A Trace Element Analysis of Lead in Human Tooth Enamel from Wadi Faynan 100, Jordan

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The environmental pollution that persists in the Wadi Faynan region of Jordan can be attributed to copper mining and smelting activities that flourished during the Early Bronze Age I (EBAI) (ca. 3600-3000 BCE). Previous surveys and limited excavations at the site of Wadi Faynan 100 (WF100) sought to understand the context this site and its role in copper metal production, but research has yet to be done on the individuals living there during the EBAI. This study examines lead (Pb) concentrations in human dental enamel to explore changes in exposure throughout individuals' development using Laser Ablation Inductively-coupled Plasma Mass Spectrometry (LA-ICP-MS). There are 17 samples from 15 individuals recovered from 5 different graves. Although 3 samples were excluded from analysis due to diagenetic alterations in the Ca/P, others provided insights on the variable nature of Pb exposure at WF100. The samples were categorized into 4 patterns of exposure: none (n=6), decreasing (n=2), and increasing (n=2) Pb exposure with age, and variable exposure (n=4). The results reveal that the pollution exposure for children is more variable than expected. It is likely that majority of these individuals may not have had direct involvement in the copper mining and smelting activities that may have occurred in Wadi Faynan 100.

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List of Abbreviations

BIAAH – British Institute at Amman for Archaeology and History

BLP – Barqa Landscape Project

EBA – Early Bronze Age

EBAI – Early Bronze Age I

EBAII – Early Bronze Age II

LA-ICP-MS – laser ablation inductively coupled plasma mass spectrometer

MIG - Metal Isotope and Geochemistry Lab

MNI – Minimum Number of Individuals

TE – Trace element

WF100 – Wadi Faynan 100

Chapter One

Exploring the Ancient and Ongoing Impacts of Environmental Pollution

1.1 Introduction

My thesis project is motivated by the legacy of environmental pollution that persist from copper mining and smelting activities that began to flourish in the Early Bronze Age (EBA) (ca. 3600-3000 BCE) in Wadi Faynan, Jordan. The goal of my thesis is to explore the role of trace elements[1] (TE) exposure, focusing primarily on lead (Pb), via analysis of tooth enamel derived from individuals buried at Wadi Faynan 100. More specifically, this work will determine whether Pb was introduced into the enamel, how Pb uptake varies between individuals, and the potential health impacts of Pb exposure for those living at WF100 during the Early Bronze Age I (EBAI). This work is essential in that it provides the first direct exploration of the impacts of paleopollution at WF100. Furthermore, this will be the first project that explores changes in exposure throughout the individual's development during the EBA in Jordan while using a microspatial analysis that is of relatively non-destructive technique.

There are several issues that revolve around environmental pollution in Faynan. In order to quantify and assess the legacy of environmental pollution that exists in the contemporary Faynan region, there must first be an understanding of the variation in TE uptake and potential health implications in the past. The existence of copper mining and smelting activities is well-documented by scholars of archaeometallurgy (Hauptmann, 2007; Grattan et al., 2005), archaeology (Wright, 1998; Barker et al., 2007; Philip, 2008; Adams, 2008; Adams et al., 2019),

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[1] Trace elements are elements that have comparably low concentrations within a sample such as zinc, copper, and iodine concentrations within the human body

and modern and ancient faunal samples (Pyatt et al., 2005; Perry et al., 2011). By obtaining important details of how the environmental pollution became embedded into the local environment, there may be strategies in the future for remediation.

Since there is a call to observe and analyze ancient skeletal remains to understand environmental pollution today, there is motivation to preserve and document the available skeletal remains from archaeological excavations. It is known throughout the Faynan region that archaeological sites such as WF100 are subject to looting and agricultural development (e.g., farming) (Findlater et al., 1998; Adams et al., 2019); therefore, damaging or destroying the human remains within, and any ability to directly explore individuals' experiences with pollution. Through my thesis research, I will highlight the complexities of surveying the contemporary Faynan environment to study ancient environmental pollution while emphasizing preservation and documentation of ancient skeletal samples.

1.2 Remediation Complexities and Health Effects of Environmental Pollution

It is known that through copper mining and smelting processes, heavy metals are slowly released into the environment. Heavy metals are metallic elements with high density (e.g., lead [Pb] and copper [Cu]) that often contribute to pollution and may be toxic to human health (Tchounwou et al., 2014). Moreover, as heavy metals become embedded in the surrounding sediments, mobilization of these heavy metals occurs through weathering, natural processes (i.e., animal waste), and anthropogenic activities (Bradl, 2005; Barker et al., 2007; Pyatt et al., 2005; Pyatt et al., 2000). Thus, the local fauna and vegetation carry high concentrations of toxic metals as a result of bioaccumulation. A study done by Pyatt and colleagues (2005) compared the lead content of modern and ancient faunal remains in the Wadi Faynan region, finding that modern goat molar enamel contained 109mg/kg of lead whereas the ancient goat molar enamel was revealed to have 203mg/kg of lead. In order to quantify the elevated concentrations observed in both the modern and ancient samples, a control goat molar enamel was extracted 12km away where pollution is not prominent (Pyatt et al., 2005). The lead concentration in the control goat molar enamel was 49mg/kg. From these results, it is clear that heavy metal pollution is significant, and persists, in the modern Faynan environment.

The question, then, becomes at what concentration and the bioavailability[2] in the environment (e.g., in air, soils, plants, animals, water, household objects) do heavy metals become toxic to humans? This question in of itself is complex as some heavy metals, such as copper, are essential to maintain homeostasis and thus undergo homeostatic regulation[3]. Consequently, the copper concentration in tooth and skeletal samples determined through experimentation may not be a true representation of the individual's exposure. Furthermore, how severe the toxicity is will be subject to an individual's age, sex and/or gender, genetics, nutritional status, activities, route of exposure, and dosage of the heavy metal in question (Tchounwou et al., 2014), causing inter- and intra- individual variation along with the possibilities for human adaptation throughout the decades. Thus, quantifying the toxicity and exposure for a group of individuals is a complex process.

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[2] The accessibility of heavy metals in the environment that allows for uptake of other living organisms. For example, Pb that is dissolved in groundwater can be ingested by humans and other animals (Dr. Chris Yakymchuk, personal communication)

[3] The process of self-regulation within the body to maintain optimal conditions; meaning excess copper will be excreted

WF100 individuals may have had direct exposure to toxic heavy metals as well as other by-products (e.g., mercury and formation of oxides) as a result of participating in copper smelting activities (Shu et al., 2021). The individuals who were living in WF100 during the EBA may have been involved in metallurgic activities such as bringing copper ores to the site, breaking and smelting the ores, and transforming the resulting metal into objects, with mining being the most likely first exposure (Barker et al., 2007; Dr. Russell Adams, personal communication). Whether working directly in metallurgic production or not, Pb exposure and uptake by bodily tissues can occur via various routes, including inhalation and/or ingestion of metal contaminated foods, and water, and dust (Pyatt et al., 2005). The TE in question, Pb, is a major contributor to environmental pollution as it is an “environmentally persistent element” (Gillis et al., 2012). Once Pb enters and is absorbed by the individual’s respiratory and gastrointestinal systems, it accumulates in the liver, aorta, brain, lungs, and is stored in teeth and bones over time (Gillis et al., 2012). As mentioned previously, the concentration at which Pb becomes toxic is dependent on the individual. According to the World Health Organization, “there is no known ‘safe’ blood lead concentration; even blood lead concentration as low as 5µg/dL” can cause irreversible damage to humans, especially children (World Health Organization, 2019). Lead poisoning symptoms slowly worsen as the concentration accumulates; starting with general fatigue, headaches, vomiting, and can eventually damage kidney function and interfere with hemoglobin synthesis (Bradl, 2005). In the case of pregnant women, any Pb that is present in the skeleton becomes mobilized into the tissues of the developing fetus; subjecting the fetus to increased risk for premature birth, and disabilities associated with mental (e.g., intellectual disability), cognitive (e.g., memory loss), and behavioural development (e.g., attention deficit/hyperactivity disorder [ADHD]) (Rísová, 2020).

The affiliated symptoms of Pb exposure give rise to the question: what health effects is the contemporary population of Faynan faced with given that it is well known that the landscape is still polluted? There are several strategies for remediation to combat heavy metals in the environment (see Bradl, 2005). This would be beneficial for the community as the local inhabitants of the Wadi Faynan region have become more sedentary in comparison to the nomadic to semi-nomadic lifestyle that was practised during the EBAI (Philip, 2008; Barker et al., 2007;). Although researching the local Bedouin in Faynan would be ideal to understand the legacy and impacts of the environmental pollution, there are ethical and political complications in regard to the solution and remediation that would not be supported by the government (Drs. Russell Adams & John Grattan, personal communications). The individuals who would potentially be involved in this contemporary research could not physically act on any alarming information as the researchers cannot provide relief because of political challenges. Although additive pollution from other periods (e.g., Roman) may be present in the environment, the EBAI WF100 work gives insight on a period when pollution was just beginning to be problematic in the environment.

1.3 Documenting and Preserving Samples

As previously discussed, the WF100 samples are important to understandings of the legacy of environmental pollution and how the contemporary concentrations may differ. It is, therefore, imperative that ancient samples, such as WF100, are preserved and well-documented. It is detailed in the heritage literature that many excavation sites in the southern Levant have been looted prior to excavation (Findlater et al., 1998; Adams et al., 2019; Barker et al., 2007). Many skeletal remains were found to be damaged and fragmented; thus, making it more difficult to identify individuals. Furthermore, environmental (e.g., erosion) and anthropogenic (e.g., farming) factors contribute to damages of ancient remains.

