QUANTIFYING AGE-RELATED BONE LOSS AND VITAMIN D DEFICIENCY

QUANTIFYING AGE-RELATED BONE LOSS AND VITAMIN D DEFICIENCY: EXPLORING CO-OCCURRENCE AND CO-MORBIDITY IN TWO 18TH-19TH CENTURY FRENCH-CANADIAN COMMUNITIES

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TITLE: Quantifying Age-Related Bone Loss and Vitamin D Deficiency: Exploring Co-Occurrence and Co-Morbidity in Two 18th-19th Century French-Canadian Communities

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Lay Abstract

This study examines skeletal health in two historical French-Canadian communities using digital X-ray images of the metacarpal bone of the index finger, and micro-CT scans of ribs. A sample of 43 individuals was chosen for X-ray analysis. Each individual's bone amount was calculated from the X-ray images, and further analysis revealed there were no significant differences in bone amount between males and females, and no differences between young adults, middle-aged adults, and older adults. Ten individuals were chosen from the sample of 43 to examine of bone quality using rib scans. Seven individuals showed signs of low-quality bone. Assessing the results alongside historical records suggests that social forces may have interacted with the biological systems that maintain skeletal health.

Abstract

This study analyzed age and sex-related bone quantity and quality patterns in the historical French-Canadian communities of Pointe-aux-Trembles and Sainte-Marie-de-Beauce. The analyses were undertaken using newly developed techniques in metacarpal radiogrammetry and rib micro-CT assessment. The patterns of bone quantity and quality were used to infer biological and social contributions to individual and community health in the past.

Second metacarpals from a sample of 43 individuals from Pointe-aux-Trembles (*f=12, m=6*) and Sainte-Marie (*f=15, m=10*) were radiographed and assessed. A 1.9cm region of interest (ROI) was isolated on the diaphyseal surface. Within this ROI, cortical and total bone areas were measured and used to calculate the cortical area index (CA_{ROI}). Patterns of bone amount by age category (15-29, 30-49, 50+) and sex were statistically analyzed. There were no statistically significant differences in CAI_{ROI} between males and females, and no significant differences were found between any of the age categories.

From the total sample of 43 individuals, rib fragments from a sub-sample of 10 individuals were chosen for micro-CT analysis. Five micro-CT slices along a 1cm segment of bone were examined and assigned scores for the appearance of mineralization defects associated with osteomalacia. Scores obtained were examined alongside the age, sex, and CAI_{ROI} data. Seven individuals in this sub-sample showed consistent evidence of mineralization defects throughout their ribs, although no patterns were noted between the presence and severity of defects and age, sex, or CAI_{ROI}.

These results highlight the bioculturally complex nature of individual and community health in the past. Pointe-aux-Trembles and Sainte-Marie both experienced frequent periods of starvation, the spread of infectious disease from urban centers, and a potential lack of vitamins necessary to develop good-quality bone in adequate amounts. Analyzing these results alongside historical context provided insight into the long-term impacts of stress events on individual and community health.

This thesis is dedicated to my very special cats, Mystery, Lady Grey, Orange Juice, and Mocha,

for reminding me that the best things in life aren't things.

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Lastly, I would like to thank my parents, Debbie and Richard Christenson, for celebrating me and reminding me of my strength, and for teaching me that I can do anything, no matter how difficult it may be.

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Declaration of Academic Achievement

The research featured in this thesis was completed by Rebecca Christenson under the supervision of Dr. Megan Brickley. Research questions and methodology were developed in consultation with Dr. Brickley and Dr. Tina Moffat. Permission to access the skeletal collections was obtained by Dr. Brickley from Dr. Isabelle Ribot at the University of Montréal. Ethics approval was granted by the Human Tissue Committee of the Hamilton Integrated Research Ethics Board (HiREB) as part of the project "Health across the Life Course: An Investigation of the Impact of the Maternal-Child Nexus and Lifeways on Non-Adult and Adult Health" (ID# 16436).

Chapter 1: Introduction

1.1 Introduction

Osteoporosis and osteomalacia are often clinically considered to be complications of aging; however, this is a modern perspective on bone health primarily from communities with developed healthcare systems. These metabolic bone disorders occur as a consequence of interruptions to the metabolic systems responsible for bone maintenance, such as the mechanisms that utilize vitamin D. Vitamin D is primarily synthesized in the skin, stimulated by UVB rays from the sun, and obtained from dietary sources where it is absorbed in the intestinal tract (Brickley et al. 2020, pp. 75-128; Minisola et al. 2021). Insufficient dietary or cutaneous intake of vitamin D or the inability to convert vitamin D to its active form impairs the process of bone mineralization (Minisola et al. 2021).

Osteoporosis is characterized by the weakening of skeletal structures through the "uncoupling" of bone resorption and formation during bone maintenance and remodelling (Compston et al. 2019; Prestwood et al. 2004). This causes bones to become fragile and increases the likelihood of fracturing. According to the World Health Organization (1998), osteoporotic bone falls at least 2.5 standard deviations below the average young adult bone mineral density in a population.

There is a wide body of clinical and biomedical data detailing the breakdown in cellular and molecular processes that regulate bone maintenance during aging (Cremers et al. 2010; Doran and Khosla 2004; Kostenuik 2013; Misra and Silverberg 2010; Parfitt 2003, 2013; Prestwood and Raisz 2004; Zebaze and Seeman 2010), but non-age-related causes of

osteoporosis, such as nutrient deficiencies, insufficient mechanical stimuli, and inflammation, are not as well studied or understood by modern epidemiological researchers (Frost 2003; Prestwood and Raisz 2004). In contrast to osteoporosis, where bone becomes brittle, incomplete mineralization in osteomalacia results in soft bone that can become deformed (Brickley et al. 2020, pp. 75-128). Like osteoporosis, osteomalacia is associated with old age; the uptake of vitamin D and the conversion to its usable state becomes less efficient with age, and individual or cultural habits may limit the ability of the elderly to obtain vitamin D through diet or exposure to the sun (Lips 2001; Mithal et al. 2009). Although the physiological causes differ, osteomalacia and osteoporosis pose a great risk for fracture, which is associated with morbidity and mortality, particularly in elderly populations (Arnold 1973; Bischoff-Ferrari et al. 2006; International Osteoporosis Foundation 2023; Minisola et al. 2021; Schnell et al. 2010; Zebaze and Seeman 2010).

Biomedical studies show predictable and consistent patterns of changing bone metabolism with age, and the sexually dimorphic ways these processes occur (Kousteni 2010; Laurent et al. 2014; Poole et al. 2004; Riggs et al. 1998; Wiren 2005). These patterns can be observed in archaeological samples (Curate et al. 2013; Ericksen 1976; Glencross and Agarwal 2011; Van Gerven et al. 1969), but they are not universal (Agarwal and Grynpas 2009; Agarwal 2012; Beauchesne and Agarwal 2014, 2017; Dewey et al. 1969; Ekenman et al. 1995; Holck 2007; Poulsen et al. 2001; Zaki et al. 2009). Current clinical studies focus on the biological, primarily genetic and age-related, factors that contribute to conditions such as osteoporosis and osteomalacia (Duncan and Brown 2008; Giguère and Rousseau 2000; Ralston and Crombrugghe 2006), but often do not consider the impact of physical and social environments on the

development of such disorders (Agarwal 2012; Riancho and Brennan-Olsen 2017; Shavers 2007). These extrinsic factors can include diet, environmental and economic barriers to obtaining vitamins and nutrients, tobacco and alcohol consumption, exercise, chronic stress, body size, and pregnancy (Agarwal and Stuart-Macadam 2003; Agarwal 2019; Choi et al. 2021; Gough Courtney et al. 2023). Modern Western populations are privileged to experience osteoporosis and osteomalacia as side effects of aging. Access to foods that have been fortified with nutrients, from infancy to adulthood, reduces the risk of developing bone disorders due to malnutrition, and access to medical care allows the treatment of disorders that would otherwise impact skeletal health. However, many modern countries do not enforce or have access to food fortifications. Communities that lack food fortifications show widespread development of skeletal complications from malnutrition and disease at every stage of life (Jones 2018; Priemel et al. 2010).

The communities of colonial French-Canada (1700-1850) are ideal for exploring the social and physical factors that contribute to health alongside the biological components. The French-Canadian colonists typically worked outdoors, where the latitude along the St. Lawrence River could provide seasonal access to sufficient sunlight for vitamin D synthesis (Chaplin and Jablonski 2013; Greer 1997; Holick 2007; Huotari and Hertzig 2008; Lips 2001; Mithal et al. 2009; Ouellet 1980; Uday and Högler 2019). Fish from the St. Lawrence River would have been a reliable source of dietary vitamin D, an essential source of vitamin D from April to October when there is insufficient UVB available to stimulate the cutaneous production of vitamin D (Chaplin and Jablonski 2013; Lu et al. 2007; Vigeant et al. 2017).

The colonies were not egalitarian, but social order was not as strict as it was in Europe, leading to fewer class disparities and creating more equalized health experiences between the poor and the rich (Geloso et al. 2023; Greer 1997). However, from the establishment of the first colonies, experiences in New France were tumultuous. Harsh winters, constant war, crop failure, and economic fluctuations consistently impacted health and well-being in the colonies (Boulet 2021; Bruckner et al. 2018; Greer 1997; Ouellet 1980). Communities often experienced infectious disease epidemics and starvation, leading to periods of poor health that had both biological and cultural origins (Bruckner et al. 2018; Ouellet 1980).

The French-Canadian settlements at Pointe-aux-Trembles and Sainte-Marie were agricultural communities that experienced epidemics, starvation, and malnutrition from the 1700s to the 1800s (Ethnoscop 2006, 2016). During preliminary analyses of these skeletons, poor health and stress indicators were noted, making these communities valuable for exploring the links between nutritional deficiencies and skeletal health. In this study, 43 individuals from Pointe-aux-Trembles (n=18) and Sainte-Marie (n=25), were assessed for patterns of age-related bone loss using metacarpal radiogrammetry. Ten individuals were subsequently chosen from the total sample of 43 to undergo further analysis for evidence of osteomalacia using micro-CT scans of rib fragments. It was hypothesized that adherence to clinical age and sex patterns in bone loss would be observed, as these trends have been observed in comparable bioarchaeological studies (ex. Glencross and Agarwal 2011). Furthermore, it was expected that evidence of osteomalacia would be associated with osteoporosis, as disrupted and incomplete bone formation would result in low amounts of bone.

Bioarchaeologists rarely encounter complete, undamaged skeletons, and must make inferences based on fragmentary remains. As explored by Brickley and Buckberry (2015), even the most incomplete and poorly preserved remains can provide a range of valuable information regarding health and disease in the past. However, limitations in analytical methods may exclude fragmentary remains; for example, traditional metacarpal radiogrammetry requires complete metacarpals for analysis. Excluding incomplete elements limits the amount of data that can be analyzed, therefore limiting our understanding of past health and disease. Expanding methods of assessment to optimize the use of fragmentary remains allows bioarchaeologists to expand the amount of information that can be collected from poorly preserved and incomplete skeletons.

The aim of this thesis, then, is to utilize new methods of assessing bone quantity (metacarpal radiogrammetry) and quality (micro-CT) in fragmentary remains to answer the following questions:

1) What is the pattern of age-related bone loss in past French-Canadian communities, and what can this tell us about past health in these communities?

2) Could vitamin D deficiency contribute to the development of osteoporosis in past French-Canadian communities, and what can this add to our understanding of the co-occurrence and co-morbidity of osteoporosis and metabolic disorders?

3) How can a biocultural approach identify the cultural and physiological factors that influence bone health on both the community level and in the lived experience of individuals in

Pointe-aux-Trembles and Sainte-Marie?

1.2 Thesis Organization

This thesis is organized into six chapters and supplemented by additional appendices. This chapter has provided an outline of the aims of this study and its importance. Chapter Two provides the necessary historical background of colonial French Canada and an overview of the biological systems involved in developing healthy and pathological bone. Chapter Three provides details on the materials, methodologies, and statistical analyses that are used in this research, and Chapter 4 reports the results of these methods and the statistical analyses. Chapter 5 discusses the observed patterns reported in the previous chapter, and provides interpretations for these patterns from a biocultural perspective. This thesis is concluded with Chapter 6, which provides a summary of key findings and recommendations for further research.

Chapter 2: Background

2.1 Theoretical Orientation

This thesis utilizes two main theoretical frameworks: the biocultural approach and lived experience phenomenology. Biocultural approaches rely on a holistic and nuanced understanding of the relationships between culture, the environment, society, and physiology to synthesize interpretations of health and disease (Goodman and Leatherman 1998; Zuckerman and Martin 2016).

Lived experience analysis narrows the scope of biocultural practice to the individual level by interpreting an individual's experience within society (Boylorn 2008; Ellis and Flaherty 1992; Finlay 2009; van Manen 1997). This approach places lived experiences in direct comparison with one another, facilitating a nuanced understanding of how lives are shaped by shared and differing social factors such as gender, race, and class (Dahlberg 2021; Dodgson 2023; Russell 2007; van Manen 1997). In paleopathology, this approach aims to define and explore the social determinants of health that influence one's susceptibility to illness and ability to recover (Fay 2006; Knudson and Stojanowski 2008; Stodder and Palkovich 2012). In order to infer individual experiences and make direct health comparisons, lived experience was explored through an osteobiographical approach.

Hosek and Robb (2019) list several core components of osteobiographical data that contribute to understandings of the entire life course until death. Limitations in the present study design make it impossible to conduct a full life course analysis for each individual, but several of the core components listed by Hosek and Robb do fit within the methodological

framework established throughout this chapter. The key layers of data used to formulate the osteobiographies of these individuals include contextual information (physical, historical, and cultural), demographic data (age and sex), health status at death (mineralization defects and cortical bone amount), and postmortem history (interment).

2.2 Social and Historical Context

Eastern Canada was first colonized by the French in 1534 by Jacques Cartier on an expedition to find a passage to China. Although Cartier's journey did not take him to China, it made the French aware of the St. Lawrence region's rich natural resources and economic potential (Le Moine 1876; Lucas 1901).

In the late 1500s and early 1600s, the first French colonists established trading forts and military outposts that grew to become the urban centers of New France (Le Moine 1876). In the 1660s and 1670s, the French monarchy began to subsidize immigration to the colonies, incentivizing French peasants and servants to become farmers in the St. Lawrence region (Dechêne 1992; Greer 1997; Lucas 1901; Ouellet 1980). Land along the St. Lawrence River was organized into manors, owned by landlords (*seigneurs*) (Geloso et al. 2023; Greer 1997; Lucas 1901; Ouellet 1980). The manors were divided into long narrow strips, that were rented by working-class French settlers, the *habitants,* in exchange for money, labor, or produce (Dechêne 1992). *Habitants* were responsible for clearing their rented land of forests and establishing a farm, and *seigneurs* were required to provide a mill and a church on their land (Dechêne 1992; Dumont et al. 1987; Greer 1997). Farmers learned to cultivate corn, beans, and squash from the

local Iroquois population, and grew vegetables and tobacco for personal use. Each farm typically owned cows, pigs, and hens, providing the family with milk, beef, pork, and eggs (Dechêne 1992; Greer 1997). Wheat, flour, oats, and hay were the main agricultural export, although some families sold eggs and produce in the urban markets (Ouellet 1980). Urban centers were populated by the clergy and the colonial military, but the majority of the urban population consisted of artisans, beggars, day laborers, and vendors (Dechêne 1992; Dumont et al. 1987; Greer 1997). During prosperous periods, the people of New France could be relatively self-sufficient and free from the rigid social castes that existed in Europe at the time. The freedom offered by the French colonies was the main attraction for many settlers (Dumont et al. 1987).

Although life in the colonies may have appeared peaceful, the people of New France experienced many hardships. The most consistent challenge that the colonizers of French-Canada faced was adapting to the cold Canadian climate (Dechêne 1992; Ouellet 1980). Obtaining adequate nutrition in the winter was difficult without crops, and starving families occasionally resorted to killing their livestock animals for food. During the spring and summer, periods of crop failure and low yield occurred commonly throughout the communities of French Canada. Soil exhaustion, plant epidemics, and unfavorable weather conditions often impacted the harvest, leading to mass starvation in the colonies (Dechêne 1992; Dumont et al. 1987; Ouellet 1980). During times of conflict with the local Indigenous communities and colonial powers, fields were frequently destroyed, impacting the health and economy of the *habitants* occupying those areas (Brandão 1997; Greer 1997; Ouellet 1980). British naval blockades in the gulf of the St. Lawrence River during times of war effectively starved French armies by preventing the import of provisions from France, starving the *habitants* as well, as they had to

surrender their produce to the French armies, occasionally at gunpoint (Greer 1997; Marston 2001). Poor sanitation and hygiene resulted in frequent smallpox, measles, and cholera epidemics that began in urban centers and spread to rural communities (Dechêne 1992; Dumont et al. 1987; Ouellet 1980).

2.3 The Bioarchaeology of Osteoporosis

2.3.1 Bone Growth, Development, and Maintenance

To properly understand how osteoporosis and osteomalacia impact the integrity of the skeleton, it is essential to understand how normal bone forms, remodels, and is maintained over time. The ossification of the skeleton begins during fetal development, where a cartilage template of the postcranial skeleton is gradually replaced by osseous tissue, primarily composed of calcium phosphate (Isojima and Sims 2021; Poole et al. 2004). During ossification, osteoblasts enter the cartilage model through the vascular network of the forming bone and rapidly deposit osteoid that mineralizes into mechanically weak woven bone (Poole et al. 2004; Scheuer and Black 2004, 18-31). Osteoblasts and osteoclasts then remodel woven bone into strong lamellar bone (Boskey 2010; Poole et al. 2004; Scheuer and Black 2004, 18-31). Vitamin D, thyroid hormones, and other growth factors contribute to the longitudinal growth of long bones, ending with the fusion of the epiphyseal growth plates, regulated by estrogen (Fraher and Watson 2004; Gascon-Barré 2004; Hendy 2004; Morris et al. 2012; Poole et al. 2004; Riggs et al. 1998; Wiren 2005). During growth, it is necessary for osteoblast activity to outpace osteoclastic resorption in order to form skeletal structures (Frost 2003; Gocha et al. 2019; Parfitt 2003,

2013). By adulthood, when the skeleton has finished most of its growth, osteoblasts and osteoclasts balance their activity to maintain the skeleton by continuously remodelling bone (Frost 2003; Gocha et al. 2019; Kostenuik 2013; Parfitt 2003, 2013).

Bone amount is adjusted over time as a response to external factors that may temporarily change bone mass. Bone adapts to the strain produced by muscles in order to maintain the strength required to resist the forces of habitual muscle use while maintaining a lightweight and proportional structure (Almeida et al. 2017; Frost 2003; Harada and Rodan 2003; Prestwood and Raisz 2004; Wallace et al. 2017; Yuan et al. 2017). This process is continuously adjusting a bone's strength and microarchitecture to adapt to changes in an individual's activity over their life course (Frost 2003; Gocha et al. 2019).

The most significant source of fluctuating bone amount is through regulating calcium homeostasis in the body (Hendy 2004). When blood calcium levels are low, the parathyroid gland secretes parathyroid hormone (PTH), which acts on the kidney to increase calcium uptake during blood filtration and stimulates the conversion of 25-hydroxyvitamin D to its active form, 1α,25-dihydroxyvitamin D_3 (1,25D) (Anderson and Atkins 2008; Brickley et al. 2020; Lanske et al. 1999; Manolagas 2000; Minisola et al. 2021; Morris et al. 2012; Ringe 2020). This active form of vitamin D facilitates the uptake of phosphorous and calcium from the small intestine, and stimulates skeletal resorption to release calcium from bone (Glorieux and Pettifor 2014; Morris et al. 2012; Nelson and Villa 2003; Ringe 2020). When blood calcium levels are too high, calcitonin produced by the thyroid stimulates osteoblasts to convert calcium from the blood into bone (Cianferotti et al. 2015; Hendy 2004).

2.3.2 Peak Bone Mass

Peak bone mass is the maximum amount of bone an individual accumulates in their lifetime (Matkovic and Landoll 2004). Peak bone mass is typically reached around the third decade of life, when skeletal growth has finished completely (Laurent et al. 2014; Matkovic and Landoll 2004; Stini 2003), and is an important factor in the later development of osteoporosis (Hernandez et al. 2003; Laurent et al. 2014; Matkovic and Landoll 2004; Streeter and Stout 2003).

It is estimated that 50%-85% of bone mass is determined by genetics, while the remaining bone mass is determined by external factors (Matkovic and Landoll 2004; Ralston and Crombrugghe 2006; Ralston 2010; Streeter and Stout 2003). The ability to consistently obtain and process nutrients essential to skeletal growth in adequate quantities is essential to achieving a high peak bone mass. The importance of calcium and vitamin D in skeletal growth is stated above, but other compounds such as phosphorous, magnesium, potassium, and zinc are also crucial to the process of bone apposition, and to maintaining bone mass and bone quality over time (Prentice and Bates 1993).

2.3.3 Sexual Dimorphism

Androgens and estrogens are vital components of skeletal growth, maturation, and maintenance (Almeida et al. 2017; Laurent et al. 2014; Poole et al. 2004). In males and females, estrogen is essential to longitudinal growth and epiphyseal fusion in the developing skeleton (Almeida et al. 2017; Börjesson et al. 2010; Poole et al. 2004). During adolescence to the start of

puberty, the physiological operation of estrogen on the skeleton is similar in males and females (Almeida et al. 2017; Poole et al. 2004; Singh et al. 2010). Estrogen is responsible for longitudinal bone growth and epiphyseal fusion during skeletal maturation (Almeida et al. 2017; Börjesson et al. 2010; Giguère and Rousseau 2000; Seeman 2002; Singh et al. 2010). After skeletal maturity is reached, estrogen continues to play a crucial role in the regulation of bone homeostasis by suppressing excessive osteoclast activity (Almeida et al. 2017; Giguère and Rousseau 2000). Estrogen regulates osteoclast and osteoblast activity through direct action on bone cells, and indirectly through the suppression of cytokines and hormones that stimulate the formation of osteoblasts and osteoclasts (Almeida et al. 2017; Giguère and Rousseau 2000; Kousteni 2010).

Once sexual maturity is reached, however, the actions of sex hormones differ between males and females, creating sexually dimorphic features in the skeleton (Almeida et al. 2017; Laurent et al. 2014; Seeman 2002). Elevated androgen levels, such as those found in males after puberty, are responsible for continuous periosteal bone growth and increased skeletal robusticity due to greater muscle mass, resulting in higher average peak bone mass in males compared to females (Almeida et al. 2017; Laurent et al. 2014; Seeman 2002; Wiren 2005). Conversely, periosteal bone accrual slows in females during puberty, and subsequent bone apposition occurs on the endocortical surface (Almeida et al. 2017; Laurent et al. 2014; Singh et al. 2010). The differences in bone apposition regulated by sex hormones result in a greater cross-sectional bone area in males and a narrower endosteal area in females (Almeida et al. 2017; Isojima and Sims 2021; Laurent et al. 2014; Singh et al. 2010).

2.3.4 Osteoporosis

Once an individual reaches their peak bone mass, the rate of bone resorption overtakes the rate of bone deposition during regular remodelling activity, resulting in decreased bone mass and increased fragility (Almeida et al. 2017; Frost 2003; Grynpas 2003; Guerri et al. 2018; Hernandez et al. 2003). The diagnostic thresholds for bone loss established by the WHO indicates that bone can be considered osteoporotic when the BMD is 2.5 standard deviations or more below the average BMD for healthy young women (World Health Organization 1998). However, the onset and rate of bone loss is not uniform, leading to different types of osteoporosis:

2.3.4.1 Type I Osteoporosis

Type I osteoporosis is marked by a sudden drop in estrogen levels during menopause, which occurs on average between the ages of 45 and 55 in females (Black and Rosen 2016; Hernandez et al. 2003; Matkovic and Landoll 2004; Prestwood and Raisz 2004; Riggs et al. 1998; Schultz 2003). Estrogen inhibits osteoclast activity, making it a crucial component of regulating regular bone turnover (Almeida et al. 2017; Giguère and Rousseau 2000; Laurent et al. 2014). The consequence of this dramatic decrease in estrogen is an increase in osteoclast activity, resulting in a sharp decline in bone mass (Almeida et al. 2017; Prestwood and Raisz 2004; Riggs et al. 1998).

2.3.4.2 Type II Osteoporosis

Type II osteoporosis is primarily age-related (Almeida et al. 2017; Schultz 2003). In advanced age, intestinal and renal calcium absorption becomes less efficient, causing the parathyroid to hyperactively release PTH in an attempt to regulate calcium homeostasis, stimulating continuous skeletal resorption (Almeida et al. 2017; Lanske et al. 1999; Prestwood and Raisz 2004 Riggs et al. 1998). Type II osteoporosis typically occurs around the age of 70, and is typically seen in females more often than males (Almeida et al. 2017; Riggs et al. 1998). Osteoporotic bone loss begins with the trabecularization of bone on the endocortical surface (Frost 2003; Isojima and Sims 2021). Due to the sexually dimorphic properties of bone explored in Section 2.3.3, males have a greater ability to resist endocortical trabecularization through the continuous outward expansion of periosteal bone that compensates for endocortical loss (Almeida et al. 2017; Isojima and Sims 2021; Seeman 2002; Szulc et al. 2006). Because periosteal bone apposition in females is limited, periosteal expansion cannot compensate for endocortical bone loss, resulting in cortical thinning, trabecularization of the cortical bone, and a decrease in bone strength (Seeman 2002; Szulc et al. 2006). However, male androgen levels decrease with age, leading to a steady decline in bone mass over time that can result in type II osteoporosis (Almeida et al. 2017; Laurent et al. 2014; Riggs et al. 1998).

2.3.4.3. Other Forms of Osteoporosis

Although osteoporosis is primarily an age-related condition, there are several factors independent of the aging processes of the body that can contribute to the development of

osteoporosis (Schultz 2003). Endocrine disorders, gastrointestinal disorders, metabolic disorders, and genetic conditions can all impact the development of the skeleton (Rauch and Glorieux 2004). During periods of inflammation or infection, the cytokines secreted from immune cells can stimulate osteoclast activity, resulting in accelerated bone loss (Brickley et al. 2020, pp. 168; Mundy 2007; Riancho and Brennan-Olsen 2017).

Insufficient mechanical loading and disuse can cause bone loss, as the bone no longer requires the strength to resist mechanical stimulus (Bauman and Cardozo 2013; Brickley et al. 2020, pp. 169-170; Frost 2003). Disuse during recovery from fractures or illness, paralysis, amputation, and sedentary lifestyles have all been linked to the development of osteoporosis (Bauman and Cardozo 2013).

Table 2.1. T- and Z-score values for the diagnosis of osteoporosis (World Health Organization 1998).

	T-Score	**Z-Score**
Normal Bone Density	T>-1	Z>-1
Osteopenia	-1>T>-2.5	-1>Z>-2.5
Osteoporosis	T<-2.5	Z<-2.5

2.3.5 Evaluating Osteoporosis in Archaeological Remains

Clinical diagnoses of osteoporosis and estimates of the prevalence of osteoporosis in a population typically rely on measurements of bone mineral density (BMD) obtained from dual energy x-ray absorptiometry (DXA) scans of the lumbar spine, proximal femur, and hip joint

(Blake and Fogelman 2007; Schultz and Wolf 2019; Siris et al. 2012; Wright et al. 2014). The values for BMD are then compared against a young, healthy control population of the same sex and ethnicity (T-score), and against a control population of the same age (Z-score) using the diagnostic values provided by the World Health Organization (Table 2.1) (Blake and Fogelman 2007; Schultz and Wolf 2019; Siris et al. 2012; World Health Organization 1998).

