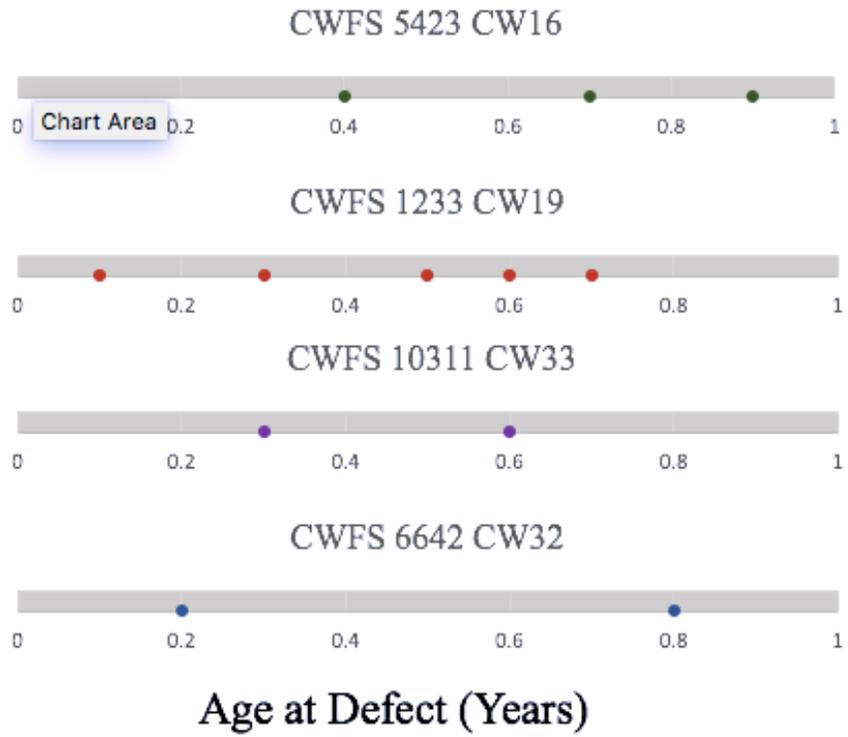
|                            |            |           |           |           |           |           |           |           |           |           |               |           |
|----------------------------|------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|---------------|-----------|
| External CWFS 10311        | CW3 3_M1   | N<br>A    | NA        | N<br>A    | N<br>A    | N<br>A    | N<br>A    | N<br>A    | N<br>A    | NA        | N<br>A        | NA        |
| Internal CWFS 10311        | CW3 3_M2   | 4.1<br>28 | 3.8<br>37 | 3.6<br>70 | 3.7<br>24 | 4.8<br>42 | 4.0<br>57 | 4.0<br>43 | 0.4<br>31 | 3.91<br>0 | 3.<br>67<br>0 | 4.8<br>42 |
| Middle CWFS 10311          | CW3 3_M2   | 3.9<br>04 | 4.0<br>62 | 4.3<br>82 | 3.8<br>33 | 4.1<br>28 | 3.4<br>58 | 3.9<br>61 | 0.3<br>12 |           | 3.<br>45<br>8 | 4.3<br>82 |
| External CWFS 10311        | CW3 3_M2   | 3.5<br>43 | 3.7<br>44 | 3.3<br>63 | 4.5<br>19 | 4.0<br>33 | 3.1<br>48 | 3.7<br>25 | 0.4<br>95 |           | 3.<br>14<br>8 | 4.5<br>19 |
| Internal CWFS 6642         | CW3 2_M1   | 3.9<br>15 | 4.6<br>57 | 3.3<br>86 | 4.4<br>30 | 4.3<br>19 | 4.4<br>17 | 4.1<br>87 | 0.4<br>62 | 3.66<br>9 | 3.<br>38<br>6 | 4.6<br>57 |
| Middle CWFS 6642           | CW3 2_M1   | 3.8<br>61 | 3.3<br>35 | 3.3<br>20 | 4.7<br>29 | 3.7<br>60 | 3.7<br>28 | 3.7<br>89 | 0.5<br>14 |           | 3.<br>32<br>0 | 4.7<br>29 |
| External CWFS 6642         | CW3 2_M1   | 2.5<br>12 | 3.2<br>35 | 3.0<br>67 | 3.3<br>09 | 3.1<br>65 | 2.8<br>93 | 3.0<br>30 | 0.2<br>92 |           | 2.<br>51<br>2 | 3.3<br>09 |
| Internal CWFS 6642         | CW3 2_C_RC | 2.3<br>63 | 2.6<br>40 | 3.1<br>70 | 3.3<br>89 | 2.9<br>17 | 2.5<br>75 | 2.8<br>42 | 0.3<br>88 | 3.40<br>2 | 2.<br>36<br>3 | 3.3<br>89 |
| middle CWFS 6642           | CW3 2_C_RC | 4.0<br>32 | 3.7<br>28 | 3.9<br>24 | 3.5<br>32 | 4.3<br>80 | 4.8<br>08 | 4.0<br>67 | 0.4<br>63 |           | 3.<br>53<br>2 | 4.8<br>08 |
| outer CWFS 6642            | CW3 2_C_RC | 3.1<br>56 | 4.2<br>20 | 4.0<br>02 | 3.0<br>80 | 2.7<br>12 | 2.6<br>04 | 3.2<br>96 | 0.6<br>69 |           | 2.<br>60<br>4 | 4.2<br>20 |
| internal lateral CWFS 6642 | CW3 2_C_RC | 2.6<br>89 | 3.2<br>49 | 3.1<br>60 | 3.2<br>82 | 2.6<br>94 | 3.1<br>31 | 3.0<br>34 | 0.2<br>71 | 3.71<br>6 | 2.<br>68<br>9 | 3.2<br>82 |
| middle lateral CWFS 6642   | CW3 2_C_RC | 3.9<br>88 | 3.3<br>11 | 3.5<br>20 | 4.3<br>85 | 3.7<br>90 | 3.1<br>63 | 3.6<br>93 | 0.4<br>54 |           | 3.<br>16<br>3 | 4.3<br>85 |
| external lateral CWFS      | CW3 2_C_RC | 4.4<br>20 | 5.4<br>54 | 4.7<br>86 | 3.6<br>90 | 5.1<br>90 | 2.9<br>80 | 4.4<br>20 | 0.9<br>38 |           | 2.<br>98<br>0 | 5.4<br>54 |