Fragmented and commingled remains are often subject to poor storage due to outdated assumptions about the quality of data that can derived from such remains, ensuring further damage to the samples (Sheridan, 2017). This is unacceptable as ancient remains are irreplaceable and rare as observed from the sparse collections of the southern Levant, apart from the well-documented Bāb edh-Dhrā collection (Lapp, 1968; Lapp, 1966; Ortner & Frohlich, 2007; Rast & Schaub, 1979; Bentley & Perry, 2008; Sheridan et al, 2014). By incorporating data from fragmented and commingled remains, it is possible to offer insights on "unique demographic profiles, gender relations, food preferences, disease stressors, medical abilities, activity patterns, family relations, heritage, or belief systems" that will further extend our knowledge about individuals in the southern Levant (Sheridan, 2017:121). The WF100 collection, for example, also contains a majority of fragmented and commingled samples, yet it has been possible to analyze the Minimum Number of Individuals (MNI), dental non-metrics and metrics, tooth development, dental wear, and pathology, thus far (DiBiase, 2020; Tucciarone, 2020).

As technology advances, opportunities to study commingled remains in new ways and gain new insights about past peoples have demonstrated that it is necessary to preserve all remains regardless of condition. This thesis, for example, used a minimally destructive technique called Laser Ablation Inductively-coupled Plasma Mass Spectrometry (LA-ICP-MS) to perform microspatial analyses that aids in the determination of Pb exposure throughout an individual’s development. As mentioned previously, this is the first project to do so anywhere in Jordan. The Department of Antiquities in Jordan have also acknowledged the rich heritage that exists in the nation and thus is willing to protect potential excavation sites around the WF100 area from farming (Adams et al., 2019). Preserving samples can be done through proper storage and documentation, using fragmented samples when possible, and using non-destructive or minimally destructive techniques when extracting elemental or isotopic data from ancient skeletal samples.

1.4 Conclusion

The copper mining and smelting activities in Wadi Faynan are historic as they have the potential to reveal a plethora of information regarding the lifestyle and struggles of individuals during the EBAI. The WF100 collection, therefore, must be documented carefully and preserved with careful storage and using minimally destructive analytical techniques. It is evident through the actions of the Department of Antiquities that Jordan is a nation that values its heritage. Through this current research on lead pollution via analyses of WF100 dental enamel, I will demonstrate how Pb was introduced into developing tissues, how Pb varies between individuals, and the possible health impacts of those living at WF100 during the EBAI; and as a result, contributing knowledge to Jordan’s rich history.

1.5 Venue for Publication

The journal *Science of the Total Environment* is my proposed venue for publication. This peer-reviewed journal emphasizes an interdisciplinary approach to understand the complex relationship between the environment and humankind. My research questions the degree of toxicity and health effects that inhabitants of Wadi Faynan 100 individuals may have faced during the Early Bronze Age which aligns with the focal point of this journal.

Chapter Two

Lead Analysis of the Dental Enamel of the Individuals from Wadi Faynan 100

2.1 Introduction: Site History

Wadi Faynan 100 initially attracted researchers at the British Institute at Amman for Archaeology and History (BIAAH) due to the sizeable walls that might indicate a “single settlement complex” (Barker et al., 2007:236). To assess whether the WF100 site was indeed a settlement zone, a landscape survey was first conducted in 1994 and 1995 by Barker and colleagues, followed by excavations in 1996 and 1997 led by Katherine Wright (Wright et al., 1998; Barker et al., 2007). The large collection of surface material (e.g., pottery and lithics) gathered during Wright’s excavations dates the WF100 site to the Early Bronze Age I (Barker et al., 2007; Adams et al., 2019; Wright et al., 1998). The result of the series of excavations discovered a suite of EBAI features such as “pits, fire installations, ephemeral walls, occupation surfaces, and a small structure with storage bin” as well as “a complex of [EBAI] buildings” that lead Wright to conclude that the WF100 site was a domestic settlement (Wright et al., 1998:58). This conclusion, however, is not supported by other researchers.

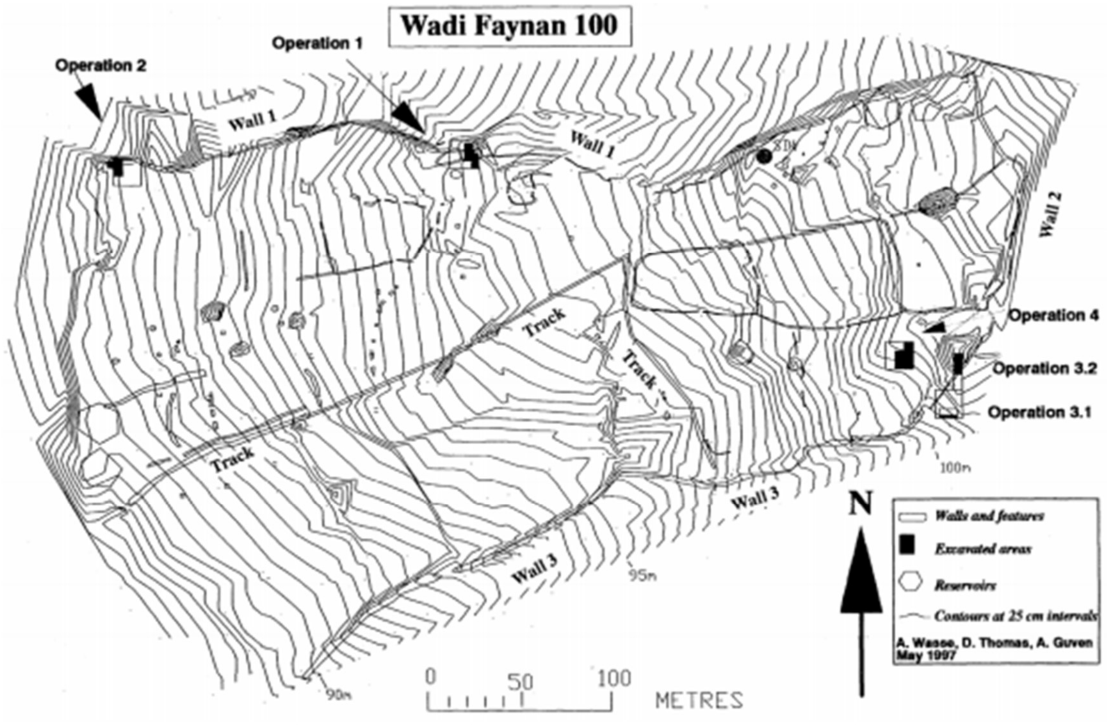

Figure 1- Wadi Faynan 100 Landscape (Wright et al., 1998:35)

Barker and colleagues continued to examine the landscape as part of the *Wadi Faynan Landscape Survey* (1996-2000) and revealed that there is little evidence for EBA domestic activity, contrary to Wright's conclusions. Apart from one area of the site that perhaps contained a structure which resembled domestic activity, a large portion of WF100 contained concentrated funerary complexes (Barker et al., 2007). Upon further investigation of the surface material, the use of the WF100 site is interpreted to consists of crafts (e.g., potting, weaving, and making stone vessels) and food production activities, in addition to metallurgical activities (e.g., smelting copper, and producing copper objects). Owing to the fact that WF100 is located about 15 kilometres away from a copper mine as well as the evidence of variety of activities that occurred on site, Barker et al (2007) suggests that there were "powerful individuals or groups at WF100 controlling both the metal-extraction process and trade in copper and copper artefacts with the outside world" (268).

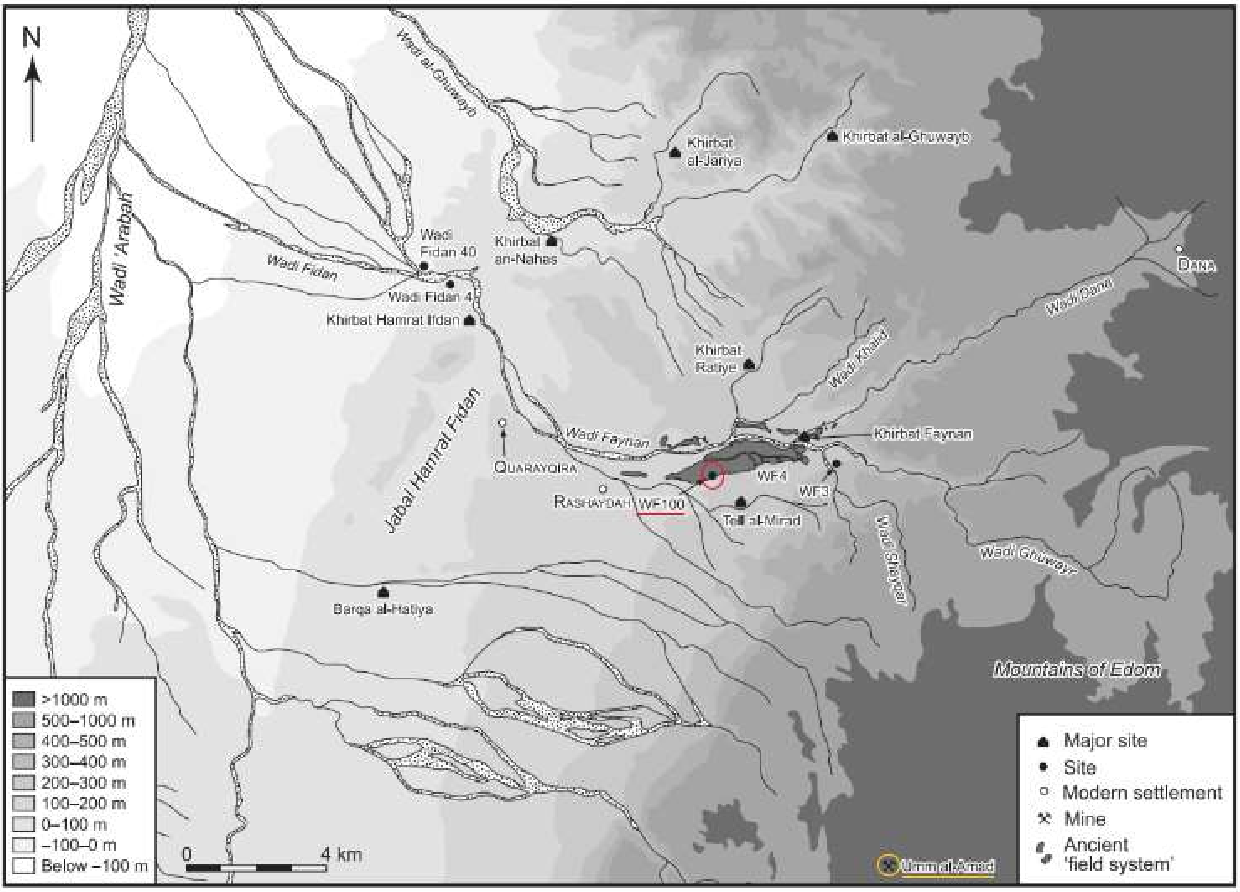

Figure 2 - Wadi Faynan 100 (WF100), indicated by the red circle, distance from the Umm al-Amad mine, indicated by the yellow circle (Barker et al., 2007:5)