Bioarchaeologists face challenges when attempting to apply clinical diagnostic techniques to skeletal material. When examining osteoporosis in skeletal remains, it is often unclear if modern control samples can be used for comparison with archaeological samples (Mays 2018; van Spelde et al. 2021). Imprecise age estimation methods, particularly in older individuals, create challenges for comparison with a cohort group of the same age, and missing, incomplete, or damaged skeletal elements limit the usefulness of evaluating the prevalence of osteoporosis using the clinical methods described above (Agarwal 2012; Brickley and Buckberry 2015; Milner and Boldsen 2012). Instead, bioarchaeologists utilize a number of techniques to examine patterns of bone loss in a given sample. Bioarchaeologists continue to use measures of BMD, but also utilize measurements of element width, medullary width, cortical thickness, cortical area, cross-sectional shape, trabecular number, thickness, spacing, and length, and more, to determine patterns of bone loss in archaeological samples (Agarwal 2019; van Spelde et al. 2021). These techniques have utilized elements across the skeleton, including the femur, tibia, radius, lumbar vertebrae, ribs, and metacarpals (van Spelde et al. 2021).

Metacarpal radiogrammetry is a technique often used by bioarchaeologists to assess patterns of bone loss in archaeological samples using the second metacarpal (MCII). Metacarpal radiogrammetry originated as a technique for clinically diagnosing osteoporosis through the

quantification of cortical bone thickness (Barnett and Nordin 1960; Guerri et al. 2018; Meema and Meema 1987). The second metacarpal was chosen by clinicians due to its visibility in radiographs of the hand, as it is the largest bone in the hand, and mostly unobscured by soft tissue and the position of other bones in the hand and wrist (Barnett and Nordin 1960; Ives and Brickley 2004). When compared to techniques utilizing the quantification of bone amount in other elements, such as the femur and hip joint, the distal radius, and the lumbar spine, it was shown that the second metacarpal is a comparable element for analysis (Ives and Brickley 2005).

Traditional metacarpal radiogrammetry quantifies cortical bone thickness through a "cortical index," a standardized percentage that represents the width of cortical bone in relation to the total diaphyseal width at the mid-shaft of the bone (Barnett and Nordin 1960; Gilmour et al. 2021; Ives and Brickley 2004; van Spelde et al. 2021). Due to the simplicity and accessibility of this technique, it has been used by bioarchaeologists to explore patterns of bone amount in archaeological samples. Metacarpals tend to survive well in archaeological contexts (Waldron 1987), and radiograph equipment is easily accessible, fast, and inexpensive. These factors make metacarpal radiogrammetry a popular choice for assessing age and sex trends in bone amount, both within and between samples. A detailed procedure on the radiogrammetric methods utilized in this study are provided in Section 3.2.3.

2.4 Vitamin D Deficiency, Osteomalacia, and Osteoporosis

Vitamin D plays a crucial role in the development and maintenance of the skeleton. Vitamin D is also responsible for the formation of *good-quality* bone (Agarwal 2021; Arnold 1973; Brickley et al. 2020, pp. 129-163). Bone quality is determined by the microarchitecture of the bone, such as the organization of bone collagen, micro-damage, and proper mineralization (Arnold 1973; Brickley et al. 2020, pp. 129-163; Grynpas 2003; Karsdal et al. 2008; Seeman and Delmas 2006; Siris et al. 2012). Osteomalacia is a condition characterized by poor-quality bone, which causes soft bone that is susceptible to fracturing and bending (Bhan et al. 2018; Brickley et al. 2020, chapter 6; Minisola et al. 2021). The main cause of poor bone quality is vitamin D resistance or deficiency, interrupting the process of normal bone metabolism (Gascon-Barré 2004; Minisola et al. 2021).

Vitamin D is primarily acquired through the exposure of the skin to UVB rays from the sun. In the skin, the compound 7-dehydrocholesterol is formed, which is converted to vitamin D_3. Latitude and the solar zenith angle impact the amount of UVB that reaches the skin; locations near the equator receive the highest amount of UVB, while locations further north and south receive less UVB (Chaplin and Jablonski 2013; Holick 2007; Huotari and Hertzig 2008; Lips 2001; Mithal et al. 2009; Uday and Högler 2019). Individuals who live in areas that do not receive adequate UVB to produce vitamin D must supplement their vitamin D intake from dietary sources. Vitamin D obtained from food, such as fish and fortified dairy, is absorbed in the small intestine (Brickley et al. 2020, pp. 83-86; Gascon-Barré 2004; Morris 2012). Vitamin D obtained from both sunlight and diet is converted in the liver from vitamin D_3 to inactive 25-hydroxyvitamin D. The conversion to its active form, 1,25-D, takes place in the kidney as a

component of maintaining calcium homeostasis, as outlined in Section 2.3.1. It is important to note that although osteomalacia is most frequently caused by dietary and cutaneous vitamin D deficiency, it is possible to develop osteomalacia as a consequence of other pathological conditions (Brickley et al. 2020, pp. 87-89). Gastrointestinal disorders, liver and kidney damage, genetic mutations, hyperparathyroidism, fluorosis, tumors, and many more conditions can impact the ability to absorb and metabolize the components necessary for proper skeletal mineralization (Brickley et al. 2020, pp. 87-89; Minisola et al. 2021).

Diagnosing osteomalacia in clinical settings primarily requires measures of serum 25-hydroxyvitamin D levels and histomorphometric analyses of bone biopsies (Bhan et al. 2018; Minisola et al. 2021). There is no consensus on the exact concentration of serum 25-hydroxyvitamin D that indicates osteomalacia, but biomedical studies typically indicate that vitamin D deficiency occurs when serum levels fall in the range of 52 to 72 nmol per litre, and less than 50 nmol per litre indicates severe deficiency and risk of osteomalacia (Bischoff-Ferrari et al. 2006; Holick 2007; Malabanan et al. 1998). Bone biopsies rely on the histomorphometric markers of delayed mineralization and measures of osteoid thickness (Bhan et al. 2018; Need et al. 2007; Uday and Högler 2019). In ostomalacic bone, osteoid fails to properly mineralize during modelling and remodelling, resulting in a high ratio of osteoid to bone (Priemel et al. 2010). In histomorphometric evaluations, osteomalacia is clinically diagnosed when osteoid volume exceeds 5%, osteoid thickness exceeds 12.5µm, and a mineralization lag time of over 100 days is observed (Bhan et al. 2018; Minisola et al. 2020; Need et al. 2007; Uday and Högler 2019).

When normal remodeling is disrupted due to osteomalacia, layers of bone that should ossify fail to mineralize or do not mineralize completely, resulting in defects in the cortical and

trabecular bone that decrease the quality and structural integrity of the bone (Bhan et al. 2018; Glorieux and Pettifor 2014; Priemel et al. 2010). Meanwhile, insufficient vitamin D impairs calcium absorption, stimulating osteoclast activity to release calcium into the blood, resulting in healthy and properly mineralized bone becoming resorbed (Glorieux and Pettifor 2014; Minisola et al. 2021; Morris et al. 2012). Defectively mineralized bone and the resorption of healthy bone results in weakened bone that becomes more susceptible to fracturing (Bischoff-Ferrari et al. 2006; Minisola et al. 2021). Therefore, while osteoporosis and osteomalacia are distinct pathological conditions, the factors listed here suggest they are linked through many of the same physiological processes.

Chapter 3: Materials and Methods

3.1 Materials

The sample in this study is composed of individuals from two historical French-Canadian cemetery collections, Pointe-aux-Trembles and Sainte-Marie, currently curated in the Department of Anthropology at the University of Montréal. Excavations were undertaken for the purpose of archaeological intervention and data rescue due to urban development at both sites (Ethnoscop 2006, 2016).

3.1.1 Pointe-aux-Trembles

The village of Pointe-aux-Trembles is located on the northeast shoreline of the Island of Montréal along the St. Lawrence River (Figure 3.1) and was officially founded in 1674 (Ethnoscop 2016). The village was initially constructed as a French Fort to protect the colonists of the Island of Montréal and to control the St. Lawrence River. Following a succession of Iroquois attacks on the colonial farms, a fortified palisade was constructed to protect families. The construction of a mill and church within the walls transformed the fort into a village. Soon after, the *Chemin du Roy* ("King's Road") was constructed to connect Montréal, Québec City, and the settlements on the north bank of the St. Lawrence River. This road passed through Pointe-aux-Trembles, which increased traffic to the village (Desjardins 2010; Robichaud 2012).

Figure 3.1. Map of Montréal, courtesy of Google (2023a). Pointe-aux-Trembles is indicated by the star.

The cemetery of the local church, Saint-Enfant-Jésus parish, was in use from 1709-1843 (Table 3.1), and by the end of this period, the cemetery contained 2500 burials. This cemetery was excavated in 2014 by Ethnoscop Ltd. during the process of developing and modernizing structures in the area. A trench of approximately 12m by 2m was excavated and included 63 graves, some of which contained multiple individuals. Graves were oriented in a variety of directions and organized in clusters, potentially representing family plots (Ethnoscop 2016). The excavation revealed graves stacked atop one another in three layers, representing three phases of use of the cemetery until its closure in 1843. The oldest layer (coded 7A11) corresponds with the earliest uses of the cemetery in 1709. The middle layer (coded 7A9) represents the first addition of new earth to the cemetery to create more space for burials. Cultural artifacts

indicate this layer of the cemetery was in use approximately from the mid-1700s to the early 1800s. The final layer (designated 7A2) was in use until 1843. Twenty-three adults were recovered from this excavation, and 18 of these adults were included in this study. The criteria for inclusion in this study are outlined in Section 3.1.3.

Table 3.1. Dates of cemetery use at Pointe-aux-Trembles and Sainte-Marie.

	Pointe-aux-Trembles	**Sainte-Marie**
Years of Use	1709-1843	1748-1878

3.1.2 Sainte-Marie

The municipality of Sainte-Marie is located approximately 50 kilometres south of Québec City, on the bank of the Chaudière River (Figure 3.2). The first settlers arrived in Sainte-Marie in 1738, and the first interments occurred in 1748 (Table 3.1), six years before the first chapel was erected on the property (Ethnoscop 2006). The cemetery was in use until the 1870s, having undergone numerous expansions in both area and height. By 1832 the cemetery reached its full capacity, and earth was added to accommodate new graves in 1840. In 1864 the cemetery became full again and was extended in length, but less than a decade later in 1873 the cemetery was raised with another layer of earth. Finally, in 1878, the cemetery was permanently closed, containing nearly 7000 burials and occupying nearly 18,000 square feet of land.

The graves in the cemetery were not relocated after its closure, leaving thousands of graves in situ beneath what is presently the parking lot of the modern Sainte-Marie Catholic Church. Excavation of the Sainte-Marie cemetery was undertaken in 2003 and 2004 by

Ethnoscop Ltd. in response to redevelopment efforts on the parish property. Nine plots with dimensions of approximately 2m by 2m were excavated. A total of 62 individuals were removed from these plots, including 29 adults. Twenty-five of these adults were included in this study. The criteria for inclusion in this study is outlined in Section 3.1.3.

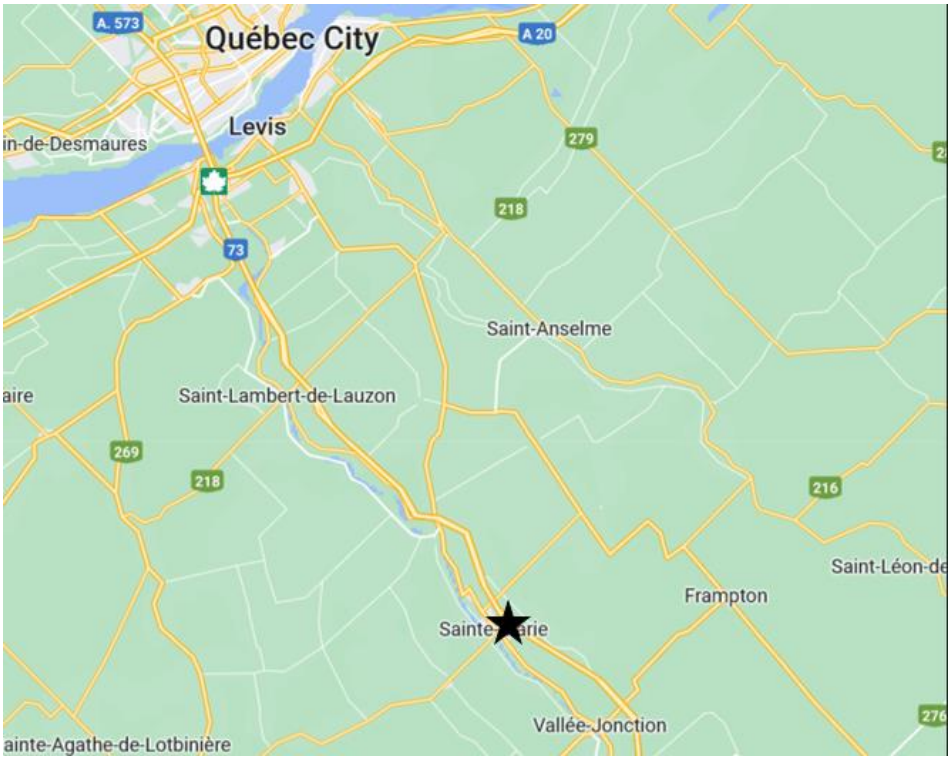

Figure 3.2. Map of Québec, courtesy of Google (2023b). Sainte-Marie is indicated by the star.

3.1.3 Criteria for Inclusion

The sample of interest for this study includes adult males and females with at least one second metacarpal (MCII) with 1.9cm of the diaphyseal surface intact. Priority was given to the right MCII, but the left was used if the right MCII was missing, fragmentary with less than 1.9cm of the diaphysis present, or altered by taphonomic change beyond the parameters established by Gilmour et al. (2021). Adults with one MCII were then assessed for age at death and sex.

Individuals were further excluded in cases where sex was indeterminate and age estimates were ambiguous. The demographic information for the final study sample is summarized in Tables 3.2 and 3.3, and Appendix A.

Table 3.2. Sample distribution by sex.

	Number of Females	**Number of Males**	**Total**
Pointe-aux-Trembles	12	6	**18**
Sainte-Marie	15	10	**25**
Total	**27**	**16**	**43**

Table 3.3. Sample distribution by age.

	Age 15-29	**Age 30-49**	**Age 50+**	**Total**
Pointe-aux-Trembles	9	5	4	**18**
Sainte-Marie	10	5	10	**25**
Total	**19**	**10**	**14**	**43**

3.2 Methods

3.2.1 Age Estimation

Age at death estimation was undertaken using a multifactorial approach, in order to counter the limitations of each method and to gather as much age information as possible from highly fragmented remains. Features of the auricular surface (Meindl and Lovejoy 1989) and pubic symphyseal surface (Brooks and Suchey 1990) were prioritized. In addition to these features, unfused long bone epiphyses (Buikstra and Ubelaker 1994), vertebral fusion (Albert et al. 2010; Albert and Maier 2013), and the appearance of the sternal rib ends (İşcan et al. 1984) were scored, particularly in cases where the features of the pelvis were not visible. Age and sex

estimations were recorded using the form in Appendix B1. After estimating age at death, individuals were placed within three age categories: 15-29, 30-49, 50+.

Individuals assigned an age of 50 years or older using the previous techniques were assessed again for indicators of advanced age through transition analysis, which has been tested as an effective technique for assessing age in individuals above 50 years of age (Fojas et al. 2018; Boldsen et al. 2002; Milner and Boldsen 2012). Transition analysis relies on the development of entheseal changes in the sacroiliac joint and its proximate muscle attachments sites and the dorsal margin of the symphyseal surface as the main sites of age-related change (Bolsden et al. 2002). The development of iliac exostoses on the posterior aspect of the auricular surface and the breakdown of the dorsal margin of the pubic symphysis are the main feature of age-related entheseal change in older individuals, indicating the individual is likely over 80 years of age (Bolsden et al. 2002).

3.2.2 Sex Estimation

Sex estimations relied mainly on the morphological features of the pelvis, such as the greater sciatic notch, the preauricular sulcus, and features of the subpubic region (Buikstra and Ubelaker 1994, pp. 16-19). Sexually dimorphic markers of the skull (Acsadi and Nemeskeri 1970) were only be utilized if the pelvic features are not visible (Appendix B1).

3.2.3 Metacarpal Radiogrammetry

3.2.3.1 Metacarpal Radiogrammetry and the ROI Method

Traditional metacarpal radiogrammetry measures cortical bone width relative to the total width of the metacarpal midpoint to calculate a cortical index (Barnett and Nordin 1960; Gilmour et al. 2021; Ives and Brickley 2004; van Spelde et al. 2021), but recent studies have expanded this traditional methodology to quantify cortical bone within a larger area (Gilmour et al. 2021). This study utilizes a newly developed method of quantifying cortical bone amount developed by Gilmour et al. (2021). Instead of measuring the midpoint width of the metacarpals to calculate a cortical index, this new technique calculates the area of cortical bone within a standardized region of interest (ROI) on the diaphyseal surface. This value is referred to as the cortical area index (CAI_{ROI}).

Second metacarpals were radiographed in groups of five using Vidisco portable digital radiography equipment at the University of Montréal. Metacarpals were secured in antero-posterior orientation on a sheet of plastic air bubble packaging and spaced one inch apart. The scale of each image was calibrated using a 23.88mm Canadian 25-cent coin.

To collect the measurements for the CAI_{ROI} calculations, the procedure outlined by Gilmour et al. (2021) was followed using ImageJ software (Version 1.53). A 1.9cm x 1.9cm square was drawn using the ROI selection tool and placed over the narrowest portion of the diaphyseal surface. If necessary, the contrast of the image was adjusted to increase the visibility of the cortical and trabecular structures within the ROI. Using the oval selection brush tool, the total bone area, including the cortical area and the medullary area, were selected and used as

the total area (TA) value. The cortical bone area (CB) was then isolated and saved as the CB value (Appendix B2). Using these values, the cortical area index in the region of interest was calculated with the following formula:

$$\mathrm{CAI_{ROI}} = 100 \times \frac{\mathrm{CB}}{\mathrm{TA}}$$

Initial measurements were taken in the field using a laptop with a 14-inch screen and a resolution of 1920x1080P, in order to obtain preliminary CAI_{ROI} values, allowing rib samples to be chosen for micro-CT assessment across a range of bone amounts. Measurements were taken a second time using a 27-inch monitor with a resolution of 3840x2160P to obtain more precise values.

3.2.3.2 Statistical Analysis

The data from both Pointe-aux-Trembles and Sainte-Marie was pooled, based on the assumption that the demographic information and conditions of each site were comparable. Utilizing historical sources, it was noted that there were no major differences in social or economic status that would result in vastly different nutrition patterns and population health (Ethnoscop 2006, 2016; Le Moine 1876; Lucas 1901). Due to this, it was deemed appropriate to pool the raw data. Pooling these numbers is beneficial for the subsequent statistical analyses, as they create a larger sample size.

Statistical tests were carried out on SPSS (Version 28.0.1.1) and considered significant at a *p-value* of ≤0.05. Before performing any comparative tests, the Shapiro-Wilk test for normality

of distribution was carried out for each age and sex category. The Shapiro-Wilk test was chosen due to the small sample sizes (n<20) in each category (Shapiro and Wilk 1965). All categories were determined to be normally distributed, therefore all subsequent comparative tests must be parametric tests.

The first test assessed the statistical differences between CAI_{ROI} values between males and females in the overall sample. Given that cortical bone area is sensitive to sex hormone levels, as outlined in Section 2.3.3, a significant difference between sexes would require the relationship with age to be considered separately for males and females, whereas no statistical difference would allow males and females to be considered together in the test for age and CAI_{ROI}.

Student's t-test was used within each age division to assess the significance of the CAI_{ROI} difference between males and females. The t-test is a parametric test that evaluates the statistically significant differences between the means of two normally distributed samples (Dakhale et al. 2012; Suchmacher and Geller 2021 pp 113-123). One-way ANOVA was then used to determine statistical differences in CAI_{ROI} values between each of the total age categories (15-29, 30-49, 50+). Results for both the t-test and ANOVA tests were considered statistically significant at $p<0.05$. Finally, age and CAI_{ROI} were compared in the total sample using Pearson's correlation coefficient (r) and linear regression analysis (r^2).

3.2.3.3 Comparative Analysis

An extensive literature review was undertaken to identify other bioarchaeological studies that provided data on age and sex trends in bone amount in archaeological samples for comparative data. A systematic search of scientific databases such as PubMed, JSTOR, and ScienceDirect using the keywords “bone mineral density,” “cortical bone loss,” “age-related bone loss,” “osteoporosis,” and “paleopathology” was undertaken. Titles and abstracts of articles were scanned for relevance. Articles were required to report skeletal data for both males and females, and had to report bone amount for each age category established in the methodology, rather than reporting overall trends. The results are reported in Appendix C.

3.2.4 Micro-CT Analysis

3.2.4.1 Sample Selection

Rib samples were collected from ten individuals for a case-study analysis of osteomalacia in Pointe-aux-Trembles and Sainte-Marie. To examine the relationship between bone amount and vitamin D deficiency, individuals with high, low, and average CAI_{ROI} values were systematically selected to represent the total CAI_{ROI} range. In addition, individuals with macroscopic skeletal lesions highly consistent with osteomalacia, such as pseudofractures in the pelvis or alterations in rib morphology (Brickley et al. 2020 pp. 117-121), were also chosen for further analysis.

3.2.4.2 Micro-CT Imaging

Rib samples were chosen for micro-CT analysis for several reasons. A study of bone survival rates determined that 40%-59% of ribs survive archaeological contexts (Waldron 1987), meaning it is likely that an individual will have at least some rib fragments that can be chosen for analysis. Ribs have a turnover of approximately 5 years, compared to other bones in the skeleton that have turnover rates or 10-20 years (Jørkov et al. 2009). The fast turnover rate in ribs means that observed defects are more representative of skeletal health at the time of their death than defects observed in other skeletal elements.

The chosen samples were analyzed using the Nikon XTH-225ST micro-CT scanner at the Ancient Images Lab of the Museum of Ontario Archaeology in London, Ontario. The rib samples were mounted in a Styrofoam cup and stabilized with green florist foam. Samples were scanned using a low kVp technique (80kVp, 173A), a molybdenum target to maximize contrast, and a voxel size of 10.5 µm. Each sample was scanned for 53 minutes, with a total of 3141 2D x-ray images taken as the mounted sample rotates in the scanner, at a rate of 1 projection per second. The 3D reconstruction was completed using X-Tec CT-Pro, V. 4.4. The files generated from the reconstruction were uploaded to Dragonfly (Version 2021.3 Build 1087) where each 2D slice and the 3D image could be visually analyzed.

3.2.4.3 Slice Analysis and Scoring

A range of histological features suggestive of osteomalacia have been explored by researchers (Section 2.4), although some are invisible in micro-CT scans. The most distinctive

histological indicator of osteomalacia is defective mineralization along cement lines (DCL). These defects form when new layers of bone fail to ossify completely during life, leaving distinct crescent-shaped structures of bone that appear partially or completely disconnected from other bone structures (Brickley et al. 2007; Priemel et al. 2010; Welsh et al. 2020). Areas of incomplete mineralization, which appear darker than mineralized bone in micro-CT scans, can also be indicative of defective mineralization. However, because bone is constantly modelling and remodelling (Frost 2003), patches of incomplete mineralization may be visible in those without osteomalacia. Areas of incomplete mineralization are noted, but not given the same scoring weight as DCLs.

Table 3.4. Defect scores and descriptions for slice analysis.

Score	Description
0	No clear defects.
1	Visible defects are small in size. Defective cement lines are visible but have not completely separated new and old bone.
2	Visible defects are more pronounced. Defective cement lines span a large area and may show partial separation between new and old bone.
3	Defects are clearly visible and seen consistently in the scan. Defective cement lines may show the complete or marked partial separation of new and old bone surfaces and may span a large area.

To assess the prevalence and consistency of DCLs throughout the rib, five equally spaced slices, spaced 250 scans apart, were chosen from within a 1cm region of interest on the shaft of the rib. From these five images, it was possible to note not only the appearance and number of mineralization defects in a single slice, but the consistency with which they occurred throughout

the sample. Utilizing several slices in this region, the chances of misidentifying diagenesis or taphonomic change as a pathological defect is reduced.

Each slice was visually analyzed and assigned a score from 0 to 3 based on the presence, appearance, and size of the DCLs (Table 3.4). Slices with DCLs that were improperly mineralized were assigned an extra half-point to the slice score. Visual depictions of the appearance of each defect type are represented in Figure 3.3-3.4. The scores from each slice were then added together to assign an overall defect status to the individual (Table 3.5).

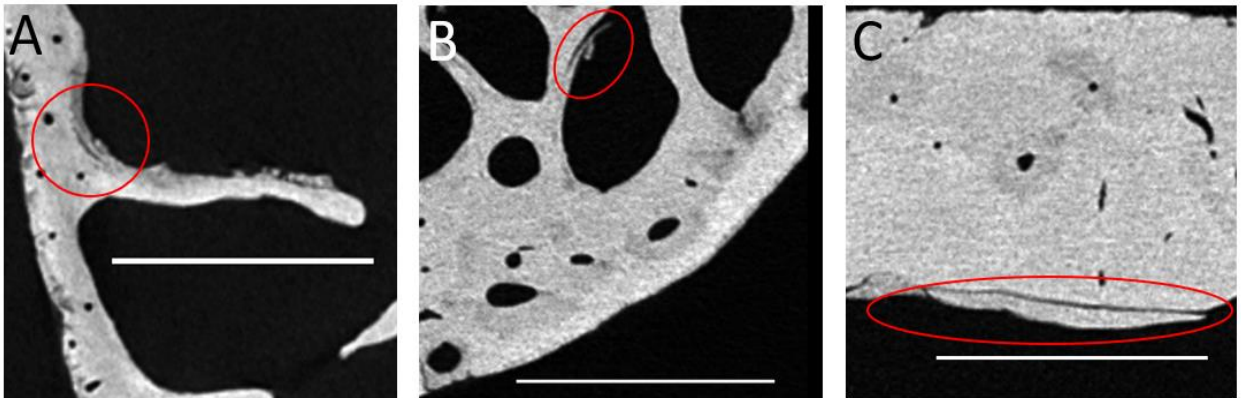

Figure 3.3. Appearance of defective cement lines with a score of 1 (Image A), 2 (Image B), and 3 (Image C). Scale bars indicate 1mm.

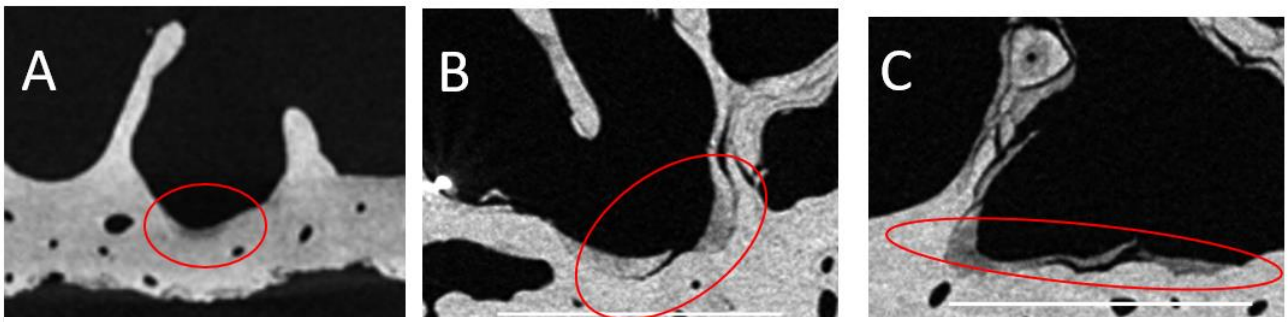

Figure 3.4. Appearance of incomplete mineralization associated with defective cement lines. The cement lines are scored as a 1 (Image A), 2 (Image B), and 3 (Image C). Scale bars indicate 1mm.