|      |  |  |  |  |  |  |  |  |  |  |  |  |  |
|------|--|--|--|--|--|--|--|--|--|--|--|--|--|
| 6642 |  |  |  |  |  |  |  |  |  |  |  |  |  |
|------|--|--|--|--|--|--|--|--|--|--|--|--|--|

Appendix Table 5: CWFS Tooth Type and Age with Tooth Types Highlighted by Colors

| Catalogue Number | Sample Number        | Tooth Type     | Age at Death (years) |
|------------------|----------------------|----------------|----------------------|
| CWFS 5158        | CW9_ M <sub>1</sub>  | M <sub>1</sub> | 4±1                  |
| CWFS 805         | CW21_ M <sub>1</sub> | M <sub>1</sub> | 7±2                  |
| CWFS 4611        | CW12_ M <sub>1</sub> | M <sub>1</sub> | young adult          |
| CWFS 4862        | CW14_ M <sub>1</sub> | M <sub>1</sub> | 10±2.5               |
| CWFS 3631        | CW27_ C_Tooth13      | Canine         | 10±2.5               |
| CWFS 5423        | CW16_ M <sub>1</sub> | M <sub>1</sub> | 15±3                 |
| CWFS 5423        | CW16_ M <sub>2</sub> | M <sub>2</sub> | 15±3                 |
| CWFS 5423        | CW16_ M <sub>3</sub> | M <sub>3</sub> | 15±3                 |
| CWFS 1233        | CW19_ M <sub>1</sub> | M <sub>1</sub> | 12±3                 |
| CWFS 1233        | CW19_ M <sub>2</sub> | M <sub>2</sub> | 12±3                 |
| CWFS 806         | CW22_ M <sub>1</sub> | M <sub>1</sub> | young adult          |
| CWFS 806         | CW22_ M <sub>2</sub> | M <sub>2</sub> | young adult          |
| CWFS 10311       | CW33_ M <sub>1</sub> | M <sub>1</sub> | 9±3                  |
| CWFS 10311       | CW33_ M <sub>2</sub> | M <sub>2</sub> | 9±3                  |
| CWFS 6642        | CW32_ M <sub>1</sub> | M <sub>1</sub> | 8±2                  |
| CWFS 6642        | CW32_ M <sub>2</sub> | M <sub>2</sub> | 8±2                  |
| CWFS 6642        | CW32_ C_RC           | Canine         | 8±2                  |

# First Molar Timeline of AL



Appendix Figure 23: CWFS First Molar AL Timeline by Individual in Years

## Second Molar Timeline of AL

CWFS 5423 CW16



CWFS 1233 CW19



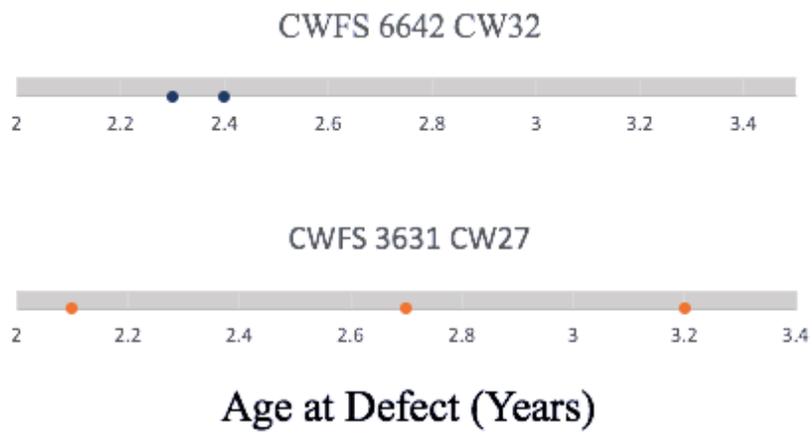
CWFS 10311 CW33



Age at Defect (Years)

Appendix Figure 24: CWFS Second Molar AL Timeline by Individual in Years

## Canine Timeline of AL



Appendix Figure 25: CWFS Canine AL Timeline by Individual in Years

## Timeline of AL Prior to Violent Death



Appendix Figure 26: Timeline for Total CWFS AL by Individual in Years. Zero represents the day of death. Negative years represent the years prior to the violent death event. AL are represented as colored circles for each individual. This graph assumes the individuals from Horizon 2 were deposited in a single event with relatively concurrent deaths.

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Emily M. Smith received her Bachelor of Arts from California State University, Monterey Bay in 2018. She aspires to become a professor to continue her extraordinary mentor's legacies of inspiring students to follow passions for the social sciences and biology.