The suggestion by Barker and colleagues (2007) may have been due to the history of copper mining production during the EBAI. The production of copper goods did not begin to develop into an industrialised scale until the beginning of the Early Bronze Age II (EBAII) (c. 2900 BC) (Adams, 2002). It has been suggested that the low-scale production of copper goods throughout the EBAI may be isolated to specific families or individuals as this process may have been "highly specialised and restricted knowledge" (Adams, 2002: 21; Levy, 1995). This can be seen through the archaeological evidence found at Wadi Fidan 4, a nearby EBAI site, where remnants of copper production (e.g., droplets of copper, slag, clay crucible fragments with adhering slag and melted copper) were only densely packed around and in specific building structures (Adams, 2002).

2.2 Barqa Landscape Project and the Wadi Faynan 100 Cemetery

The Barqa Landscape Project (BLP) also suggests that WF100 is not simply a domestic activity site. In 2019, BLP surveyed the landscape, concluding that the WF100 area contains "evidence of metallurgy as well as a significant number of tombs of a variety of types, including cist and megalithic tombs, possibly surrounded by large enclosing walls" (Adams et al., 2019:8). One of the goals of the BLP was to deepen the understanding of copper smelting and production activities that occurred in the Faynan region along with how these activities impacted the environmental pollution of the area. Upon the discovery of stone-built charnel houses near the main Faynan village, the BLP team was able to recover human skeletal remains that could potentially reveal the effects of copper smelting and production on an ancient population in the EBAI.

The Wadi Faynan 100 excavations of 2019 examined 5 graves clustered nearby each other, all of which were looted to some degree prior to excavation. The entrance to Grave 1 is marked by a steppingstone with two larger stones on either side of it (Adams et al., 2019). The grave itself was roughly 1.8m (north to south) by 1.2m (east to west) in size, with a depth of 25cm. Within this grave, fragments of human skeletal remains represented an adult in addition to one subadult cranial fragment, and fragments of a vessel. To the west of Grave 1, smaller stones can be seen at the entrance of Grave 2. The size of Grave 2 is roughly measured to be 1.5m (north to south) by 1m (east to west), with a depth of 10cm. There was a small amount of fragmented adult human remains that was recovered from Grave 2, including an intact mandible. A small basalt mould was also retrieved from this grave. The entrance to Grave 3 can be noted by one steppingstone with two larger stones, about 80cm in height from ground level, on either side of it, similar to Grave 1, but much larger. The dimensions of Grave 3 was approximately 3m (north to south) by 1.5 (east to west), with a depth of 1m. Fragmented human and faunal remains were found in Grave 3, including a cranial and postcranial remains from a subadult, and articulated metatarsals, phalanges, and tarsals from one adult. Teeth were retrieved from the subadult mandible. Most notably, several beads (Figure 3) were recovered in situ near the neck and shoulder of the subadult remains, as well as two small complete vessels within Grave 3. Grave 4 was outlined by the stone walls, but no human remains and limited artefacts found in this grave, a question arises if this grave was used for the purpose of being a grave. Grave 4 was roughly 1.5m (north to south) by 1m (east to west), with a depth of 20cm. Lastly, Grave 5 is located to the east of Grave 4. The dimensions of Grave 5 was roughly 2m (north to south) by 1.2m (east to west), with a depth of 35cm. Interestingly, Grave 5 has a double stone wall (Figure 4) that outlined this grave. Inside it, three flat stones were visible where disarticulated human bone were found beneath. Furthermore, three adult crania were discovered, as well as two fragments of occipital and frontal bone of a juvenile cranium. The 3 crania were placed together in the northeast corner of the burial, facing east. Along with other fragmented human and faunal bones, a vessel, fragmented of copper casting mould, and a copper awl were also retrieved from this grave. The most essential recovery amongst all the graves were the dental remains as they serve as the key into illuminating the environmental exposure this ancient population was exposed to during the EBAI.

Figure 3 – Beads found in situ with subadult internment in Grave 3 (Adams et al., 2019:14)

Figure 4 - Grave 5 at Wadi Faynan 100 (Adams et al., 2019:16)

2.3 The Use of Human Dental Enamel to Explore Pb Exposure

Although teeth are comprised of three distinct tissues (i.e., enamel, dentine, and cementum) (Simpson et al., 2020), bioarchaeologists prefer to analyze the enamel and dentin tissues. Enamel is chemically inert and rigid in structure (96% inorganic and 4% organic constituents) (Burton, 2008; Kohn et al., 1999) and incrementally develops as the individual ages, with formation completing by the time the crown erupts and does not undergo remodelling (Aurora & Austin, 2013). Possible ionic exchange may occur with *in vivo* interactions between the enamel crown and the saliva during the mineralization and demineralization periods of enamel (Simpson et al., 2020), but only impacts the outer 50-100 microns of surface enamel. Moreover, there are methodological procedures that can potentially remove diagenetic elements on the surface enamel (e.g., pre-ablating the surface of the enamel using LA-ICP-MS) and ways to decrease the chances of encountering diagenetically altered enamel (i.e., collecting data away from the surface enamel and closer towards the enamel-dentin junction). In comparison, dentin and cementum are more likely to have problems with diagenesis due to their chemical and physical structure.

In contrast to carbon (C), hydrogen (H), nitrogen (N), and oxygen (O) that compose 96.5% of all living organisms (Telser, 2002), trace elements are found in considerably smaller concentrations. As enamel grows incrementally throughout an individual's development, trace elements will usually substitute for an abundant element with similar chemical properties within a compound or crystal structure (Gagan & Abram, 2011). Trace elements can be divided into categories of essential and non-essential regarding their roles in maintaining homeostasis within the body. Homeostasis is the complex act of the chemical and physical mechanisms within the internal milieu of the human body that uphold a balance to ensure survival (Modell et al., 2015). This means that essential trace elements introduced into the body may be subject to altered elemental concentrations due to homeostatic regulation. It is, therefore, advantageous and a less complex process to choose elements to that are non-essential to avoid erroneous conclusions based on skewed data results. In regard to copper smelting and production, there are quite a few elements that can help measure the impact of copper smelting through the elements found in raw copper ores such as copper, nickel, arsenic, lead, bismuth, zinc, and antimony; but not all sources of copper contain all these elements (Nikolić et al., 2009). Among these elements, lead in particular stands out as it has no known biological function within the human body and is often associated with environmental pollution (Gillis et al., 2012; Flora et al., 2012).

With the evidence provided, analyzing the human dental enamel to explore Pb exposure is the best choice given that the tooth samples are from the EBA and could be subject to diagenesis. Given the excellent preservation of dental enamel, it's absorption of trace elements during formation and its known timing of incremental growth, this tissue provides an ideal opportunity to study Pb exposure over the development of individuals from WF100.

2.4 Methodology

2.4.1 Sample Selection Process

Each tooth sampled was chosen from the WF100 dental collection that was excavated in 2019 (see Tucciarone 2020 for more details regarding this collection). Teeth chosen were well preserved and had little to no wear of the enamel. Teeth that are known to come from different individuals were prioritized to ensure that teeth belonging to the same person were not sampled twice. In three instances, a second tooth from an individual was also sampled so as to allow for analysis of a longer period of lead exposure for each individual. In total 17 tooth samples used for analysis is listed in Table 1.

Tooth Identification[a]	**Tooth Type[b]**	**Age (years)**	**Notes**
19.1.1.010	C^1	4.5 +	Has linear enamel hypoplasia, 3 lines
19.2.1.002	M_1	4.5 +	
19.2.1.003	M_1	4.5 – 5.5	
19.3.1.016	Ri^2	2.5 – 5.5	
19.3.1.077	RI^2	> 8.5	
19.3.2.091	RI^2	8.5 +	
19.3.3.113	I	Unknown	Associated with subadult skeleton found in Grave 3
19.3.99.154	RI^2	6.5	
19.3.99.167	RI^2	10.5 +	
19.3.99.172	Ri^1	2.5 – 5.5	
19.5.4.028	RM^1	9.5 +	Belongs to individual 2
19.5.4.031	RM^1	9.5 +	Belongs to individual 3
19.5.4.032	RM^1	3.5 – 4.5	Belongs to individual 4
19.5.4.014	M	Unknown	Belongs to individual 1
Tooth Samples to Extend Period of Development			
19.3.3.121	m	Unknown	Associated with subadult skeleton found in Grave 3
19.5.4.024	LM^3	22.4 +	Belongs to individual 2
19.5.4.033	Rm^2	2.5 – 10.5	Belongs to individual 4

Table 1 – Summary of sample collection including additional notes. Retrieved from Julia Tucciarone's 2020 MA Thesis and the WF100 Dental Inventory at ACEBioLab in the University of Waterloo. [a]Tooth identification is created as follows: "Year of excavation". "Grave number". "Locus number". "Tooth number". [b]The key to "Tooth Type" is as follows: "R" or "L" at the beginning represents the side of the mouth the tooth is on. The second letter represents the type of tooth (e.g., M = molar; C = canine; I = incisor). The capital letter represents that it is a permanent tooth, whereas a lowercase letter means it is a deciduous tooth. Lastly, the superscript number represents that the tooth is on the maxilla, whereas the subscript number represents that the tooth is on the mandible. The number is according to which tooth it is (e.g., there are three polars, two premolars, and two incisors)

2.4.2 Sample Preparation for LA-ICP-MS

Tooth samples were photographed on all sides for documentation prior to the preparation process using an Olympus BX53M Upright Microscope. Peel-a-Way plastic moulds were inscribed with the tooth identification number and each tooth sample was placed inside using putty. EpoFix Resin and hardener (Struers) were mixed by weight using a 25:3 ratio and stirred slowly with a wooden stick until the solution appeared transparent. The resin was slowly poured into the labeled moulds containing the tooth samples, then placed under a vacuum for 20 minutes and left to cure for 48 hours. Afterwards, the plastic moulds were taken off and each resin block was labelled using a scriber. Each sample was placed in a chuck to prepare for sectioning. The chuck was attached to a flange at a 45^o angle to the blade and cut longitudinally into 1.5mm thin sections using a Buehler Isomet slow-speed saw. The thin sections were then polished using a Buehler EcoMet 30 Manual Twin Grinder Polisher to ensure a flat and even surface. The thin sections were mounted on petrographic slides using Crystalbond adhesive.