Table 3.5. Defect category derived from total defect score.

Total Defect Score	Overall Defect Category
0.0-3.5	No significant defects
4.0-7.5	Mild defects
8.0-11.5	Moderate defects
12.0+	Severe defects

3.2.4.4 Interpretations Through Osteobiography

Due to the small sample size, it was not possible to perform a statistical analysis of defect scores in relation to age, sex, or CAI_{ROI}. Instead, the defect scores were interpreted through an osteobiographical approach, exploring the experiences of the individual situated within the general characteristics of the sample, and the broader social and cultural context in which the sample lived.

Chapter 4: Results

4.1 Introduction

This chapter outlines the results of this study, beginning with an analysis of the relationship between age, sex, and the total cortical area of the mid-diaphyseal region of interest (CAI_{ROI}) values obtained using the radiogrammetric procedure outlined in Section 3.2.3 (Appendix D). Following the CAI_{ROI} data analysis, observational results of the ten rib micro-CT scans are reported. Finally, the CAI_{ROI} data and the micro-CT results will be summarized and compared in the ten individuals selected for rib scans.

4.1.1 Sample Size and Distribution

The total sample includes 43 individuals; 18 individuals were chosen from Pointe-aux-Trembles, and 25 individuals were chosen from Sainte-Marie. Of these 43 individuals, rib samples were chosen from 10 individuals for micro-CT scanning for an observational analysis of mineralization defects associated with osteomalacia likely caused by vitamin D deficiency.

4.2 Metacarpal Radiogrammetry

4.2.1 Sex and CAI_{ROI}

As explored in Section 2.3.3, the processes of bone accumulation and age-related bone loss follow sex-related patterns, particularly as estrogen levels fluctuate throughout a female's

lifespan. All data was determined to be normally distributed (Appendix E1). In order to determine if further calculations of CAI_{ROI} should be separated by sex, student's t-test was used to test for statistical differences in CAI_{ROI} values by sex. A test in the 15-29 age category (*f=11, m=8*), the 30-49 age category (*f=8, m=2*), the 50+ age category (*f=8, m=6*), and a test for the total sample (*f=27, m=16*) were carried out (Appendix E2).

In each of the four analyses, there were no statistically significant differences in the CAI_{ROI} values between males and females ($p>0.05$). Because there are no differences between the sexes in any age group, it is appropriate to combine male and female data for further analyses.

4.2.2 Age and CAI_{ROI}

The 15-29 age category had the widest range of CAI_{ROI} values of all three age groups (Appendix E3), and contained the individuals with both the highest overall CAI_{ROI} value (2E13) and the lowest overall CAI_{ROI} value (7A9-S45). The CAI_{ROI} ranges become narrower and the median values decrease with age (Figure 4.1). To statistically analyze the relationship between CAI_{ROI} and age observed in Figure 1, one-way ANOVA and Pearson's correlation coefficient (*r*) were applied (Appendix E4).

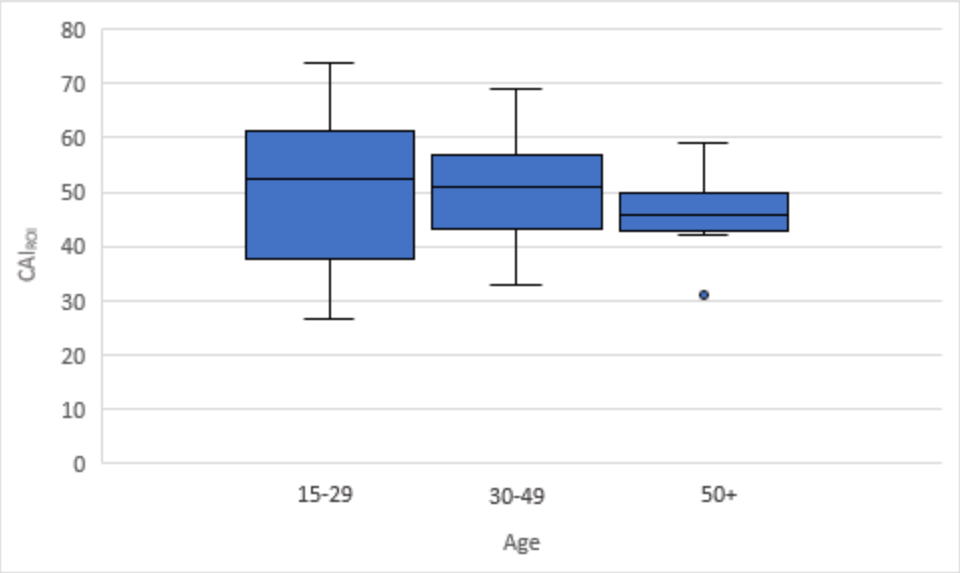

Figure 4.1. Box plot of cortical area index (CAI_{ROI}) in relation to age (*n*=43).

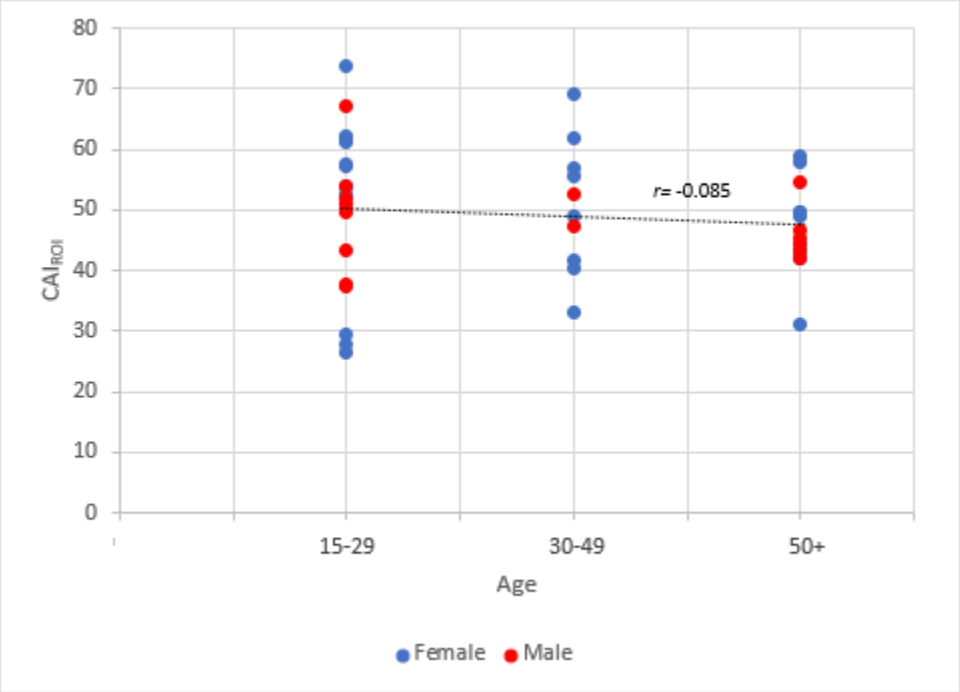

Figure 4.2. Scatter plot depicting the relationship between age and cortical area index (CAI_{ROI}) (*n*=43).

To assess the relationship between age and CAI_{ROI}, one-way ANOVA was used to compare the CAI_{ROI} values of each age group for statistically significant differences. The results from each test reveal that there are no statistically significant differences in the average CAI_{ROI} values between any of the age categories ($p>0.05$).

Pearson's correlation coefficient was applied to the total sample to assess the strength of the correlation between age and CAI_{ROI}. Pearson's correlation coefficient represents a number between -1 and 1, where the closer the *r* value is to 0, the weaker the relationship between the variables. An *r* value of -0.085 was calculated for the relationship between age and CAI_{ROI}, indicating an extremely weak negative correlation between age and CAI_{ROI} for this sample (Figure 4.2), although this was determined not to be statistically significant.

4.3 Micro-CT Analysis

Rib samples from ten individuals were chosen from the total sample for micro-CT scanning. The chosen sub-sample consisted of seven individuals from Pointe-aux-Trembles (*f=5, m=2*) and three individuals were chosen from Sainte-Marie (*f=2, m=1*). Mineralization defects were scored on the scale described in Section 3.2.4 and reported in Appendix F.

4.3.1 Pointe-aux-Trembles

4.3.1.1 7A2-S2

The age and sex assessment of individual 7A2-S2 estimated that this individual is a female in the age category of 30-49, and the radiogrammetric assessment of their metacarpal indicated a CAI_{ROI} of 69.045. The micro-CT scan of individual 7A2-S2's left rib indicates

significant fungal tunnelling and taphonomic damage, rendering it difficult to view potential mineralization defects. The trabecular spacing is inconsistent throughout the rib, transitioning from a healthy microarchitectural network to areas of sparsely arranged trabeculae. The cortical bone is thin, particularly in the areas where there are many trabecular structures. There are several instances of defective cement lines in the rib, particularly in the areas with a strong trabecular network (Figure 4.3). A total score of 6.5 was assigned to this individual, placing them in the mild defect category.

4.3.1.2 7A2-S11

Individual 7A2-S11 is estimated to be a female in the 30-49 age category, with a CAI_{ROI} value of 32.956. The left rib fragment chosen for scanning is damaged on its external surface, and the images of the internal structures show evidence of fungal tunnelling and several soil deposits within the trabecular structure. The trabeculae are sparse and the cortical bone is thin, particularly along the lateral portion of the rib. There are several small, consistent cases of defective cement lines and improper mineralization throughout the scan. This individual was assigned a score of 10.5, placing them in the moderate defect category.

4.3.1.3 7A2-S20

Individual 7A2-S20 is estimated as a female within the 15-29 age category. Their CAI_{ROI} was determined to be 29.382. The trabeculae of the rib are extremely sparse and the cortical area is thin. There are numerous areas of improper mineralization within the cortical bone, and

a small number of defective cement lines (Figure 4.4). The sum of defect scores is 5.5, assigning them to the mild defect category.

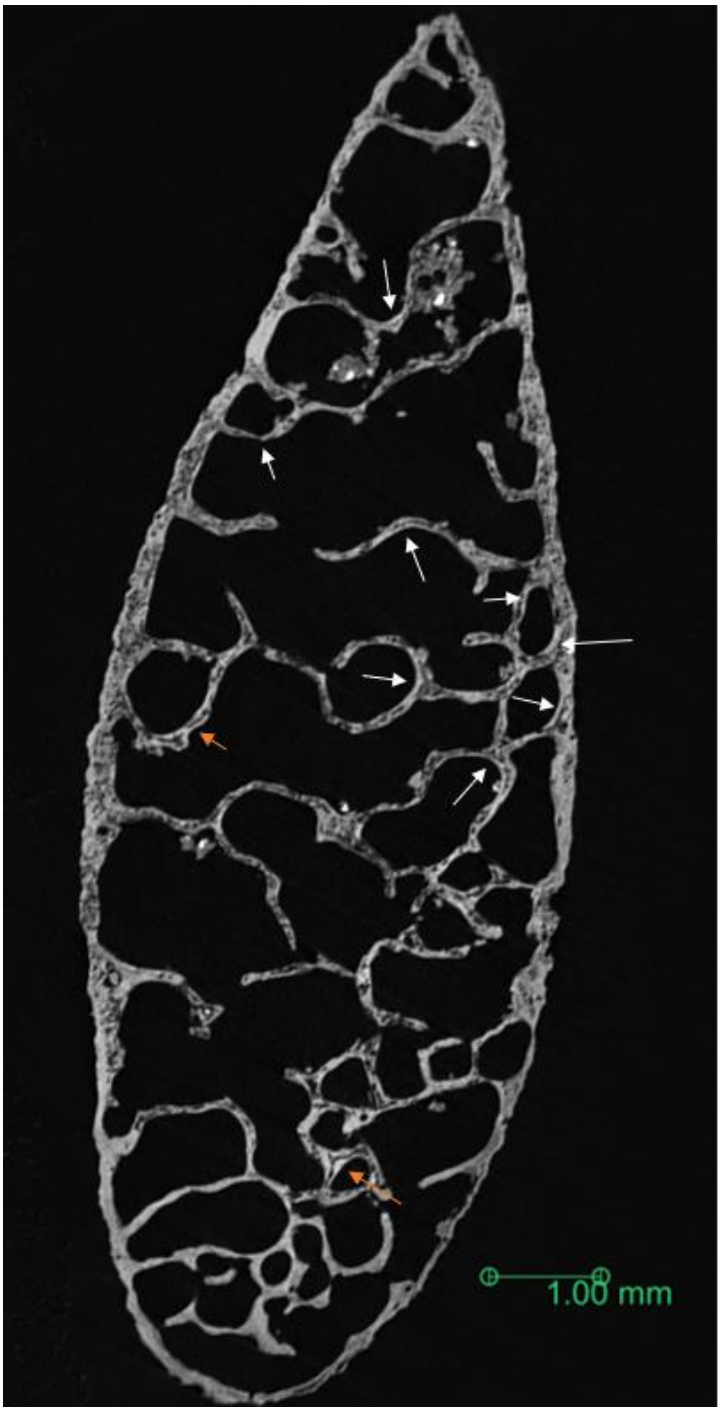

Figure 4.3. Defective cement lines (DCL) in individual 7A2-S2, slice 1300. White arrows indicate stage 1 DCLs, orange arrows indicate stage 2 DCLs.

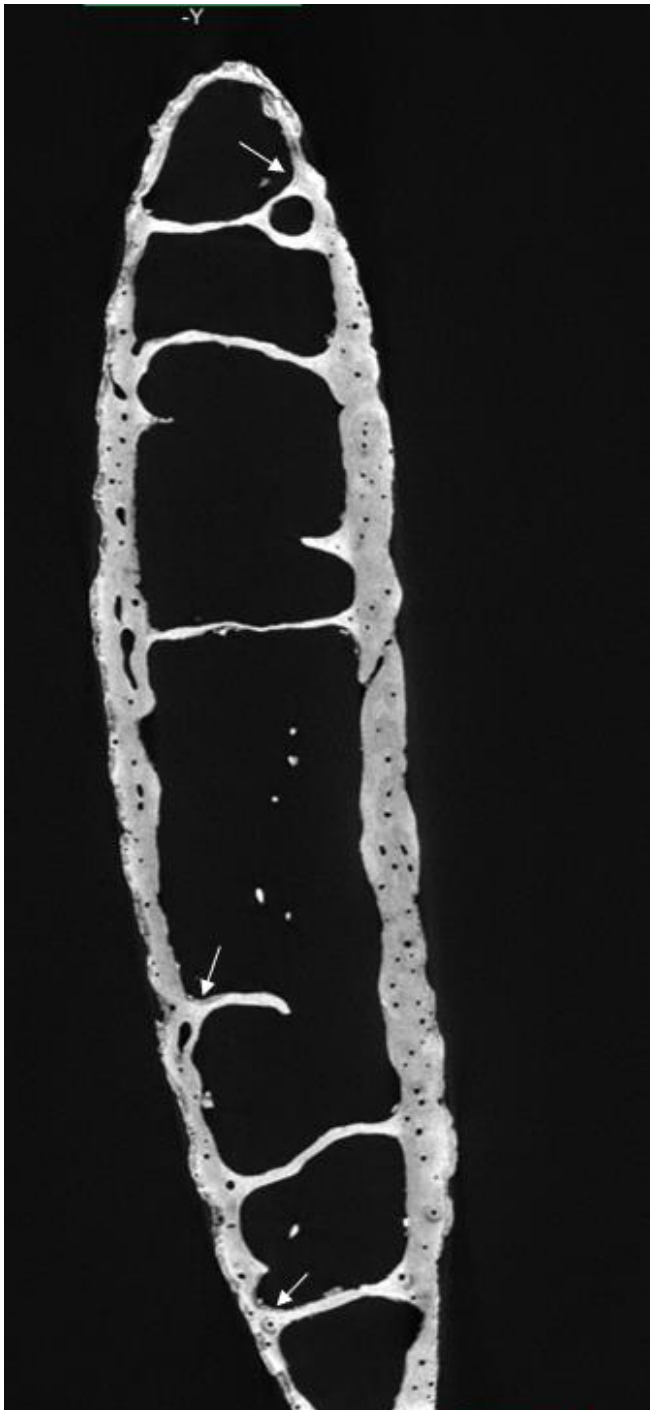

Figure 4.4. Defective cement lines (DCL) in individual 7A2-S20, slice 1350. White arrows indicate stage 1 DCLs.

4.3.1.4 7A9-S38

The age and sex estimates for individual 7A9-S38 determined they are likely male within the 15-29 age category, and their CAI_{ROI} value is 67.181. The rib scan for this individual shows considerable taphonomic damage and soil infilling; however the cortical area and trabecular network are healthy. Any potential mineralization defects are ambiguous, and do not appear consistently throughout the scans, receiving a defect score of 0.

4.3.1.5 7A9-S46

Individual 7A9-S46 is likely a female, in the 50+ age category, with a CAI_{ROI} of 49.569. The scan of the rib shows extensive fungal damage to both the thinned cortical bone, which shows extreme evidence of endocortical trabecularization, and sparse trabecular structures. In portions of the bone that are not damaged, several areas with long defective cement lines are visible throughout the rib (Figure 4.5). This score assigned to this individual was 6.5, assigning them to the mild defect category.

4.3.1.6 7A11-S19

This individual was estimated to be a male in the 50+ age category. The radiogrammetric assessment of their metacarpal indicated a CAI_{ROI} of 43.313. The trabecular structure is sparse and the cortical bone is damaged by extensive fungal tunnelling and other taphonomic damage. Despite these factors limiting the visibility of potential defects, several mineralization defects are consistently visible throughout the scan. This individual was assigned a total score of 12.5, indicating severe defects.

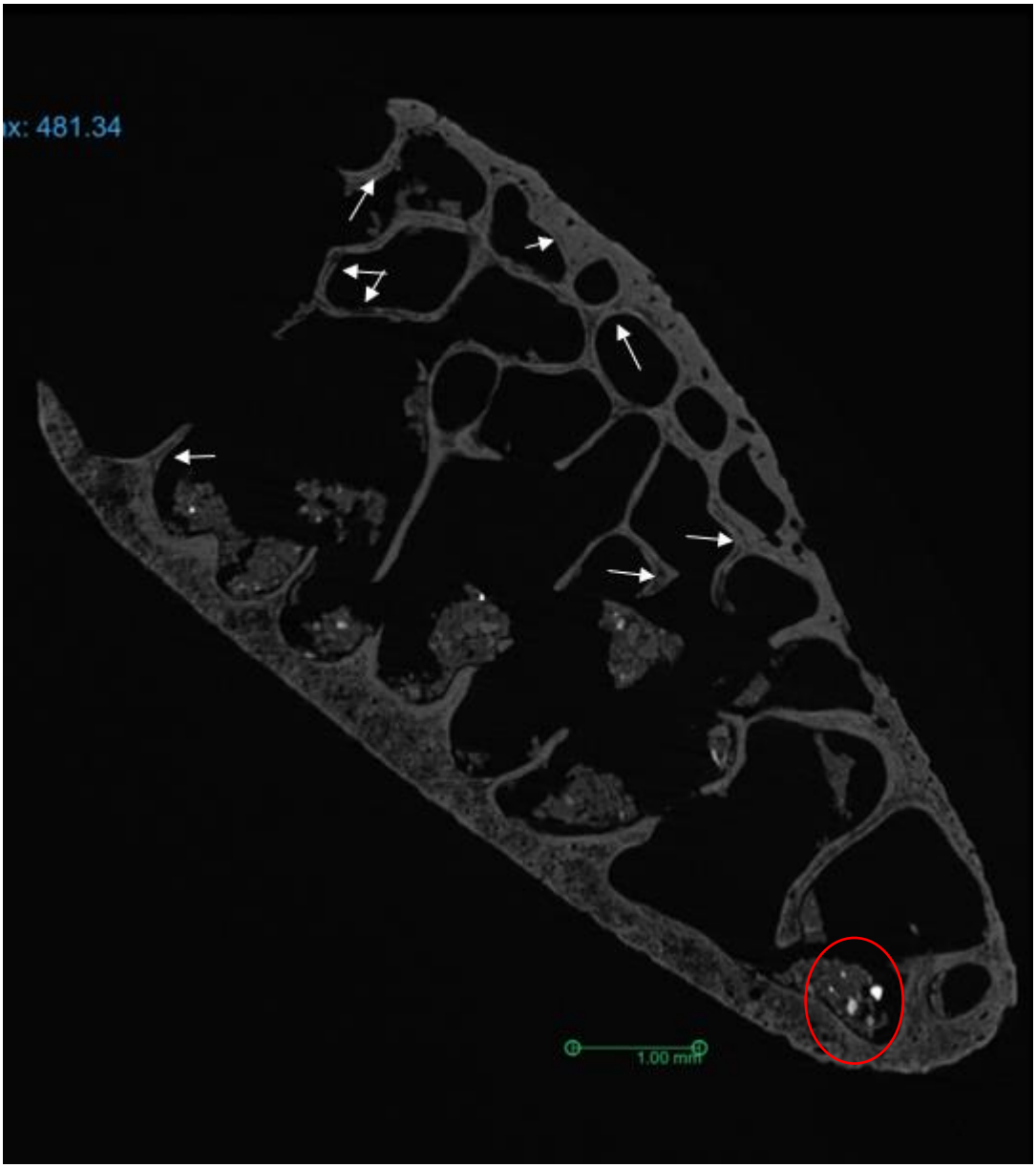

Figure 4.5. Defective cement lines (DCL) in individual 7A9-S46, slice 450. White arrows indicate stage 1 DCLs. The white areas within the red circle are soil inclusions within the rib.

4.3.1.7 7A11-S42

Individual 7A11-S42 is estimated to be a female within the 15-29 age category, with a CAI_{ROI} value of 27.813. The internal structures of the scanned rib fragment are extensively

damaged, and there are several large soil deposits within the bone. The intact trabeculae are thin and sparse, and the cortical bone is extremely thin. Small areas of DCLs throughout the scans resulted in a score of 4.5, placing them in the mild defect category.

4.3.2 Sainte-Marie

4.3.2.1 2B9

This individual is likely a female in the 50+ age category. Their CAI_{ROI} value is 31.012, and the scan of their rib had a defect score of 1.0, indicating no significant mineralization defects. The trabeculae, while sparse, are relatively thick, and the cortical bone appears healthy.

4.3.2.2 2E13

Individual 2E13 was assessed as a young female within the 15-29 age group. The radiogrammetric assessment of their metacarpal indicated a CAI_{ROI} of 73.856. Despite some taphonomic damage to the internal structures of the rib, the trabecular network and cortical bone appear healthy. The scan shows several large cases of defective cement lines that persist throughout the rib, and several cases of improper mineralization (Figure 4.6a, b). This individual was assigned a defect score of 14.5, indicating severe defects.

4.3.2.3 2G4

Individual 2G4 is a probable male within the 15-29 age category, with a CAI_{ROI} of 43.449. Despite slight fungal damage and cracking in the cortical bone, the internal structures of the rib are easily visible. The trabeculae are sparse in some areas throughout the rib, but the cortical

bone is healthy and has undergone minimal thinning. This individual received a total defect score of 2.0, indicating there are no significant defects present.

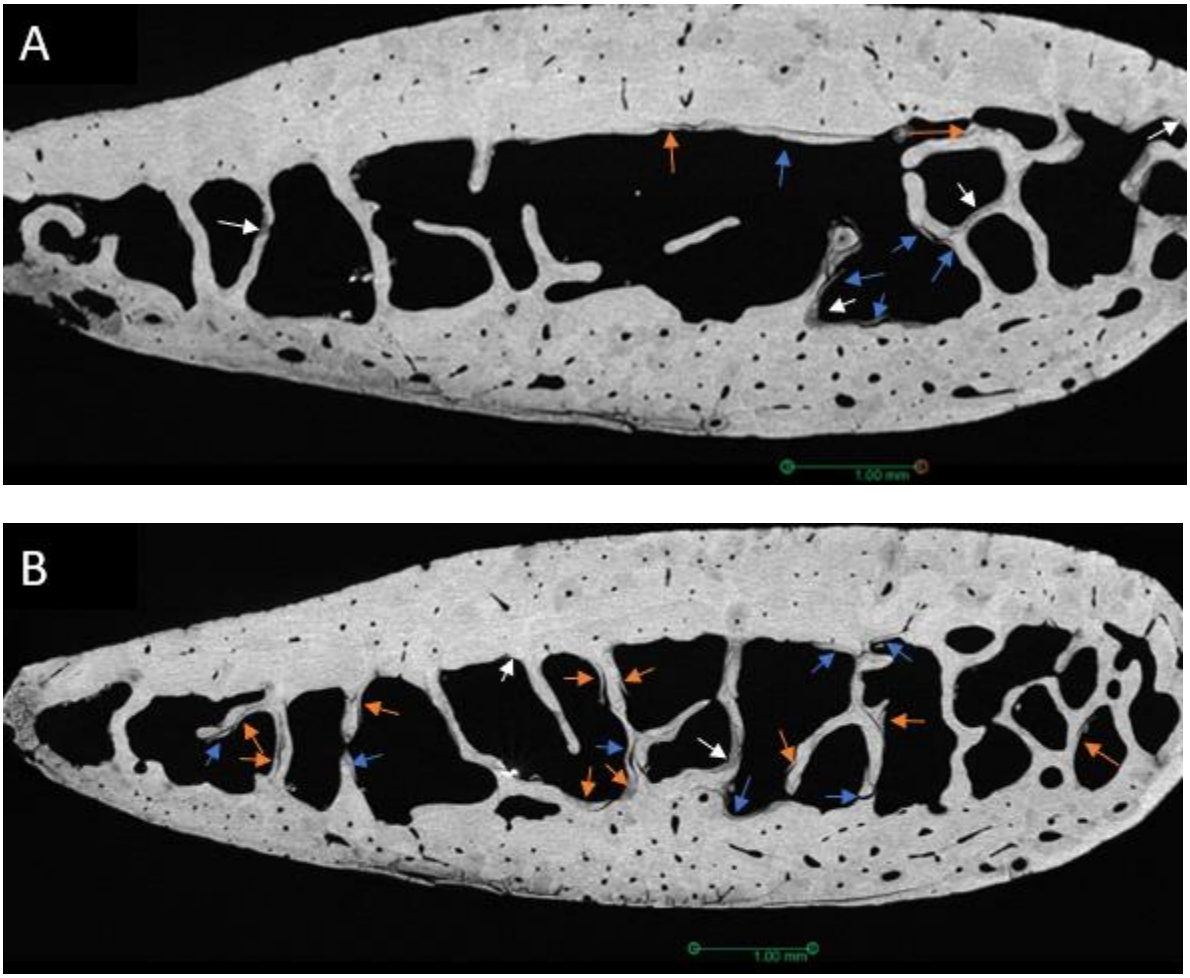

Figure 4.6. Defective cement lines (DCL) in individual 2E13, slice 1300 (A) and 1800 (B). White arrows indicate stage 1 DCLs, orange arrows indicate stage 2 DCLs, and blue arrows indicate stage 3 DCLs.

4.3.3 Mineralization Defects and CAI_{ROI}: Comparison and Summary

The CAI_{ROI} data and the mineralization defect scores for the ten individuals chosen for micro-CT scanning are compared in Table 4.1. Several individuals with high CAI_{ROI} values showed substantial evidence of mineralization defects, particularly individual 2E13. Individual 2E13 is a

female in the 15-29 age category, and has the highest overall CAI_{ROI} in the total sample; however, the scanned rib from 2E13 shows the most severe and numerous mineralization defects of the entire sub-sample. In contrast, individual 2B9 is an older female in the 50+ age category with one of the lowest overall CAI_{ROI} values, and shows no clear evidence of mineralization defects in the micro-CT scan. There does not appear to be a clear relationship between CAI_{ROI}, age, and the presence or severity of mineralization defects in this sample.