2.4.3 LA-ICP-MS Specifications

Tooth samples were analyzed using an Agilent 8800 QQQ-ICP-MS in sequence with an Analyte G2 193mm Excimer laser ablation unit in the Metal Isotope Geochemistry Lab (MIG) at the University of Waterloo. Detailed operating conditions of both instruments are summarized in Table 2. A line analysis was conducted on the enamel for each tooth as well as 2-7 spots on the dentin. The reference materials include NIST 610, NIST 612, and fragments of Durango apatite. The internal standard used for both dentin and enamel is ^{43}Ca, with an assumed concentration of 39.4 wt. % Ca.

For enamel line analysis, a preablation line removing surface contamination was performed with an 85µm diameter laser spot operating at 2 J cm^{-2}, frequency of 20Hz, and a scan speed of 100µm sec^{-1}. Reference materials were ablated for 30 seconds every 3-4 unknowns. Teeth samples were ablated using a laser scan speed of 10µm sec^{-1}, a frequency of 20Hz, and a fluence of 4J cm^{-2}, with a circular spot diameter of 15 and 65µm. The 15 µm analysis was to determine major element rations (^{43}Ca and ^{31}P) as well as ^{208}Pb and ^{238}U. The larger (65 µm) transect was to analyze various trace elements (Table 2). The larger laser spot scan was performed on top of the 15 µm diameter ablation trail run to maintain spatial consistency between the two transects. The first set was using a 15 µm laser beam. For the smaller beam, the following masses were measured with integration times in parentheses: ^{208}Pb (20ms), ^{238}U (20ms), ^{31}P (10ms), ^{43}Ca (10ms). For the larger beam (65 µm), the following masses were measured: ^{43}Ca (10ms) and 20ms integration times for: ^{47}Ti, ^{49}Ti, ^{51}V, ^{53}Cr, ^{55}Mn, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{75}As, ^{77}Se, ^{95}Mo, ^{107}Ag, ^{111}Cd, ^{117}Sn, ^{121}Sb, ^{193}Ir, ^{197}Au, ^{202}Hg, ^{205}Tl, ^{208}Pb, ^{209}Bi, and ^{238}U. The enamel line was ablated as close to the dentine-enamel junction as possible, avoiding any cracks. In sample 19.2.1.**002**, two enamel lines were ablated to avoid ablating over a visible crack.

Photon Machines 193nm ArF excimer laser	
Cell	Two volume Helex cell
Sample transport tubing	1.5 m length (to Agilent), PTFE 2 mm x 4 mm
MFC 1	0.375 L min^{-1} (He)
MFC 2	0.125 L min^{-1} (He)
MFC 3	0.85 min^{-1} (Ar)
Washout time	<1 s
Wavelength	193 nm ArF
Fluence	4 J cm^{-2}
Spot size	15, 20 and 65 µm diameter circle
Scan speed	10 µm s^{-1} (line)
Repetition rate	20 Hz (line), 8 Hz (spot)
Duration	20 seconds (spot)
Agilent Technologies 8800 ICP-MS Triple Quadrupole	
RF power	1550 W
RF matching	1.80 V
Sample cone	Nickel (x-lens)
Skimmer cone	Nickel (x-lens)
Sample depth	3.7 mm
Dilution gas	0.24 L min^{-1} (Ar)
Reflected power	12 W
Masses measured (integration times)	(1) 15 µm (line) and 20 µm (spot): ^{208}Pb (20 ms), ^{238}U (20 ms), ^{31}P (10 ms), ^{43}Ca (10 ms) – 60 ms total integration time. (2) 65µm (line and spot): ^{43}Ca (10 ms), 20 ms for: ^{47}Ti, ^{49}Ti, ^{51}V, ^{53}Cr, ^{55}Mn, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{75}As, ^{77}Se, ^{95}Mo, ^{107}Ag, ^{111}Cd, ^{117}Sn, ^{121}Sb, ^{193}Ir, ^{197}Au, ^{202}Hg, ^{205}Tl, ^{208}Pb, ^{209}Bi, and ^{238}U.
Scan type	Single Quadrupole mode

Table 2 - Instrument Parameters. Retrieved through personal communication from Dr. Chris Yakymchuk at the University of Waterloo

2.4.4 Analysis of Diagenesis

Diagenesis is the substitution and adsorption of ions in the mortuary environment that causes the original elemental concentration in skeletal sample to change (Liberman & Meadow, 1992) and is likely to occur in ancient skeletal material. According to Szostek and coworkers

(2012), “in diagenetically unchanged bone or tooth, the Ca/P should fall within 1.8-2.7” (p. 101). Therefore, the Ca/P was calculated for the enamel data using Durango apatite reference material to normalize the data. From the enamel lines, a majority of the tooth samples obtained data points that fall within the 1.8-2.7 acceptable ratio, with the exception of four tooth samples whose Ca/P averages fall outside of this acceptable ratio: 19.3.2.091 (RI^2), 19.3.1.077 (RI^2), 19.3.1.016 (Ri^2), and 19.5.4.028 (RM^1). This suggests that these tooth samples have been diagenetically altered and may not accurately reflect the individual’s lead exposure throughout their lifetime. The summary for Ca/P mean calculation for enamel is in Table 3.

Tooth Identification	**Ca/P Mean[a] ± SD[b]**
19.1.1.010	N/A[c]
19.2.1.002 (Enamel line 1)	1.88 ± 0.12
19.2.1.002 (Enamel line 2)	1.91 ± 0.15
19.2.1.003	1.83 ± 0.15
19.3.1.016	**1.75 ± 0.23**
19.3.1.077	N/A
19.3.2.091	**1.74 ± 0.15**
19.3.3.113	1.82 ± 0.15
19.3.99.154	1.88 ± 0.16
19.3.99.167	1.84 ± 0.18
19.3.99.172	N/A
19.5.4.028	**1.76 ± 0.11**
19.5.4.031	1.82 ± 0.12
19.5.4.032	1.81 ± 0.13
19.5.4.014	1.87 ± 0.09
19.3.3.121	1.89 ± 0.13
19.5.4.024	1.92 ± 0.12
19.5.4.033	1.90 ± 0.10

Table 3 - Summary of Ca/P values for enamel where the bolded lines represent values outside of the acceptable 1.8 - 2.7 Ca/P range. [a]Arithmetic mean was used for calculations; [b]SD = Standard deviation; [c]N/A values means all the of the data are below 1ppm and could not calculate a Ca/P

2.4.5 Data Reduction

Concentrations below 1ppm are not considered further. Furthermore, any spikes in data were removed as these may be due to the instrument fluctuation rather than values reflecting the sample. The sample initially consisted of 17 samples, but 4 tooth samples were removed due to being diagenetically altered: 19.3.2.**091** (RI^2), 19.3.1.**077** (RI^2), 19.3.1.**016** (Ri^2), and 19.5.4.**028** (RM^1).

2.5 Results

Within this sample, there are four types of patterns that can be observed over developmental time within the enamel of the WF100 teeth sampled: 1) no Pb exposure; 2) decreasing Pb exposure with age; 3) increasing Pb exposure with age; and 4) variable exposure. A summary of enamel Pb concentrations and the corresponding descriptive statistics can be seen in Table 4.

Tooth Identification	Tooth Type	Mean[a] (ppm)	SD[b]	Range (ppm)	Ca/P[c] Mean ± SD
No Pb exposure					
19.1.1.010	C^1	N/A[d]	N/A	N/A	N/A
19.2.1.003	M$_1$	1.2	0.4	1.0 – 2.6	1.83 ± 0.15
19.3.1.077	RI^2	N/A[d]	N/A	N/A	N/A
19.3.99.154	RI^2	1.7	0.4	1.1 – 2.3	1.88 ± 0.16
19.3.99.172	Ri^1	N/A[d]	N/A	N/A	N/A
19.5.4.024	LM^3	1.1	0.1	1.0 – 1.2	1.92 ± 0.12
Decreasing Pb exposure with age					
19.3.2.091*	RI^2	1.5	0.4	1.0 – 2.4	1.74 ± 0.15
19.5.4.028*	RM^1	2.2	0.6	1.0 – 3.6	1.76 ± 0.11
Increasing Pb exposure with age					
19.3.99.167	RI^2	1.7	0.6	1.0 – 4.9	1.84 ± 0.18
Variable Exposure					
19.2.1.002	M$_1$	1.6	0.4	1.0 – 3.0	1.89 ± 0.14
19.3.1.016*	Ri^2	4.4	5.7	1.0 – 36.8	1.75 ± 0.23
19.5.4.031	RM^1	1.3	0.4	1.0 – 3.5	1.82 ± 0.12
19.5.4.014	M	1.3	0.2	1.0 – 2.0	1.87 ± 0.09
19.5.4.032	RM^1	1.8	0.5	1.0 – 3.4	1.81 ± 0.13
19.5.4.033	Rm^2	1.7	0.6	1.0 – 4.0	1.90 ± 0.10
19.3.3.121	m	11.6	9.2	1.0 – 30.8	1.89 ± 0.13
19.3.3.113	I	11.6	11.0	1.0 – 44.1	1.82 ± 0.15