Table 4.1. Summary of age, sex, cortical bone area (CAI_{ROI}), and mineralization defect scores (*n*=10).

	Age	Sex	CAI_{ROI}	Mineralization Defects
7A2-S2	30-49	F	69.045	6.5
7A2-S11	30-49	F	32.956	10.5
7A2-S20	15-29	F	29.382	5.5
7A9-S38	15-29	M	67.181	0.0
7A9-S46	50+	F	49.569	6.5
7A11-S19	50+	M	43.313	12.5
7A11-S42	15-29	F	27.813	4.5
2B9	50+	F	31.012	1.0
2E13	15-29	F	73.856	14.5
2G4	15-29	M	43.449	2.0

Chapter 5: Discussion

5.1 Introduction

The previous chapter presented a detailed statistical analysis of the calculated cortical area index values (CAI_{ROI}), determined from the second metacarpals of the individuals Pointe-aux-Trembles and Sainte-Marie. Following the statistical analysis, micro-CT images of ribs from the 10 selected individuals were analyzed individually and scored for evidence of mineralization defects associated with vitamin D deficiency. In this chapter, patterns of age-related bone loss at the sample level in Pointe-aux-Trembles and Sainte-Marie will be discussed and compared to expected trends observed in clinical data and to other bioarchaeological studies of the same nature. The results of the rib micro-CT assessment will be discussed in-depth through individual osteobiographical accounts. This chapter will close with a discussion of osteoporosis and osteomalacia as social history in historical French-Canada.

5.2 Metacarpal Radiogrammetry

Using the metacarpal radiogrammetry method developed by Gilmour et al. (2021), the current study revealed no relationship between age and cortical bone amount in the study sample, nor were there significant differences in cortical bone amount between sexes. These results do not follow the expected trends outlined in clinical sources using living individuals. Clinical data shows that bone reaches its peak density near the third decade of life and begins to decline shortly after this period (Agarwal 2021; Compston et al. 2019; Keaveny and Yeh 2002; Manolagas 2000; Prestwood and Raisz 2004). Medical literature also documents sex-based

differences in bone accumulation and total mass, with males reaching higher peak bone levels than females, while females lose more extreme bone levels in older age due to menopause (Black and Rosen 2016; Isojima and Sims 2021; Laurent et al. 2014; Manolagas 2000; Matkovic and Landoll 2004; Riggs et al. 1998). An extremely weak negative correlation between age and CAI_{ROI} was identified using Pearson's correlation coefficient (r=-0.085), indicating a slight relationship between bone loss and old age. However, this value was not statistically significant ($p>0.05$). It is unexpected that this study would find no age or sex-based discrepancies in CAI_{ROI} in the individuals from Pointe-aux-Trembles and Sainte-Marie.

5.2.1 Comparative Analysis

Many cautions must be taken when comparing data from archaeological samples to modern medical data. Small sample sizes (Wissler et al. 2022), and poor element preservation (Brickley and Buckberry 2015; de Boer and van der Merwe 2016; Gilmour et al. 2021) are the main limiting factors in bioarchaeological research. Therefore, other studies on bone loss in archaeological samples serve as effective sources of comparative data. Approximately 70 bioarchaeological studies investigating age and sex trends in bone were identified. Of the 70 studies, 13 papers considering a total of 1966 individuals met the inclusion criteria outlined in Section 3.2.3.3. Three trends were revealed from the results of the comparative studies: 1) Adherence to clinical age and sex trends, 2) Age-related bone loss with sex-based deviations from clinical data, 3) No relationship between age, sex, and bone loss. The results of this literature review are presented in Table 5.1.

Table 5.1. Summary of observed age and sex trends in comparative studies.

Reference	Location and Sample Groups	Age-Related Bone Loss	Sex-Based Differences in Bone Amount	No Age or Sex Trends
Agarwal 2012	Rural England	✓		
	Urban England	✓	✓	
Agarwal and Grynpas 2009	England	✓	✓	
Beauchesne and Agarwal 2014	Italy	✓		
Beauchesne and Agarwal 2017	Italy Sample 1	✓	✓	
	Italy Sample 2	✓		
	Italy Sample 3	✓	✓	
Curate et al. 2013	Portugal	✓	✓	
Dewey et al. 1969	Sudan Sample 1			✓
	Sudan Sample 2	✓	✓	
	Sudan Sample 3			✓
Ekenman et al. 1995	Sweden			✓
Ericksen 1976	Southwest United States	✓	✓	
	Midwest United States	✓	✓	
	Alaskan Coast	✓	✓	
Glencross and Agarwal 2011	Turkey	✓	✓	
Holck 2007	Norway Sample 1	✓		
	Norway Sample 2	✓		
	Norway Sample 3	✓		
Poulsen et al. 2001	Denmark			✓
Van Gerven et al. 1969	Midwest United States	✓	✓	
Zaki et al. 2009	Egypt	✓	✓	
Total		**18**	**12**	**4**

In reviewing bioarchaeological literature from a wide range of spatial and temporal contexts, many studies commonly reported trends which followed the age and sex expectations established by clinical data. In a study by Glencross and Agarwal (2011), metacarpal radiogrammetry was used on the second metacarpals of 49 adults (f=27, m=22) from the

Neolithic community of Çatalhöyük, Turkey. Individuals were placed in three age groups similar to the categories established in this study, and it was ultimately found that the cortical bone amounts measured in this sample adhere to the age and sex trends set by clinical data.

Curate et al. (2013) examined 196 individuals of known age, sex, and ancestry from a rural community cemetery in central Portugal, occupied from the mid-19th to early-20th century. Dual X-ray absorptiometry of the proximal femur was used to measure the bone mineral density (BMD) of these individuals. The authors observed a significant decrease in BMD with age and a pronounced discrepancy in BMD between males and females, particularly in the older age groups.

Van Gerven et al. (1969) measured femoral cortical bone thickness in 43 individuals (f=23, m=20) excavated from a prehistoric Mississippian site, using roentgenographic x-ray images and direct measurements from femoral slices. Statistical analyses of these measurements show a significant decrease in cortical bone amount with age in the total sample, and substantial sex-based differences in bone amount, as females lost significantly more bone with age compared to males. A later study of three Indigenous archaeological samples by Ericksen (1976) utilized the same roentgenographic methods on the humerus and femora of these individuals. This study too found the same results as the above studies, consistent with clinical trends.

Bioarchaeological studies frequently report deviations in the sex-based trends established in clinical literature, particularly in female skeletons. While male samples typically adhere to the gradual progression of bone loss over time, the timing and ultimate trajectory of

changes in bone amount is considerably different in females in many studies compared to modern medical trends and their male counterparts. Agarwal and Grynpas (2009) measured vertebral bone loss in a British medieval assemblage and observed that while males follow the expected pattern of bone loss over time, the female cohort reached the lowest levels of bone by middle age (30-49), and did not undergo any significant loss following this initial drop. Zaki et al. (2009) also report an initial early reduction in BMD between the second and third decades of life in an assemblage of Egyptian skeletons, particularly in the female study sample.

Bioarchaeological studies of age-related bone loss frequently report no statistically significant differences in bone amount between sexes. In an Imperial Roman assemblage, Beauchesne and Agarwal (2014) found no differences in cortical bone index between males and females in any age category (18-29, 30-49, 50+). Similar results were reported by Holck (2007) in a study of BMD in prehistoric, Viking Age, and medieval samples in Norway. There were no significant differences in BMD between males and females in each of the three samples. This trend is also observed in Agarwal (2012) and Beauchesne and Agarwal (2017), among other papers.

The least-commonly observed results report no relationship between age, sex, and bone amount. Ekenman et al. (1995) radiographically determined BMD in 343 individuals from a medieval cemetery in Stockholm and found no changes in bone amount over time for males or females. Poulsen et al. (2001) estimated the BMD of 49 individuals excavated from a Danish Christian cemetery and found no change in BMD over time in males, and an *increase* in BMD with age in females. During the literature review, only one study reported results similar to those of this thesis. In a study of three agricultural communities from different time periods

(350 B.C.- A.D. 350, A.D. 350- A.D. 550, A.D. 550- A.D. 1300) in modern Sudan by Dewey et al. (1969), two of the study groups showed extreme fluctuations over time in both the male and female samples and ultimately showed no correlation between age, sex, and cortical bone amount.

5.2.2. Bone Amount as Bioculture

In Section 2.3, the biological processes responsible for the accumulation and loss of bone are outlined from a clinical perspective, with emphasis placed on the role of genetics and sex hormones as determinants of peak bone mass and age-related bone loss. Particular emphasis is placed on managing postmenopausal osteoporosis, as clinicians provide statistics and estimates that place females at a much higher risk of osteoporosis compared to males. For example, one in three women are likely to experience osteoporotic fractures with age compared to one in five men, and 50-year-old white women have a 16% risk of experiencing an osteoporotic vertebral fracture compared to white men of the same age at 5% (International Osteoporosis Foundation 2023). Bioarchaeologists use this modern clinical data as a foundation for interpreting past bone loss, and need to fully account for the social and cultural factors that constantly influence bone health, morphology, and maintenance (Agarwal and Beauchesne 2011). This weakness is particularly significant in studies of female samples, as there is an assumption that females are inherently more vulnerable and experience greater frailty than males in the same sample (Agarwal and Beauchesne 2011; Beauchesne and Agarwal 2017). This attitude can be summarized neatly in a conclusion drawn by Ericksen (1976): “It appears that a

greater rate of aging bone loss in females is a universal fact of life." As this study and many other biomedical and bioarchaeological studies illustrate, bone loss with age is *not* a universal experience, regardless of sex. Instead, it is a process strongly influenced by social, cultural, and individual factors.

The social and cultural variables in New France likely played an essential role in the results of this study, particularly in the varied results in the youngest age category. While it is possible that individuals in this age group may not have reached peak bone mass yet at the time of death, other studies do not show this same amount of extreme variation before peak bone mass is reached. Significant genetic differences can be ruled out as a contributor to the widely spread results, as the genetic homogeneity of New France is particularly well documented (Scriver 2001). Instead, the vast differences in cortical bone amount in the young sample of Pointe-aux-Trembles and Sainte-Marie can be explored further through the complex social history of New France.

The unusual results in the youngest female sample were likely impacted by the status and expectations of women in Quebec during this era. Women in the French-Canadian colonies were typically married in their late teens or early 20s, and became mothers shortly after marriage. The fertility rate in Lower Canada was higher than that of women in France, and the interval between births was short (Landry 1993). Due to this high fertility and shortened inter-birth interval, women in New France likely had a child every two years, from the time of marriage until they reached menopause (Greer 1997). It was not unusual for the women in the French-Canadian colonies to have ten or more children in their lifetime. Although the extent to which pregnancy and lactation result in visible differences in bone amount in archaeological

skeletons is debated, clinical data has documented that pregnant and breastfeeding women undergo detectable reductions in BMD to meet fetal and neonatal calcium requirements (Kovacs 2016; O'Brien 2021). Pregnancy is clinically associated with a 1-4% decrease in total bone amount across the skeleton, but this amount is recovered within 18-20 months after birth (Ensom et al. 2002; Karlsson et al. 2001; Møller et al. 2012; O'Brien et al. 2021; Pearson et al. 2004). While this reduction in bone amount is not associated with an increase in the risk of osteoporosis, women in New France were undergoing subsequent pregnancies during this recovery period, which would have prevented them from reaching their peak bone mass.

These women also show the highest cortical area amounts, as is expected in the youngest age category. The females in the upper quartile of the 15-29 age category have more cortical bone than the males in the group, which is unusual by modern clinical standards. During the 1700s and 1800s, French-Canadian women were not only responsible for domestic labor, many women performed manual labor alongside their husbands to maintain their farms and livestock (Dumont et al. 1987; Greer 1997). This may have provided the mechanical stimulation necessary to accrue more bone mass.

In context with the social and cultural realities that these women occupied, it is not so unusual that they would represent the highest and lowest bone amounts in the total sample. Further social and cultural factors that may have influenced the results for both sexes will be discussed in Section 5.4.

5.3 Osteobiographical Accounts

5.3.1 Pointe-aux-Trembles

5.3.1.1 7A2-S2

As a middle-aged female (30-49), individual 7A2-S2 shows the highest CAI_{ROI} of the individuals from Pointe-aux-Trembles, and is the second highest in the total combined sample from Pointe-aux-Trembles and Sainte-Marie, calculated at 69.045 (Figure 5.1). In contrast, the micro-CT scan of this individual's rib fragment indicates very little cortical bone, and a sparse trabecular structure, with a mild defect score of 6.5.

The high CAI_{ROI} of this individual suggests they obtained the proper nutrients to achieve a high peak bone mass during skeletal development, and had the ability to maintain this bone mass throughout adulthood. It is likely that this individual had children, experienced pregnancy-related bone loss, and managed to recover their pre-pregnancy bone amount. Modern clinical studies have observed that BMD can return to pre-pregnancy levels within 12-18 months (Ensom et al. 2002; Karlsson et al. 2001; Møller et al. 2012; O'Brien et al. 2021; Pearson et al. 2004). Fertility decreases in the third decade of a female's life (Committee on Clinical Consensus—Obstetrics 2022); therefore, it is possible that they were no longer able to conceive, or conception became difficult and resulted in a longer inter-birth interval. Assuming that this individual was indeed a mother, based on the fertility data of the French-Canadian colonies, the high CAI_{ROI} value obtained from their metacarpal suggests that they had not been pregnant or breastfeeding for an extended amount of time—long enough that their bone amount was able to recover.

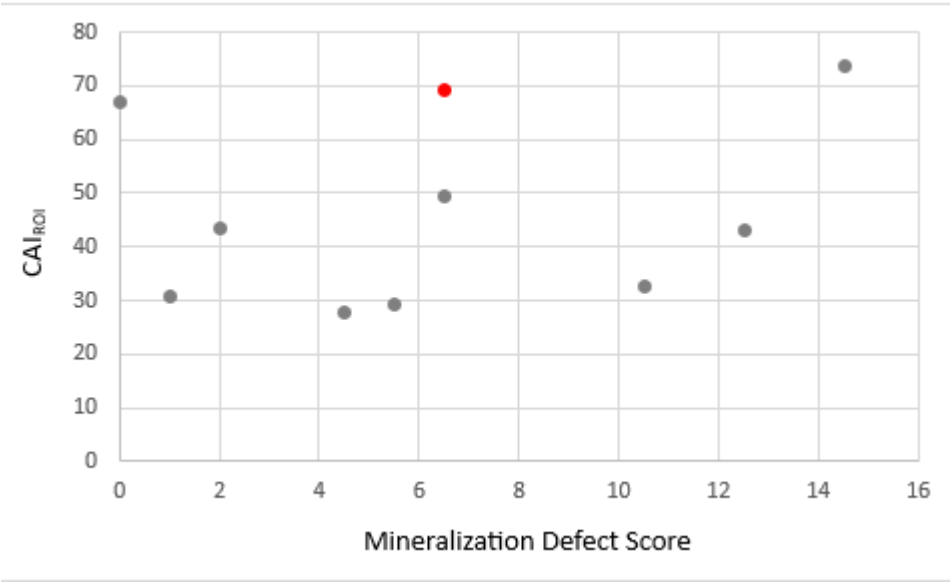

Figure 5.1. Cortical area index (CAI$_{ROI}$) and mineralization defect score of Individual 7A2-S2 (red dot) in the sub-sample (*n*=10).

5.3.1.2 7A2-S11

Individual 7A2-S11 is a female between the age of 30-49. This individual has a CAI$_{ROI}$ value of 32.956, one of the lowest in the Pointe-aux-Trembles sample and in the lowest 10% of the total combined sample. Initial assessments indicated this individual was possibly suffering from osteomalacia, particularly due to the state of the pelvis and hip joint. A fracture near the left acetabulum shows evidence of healing and extensive new bone formation in the area around the joint. The fracture is bordered by a poorly mineralized callus, a feature which Brickley et al. (2020, pp. 117-120) describe in pseudofractures caused by osteomalacia. The head of the left femur is flattened and articulates with the posterior aspect of the proximal femur, creating a false joint in the fractured acetabulum. The micro-CT analysis of this individual's rib assigned this individual a defect score of 10.5, which was a relatively high compared to others in the sample (Figure 5.2).

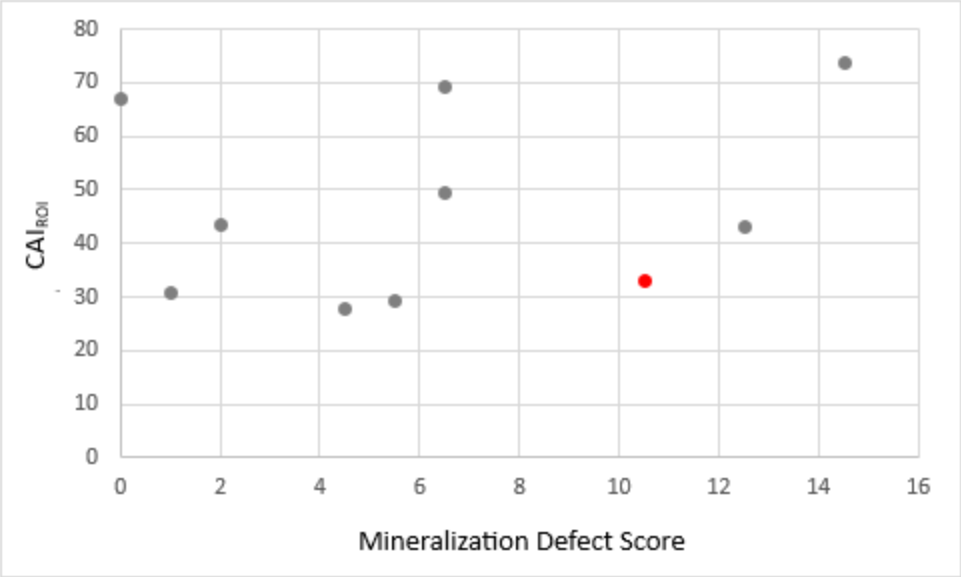

Figure 5.2. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 7A2-S11 (red dot) in the sub-sample (*n*=10).

The skeletal evidence presented here suggests that individual 7A2-S11 consistently experienced poor health during their lifetime. Their low CAI_{ROI} may have been caused by interrupted bone development due to malnutrition or infection during growth, the strain of serial pregnancies and periods of breastfeeding, skeletal resorption as a consequence of disease, or a combination of these, and many more, factors. The state of the hip joint likely limited their mobility and greatly decreased their quality of life further (Schnell et al. 2010). Although this individual is young by modern standards, it is important to note that the settlers of French Canada usually did not live past the age of 40 (Boulet 2021); therefore, despite this individual's experience with potential infectious disease and malnutrition, coupled with the challenges presented by the pathological conditions in their hip, they did manage to reach the average life expectancy of their time. It is likely that individual 7A2-S11 had been unwell for much of their life, and their death was likely not sudden.

5.3.1.3 7A2-S20

There is less skeletal data available for this individual compared to others in the sample, due to the condition of their burial. The site report notes this individual's burial was "very disturbed" and truncated by another trench, leaving only skull fragments, thoracic fragments, and a select few bones of the hand. Using the skull, this individual was estimated as female, and the status of the vertebral fusion indicated they were between the age of 20 and 29, placing them in the youngest age category for this study. The CAI_{ROI} value for this individual is considerably low at 29.382, placing them in the lowest 5% of the total sample (Figure 5.3). The cortical bone of the rib is thin, and the trabeculae are sparse for this age category. It is possible that this individual had undergone some form of nutritional stress in the past that impacted their bone development, but it is unclear if this is related to osteomalacia as the visible defects in the rib scan only had a score of 5.5.

Similar to individual 7A2-S11, it is possible that this individual was unwell for an extended period of time, and this contributed to their death. The low bone amount observed in this individual could be due to complications during skeletal development that impaired skeletal growth, or temporary loss of bone due to pregnancy and breastfeeding, for example.

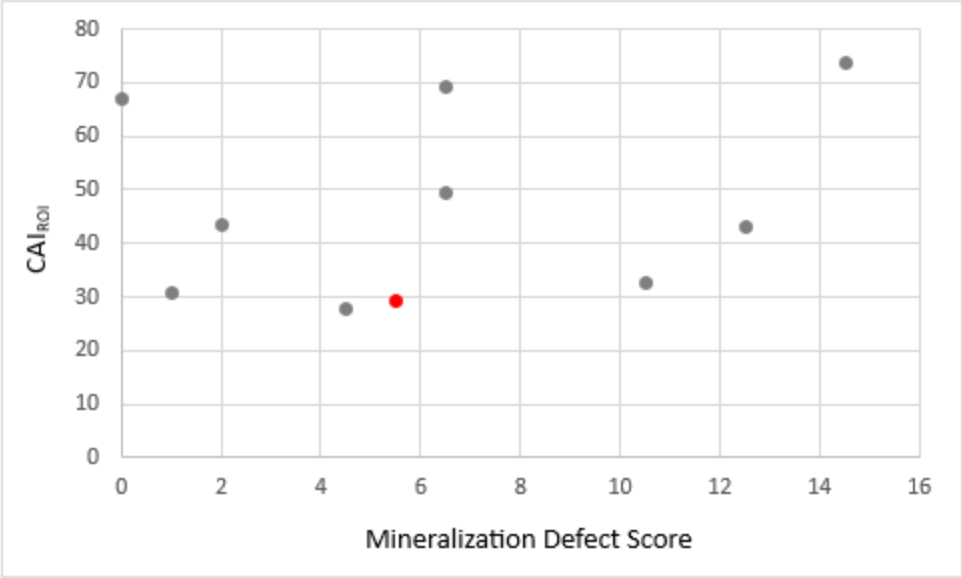

Figure 5.3. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 7A2-S20 (red dot) in the sub-sample (*n*=10).

5.3.1.4 7A9-S38

This individual was estimated to be a male between the ages of 14 and 19 based on the fusion status of several epiphyseal sites across the skeleton, making them potentially the youngest individual in the entire sample examined in this study. The present elements of their skeleton bore no obvious signs of pathology, and no mineralization defects were visible in the scan of their rib, which showed an otherwise robust cortical area and a healthy trabecular structure. The CAI_{ROI} value obtained from the second metacarpal is 67.181, the second highest value from Pointe-aux-Trembles and within the top 10% of the total combined sample (Figure 5.4). Based on the skeletal evidence, they accrued a healthy amount of bone for their cohort and likely would have accumulated more bone as their skeleton reached maturity.

It is likely that this individual performed manual labor, either on their family's farm or in Montréal. If they were on the older side of the age range assigned to them, it is also fairly likely

that they were married and had started a family. Based on the available characteristics of this individual, they were probably a stereotypical, French-Canadian laboring male who was in good health. It is quite likely, then, that this individual died suddenly, and it is unclear what factors may have contributed to their death.

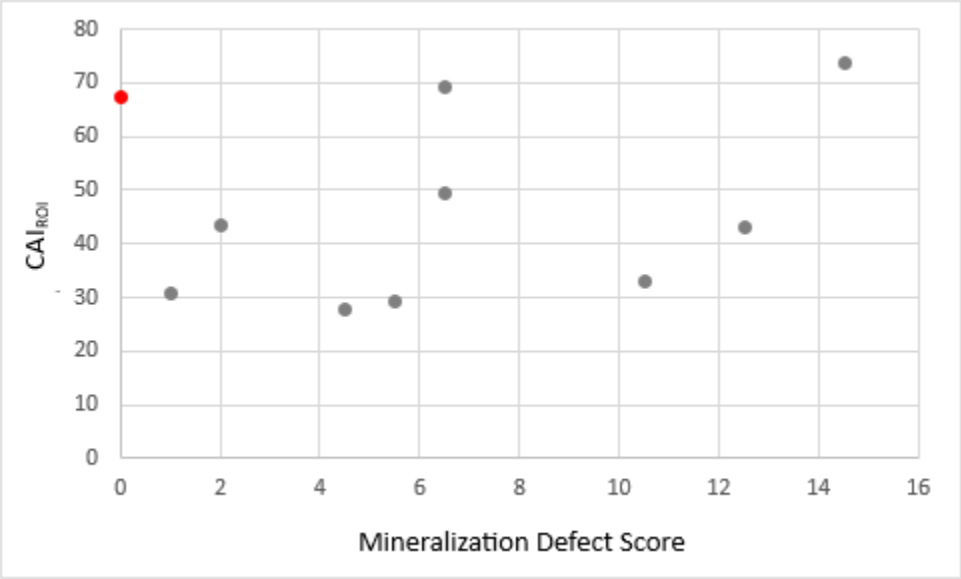

Figure 5.4. Cortical area index (CAI$_{ROI}$) and mineralization defect score of Individual 7A9-S38 (red dot) in the sub-sample (*n*=10).

5.3.1.5 7A9-S46

This individual was located in a densely populated sector of the cemetery, positioned beneath individual 7A2-S20 and similarly truncated by a trench. Much of their skeleton was missing or badly fragmented. It was possible to estimate their sex as female, and the features of the pelvis indicate they are likely of an advanced age: the morphology of the auricular surface indicates they are above the age of 60, while the presence of iliac exostoses suggests they may be above the age of 80 (Milner and Boldsen 2012). Their cortical area amount is 49.569, which

falls near the median CAI_{ROI} in both the Pointe-aux-Trembles and total samples (Figure 5.5). This individual received a mineralization defect score of 6.5.

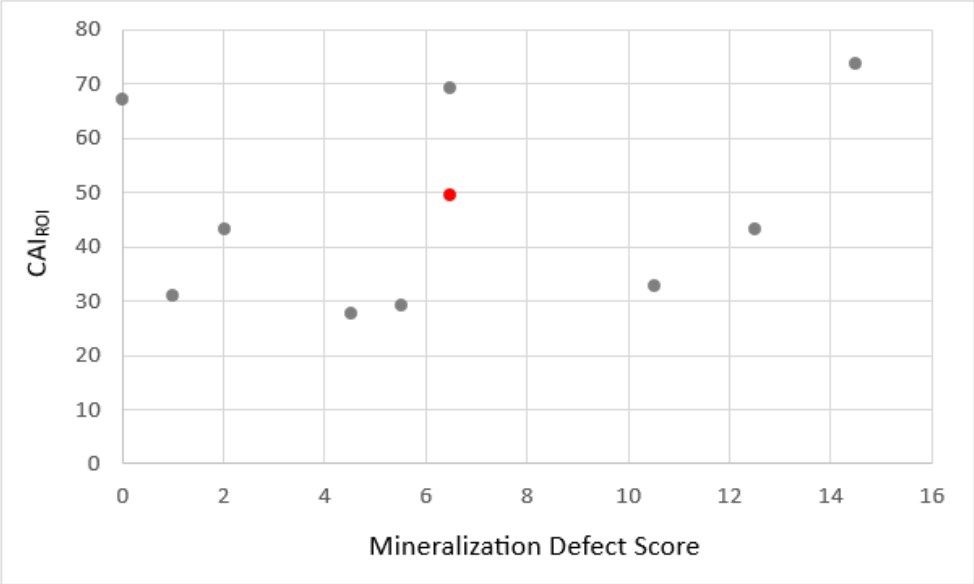

Figure 5.5. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 7A9-S46 (red dot) in the sub-sample (*n*=10).

The defects in the rib indicate this individual may have experienced osteomalacia. Given that this individual was very old, the onset of osteomalacia may have been caused by the cumulative inefficiency of physiological processes with age (Clegg et al. 2013; Weiss 2011). As individuals age, the ability to regulate homeostasis in the body begins to fail (Clegg et al. 2013). Systems essential to the regulation of vitamin D levels commonly become less efficient in the elderly. The synthesis of vitamin D in the skin becomes less efficient in older individuals (Brickley et al. 2020, pp.81-82), and the decrease in kidney function, which synthesizes active vitamin D, is one of the most common complications of aging (Coresh and Astor 2006).

Although this individual may have been experiencing the negative effects of old age at the time of their death, their CAI_{ROI} amount is very high for an older individual. Considering

their bone mass in advanced age is relatively high compared to others in their age cohort, it may be assumed that their peak bone mass was quite high. This suggests they had access to sufficient nutrition during growth and development, adequate mechanical stimulus, a genetic predisposition to high bone amount, or a combination of these factors. Without more skeletal elements it is difficult to make a complete assessment of their health. However, since life expectancy rarely exceeded 40 years of age in the colonies (Boulet 2021), is probable that this individual lived a long, relatively healthy life in Pointe-aux-Trembles.

5.3.1.6 7A11-S19

Individual 7A11-S19 was located in a cluster with five other individuals (including 7A11-S42), and is missing their skull, several ribs, and both feet. Several of the long bones were severely fragmented. Using the auricular surface of the pelvis, they were estimated to be an older male in their 60s. The CAI_{ROI} value calculated for this individual is 43.313, placing them in the lowest quartile in the Pointe-aux-Trembles sample and ranking them middle-low in the total sample (Figure 5.6). The micro-CT scan of their rib shows the thinning of the cortical bone through increased porosity and the coalescence of these porous areas, and the trabecular structure is almost nonexistent. The visible defects in the rib scan were quite severe, at a score of 12.5.

It is possible that this individual was experiencing age-related bone loss based on the low CAI_{ROI} value of their second metacarpal, the porosity of their rib fragment, and the breakdown of the trabeculae in their rib. Their age, several decades above the average life expectancy, suggests that they had been relatively healthy throughout their lifetime until this

point. The severe mineralization defects, then, may be due to the physiological changes associated with age, explained in Section 5.3.1.5, or may be due to another pathological condition that is not age-related. It is possible that this individual died of old age rather than a form of illness.

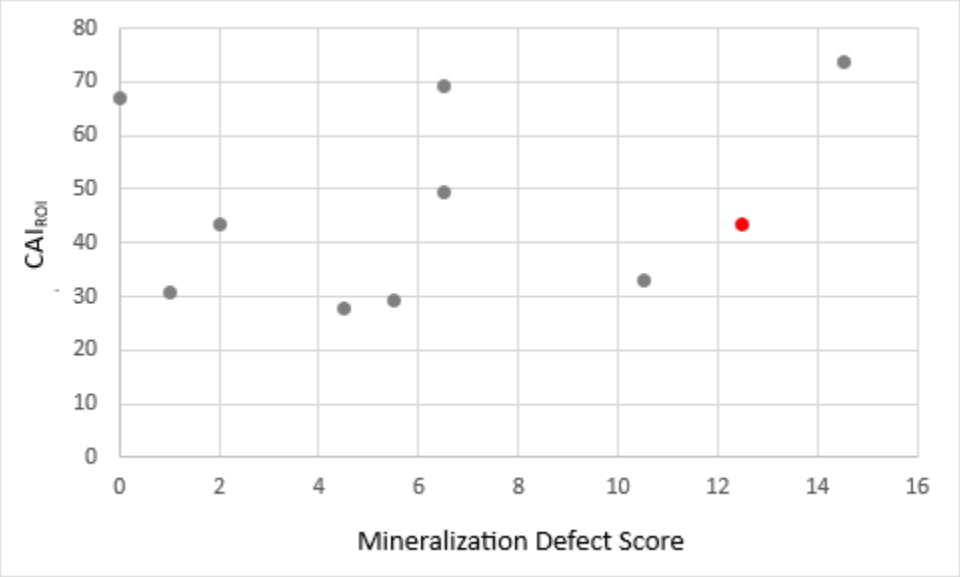

Figure 5.6. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 7A11-S19 (red dot) in the sub-sample (*n*=10).

5.3.1.7 7A11-S42

This individual was located in the same sector as 7A11-S19, and was located beneath three other individuals within this cluster. Many of their skeletal elements are poorly preserved or absent, as they were truncated by a trench and were very disturbed. The features of the skull suggest this individual is female, and the status of vertebral fusion indicates that they were 16-20 years old, one of the youngest in the sample. Due to the incomplete nature of the skeleton and the poor preservation of the remains that were present, there was no gross pathology visible. However, this individual has the second-lowest CAI_{ROI} value obtained in both the Pointe-

aux-Trembles sample and in the total study sample, calculated at 27.813 (Figure 5.7). Micro-CT scans of the rib show very thin cortical bone and a sparse trabecular structure, and they were assigned a mineralization defect score of 4.5.

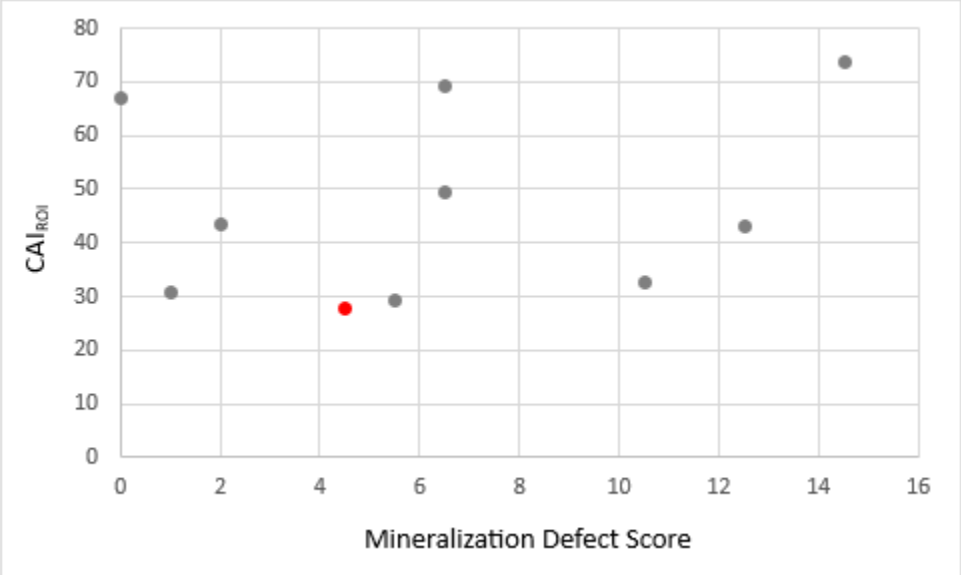

Figure 5.7. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 7A11-S42 (red dot) in the sub-sample (*n*=10).

The limited skeletal information available suggests that this individual was not in good health at the time of their death. Their estimated age at death indicates that they had not completed skeletal growth and therefore did not have the chance to accumulate their peak bone mass. However, the observed CAI_{ROI} value was so low that it is unlikely they would have accumulated enough bone to be comparable to others in their age cohort with high CAI_{ROI} once they reached skeletal maturity. This individual is so young that they could have had only one or two pregnancies before death, ruling out repeated pregnancies and periods of lactation as a source of the low bone amount. Instead, it is likely that malnutrition or infectious disease impeded skeletal growth in this individual, and impacted their quality of life.

5.3.2 Sainte-Marie

5.3.2.1 2B9

Individual 2B9 has the lowest CAI_{ROI} value in the Sainte-Marie group, at 31.012, and is in the lowest 10% of the total sample (Figure 5.8). The scan of their rib shows a robust cortical area, with a low number of trabeculae. Based on the pelvic features, they are most likely a female above the age of 50. The rib scan received a defect score of 1.0, indicating there were no significant defects present, but it is possible that they were experiencing the effects of age-related bone loss. If this individual had consecutive pregnancies until they reached menopause, they would not have the ability to compensate for lost bone before they reached their peak bone amount, and subsequently began to lose bone due to the uncoupling of bone deposition and bone resorption with age. Despite this, this individual lived beyond the average life expectancy of the time, indicating that they had been relatively healthy for much of their life.

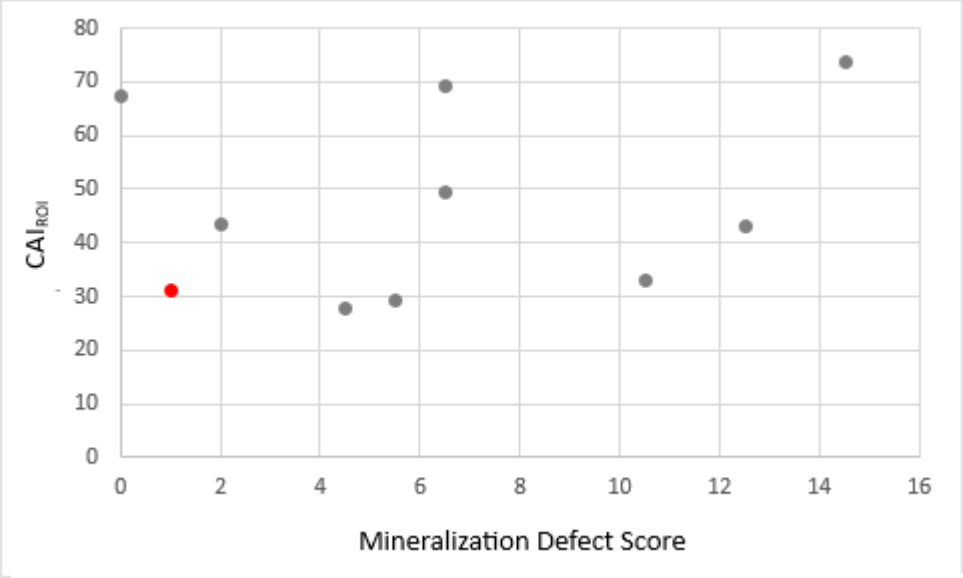

Figure 5.8. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 2B9 (red dot) in the sub-sample (*n*=10).

5.3.2.2 2E13

Based on the incomplete fusion of the vertebral epiphyses, individual 2E13 is likely between the ages of 16 and 20, and is likely female based on the morphology of their skull. This individual has the highest CAI_{ROI} value of both the Sainte-Marie and the total sample at 73.856 (Figure 5.9). The micro-CT scan of the rib indicates a robust cortical area and consistent trabecular network, which showcases evidence of severe mineralization defects.

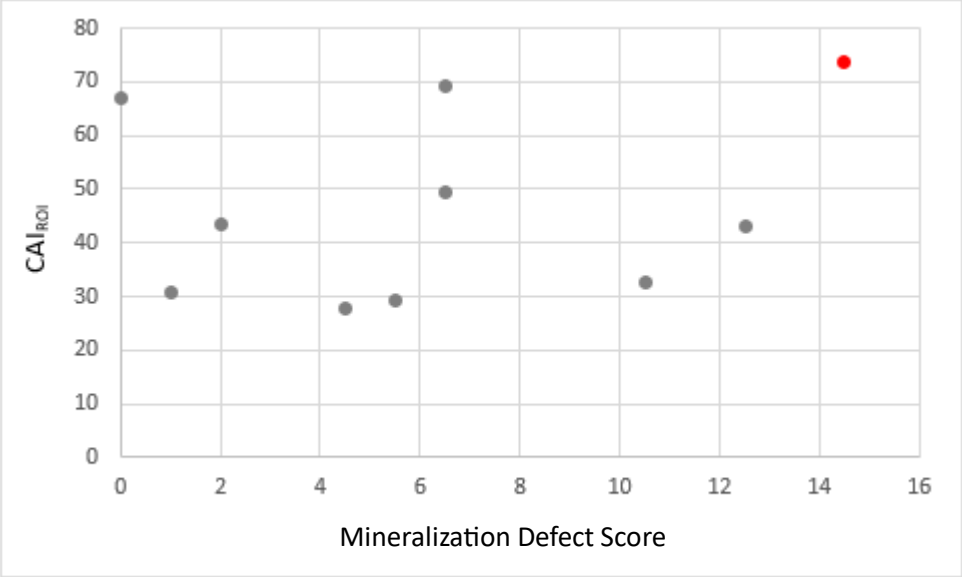

Figure 5.9. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 2E13 (red dot) in the sub-sample (*n*=10).

Although they have a high bone amount, the appearance of their bone in the micro-CT scan of the ribs shows severe defects in the bone microstructures, with the highest overall defect score of 14.5. This individual had osteomalacia when they died, a condition that could be indicative of vitamin D deficiency, or another chronic disease that would have resulted in the malabsorption of the essential nutrients for developing good quality bone. This individual, one of the youngest in the sample, has the highest bone amount from both Pointe-aux-Trembles

and Sainte-Marie, despite never reaching their peak bone mass. These factors suggest this individual did not experience long-term vitamin D deficiency, as they were able to accrue and maintain high levels of bone during growth, and instead developed osteomalacia shortly before their death.

5.3.2.3 2G4

Individual 2G4 was assessed as male within the 15-29 age category, although the assessment of their pelvis results in a more precise estimate of 20-24 years old. The CAI_{ROI} value measured from this individual's second metacarpal is 43.449, which falls in the middle-low range of CAI_{ROI} values for both the Sainte-Marie and the total samples (Figure 5.10).

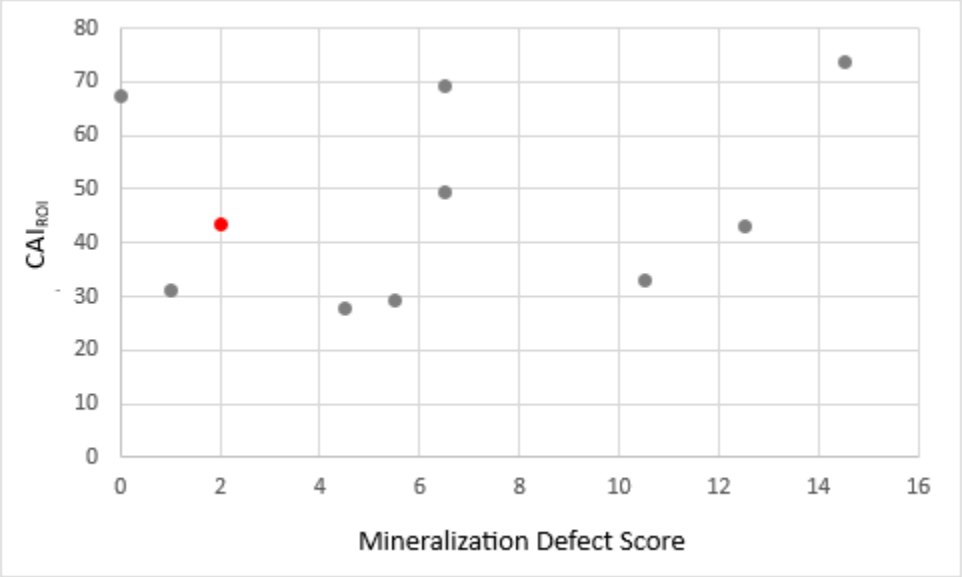

Figure 5.10. Cortical area index (CAI_{ROI}) and mineralization defect score of Individual 2G4 (red dot) in the sub-sample (*n*=10).

The ribs show a healthy cortical bone structure, although the trabecular geometry is quite sparse. There were some mineralization defects present, but they were not consistent

throughout the rib and were mild in appearance. This individual was assigned an overall defect score of 2.0, which classifies them as having no defects. Despite the low CAI_{ROI} value, this individual appeared to have a healthy skeleton, indicating that their death may have been sudden.

5.4 Osteoporosis, Vitamin D Deficiency, and Community Health in Quebec

In colonial French-Canada, disease, starvation, and economic fluctuations were linked, and constantly influenced community health. Although communities in the French colonies were somewhat isolated, they were constantly experiencing epidemic events transmitted from a range of sources. Tuberculosis, pneumonia, measles, smallpox, typhus, and cholera were some of the most common infectious diseases experienced in Quebec during the 1700s and 1800s (Boulet 2021; Bruckner et al. 2018; Dawson 1854; Greer 1997; Sheriff 1849). Poor sanitation in urban centers such as Montréal and Québec City, and the spread of disease to the colonial ports from ships were the primary causes of infection. The low population density in the colonies meant urban diseases did not always travel to rural communities such as Pointe-aux-Trembles and Sainte-Marie (Bruckner et al. 2018; Charters 2009), but the construction of the *Chemin du Roy* that connected much of New France could have created a pathway for travelers to spread disease (Desjardins 2010; Robichaud 2012). Medical care in the French-Canadian colonies was primarily given by military surgeons, rather than physicians trained in clinical medicine, and thus their experience in identifying, describing, and treating diseases was limited (Boulet 2021). Rural care was primarily left to these surgeons, as the physicians that were present in French Canada during the 1700s and 1800s typically gathered in Québec City,

where they could treat government officials, rather than in villages and *seigneuries*. Therefore, when epidemics did break out in rural communities, they were rarely equipped with the knowledge to properly treat or mitigate infectious diseases. Infectious disease is the primary reason why the life expectancy in the French-Canadian colonies was so low; therefore, it is likely that infectious disease contributed to the deaths of the majority of these individuals. Repeated and prolonged exposure to infectious diseases has consequences for skeletal development (Section 2.3.4), which could explain some of the low CAI_{ROI} values observed in this sample. The observation of mineralization defects in the majority of the individuals selected for micro-CT analysis suggests the possibility that interrupted vitamin D metabolism was widely experienced in the colonies. This could be due to the insufficient seasonal exposure to UVB experienced at this latitude, but it is also possible that these interruptions occurred as a result of behavioral changes in those experiencing infectious disease. For instance, those who are ill may experience appetite loss and may avoid eating nutritious meals, or may be unable to properly digest and absorb nutrients from nutritive foods due to complications such as vomiting or diarrhea. As well, individuals may stay indoors during their recovery, limiting their exposure to the sun. Avoiding sunlight and nutritious foods as a consequence of infectious disease can result in vitamin D deficiency, causing systemic metabolic disruptions. It is another possibility that the frequency of osteomalacia noted in this study is reflected in individuals who were already ill before death, not those who recovered and survived. This concept is addressed in more detail in Section 5.5.

Starvation and malnutrition were common experiences in the French-Canadian colonies, which has implications for skeletal health. The colonies frequently experienced food shortages,

particularly after the British took possession of New France in 1759 (Ouellet 1980). The blockade of the St. Lawrence River by the British navy during the Seven Years' War created the most severe famine experienced in French Canada during the colonial era (Charters 2009; Marston 2001). When the British gained control of the French-Canadian colonies after the Seven Years' War, changes in the political and economic policies of the colonies often caused hardship for the French colonists (Charters 2009; Ouellet 1980). The British economy absorbed most of the excess capital and resources during times of economic expansion, but high taxes and required export quotas alienated *habitants*, impacting their ability to maintain self-sufficiency on their farms (Ouellet 1980). It is possible that some individuals examined in this study had lived during this tumultuous period. Independently of the stress of war and taxes, starvation during long winters and periods of crop failure resulted in famine in the colonies.

Malnutrition and infectious disease are often linked, as they interact to increase the severity of one another. Malnutrition can negatively impact immune function, not only making individuals more susceptible to disease but making recovery more difficult (Thapar and Sanderson 2004). Infectious disease can result in nutrient loss through the malabsorption and excretion of vitamins or minerals, thus requiring the breakdown of tissues within the body to access sources of stored nutrients (Brown 2003; Guerrant et al. 2008; Thapar and Sanderson 2004). This leads to a cycle of infection and malnutrition that can impact skeletal growth and peak bone mass in juveniles and adolescents, and skeletal maintenance in adults (Norman et al. 2021; Prentice and Bates 1993). Understanding the consequences of malnutrition and infectious disease and placing them in the context of the French-Canadian colonies, which

consistently experienced both, explains why low bone amount and mineralization defects are prevalent in this sample.

There are possible genetic factors that could have contributed to the widespread experience of vitamin D deficiency in Quebec, and while they are important to mention, it is unlikely that these genetic influences impacted the sample of this study. The French-Canadian population of modern Quebec is descended from approximately 8500 original settlers of the colonies in the 1600s, resulting in limited genetic variation in the generations following these initial settlers (Laberge et al. 2005; Scriver 2001). The genetic isolation of the French colonies resulted in a population that experienc an unusually high prevalence of Mendelian diseases. The population of French-Canada currently has the highest prevalence of pseudo-vitamin D deficiency rickets (PDDR) in the world (Glorieux and Pettifor 2014). Genetic linkage studies have estimated that the genetic carrier frequency for PDDR is 1/26 in southern Quebec, compared to a frequency of <1/500 elsewhere (Labuda et al. 1996). PDDR is an autosomal recessive disorder characterized by a mutation in the genetic coding of the enzymes responsible for the hydroxylation of vitamin D into its usable form (Scriver 2001; Glorieux and Pettifor 2014; Laberge et al. 2005). It is unlikely that individuals with PDDR can survive until adulthood without medical intervention (Glorieux and Pettifor 2014), ruling this out as a factor contributing to the health of adults in the past. However, this adds another avenue of exploration in further studies of infant mortality in these communities.

Ultimately, the social, cultural, and environmental contributors to the low bone amounts noted in this study are likely more influential than age-related processes in this sample. Individuals in the French-Canadian colonies rarely lived beyond the age of 40, and aging

beyond the sixth decade of life, the period where age-related bone loss typically becomes classified as osteoporosis, was even more uncommon (Boulet 2021). The presence of at least mild mineralization defects in nearly all of the scanned rib samples suggests that vitamin D deficiency in this sample was systemic, caused by community-wide health events, genetic susceptibility to vitamin D deficiency, or both.

5.5 Limitations and Future Research

This study operates on the assumption that the sample represents the health status of the entire communities at Pointe-aux-Trembles and Sainte-Marie. Realistically, the sample size of this study is too small to be representative of the entire population. The availability of viable skeletal elements was limited due to taphonomic damage, the removal of some individuals periodically as the cemeteries were expanded, the inability to excavate the remains of all individuals at the sites, and the commingling of remains due to the dense burials. Limitations in time and resources only allowed 10 rib samples to be used in the micro-CT analysis, which limits the scope of our interpretation of vitamin D deficiency and osteomalacia at the population level. The visibility of mineralization defects in several of the rib samples was obscured by damage caused by fungal tunnelling (Jans et al. 2004; Mazzoli et al. 2018).

The concept of the osteological paradox, explored by Wood et al. (1992) and revisited by DeWitte and Stojanowski (2015), outlines some of the major challenges and limitations of paleopathological research. While these limitations do not apply to all paleopathological studies (DeWitte and Stojanowski 2015), they do apply to this research. For instance, the

concept of selective mortality suggests that assemblages only represent individuals who died, not those who were at risk of death and survived. We cannot observe whether individuals experienced low bone amount during childhood due to illness or malnutrition and subsequently recovered when the stress event ended, for example. This study also assumes that individuals in a population are equal in their susceptibility to disease and risk of death. Ultimately, individuals in a population vary in their frailty due to a multitude of genetic, socioeconomic, environmental, and temporal factors.

Despite these limitations, this research has implications for future studies on skeletal health. This study is the first to implement a quantitative system for recording mineralization defects in micro-CT scans, allowing for the consistent collection of data that can be used for inter- and intrapopulation comparisons. Future studies with the resources to perform full pathological analyses of the skeletons and examine more than a small subset of the sample to view mineralization defects are recommended. Although it is a time-consuming process, such detailed studies can provide even deeper insights into past health. Further explorations of metabolic bone disease within other historical French-Canadian communities will create a wider understanding of health and disease in Quebec during the colonial era. Comparing and contrasting this data with European assemblages can provide further information on the ways different cultures, societies, and environments influenced biological processes in past populations.

Chapter 6: Conclusion

Metabolic bone diseases such as osteoporosis and osteomalacia are heavily influenced by cultural and environmental factors, in addition to biological factors. The aim of this thesis was to determine patterns of osteoporotic bone loss and osteomalacia in historical French-Canadian communities to provide insight into lived experiences and community health in the past. This was completed through the application of a newly developed method of metacarpal radiogrammetry (Gilmour et al. 2021) and a pilot project for interpreting mineralization defects developed for this thesis.

This research created an opportunity to apply new and developing analytical techniques to fragmentary archaeological remains, allowing researchers to gather information beyond the parameters of traditional data collection techniques. The remains recovered from Pointe-aux-Trembles and Sainte-Marie were generally poorly preserved; therefore, it was necessary to use techniques that did not rely on complete elements for analysis. Using the metacarpal radiogrammetry method developed by Gilmour et al. (2021), it was possible to use fragmentary metacarpals that would have otherwise been excluded in traditional radiogrammetric methods. The technique developed for scoring mineralization defects in the ribs requires only a 1cm area of bone for analysis, allowing for the inclusion of fragmentary ribs.

Medical research emphasizes the importance of biological determinants of metabolic bone disease, particularly genetics, age, and sex. It was expected to view a pattern of bone accumulation and loss that follows the age and sex trends established by clinical data, as they have been observed in many bioarchaeological studies of age-related bone loss (see Curate et

al. 2013, Ericksen 1976, Glencross and Agarwal 2011, Van Gerven et al. 1969). By exploring patterns of bone amount by sex and age in Pointe-aux-Trembles and Sainte-Marie through metacarpal radiogrammetry, it was determined that bone amount was not significantly linked to age or sex. Instead, the youngest individuals in the sample experienced the highest bone amounts, as expected, and the lowest bone amount, an unexpected result. Females in the youngest age category show particularly variable bone amounts, indicating that bone amount is not strictly biologically determined.

Seven of the ten individuals analyzed for osteomalacia showed at least some evidence of mineralization defects throughout their ribs. It was expected that evidence of osteomalacia would be related to osteoporosis; however, there were no patterns in the presence or severity of defects by sex, age, or cortical area index (CAI_{ROI}), suggesting that vitamin D deficiency may have been a widespread issue in Pointe-aux-Trembles and Sainte-Marie.

The results of this thesis were interpreted through a historical and cultural lens, providing insight into individual and community health in French Canada in the 1700s and 1800s. Through this approach, social determinants of health such as social roles, food insecurity, sanitation, economic fluctuations, and the environment were given as much analytical weight as the biological factors of bone health.

Within the cultural and social contexts explored through biocultural theory, a lived experience framework made it possible to further understand these individuals not as just "constituents of samples" (Hosek and Robb 2019), but as dynamic humans. Approaching lived experience through osteobiography allowed a deeper exploration of the co-occurrence of

osteoporosis and osteomalacia on the individual level, and in understanding individual experiences, it was possible to extrapolate this relationship to the total sample level.

Ultimately, this study suggests that health patterns observed in Pointe-aux-Trembles and Sainte-Marie may deviate from health patterns reported in modern clinical literature and other bioarchaeological studies. The ways society and culture developed in the St. Lawrence region created communities that were distinct from other North American colonies and European cities. Patterns of bone amount that have not been observed in other archaeological samples, and the prevalence of mineralization defects in the sample implies that individuals in these communities may have experienced widespread health issues that impacted their ability to accumulate and maintain bone during their lifetime. This claim is supported by historical sources, which document frequent periods of illness and starvation.

Although the sample size in this study is too small to make unequivocal statements regarding the health of these communities on the population level, the osteobiographical approach provides a unique view inside the lived experiences of these individuals that is otherwise invisible from the sample level. Further explorations of the interaction between disease, malnutrition, growth, and aging can create further insight into the lived experiences in these two communities.