Table 4 - Summary of enamel Pb concentration for each tooth sample
[a]Arithmetic mean; [b] SD = Standard Deviation; [c]Ca/P used to identify possible diagenesis; [d]All of the data are below 1ppm, indicating that these individuals had no Pb exposure; *These samples were removed due to being diagenetically (i.e., Ca/P ratio outside of the range of 1.8 – 2.7)

2.5.1 – No Pb Exposure

There are 6 samples (35%) that show no Pb exposure in the enamel: 19.1.1.**010** (C^1), 19.2.1.**003** (M$_1$), 19.3.1.**077** (RI^2), 19.3.99.**154** (RI^2), 19.3.99.**172** (Ri^1), 19.5.4**.024** (LM^3). The detection limit of the LA-ICP-MS instrumentation is around 1ppm; thus, all six samples reveal to have little to no Pb concentration as majority of the data points fell below 1ppm. In the cases where a mean was calculated, Pb was occasionally detected in the enamel, but no where else on the enamel line that was analyzed. Samples 19.3.99.**172**, 19.1.1.**010**, and 19.3.1.**077** had values all below 1ppm and could not construct a graph. Sample 19.5.4.**024** is an upper left permanent third molar (LM^3). Initial calcification of the enamel for an upper third molar begins around 7 to 10 years, and the crown fully forms at around 12 to 16 years (Hillson, 1996:123-124). This sample was originally used to extend period of development for sample 19.5.4.**028**, but due to sample 19.5.4.**028** being diagenetically altered, will be analyzed individually. The enamel graph for sample 19.5.4.**024** can be seen in Figure 6. The approximate ages of enamel formation are depicted by the blue line in each graph.

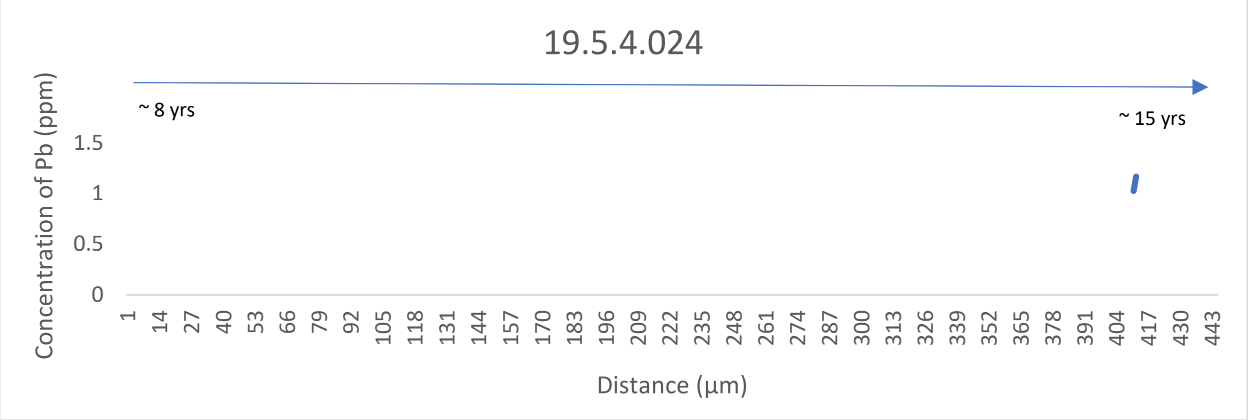

Figure 5 - Concentration of Pb in Enamel for sample 19.5.4.**024** (LM^3). The lack of data points is due to most of the data falling below 1ppm

Sample 19.3.99.**154** is an upper right permanent second incisor (RI^2). Initial calcification of the enamel for an upper second incisor begins at around 8 to 10 months, and the crown fully forms at around 4 to 5 years (Hillson, 1996). The enamel graph for sample 19.3.99.**154** can be seen in Figure 7.

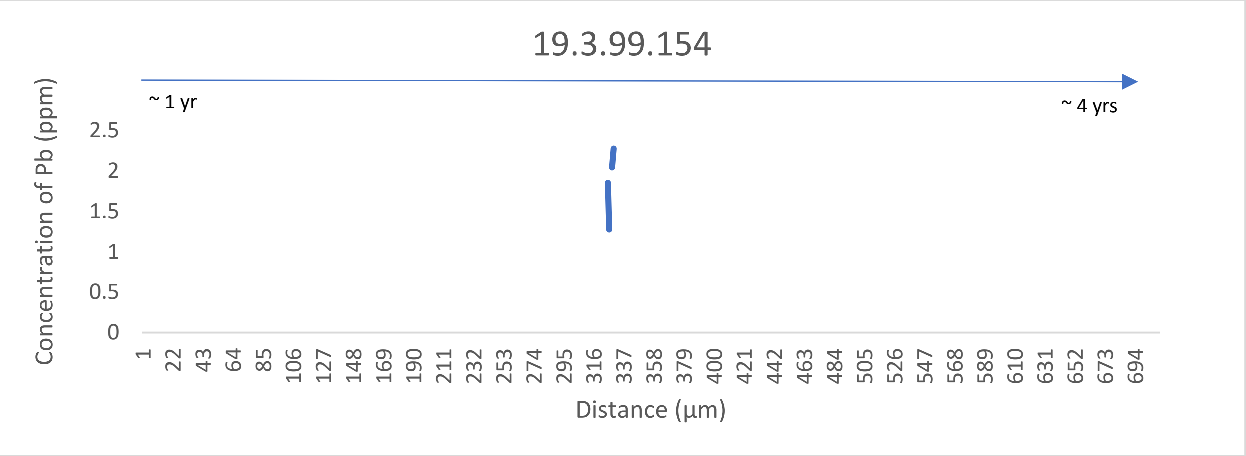

Figure 6 - Concentration of Pb in Enamel for sample 19.3.99.**154** (RI^2). The lack of data points is due to most of the data falling below 1ppm

Sample 19.2.1.**003** is a lower permanent first molar (M$_1$). The permanent first molar initial calcification begins *in utero*, and the crown fully forms around 2.5 to 3 years (Hillson, 1996). The enamel graph for sample 19.2.1.**003** can be seen in Figure 8.

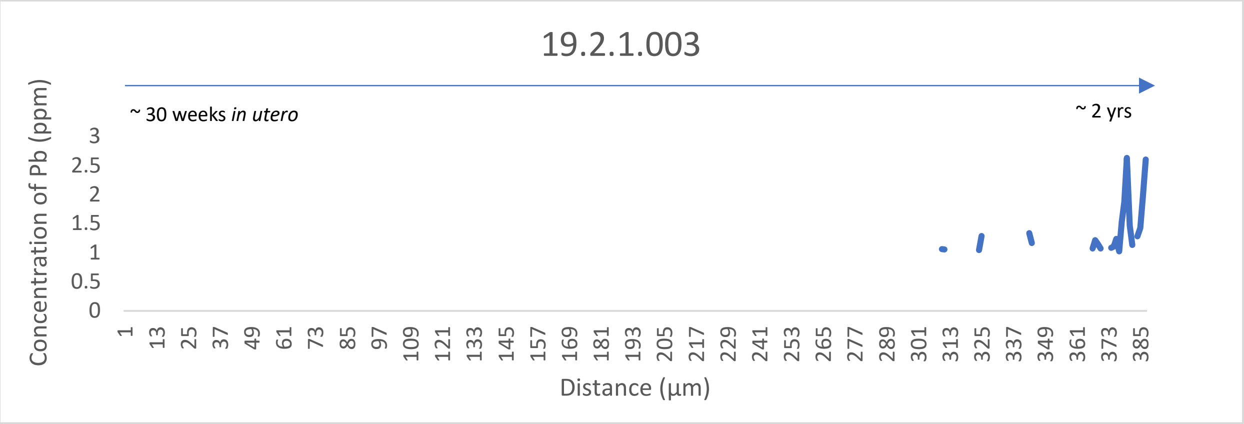

Figure 7 - Concentration of Pb in Enamel for sample 19.3.3.**003** (M$_1$). The lack of data points is due to most of the data falling below 1ppm

2.5.2 Decreasing Pb exposure with age

There are two samples (12%) listed in Table 4, 19.3.2.**091** and 19.5.4.**028**, that fall in the "decreasing Pb exposure with age" category, however, both samples are diagenetically altered based on their Ca/P values and will not be included in analysis.

2.5.3 Increasing Pb exposure with age

There is one sample (6%) that shows an increasing Pb exposure with age: 19.3.99.**167**. Sample 19.3.99.**167** is an upper right permanent second incisor (RI^2) with a mean of 1.670 ± 0.589ppm of Pb in the enamel. The age estimation is around 8 months to 5 years since the initial calcification of the enamel begins at around 8 months to a year, and the crown is fully formed around 4 to 5 years (Hillson, 1996). The enamel graph for sample 19.3.99.**167** can be seen in Figure 9 below.

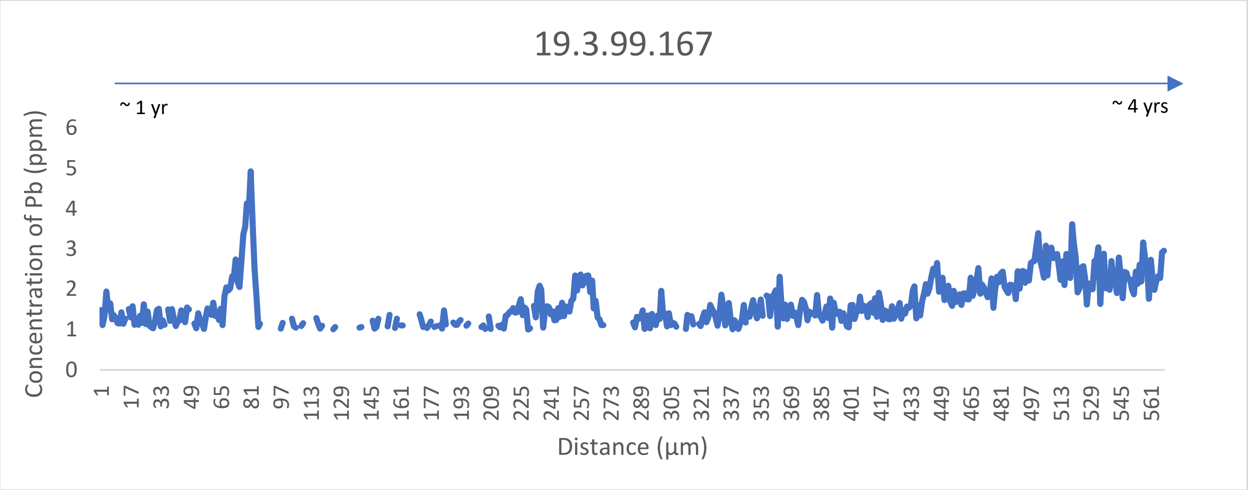

Figure 8 - Concentration of Pb in enamel of sample 19.3.99.**167** (RI^2)

2.5.4 Variable Exposure

There are a total of 8 samples (47%) that have variable exposures, with some of those samples belonging to the same individual. Sample 19.5.4.**032** and 19.5.4**.033** both belong to Individual 4. Sample 19.5.4.**033** (Figure 9) is a deciduous molar (m) with a mean of 1.672 ± 0.568ppm of Pb in the enamel. The initial calcification to a fully formed crown ranges from 14.5 weeks *in utero* to 11 months after birth (Hillson, 1996). Sample 19.5.4.**032** (Figure 10) is an upper right permanent first molar (RM^1) with a mean of 1.781 ± 0.580ppm of Pb in the enamel. The initial calcification of the enamel begins *in utero* and the crown is complete at around 2.5 to 3 years (Hillson, 1996). Both samples exhibit a different trend despite being from the same person with 19.5.4.**032** revealing a decreasing Pb exposure with age whereas 19.5.4.**033** shows a periodic exposure. The enamel graphs can be seen below.

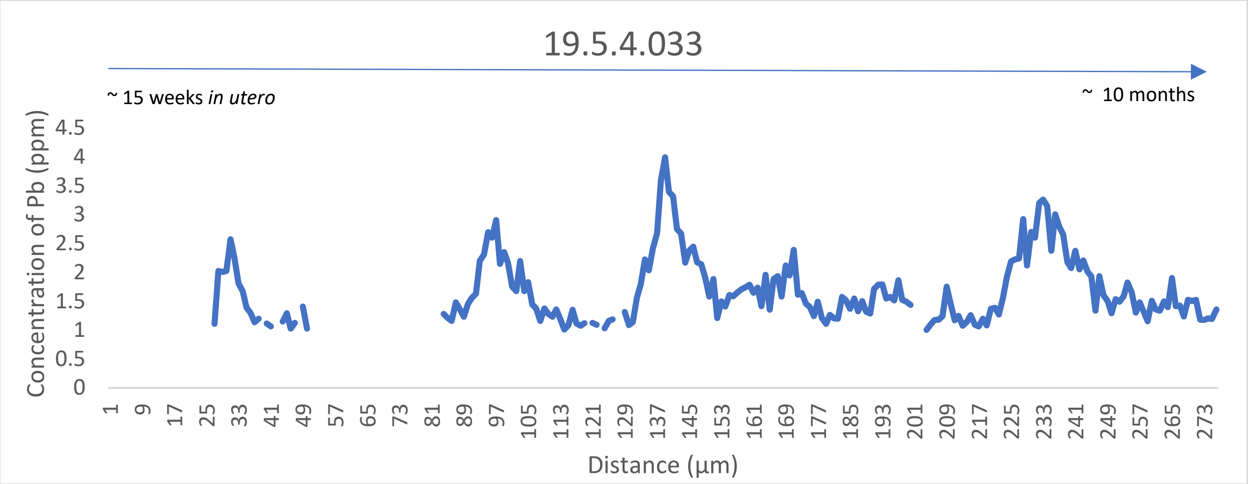

Figure 9 - Concentration of Pb in enamel for sample 19.5.4**.033** (m)

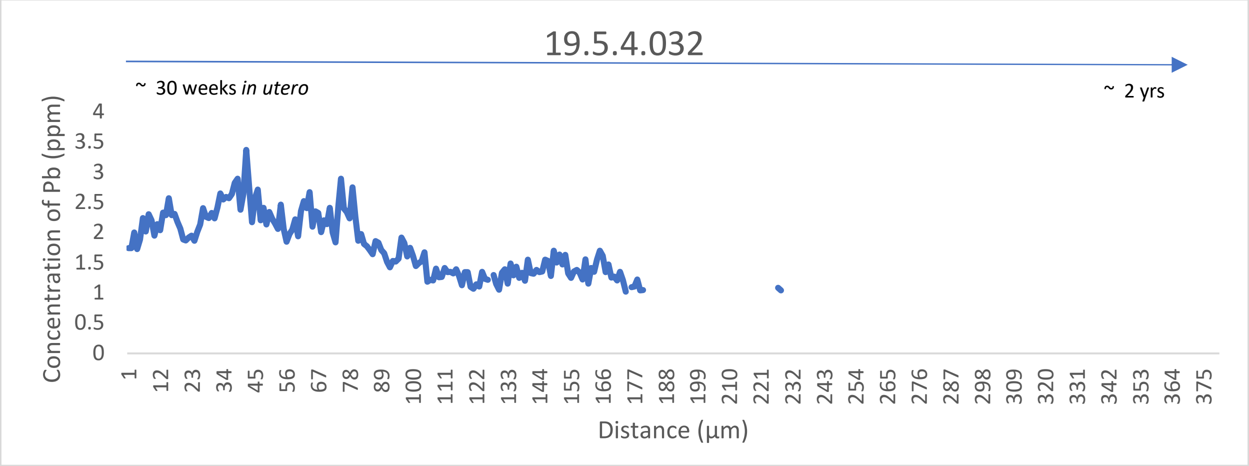

Figure 10 - Concentration of Pb in enamel for sample 19.5.4.**032** (RM^1)

Sample 19.3.3.**121** and 19.3.3.**113** were both retrieved from the subadult mandible found in Grave 3. Sample 19.3.3.**121** (Figure 11) is a deciduous molar with a mean of 11.636 ± 9.219ppm of Pb in the enamel. Initial calcification begins at around 14.5 to 16 weeks *in utero* and develops a fully formed crown around 6 to 11 months after birth (Hillson, 1996). Sample 19.3.3.**113** (Figure 12) is a permanent incisor (I) with a mean of 11.569 ± 11.012ppm of Pb in the enamel. Initial calcification of an incisor begins at around 3 to 4 months and develops a fully formed crown around 4 to 5 years (Hillson, 1996). The trends for both these samples differs as 19.3.3.**121** reveals a decreasing Pb exposure with age whereas 19.3.3.**113** increases Pb exposure with age. Both enamel graphs can be seen below.

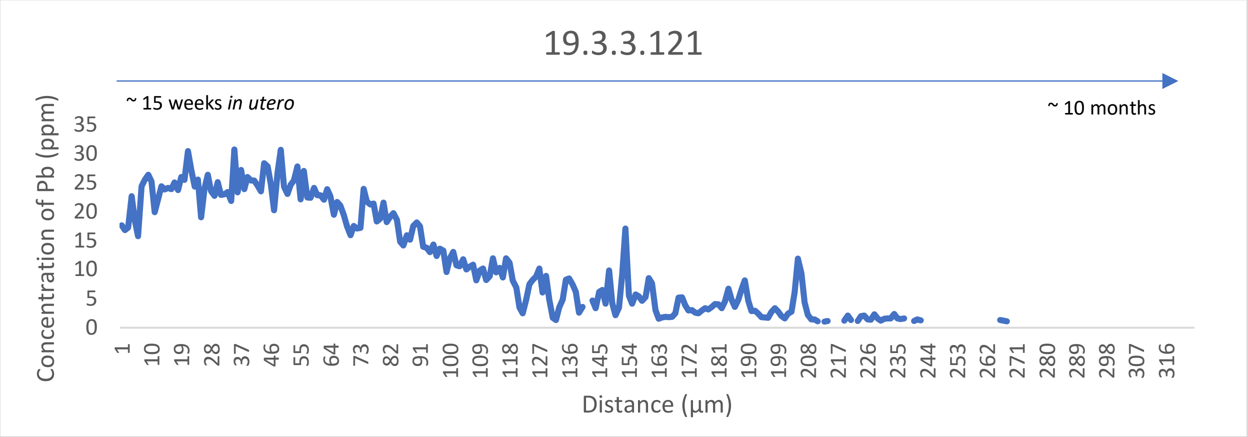

Figure 11 - Concentration of Pb in enamel for sample 19.3.3.**121** (m)

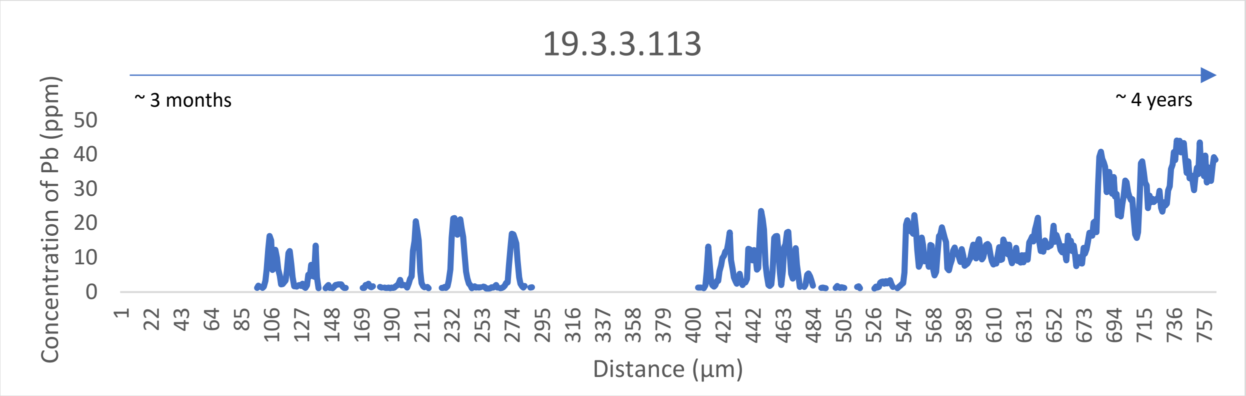

Figure 12 - Concentration of Pb in enamel for sample 19.3.3.**113** (I)

Sample 19.2.1.**002** was sampled in two lines in order to avoid a crack in the enamel that could potentially cause skewed data. The mean of the tooth is 1.571 ± 0.396ppm of lead in the enamel. The tooth is a lower permanent first molar (M_1), suggesting that the age range for the individual begins *in utero* with initial calcification of the enamel, to 2.5 to 3 years when the crown is fully formed (Hillson, 1996). The enamel graph for sample 19.2.1.**002** can be seen in

Figure 13.