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Appendices

Appendix A: Skeletal Sample

Age, Sex, and Cortical Area Index (CAI_{ROI}) Data

Table A1. Age, Sex, and Cortical Area Index (CAI_{ROI}) data

Individual	**Sex**	**Age Estimate**	**Age Category**	**CAI_{ROI}**
Pointe-aux-Trembles				
7A11-S42	F	14-20	15-29	27.813
7A9-S13	F	15-24	15-29	61.132
7A9-S38	M	14-19	15-29	67.181
7A9-S45	F	18-25	15-29	26.518
7A2-S20	F	20-29	15-29	29.382
7A9-S9	F	25-29	15-29	53.959
7A9-S27	F	23-35	15-29	57.575
7A11-S60	F	>25	15-29	61.848
7A11-S61	F	15-24	15-29	62.069
7A2-S5	M	30-34	30-49	52.715
7A2(9)-S23	F	30-34	30-49	61.808
7A2-S2	F	23-35	30-49	69.045
7A2-S11	F	41-50	30-49	32.956
7A9-S16	M	>24	30-49	47.406
7A9-S31	M	50-63	50+	45.289
7A11-S19	M	50-77	50+	43.313
7A9-S15	M	66-80	50+	44.456
7A9-S46	F	60-87	50+	49.569
Sainte-Marie				
2F4	M	14-19	15-29	49.570
2E10	F	14-15	15-29	57.231
2E13	F	16-20	15-29	73.856
2B7	M	20-30	15-29	37.543
2B15	M	20-30	15-29	37.637
2G4	M	20-24	15-29	43.449
2B8	M	25-29	15-29	50.846
2F	M	20-24	15-29	51.892
2B14	F	20-29	15-29	52.520
2 E8	M	20-24	15-29	53.996
2G6	F	20-39	30-49	40.266
1G5	F	35-39	30-49	55.672
2E14	F	30-39	30-49	57.066
2B16	F	>25	30-49	41.861
2A14	F	40-50	30-49	48.914
2B9	F	50-60	50+	31.012

2B11	F	45-59	50+	49.130
2G2	M	>55	50+	54.598
2B3	F	60+	50+	42.900
2E11	F	60+	50+	49.796
2G12	F	60+	50+	58.929
2E12	F	80+	50+	42.154
2F1	M	80+	50+	42.187
2B10	M	80+	50+	46.631
2E9	F	80+	50+	57.808

Appendix B: Skeletal Recording Forms

B1: Age and Sex Recording Form

B2: Metacarpal Radiogrammetry Recording Form

B1: Age and Sex Recording Form

Site: Date:

Individual:

Sex

Pelvis:

Ventral Arc (1-3) _____

Subpubic Concavity (1-3) _____

Ischiopubic Ramus Ridge (1-3) _____

Greater Sciatic Notch (1-5) _____

Preauricular Sulcus (0-4) _____

Estimated Sex (Pelvis): _____

Skull:

Nuchal Crest (1-5) _____

Mastoid Process (1-5) _____

Supraorbital Margin (1-5) _____

Glabella (1-5) _____

Mental Eminence (1-5) _____

Estimated Sex (Skull): _____

Age

Epiphyseal Fusion _____

Pubic Symphysis (1-6) _____

Auricular Surface (1-8) _____

Transition Analysis:

-Iliac Exostoses _____

-Dorsal Margin _____

Estimated Age: _____

Notes/Comments:

B2: Metacarpal Radiogrammetry Recording Form

Site: Date:

Individual:

Left: _____ Right:_____

Complete: _____ _____

<25% 25%-50% 50%-75% >75%

Cortical bone area (CB):

Total bone area (TA):

ROI cortical area index (CA_{ROI}):

Appendix C: Comparative Analysis

Table C1.1. Summary of Comparative Studies that Met the Selection Criteria

Reference	Location of Study	Time Period	N	Methods	Author Conclusions
Agarwal 2012	England (Rural)	11th-16th century	f=30, m=24	Trabecular microstructure (L4)	No significant differences in bone amount between sexes, consistent age-related bone loss
	England (Urban)	11th-14th century	f=41, m=32		Significant sex and age differences: older females (50+) have significantly less bone than older males
Agarwal and Grynpas 2009	England	11th-16th century	f=31, m=27	Bone mineral density, digital x-ray absorptiometry	Males show steady age-related bone loss, females lose BMD at an earlier age
Beauchesne and Agarwal 2014	Velia, Italy	1st-2nd century	f=32, m=39	Metacarpal radiogrammetry	Age-related bone loss, no statistically significant sex differences in cortical index for each age group
Beauchesne and Agarwal 2017	Velia, Italy	1st-2nd century	f=30, m=40	Rib cross-sectional area	Follows clinical age and sex trends
			f=26, m=26	Rib histomorphometry	Bone formation rate decreases significantly between all age groups, no significant differences between sexes
			f=19, m=28	Trabecular microstructure (L4)	Trabecular spacing and number decrease with age, slight sex differences found.
Curate et al. 2013	Portugal	19th-20th century	f=98, m=98	Bone mineral density (proximal femur), digital x-ray absorptiometry	Significant sex and age differences, older females have significantly less bone than older males.
Dewey et al. 1969	Sudan	350 B.C.-A.D. 350	f=29, m=17	Cortical thickness, femur	Males follow expected age-related bone loss trends, cortical thickness in females is lowest from age 32-41 and increases by age 42-50.
		A.D. 350-A.D. 550	f=63, m=42		Follows clinical age and sex trends
		A.D. 550-A.D. 1300	f=28, m=24		Male cortical thickness increases with age, female cortical thickness fluctuates with age.
Ekenman et al. 1995	Sweden	14th-15th century	f=156, m=187	Bone mineral density, cortical thickness	No significant differences in bone amount between sexes, no age-related bone loss
Ericksen 1976	Southwestern United States	A.D. 1130	n=142	Cortical thickness, femur and humerus	Adheres to clinical age and sex trends
	Midwestern United States	A.D. 1550-A.D. 1845	n=134		
	Alaskan Coast	18th-20th century	n=123		
Glencross and Agarwal 2011	Turkey	7400 B.C.-6000 B.C.	f=27, m=22	Metacarpal radiogrammetry	Adheres to clinical age and sex trends
Holck 2007	Norway	5000 B.C.-A.D. 800	f=13, m=23	Bone mineral density, femur	No sex differences, age-related bone loss
		A.D. 800-A.D. 1050	f=15, m=23		
		A.D. 1050-A.D. 1536	f=54, m=57		

Poulsen et al. 2001	Denmark	A.D. 1000-A.D. 1250	f=20, m=29	Bone mineral density, femoral neck	No age-related bone loss in males, increase in bone mineral density with age in females.
Van Gerven et al. 1969	Midwestern United States	A.D. 1540-A.D. 1700	f=23, m=20	X-ray measurements of femoral cortical thickness, periosteal diameter	Age-related bone loss in males and females, females lost significantly more bone than males
Zaki et al. 2009	Egypt	2687 B.C.-2191 B.C.	f=31, m=43	Bone mineral density, various skeletal sites	Significant age-related bone loss in males and females, females lose bone earlier than males.

Appendix D: Metacarpal Radiogrammetry

D1: Pointe-aux-Trembles Data and Radiographs

D2: Sainte-Marie Data and Radiographs

D1: Pointe-aux-Trembles

Table D1.1. Metacarpal Bone Measurements for the Pointe-aux-Trembles sample

Individual	Cortical Bone Area	Total Bone Area	CAI_{ROI}	Radiograph
7A11-S42	43.758	157.332	27.813	D1.2
7A9-S13	95.748	156.625	61.132	D1.3
7A9-S38	108.642	161.715	67.181	D1.3
7A9-S45	43.133	162.653	26.518	D1.3
7A2-S20	40.659	138.382	29.382	D1.3
7A9-S9	83.771	155.248	53.959	D1.3
7A9-S27	83.998	145.839	57.575	D1.1
7A11-S60	80.983	130.938	61.848	D1.1
7A11-S61	99.943	161.020	62.069	D1.2
7A2-S5	88.969	168.774	52.715	D1.1
7A2(9)-S23	87.716	141.918	61.808	D1.2
7A2-S2	97.338	140.976	69.045	D1.2
7A2-S11	43.606	132.316	32.956	D1.1
7A9-S16	85.463	180.279	47.406	D1.4
7A9-S31	76.511	168.938	45.289	D1.2
7A11-S19	73.219	169.046	43.313	D1.4
7A9-S15	84.776	190.697	44.456	D1.1
7A9-S46	70.377	141.979	49.569	D1.4

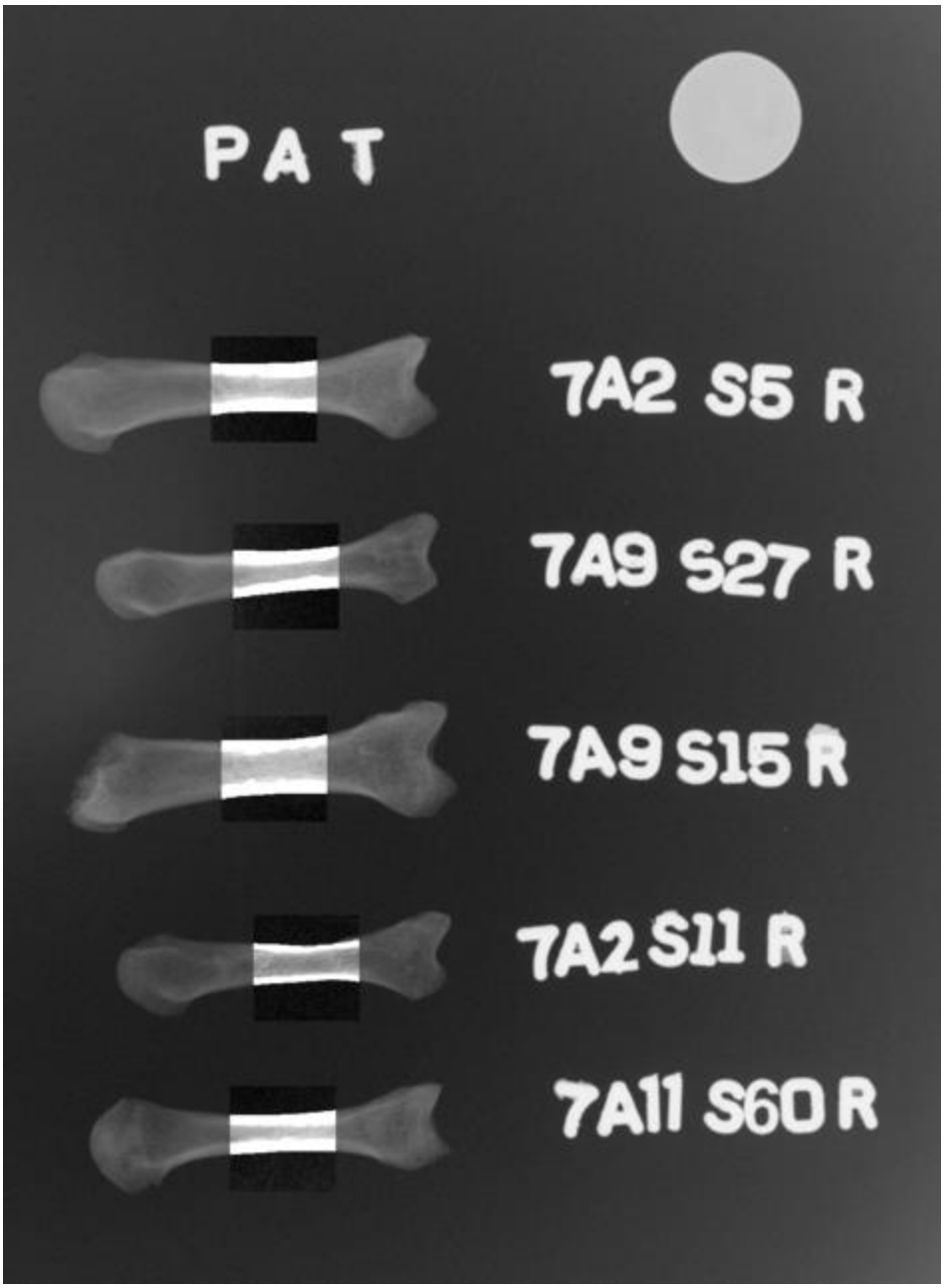

Figure D1.1. Metacarpal radiographs of individual 7A2-S5, 7A9-S27, 7A9-S15, 7A2-S11, and 7A11-S60

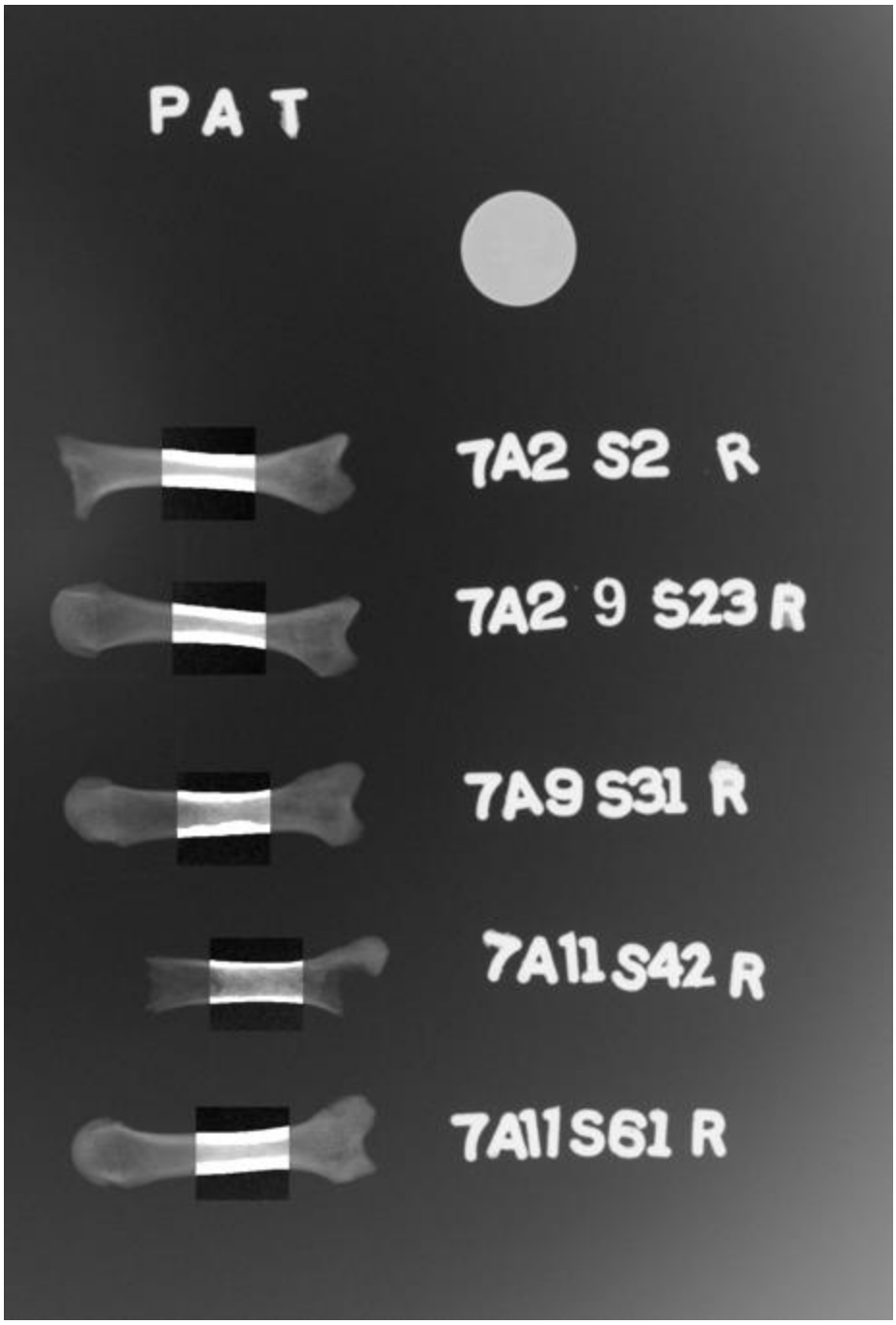

Figure D1.2. Metacarpal radiographs of individual 7A2-S2, 7A2(9)-S23, 7A9-S31, 7A11-S42, and 7A11-S61

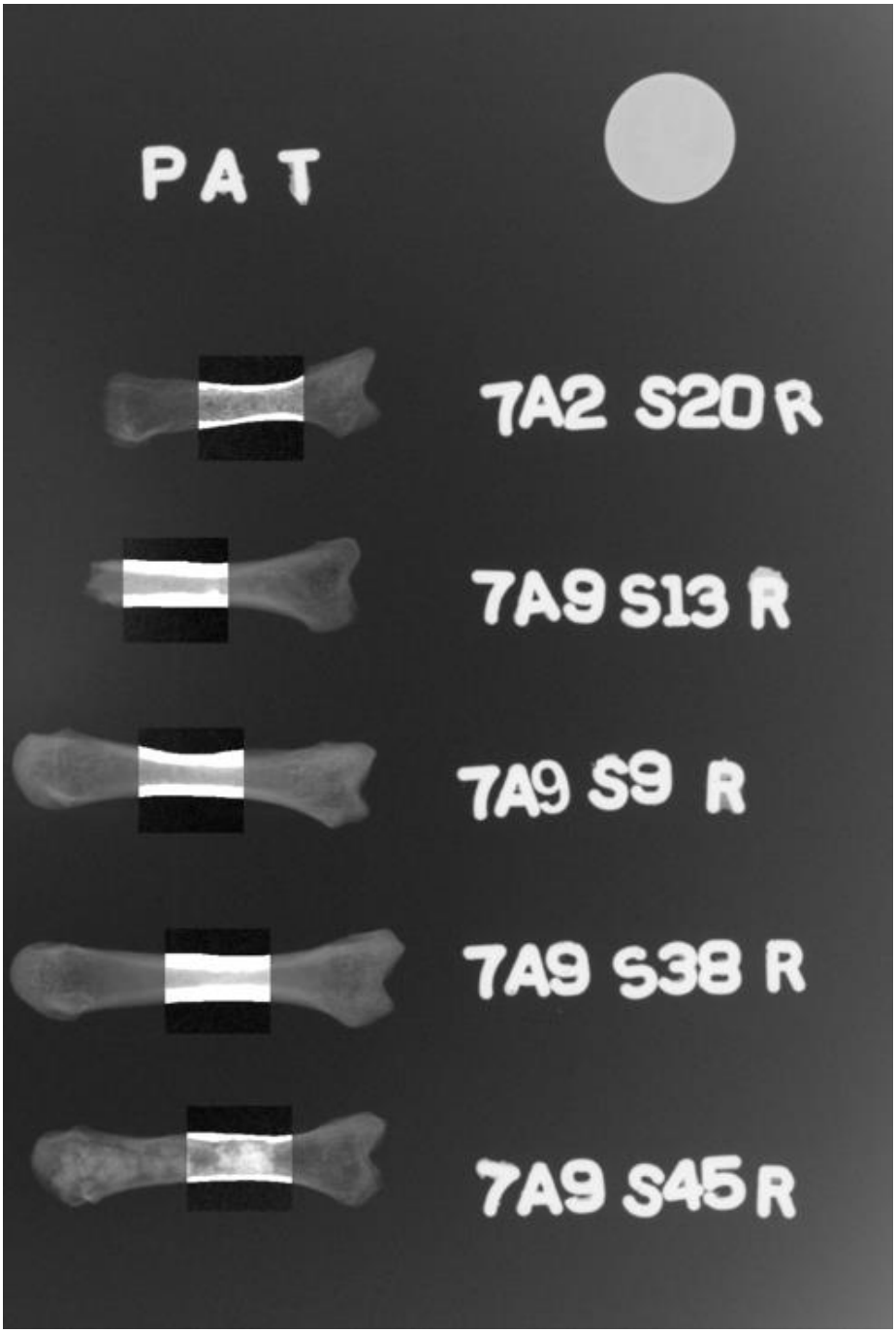

Figure D1.3. Metacarpal radiographs of individual 7A2-S20, 7A9-S13, 7A9-S9, 7A9-S38, and 7A9-S45

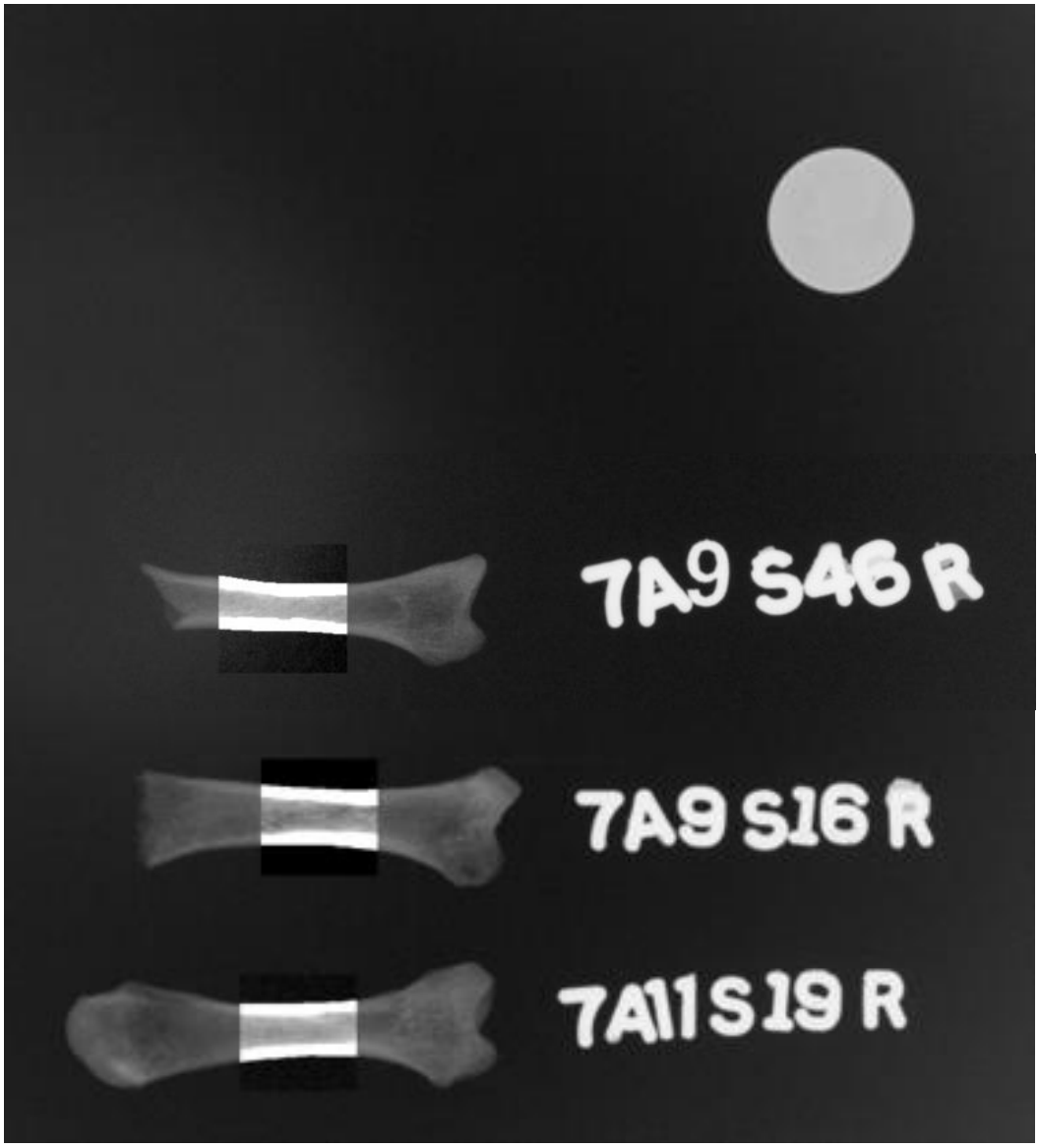

Figure D1.4. Metacarpal radiographs of individuals 7A9-S46, 7A9-S16, and 7A11-S19

D2: Sainte-Marie

Table D2.1. Metacarpal Bone Measurements for the Sainte-Maries sample

Individual	Cortical Bone Area	Total Bone Area	CAI_{ROI}	Radiograph
2F4	71.958	145.165	49.570	D2.1
2E10	84.093	146.936	57.231	D2.1
2E13	94.161	127.493	73.856	D2.5
2B7	78.545	209.213	37.543	D2.4
2B15	76.135	202.286	37.637	D2.6
2G4	69.308	159.514	43.449	D2.6
2B8	92.166	181.266	50.846	D2.2
2F	90.984	175.333	51.892	D2.2
2B14	76.553	145.761	52.520	D2.4
2E8	103.612	191.89	53.996	D2.2
2G6	70.484	175.048	40.266	D2.5
1G5	76.076	136.65	55.672	D2.6
2E14	85.494	149.816	57.066	D2.5
2B16	57.495	137.349	41.861	D2.4
2A14	63.467	129.751	48.914	D2.1
2B9	39.771	128.244	31.012	D2.3
2B11	77.915	158.588	49.130	D2.3
2G2	112.897	206.778	54.598	D2.4
2B3	63.033	146.931	42.900	D2.5
2E11	73.856	148.316	49.796	D2.4
2G12	80.655	145.351	58.929	D2.3
2E12	55.845	132.477	42.154	D2.2
2F1	70.671	167.518	42.187	D2.3
2B10	101.567	217.808	46.631	D2.2
2E9	80.907	139.958	57.808	D2.5