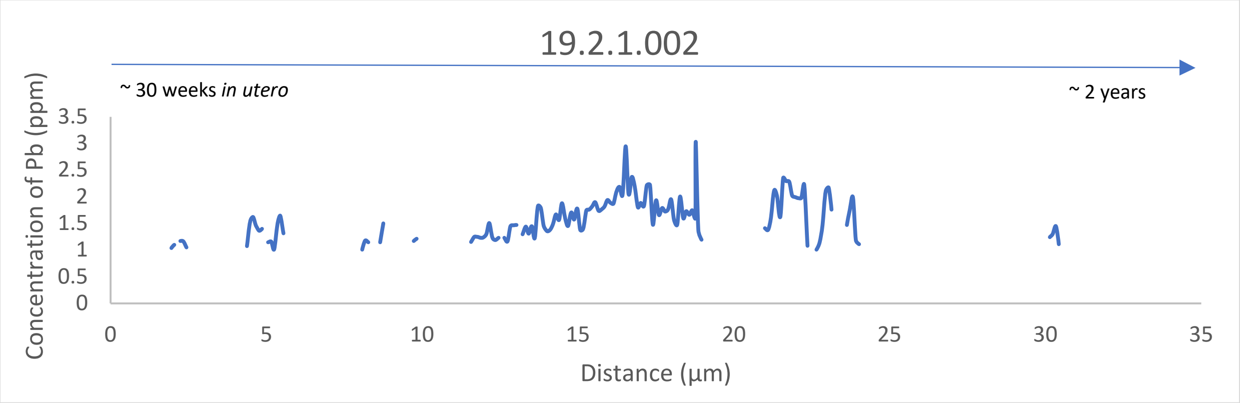

Figure 13 - Concentration of Pb in enamel of sample 19.2.1.**002** (M_1)

Sample 19.5.4.**031** is an upper right permanent first molar (RM^1) with a mean of 1.255 ± 0.359ppm of Pb in the enamel. The initial calcification beings *in utero*, and the crown is fully formed at 2.5 to 3 years (Hillson, 1996). The enamel graph can be seen in Figure 14.

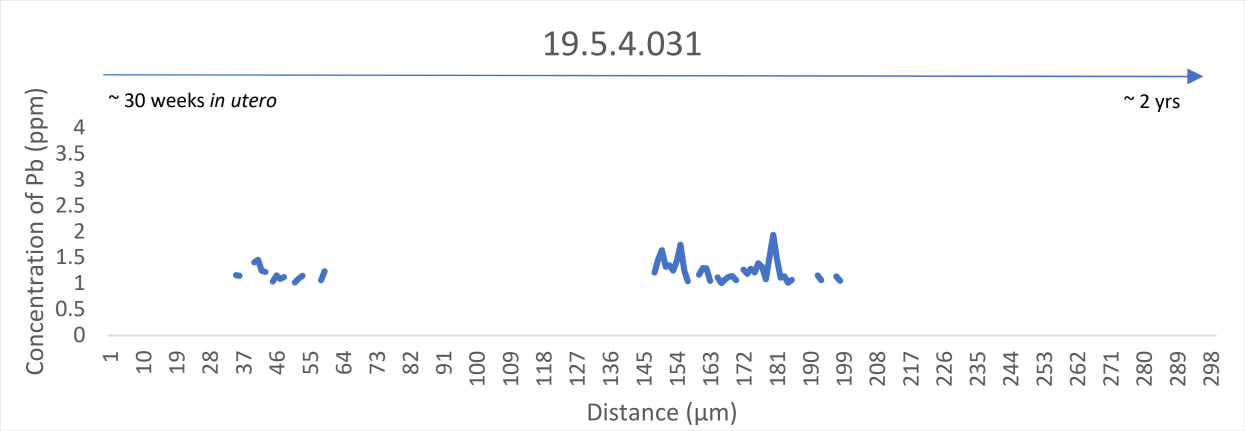

Figure 14 - Concentration of Pb in enamel for sample 19.5.4.**031** (RM_1)

The last sample is 19.5.4.**014** which is a permanent molar (M) with a mean of 1.257 ± 0.210ppm of Pb in the enamel. Due to the fragmentary nature of this sample, the type of molar could not be distinguished. The age estimation for initial calcification can begin in utero to 10 years, and the crown is fully formed around 2.5 to 16 years (Hillson, 1996). The enamel graph can be seen in Figure 15.

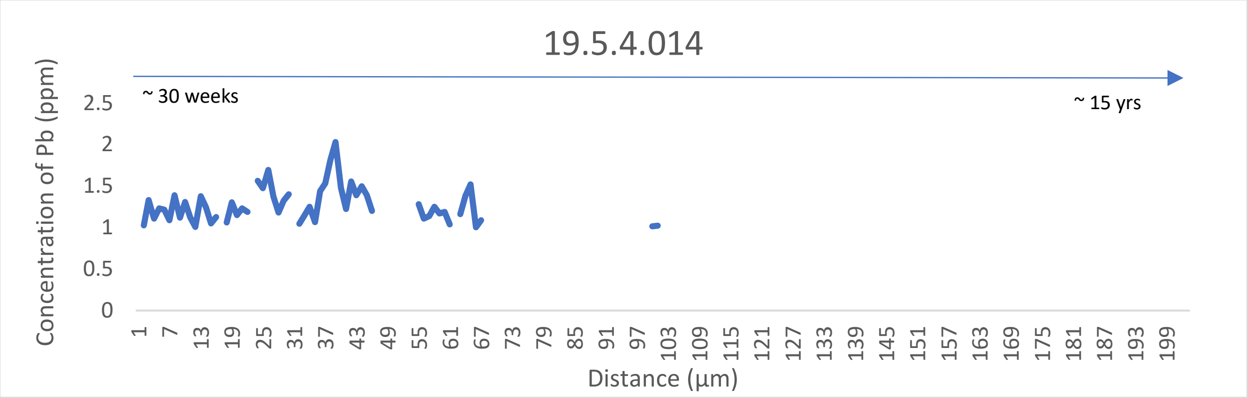

Figure 15 - Concentration of Pb in enamel for sample 19.5.**014** (M). Age estimation is rough as the molar type is unknown

2.6 Discussion

With the Wadi Faynan region being known for copper mining and smelting activities and the proximity of WF100 to a copper mine, this raises the question of why several individuals show no Pb exposure in their enamel. In a study done by Grattan and colleagues (2003), they observed the varying copper concentrations in traditional Bedouin campsites based on the distance from industrial waste in the form of black slag. Although the study done by Grattan and colleagues analyzes copper, Pb is one of the main metals produced as a by-product in the process of smelting copper (He et al., 2013). The trend found in this study by Grattan et al (2003) was that as the location of the Bedouin campsite increased distance from the industrial waste, the concentration of copper in the sediments within the campsite decreased. The closest Bedouin tent was 20m from the industrial waste, with about 8,000 – 16,000 mg/kg of copper. In comparison, the farthest Bedouin tent was 150m but interestingly produced 2,600 mg/kg of copper. This is revealing that perhaps the distance from a copper mine is not the only factor impacting an individual's Pb exposure. Since these heavy metal elements are found within the sediments of the living quarters of these Bedouin campsites, there is an opportunity for Pb to enter the human body through inhalation (e.g., particle dusts) or ingested through foods. With these results in mind, samples demonstrating an absence of Pb in their enamel (19.2.1.**010** [C^1] and 19.3.1.**077** [RI^2]) likely did not live in proximity to copper mines, smelting, or production during the first few years of life. Although samples 19.2.1.**154** (RI^2) and 19.5.4.**024** (LM^3) produced a mean, this was due to the fact that a miniscule amount of Pb was found in a small portion of the enamel during a very brief period of development. Since the majority of the enamel showed no Pb exposure, samples 19.2.1.**154** and 19.5.4.**024** may also have not lived in a heavy metal polluted area and the family later buried these individuals at WF100.

Sample 19.3.99.**172** (Ri^1) also shows no Pb exposure, but because this tooth sample is deciduous, this allows comment on the Pb exposure that the mother was subject to during the last 7-10 years of her life. As mentioned previously, the calcification of a deciduous upper incisor begins as early as 13 weeks *in utero*. If the mother was exposed to Pb, the Pb would be mobilized into the fetus. This is because Pb is stored on the skeleton (i.e., teeth and bones) from past exposure (Rísová, 2019). The movement of Pb from the mother to the fetus is further exacerbated postnatally as lactation triggers an increase of bone resorption (Rísová, 2019). This means that both the mother and this individual may not have lived in polluted areas such as Wadi Faynan due to the no Pb exposure in the enamel, however, they were buried at WF100.

For sample 19.2.1.**003** (M_1), the majority of this individual's enamel showed no Pb exposure, with some Pb appearing only in the very latest period of enamel. At around 95 days[4] from the formation of the lower permanent first molar of this individual, there is a peak of Pb exposure found within this sample. This could mean that this individual migrated from a place of no environmental pollution into Wadi Faynan, where they may have lived for a short period of time before they died and were buried.

The fact that there were six individuals (40%) that show no Pb exposure in a location where heavy metal pollution persists is interesting and may reveal that WF100 is potentially a location where kin groups migrate to bury their dead. Perhaps during the EBAI, the scale of pollution was in the beginning stages or the approximate 15km distance from the copper mine did indeed play a factor on the magnitude of exposure on these individuals. There are similarities between the burials of WF100 and those of Bab edh-Dhra', to the north, where human remains in both locations were found as secondary burials in charnel houses (Rast & Schaub, 1979). Moreover, Grave 5 in WF100 had several skulls that were grouped together and facing the same direction which is also a practice documented at Bab edh-Dhra' during excavations of EBA burials. The similarities in mortuary behaviour at the two sites, and the fact that there was no Pb in the enamel of these 6 samples in a location where heavy metal pollution is documented for other individuals, may reveal that those 6 people from the WF100 burial site may have been brought to this location specifically for the purpose of burial. While this remains a possibility, more research needs to be done as current findings during the *Barqa*

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[4] The peak was at 380μm from the cusp of the tooth, which is equivalent to 95 days if 4μm = 1 day (Dr. Alexis Dolphin, personal communication)

Landscape Project in 2019 suggests that the local population was buried locally (Dr. Russell Adams, personal communication).

The increasing pattern seen in Sample 19.3.99.**167** (RI^2) indicates a steady rise in Pb exposure over a period of time. The Pb concentrations at the beginning of the graph, when the individual was around the age of 1 year, seen in Figure 8 may reveal that the mother transferred Pb to this individual through breast milk. In a weaning study done by Stantis and colleagues (2020) on breastfeeding and weaning practices in Near Eastern populations during the Bronze Age (ca. 2,800 – 1,200 BCE), they revealed that the process of weaning may have begun around 4 to 8 months of age until about 2.3 to 2.8 years of age when weaning is complete. In comparison to other graphs where there are intervals of no and periodic Pb exposures, the graph (Figure 8) for sample 19.3.99.**167** (RI^2) shows a consistent and steady increase of Pb exposure. At this time, there are not enough data to definitively answer the question of why there is an increase of Pb exposure as this individual ages. There must be further research done to examine an accurate histology and timeline of this individual's age as the Pb concentration increases.

Sample 19.2.1.**002** (M$_1$) reveals a variable exposure to Pb, where periods of no exposure at all are interspersed with periods of significant Pb uptake by the enamel. A lower permanent first molar initially calcifies *in utero*, about 30 weeks after fertilization (Hillson, 1996), and as seen in Figure 13, there are intermittent exposures of Pb. It might be surprising to see intervals of no exposures to Pb if this individual continued to live in the Wadi Faynan region because of possible Pb-laden-dusts produced from copper smelting and the integration of Pb into sediments and surrounding vegetation in the region (Grattan et al., 2003). The lack of Pb exposure through out life and concentrated Pb exposure during a short periods of exposure may indicate a series of short migration intervals between the ages of 30 weeks *in utero* and 2 years of age for this individual. This possibility of periodic exposure due to migration to and from WF100 may also be extended to sample 19.5.4.**031** (RM^1) have durations of no Pb exposure during an interval of their life.

Sample 19.5.4.**014** (M) only shows Pb exposure during the earliest period of enamel development of the permanent molar, which can begin to calcify as early as 28-32 weeks after fertilization if it is a first molar, or as late as 7 years if it is a third molar (Hillson, 1996). Due to the fragmentary state of this sample, it is difficult to assess a specific age range for this tooth. Although, due to the latter period of no Pb exposure, this may indicate that this individual was moving around the landscape. This means that if the mother, *in utero*, transferred the stored Pb to the developing fetus from her skeleton along with ingested foods containing Pb, this exchange may be variable in concentration but constant due to being in the same environment as there is a high degree of Pb maternal-fetal transfer (Chen et al., 2014) (see also Figure 9 as this sample is a deciduous molar that was calcified *in utero* and continues until crown completes at 11 months). Likewise, if the mother had stored Pb from her own exposures, this may also be translated into the diet (e.g., breastmilk) of this individual during the first couple years of their life. This means that early Pb exposure occurred *in utero*. The limited exposure seen afterwards until the second period of exposure could also be due to being in the proximity of smelting activities. Like other samples with no Pb exposure, this individual may have lived a life outside of the Wadi Faynan region for period of time as indicated by a large interval of no Pb concentration in the enamel (see Figure 15 for the enamel graph for sample 19.5.4.**014**).

Individual 4 consists of two samples: 19.5.4.**033** (Rm^2) and 19.5.4.**032** (RM^1). The enamel graph of 19.5.4.**033** (Rm^2) (Figure 9) reveals information about the mother's diet and exposure to Pb since initial calcification of a deciduous second molar begins around 16 weeks after fertilization and the crown is complete around 11 months after birth (Hillson, 1996). The constant Pb exposure could potentially mean that the mother either has Pb stored in her skeleton, or she was ingesting Pb contaminated foods that were transferred to the fetus. The elevated and periodic increases of Pb seen in the enamel graph (Figure 9) may reveal that the mother was ingesting foods that were more potent in Pb periodically. It is possible that one of the reasons that an individual may move around the landscape could be their involvement in a support-population such as exporting and importing goods and providing foods for the workers at Faynan, but more research must be done on the WF100 site, and the individuals buried there. This theory can be observed in the enamel graph (Figure 10) of sample 19.5.4.**032** (RM^1). The initial calcification of an upper permanent first molar begins *in utero* and completes the crown at the age of 2.5 to 3. At the beginning of the graph, there is a decreasing concentration of Pb as this individual move from the womb environment of their mother, to being fed breastmilk during the first couple years of life. The period of no Pb exposure during the later half may be due migrating to a location where there is no environment pollution for the reasons of exporting copper goods, or because the family was nomadic.

The last two samples, 19.3.3.**121** (m) and 19.3.3.**113** (I), are associated with a subadult skeleton from Grave 3. Both of these samples, in comparison to the rest of the sample collection, have extremely high concentrations of Pb in their enamel. The range of the samples 19.3.3.**121** (m) and 19.3.3**113** (I) is 1.025 – 30.760ppm and 1.001 – 44.094ppm, respectively.

This may indicate that this individual lived in close proximity and perhaps the family was directly involved with the activities of copper smelting during the intervals of elevated Pb concentrations. This would include the mother as well as the tooth sample of 19.3.3.**121** is a deciduous molar which calcifies as early as 14.5 – 17 weeks after fertilization and completes the formation of the crown at 6 months after birth (Hillson, 1996). The decline in Pb concentration may be because of a temporary switch in roles in the economy of copper production in Wadi Faynan that does not involve direct interactions with copper smelting such as exporting the copper goods to other locations. The increase of Pb concentration in sample 19.3.3.**113** (I) which period of development occurs later in this individual's life may be the re-introduction into the activities that was practiced before that involved direct interactions with copper smelting.

It is difficult to compare these samples to other literature as this project is unique in that the Pb concentration is obtained sequentially across the development period of the enamel of the individual while other studies analyze the total concentration of Pb in an entire area of the enamel (i.e., enamel surface). Therefore, it is difficult to pinpoint a specific role, if any, each individual played or the relation they may have in the copper smelting and production activities that occurred in WF100 during the EBAI. Based on the mean concentrations of the samples in this study (seen in Table 4), the individual associated with the subadult skeleton in Grave 3 is the most likely to have been in a family that was involved in the copper production process as part of the selected few who had the knowledge and access to copper metal. The other samples who have variable exposures of Pb may have had a supporting role in the economy of Wadi Faynan such as importing and exporting copper goods, practising the nomadic lifestyle, or lived in proximity of specialized individuals who were smelting copper. Perhaps the many prestigious items that could have been buried initially with these individuals may have been lost through looting, but there are other indications of grave goods found within the WF100 charnel house such as beads (Figure 2), a copper awl, and the assortment of pottery found within the graves.

As for the health implications these individuals may have faced, it is difficult to assess the degree to which these individuals were impacted due to Pb as many of these tooth samples age estimation is near the first few years of life. There is literature on the effects of Pb on developing fetuses where there is an increase chance to develop disabilities associated with mental, cognitive, and behavioural development (Rísová, 2020). The next steps for this research is to investigate more samples within the WF100 collection, expanding the age estimation into later years of life.

2.7 Conclusion

Many of the samples that were studied in this investigation of the Wadi Faynan 100 cemetery revealed that the pollution exposure for children is more variable than expected. Apart from the subadult skeleton found in Grave 3 with the increased Pb concentrations, the majority of the means calculated from the samples were below 1.800ppm of Pb in the enamel. Given that the Faynan region has documented copper mining and smelting activities, and that WF100 is about 12 kilometre away from the nearest mining site, this may indicate that these individuals may not have direct involvement in the copper mining and smelting activities. This further adds to the evidence that the access to copper metal and the knowledge of the copper production process may only be given to specialized individuals within a community. The charnal houses in WF100 in which these samples were excavated resembles that of the Bab edh-Dhra' cemeteries, where it is possible that kin groups had migrated from a non-polluted environment into WF100 to bury their dead. Therefore, the children who were buried at WF100 may not be equally at risk to lead pollution as the family role in the economy and migration patterns may dictate their exposure. This preliminary study demonstrates that the EBAI in WF100 is more heterogeneous in Pb exposure than what was expected. Since this is the first study of its kind to explore the childhood development while possibly being exposed to pollutants, more research needs to be conducted at the WF100 site to illuminate information regarding the lifestyle and struggles of individuals during the EBAI.

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