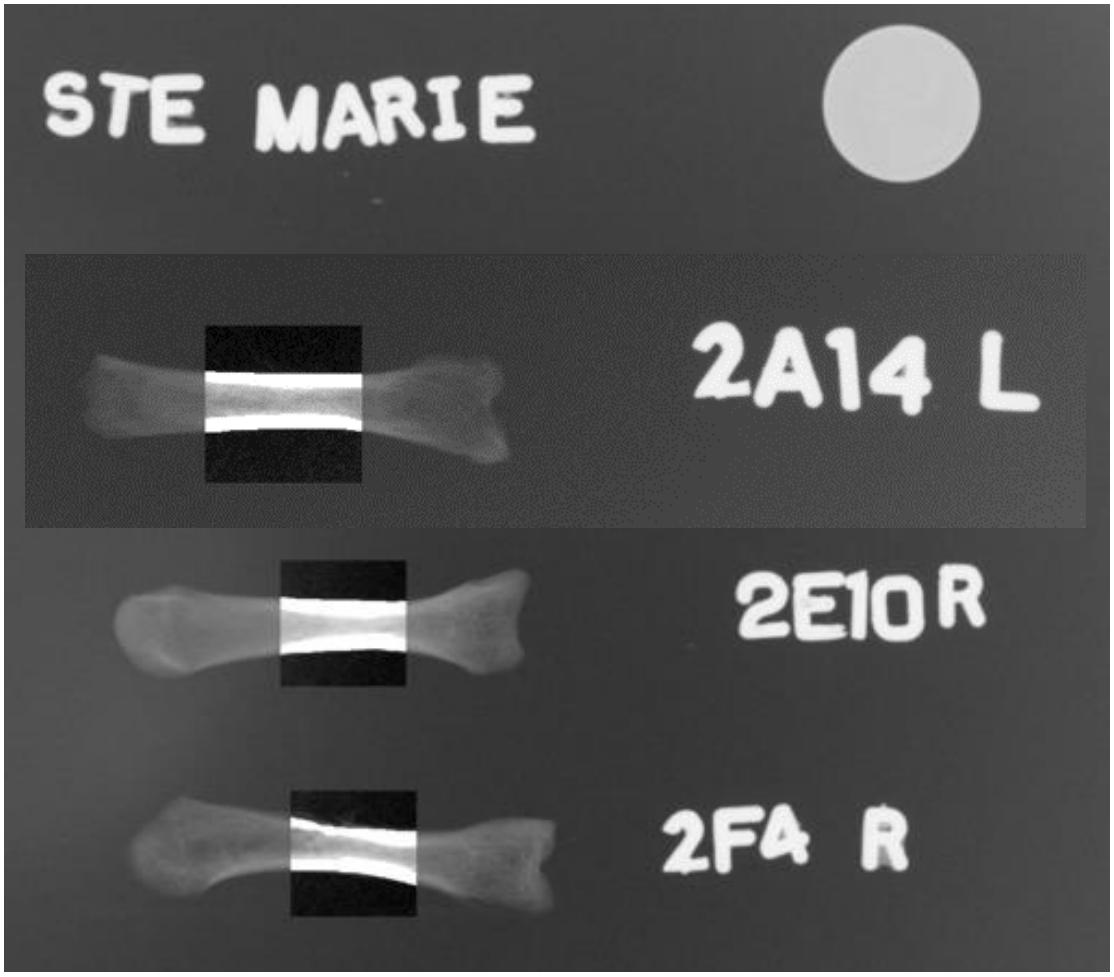

Figure D2.1. Metacarpal radiographs of individual 2A14, 2E10, and 2F4

Figure D2.2. Metacarpal radiographs of individual 2E8, 2E12, 2B10, 2B8, and 2F

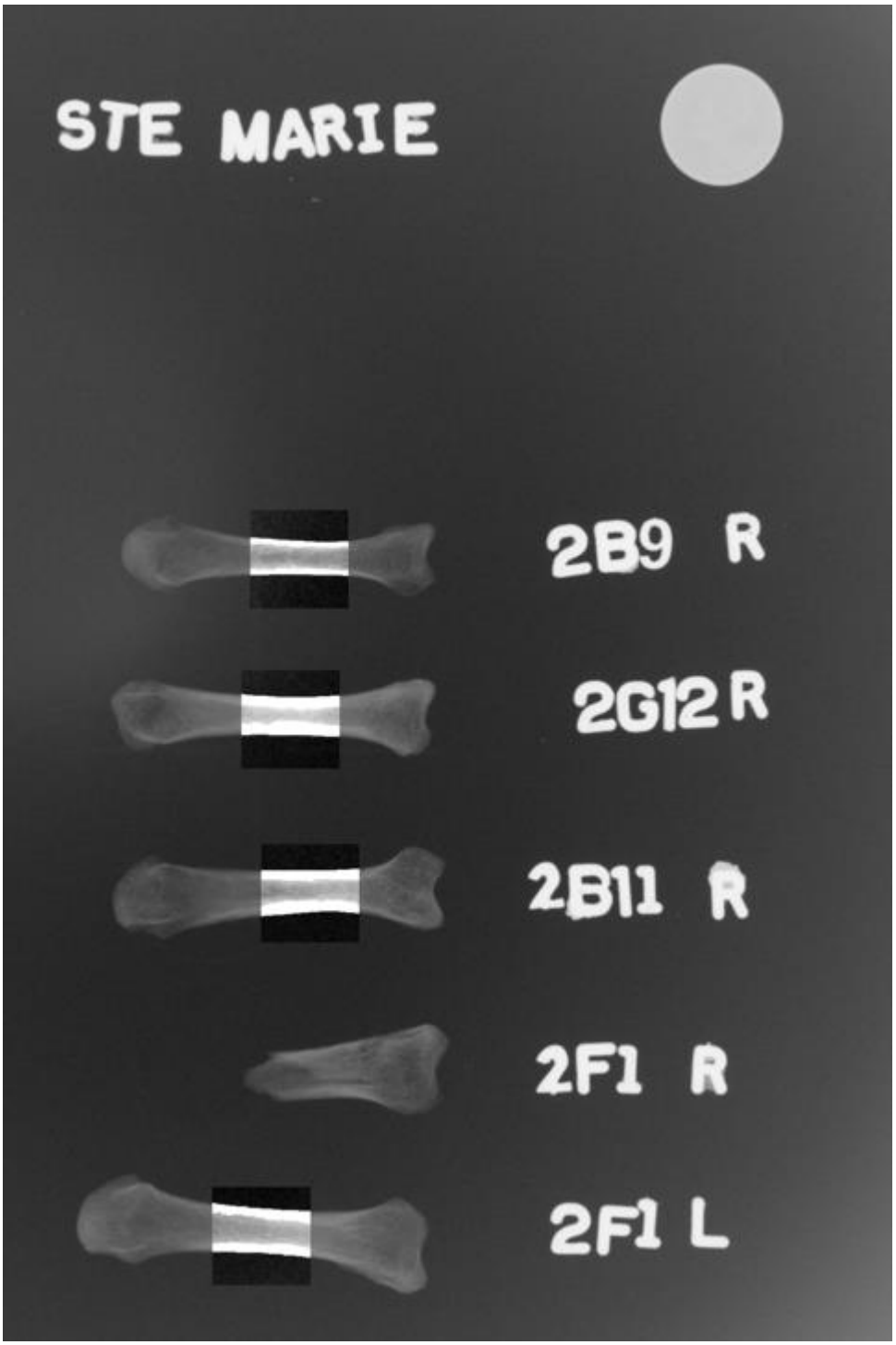

Figure D2.3. Metacarpal radiographs of individuals 2B9, 2G12, 2B11, and 2F1

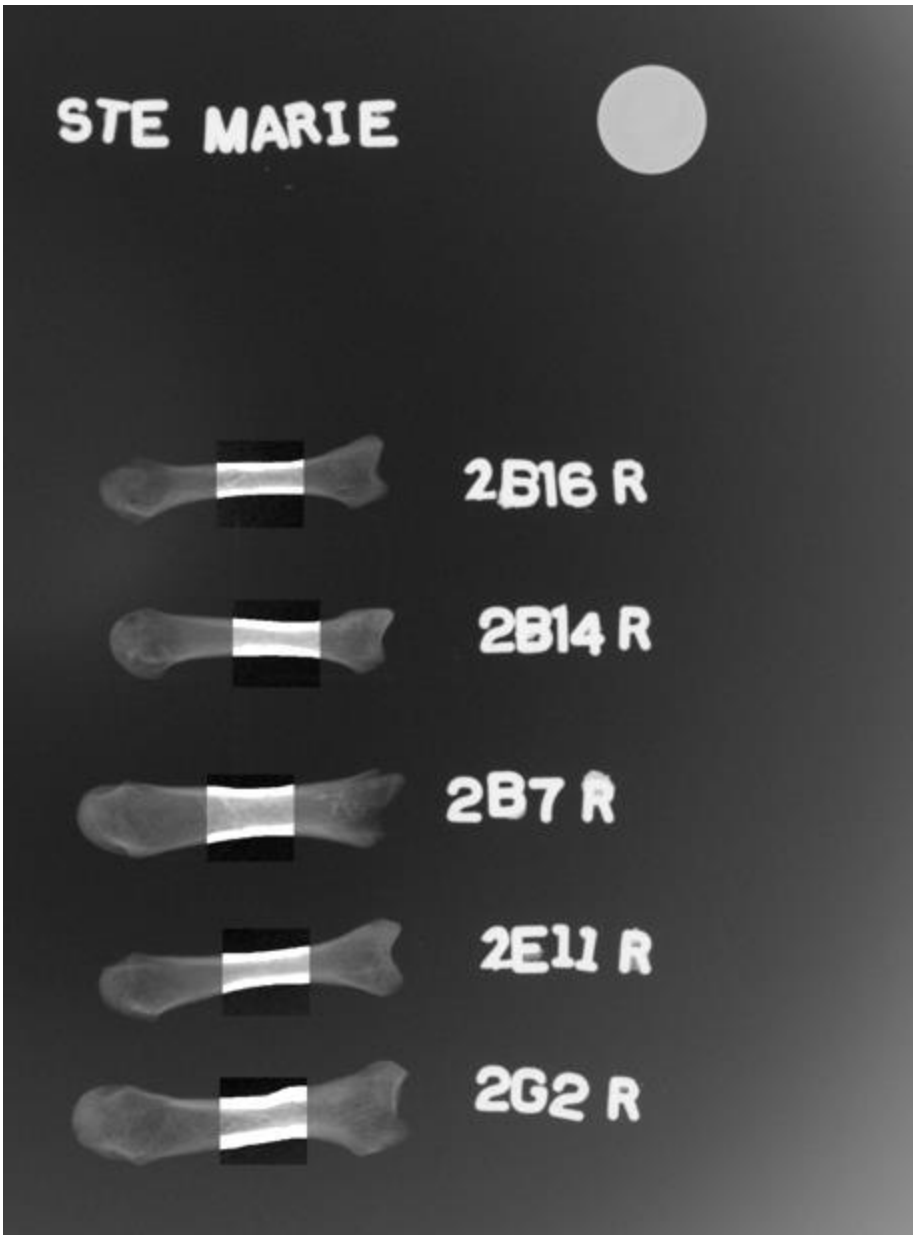

Figure D2.4. Metacarpal radiographs of individual 2B16, 2B14, 2B7, 2E11, and 2G2

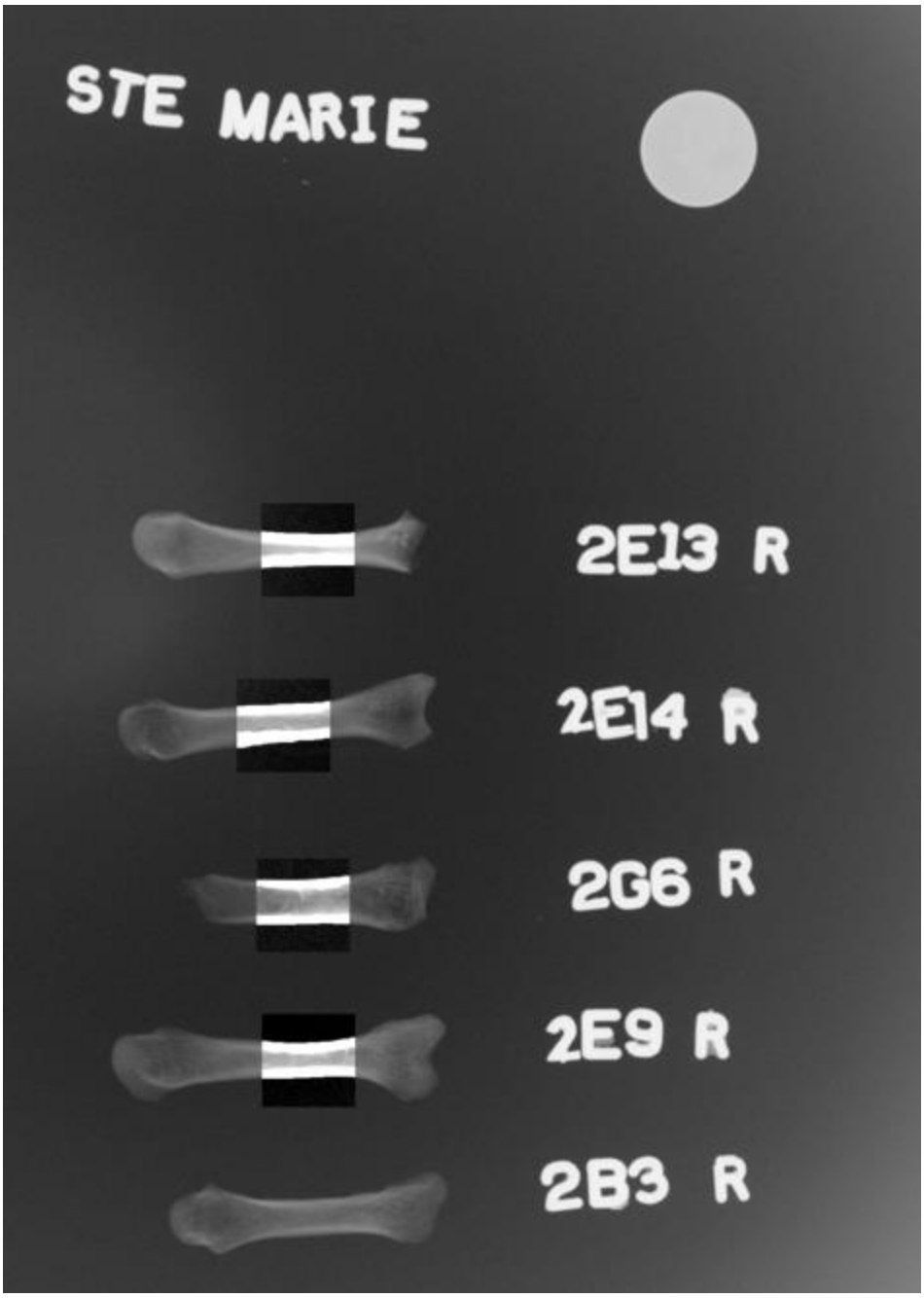

Figure D2.5. Metacarpal radiographs of individual 2E13, 2E14, 2G6, 2E9, and 2B3

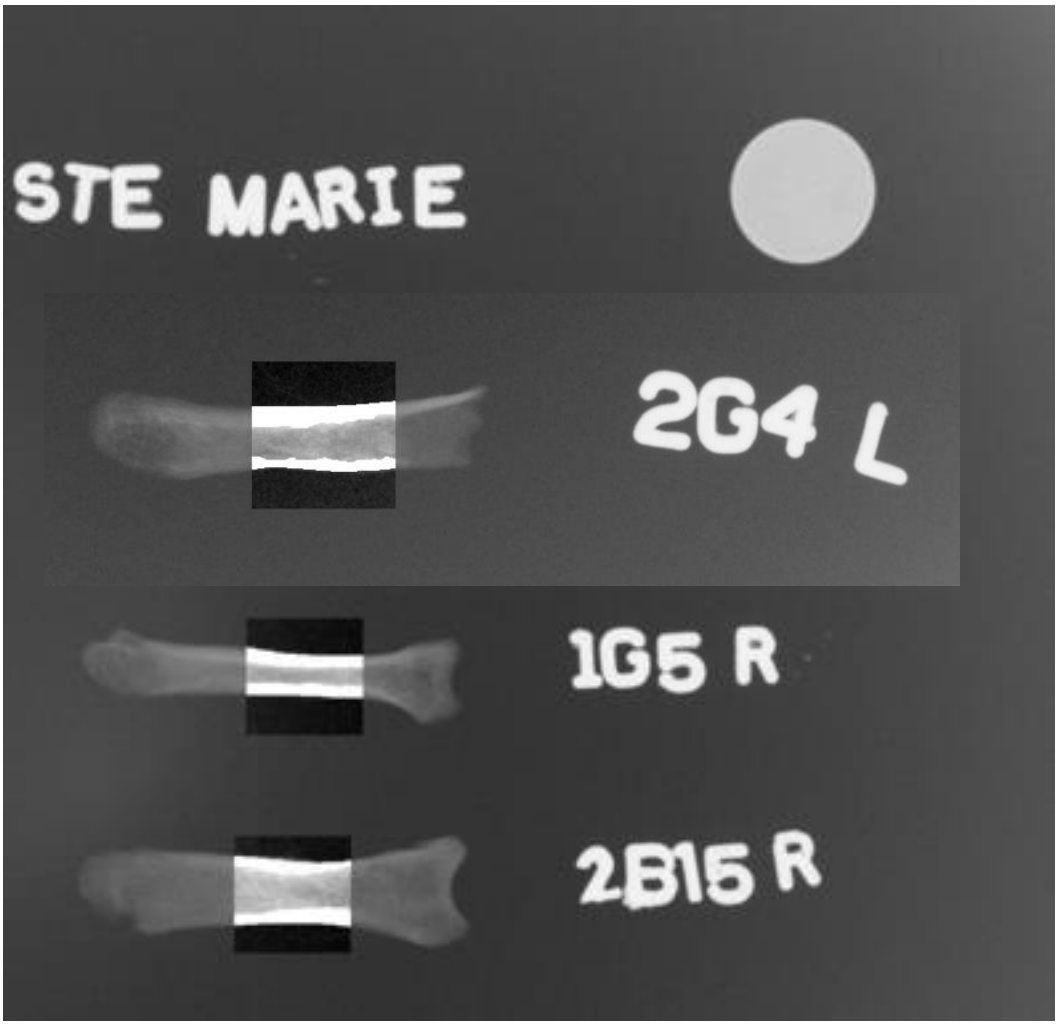

Figure D2.6. Metacarpal radiographs of individual 1G5, 2B15, and 2G4

Appendix E: Statistical Data

E1: Shapiro-Wilk Normality Tests

E2: T-Test

E3: Descriptive Statistics

E4: ANOVA

E1: Shapiro-Wilk Normality Tests

Table E1.1. Shapiro-Wilk normality test for each sex category

	Sex	**Shapiro-Wilk**		
		Statistic	***df***	**Sig.**
CAI_{ROI}	**Male**	.933	16	.271
	Female	.951	27	.230

Table E1.2. Shaprio-Wilk normality test for each age category

	Age	**Shapiro-Wilk**		
		Statistic	***df***	**Sig.**
CAI_{ROI}	**15-29**	.949	19	.374
	30-49	.993	10	.999
	50+	.944	14	.468

E2: Student's T-Test

Table E2.1. T-test for comparing sex and cortical area index (CAI_{ROI})

Age Category	***t*-value**	**Degrees of Freedom**	***p*-value**
15-29	-0.352	17	0.729
30-49	-0.098	8	0.924
50+	-0.0393	12	0.702
Total Sample	-0.671	40.992	0.506

E3: Descriptive Statistics

Table E3.1. Descriptive statistics for cortical area index (CAI_{ROI}) by age category

	N	**Range**	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
15-29	19	47.338	26.518	73.856	50.317	13.425
30-49	10	36.089	32.956	69.045	50.771	10.776
50+	14	27.917	31.012	58.929	46.984	7.222
Total Sample	43	47.338	26.518	73.856	49.337	11.002

E4: ANOVA

Table E4.1. ANOVA results for the comparison of cortical area index (CAI_{ROI}) and each age group

Multiple Comparisons						
Age Group 1	**Age Group 2**	**Mean Difference**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
15-29	**30-49**	-.454216	4.353622	.994	-11.05058	10.14215
	50+	3.332970	3.925045	.675	-6.22027	12.88621
30-49	**15-29**	.454216	4.353622	.994	-10.14215	11.05058
	50+	3.787186	4.613920	.692	-7.44272	15.01710
50+	**15-29**	-3.332970	3.925045	.675	-12.88621	6.22027
	30-49	-3.787186	4.613920	.692	-15.01710	7.44272

Appendix F: Micro-CT Data

F1: 7A2-S2 Scores and 5 Scan Slices

F2: 7A2-S11 Scores and 5 Scan Slices

F3: 7A2-S2 Scores and 5 Scan Slices

F4: 7A9-S38 Scores and 5 Scan Slices

F5: 7A9-S46 Scores and 5 Scan Slices

F6: 7A11-S19 Scores and 5 Scan Slices

F7: 7A11-S42 Scores and 5 Scan Slices

F8: 2B9 Scores and 5 Scan Slices

F9: 2E13 Scores and 5 Scan Slices

F10: 2G4 Scores and 5 Scan Slices

F1: 7A2-S2 Scores and 5 Scans

Table F1.1. Slice scores for individual 7A2-S2

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
300	1	0	1.0
550	1	0	1.0
800	1	0	1.0
1050	1	0.5	1.5
1300	2	0	2.0
	6	0.5	6.5

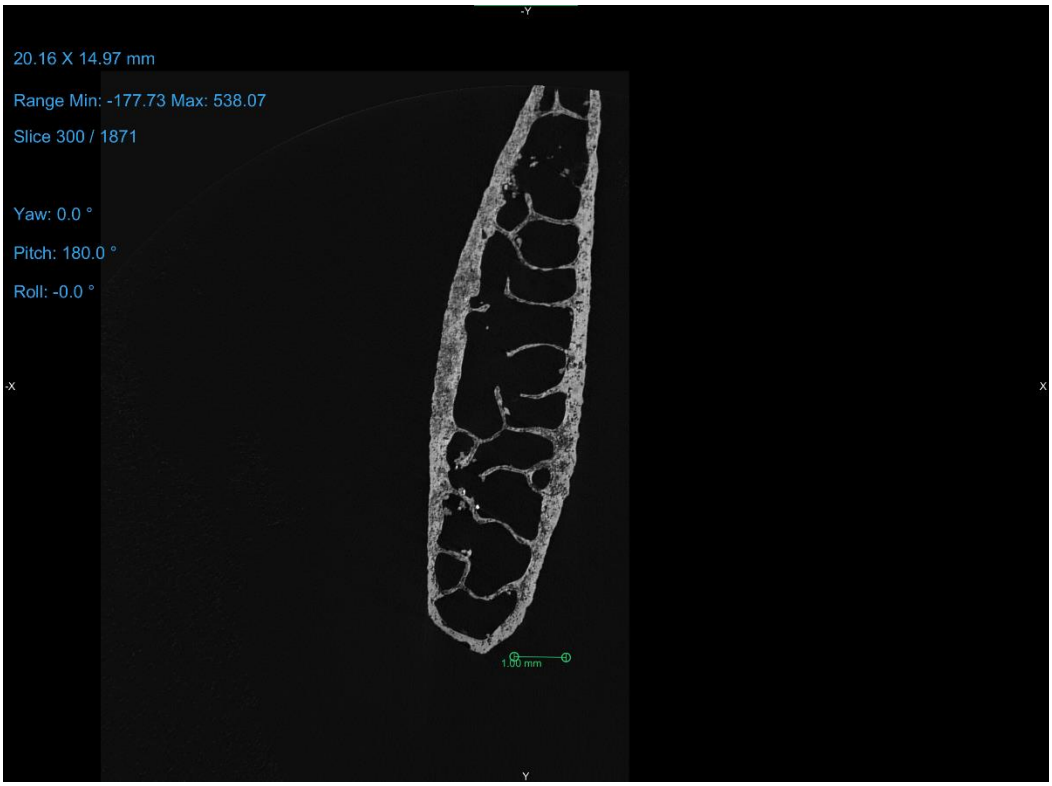

Figure F1.1. Micro-CT of individual 7A2-S2, slice 300

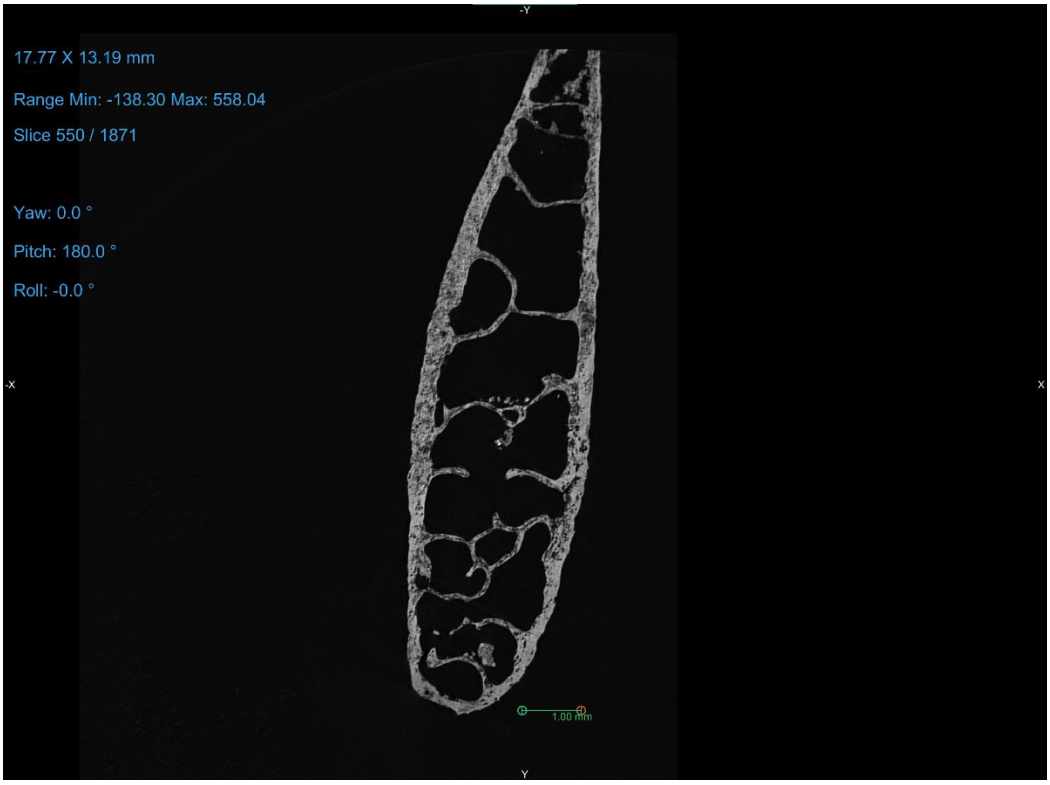

Figure F1.2. Micro-CT of individual 7A2-S2, slice 550

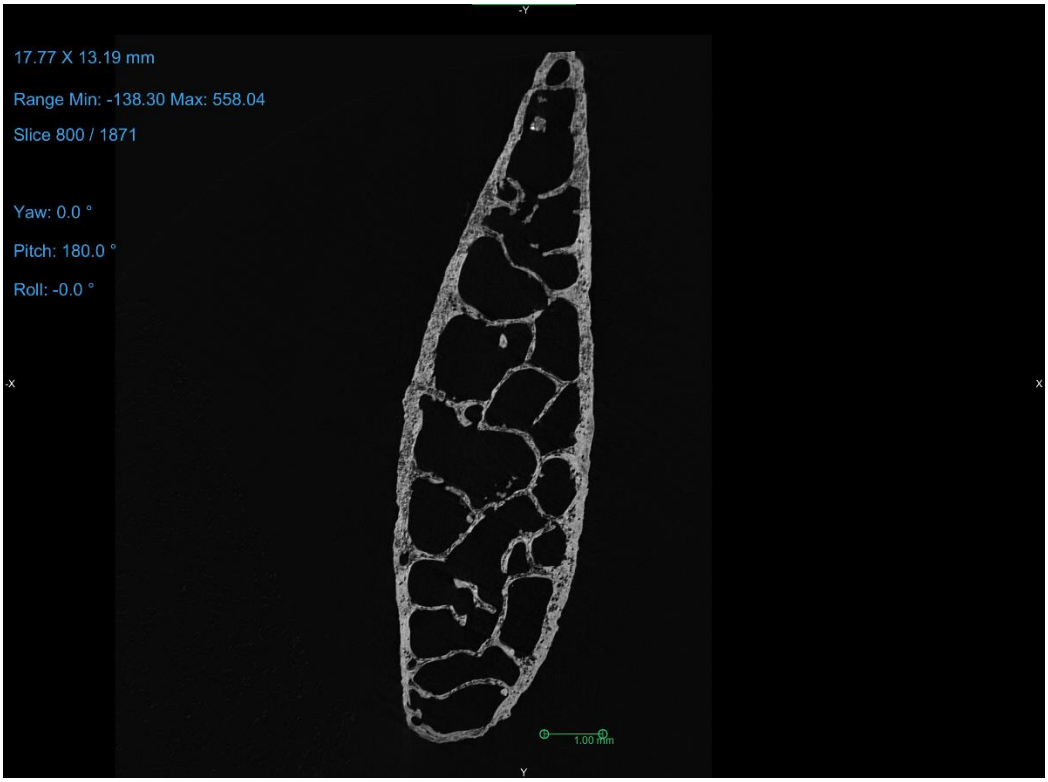

Figure F1.3. Micro-CT of individual 7A2-S2, slice 800

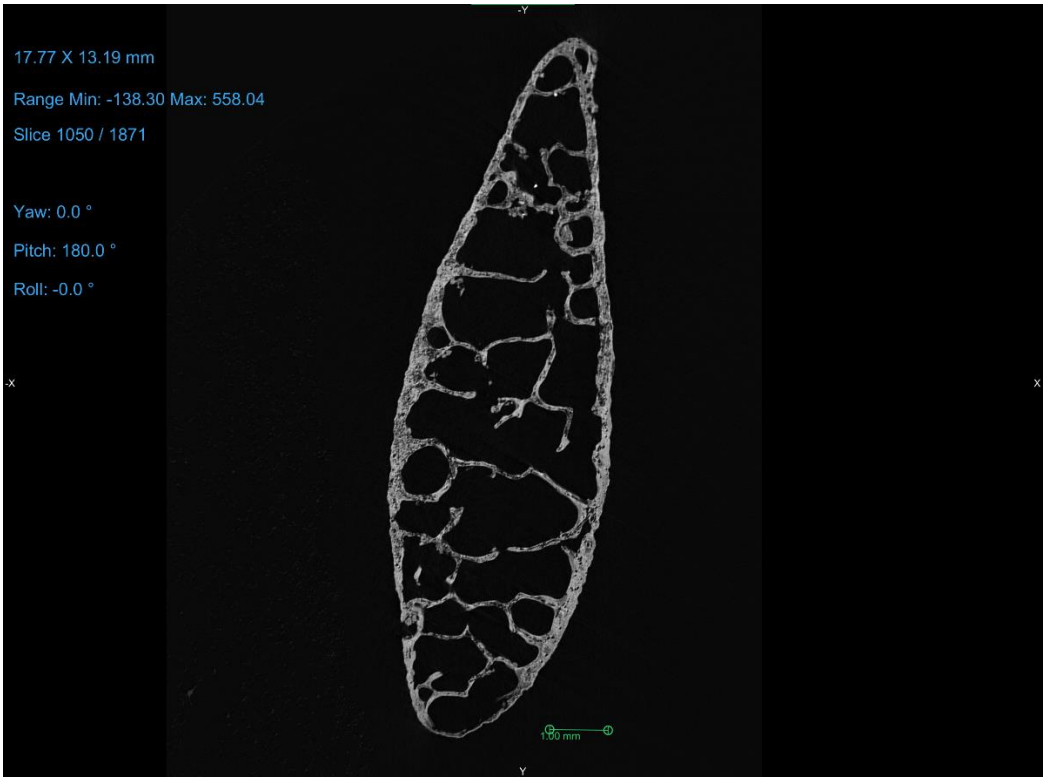

Figure F1.4. Micro-CT of individual 7A2-S2, slice 1050

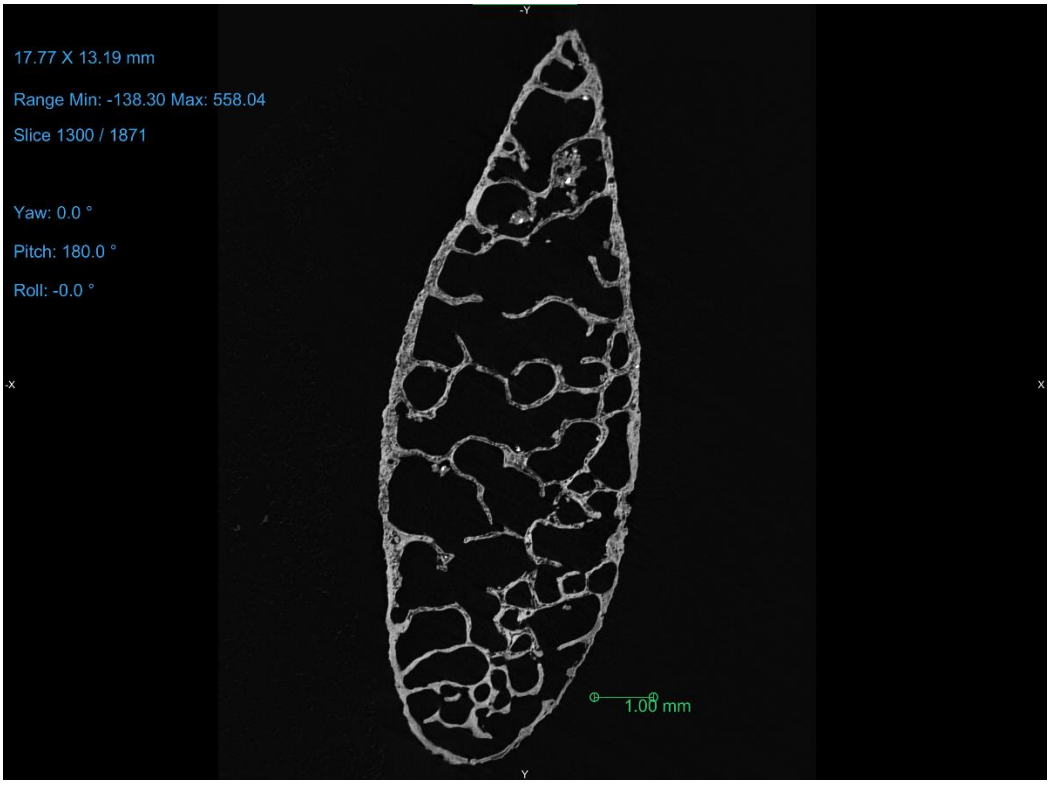

Figure F1.1. Micro-CT of individual 7A2-S2, slice 1300

F2: 7A2-S11 Scores and 5 Scan Slices

Table F2.1. Slice scores for individual 7A2-S11

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
500	1	0.5	1.5
750	1	0.5	1.5
1000	1	0.5	1.5
1250	3	0.5	3.5
1500	2	0.5	2.5
	8	2.5	10.5

Figure F2.1. Micro-CT of individual 7A2-S11, slice 500

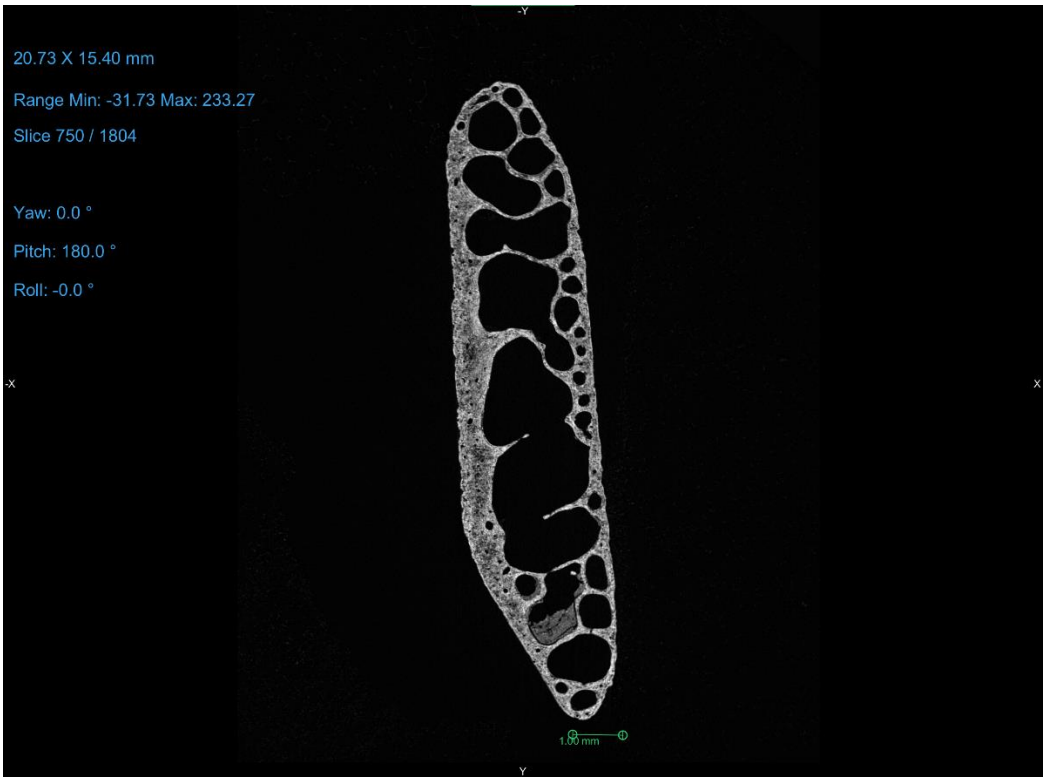

Figure F2.2. Micro-CT of individual 7A2-S11, slice 750

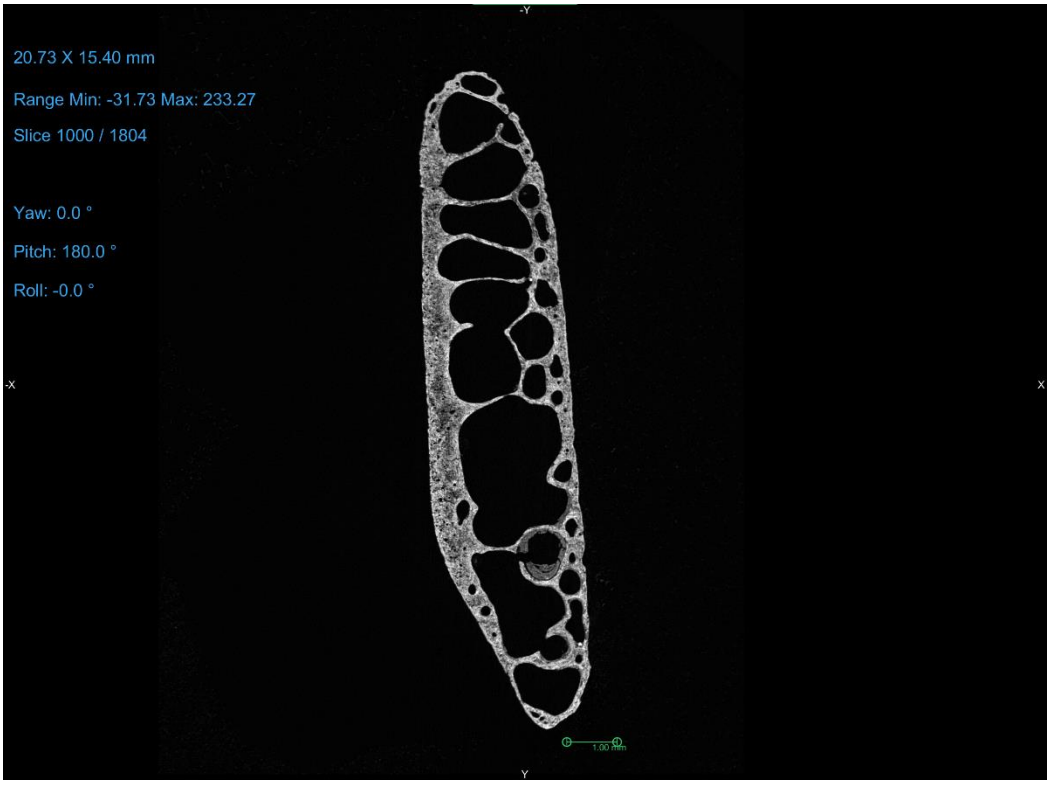

Figure F2.3. Micro-CT of individual 7A2-S11, slice 1000

Figure F2.4. Micro-CT of individual 7A2-S11, slice 1250

Figure F2.5. Micro-CT of individual 7A2-S11, slice 1500

F3: 7A2-S20 Scores and 5 Scan Slices

Table F3.1. Slice scores for individual 7A2-S20

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
350	0	0	0.0
600	1	0	1.0
850	1	0.5	1.5
1100	1	0.5	1.5
1350	1	0.5	1.5
	4	1.5	5.5

Figure F3.1. Micro-CT of individual 7A2-S20, slice 350

Figure F3.2. Micro-CT of individual 7A2-S20, slice 600

Figure F3.3. Micro-CT of individual 7A2-S20, slice 850

Figure F3.4. Micro-CT of individual 7A2-S20, slice 1100

Figure F3.5. Micro-CT of individual 7A2-S20, slice 1350

F4: 7A9-S38 Scores and 5 Scan Slices

Table F4.1. Slice scores for individual 7A9-S38

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
550	0	0	0.0
800	0	0	0.0
1050	0	0	0.0
1300	0	0	0.0
1550	0	0	0.0
	0	0	0.0

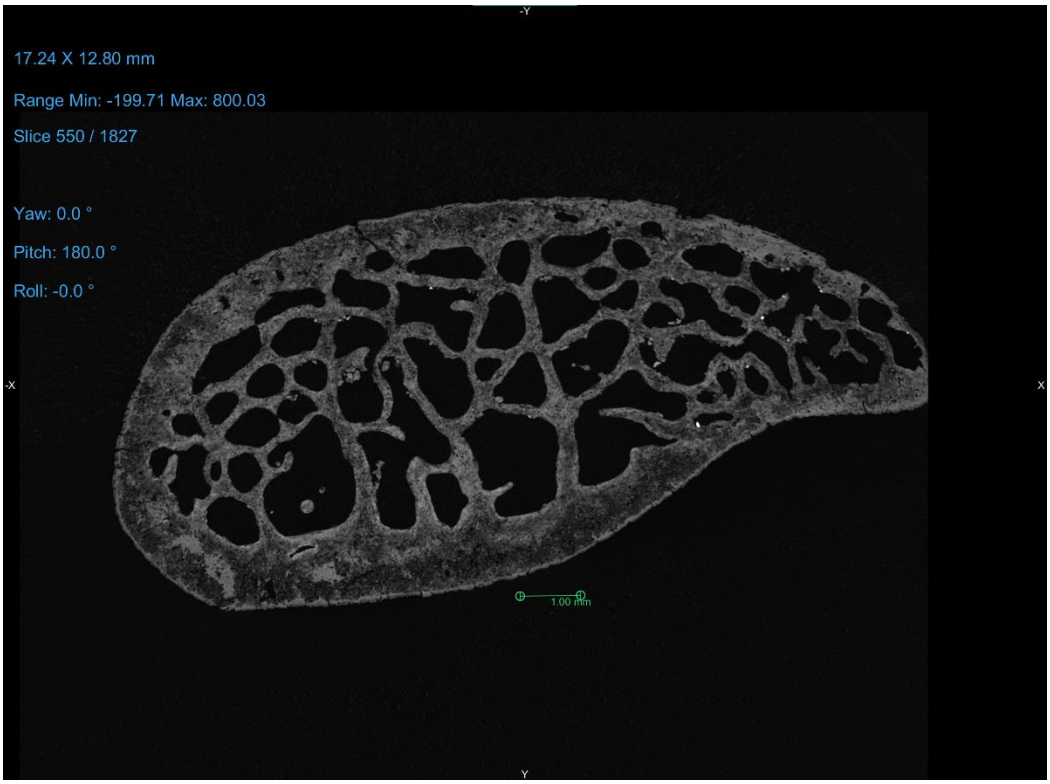

Figure F4.1. Micro-CT of individual 7A9-S38, slice 550

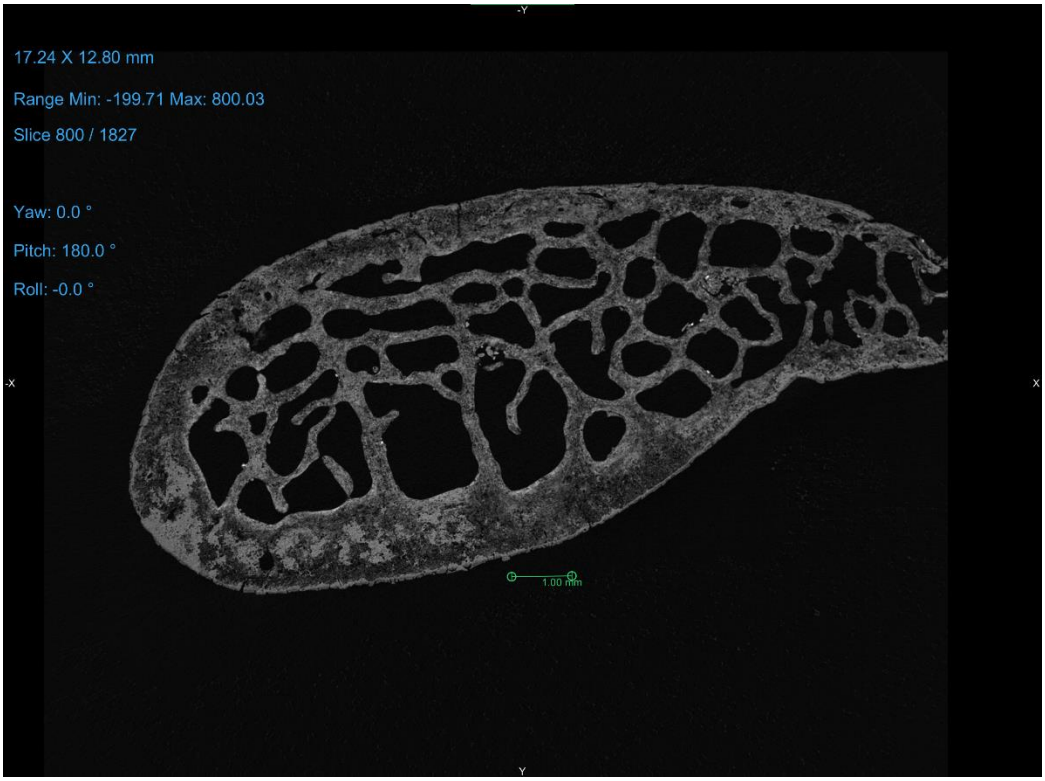

Figure F4.2. Micro-CT of individual 7A9-S38, slice 800

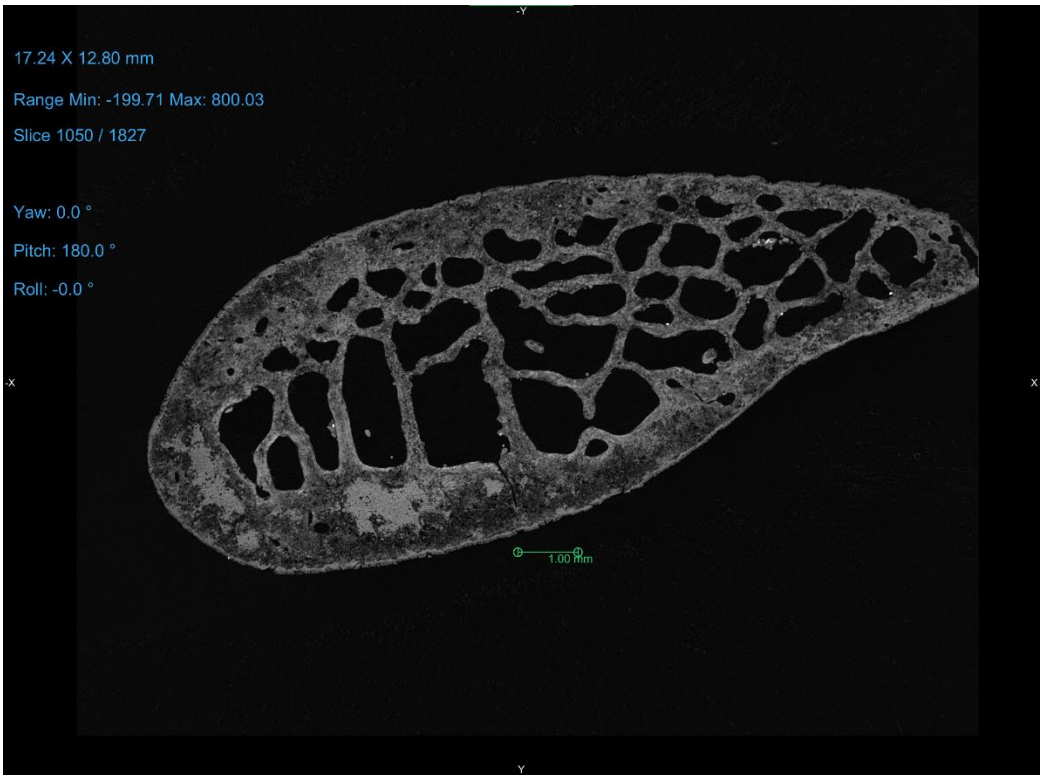

Figure F4.3. Micro-CT of individual 7A9-S38, slice 1050

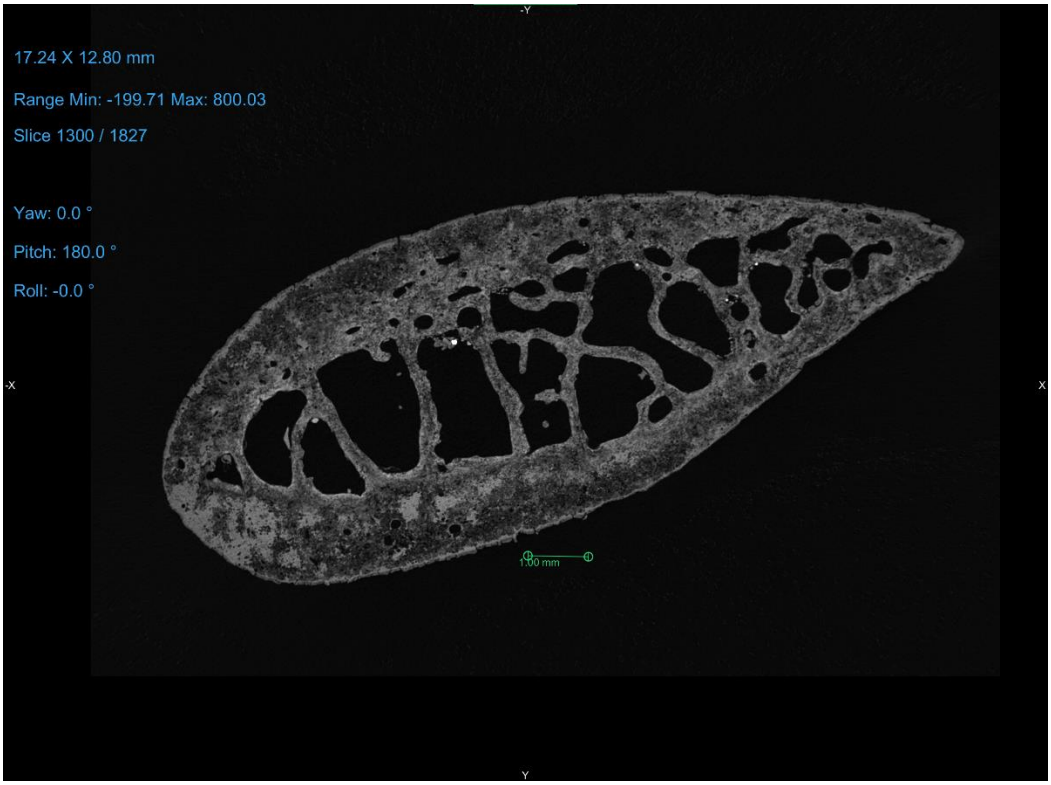

Figure F4.4. Micro-CT of individual 7A9-S38, slice 1300

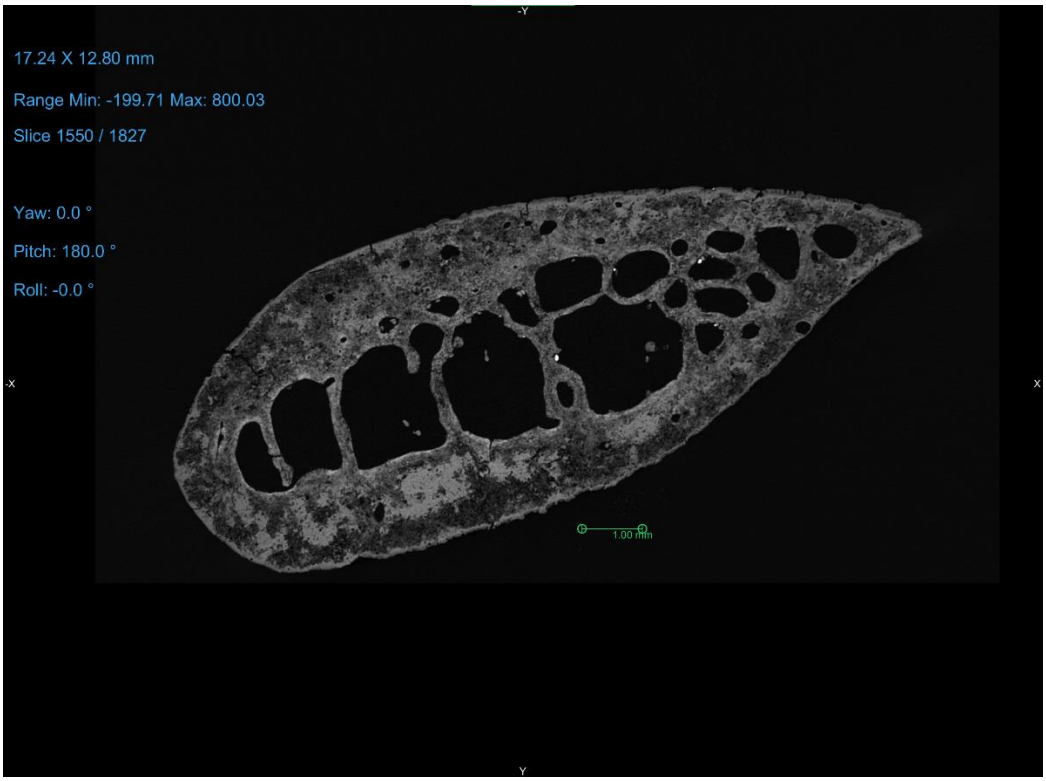

Figure F4.5. Micro-CT of individual 7A9-S38, slice 1550

F5: 7A9-S46 Scores and 5 Scan Slices

Table F5.1. Slice scores for individual 7A9-S46

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
450	2	0.5	2.5
700	1	0	1.0
950	2	0	2.0
1200	1	0	1.0
1450	0	0	0.0
	6	0.5	6.5

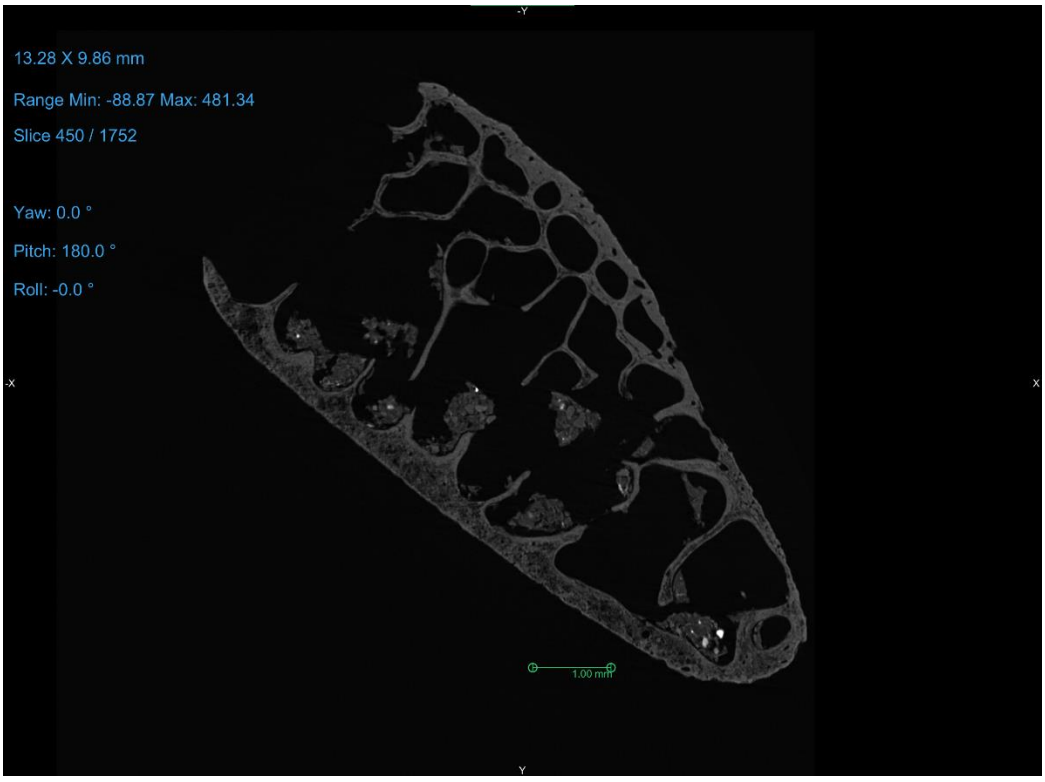

Figure F5.1. Micro-CT of individual 7A9-S46, slice 450

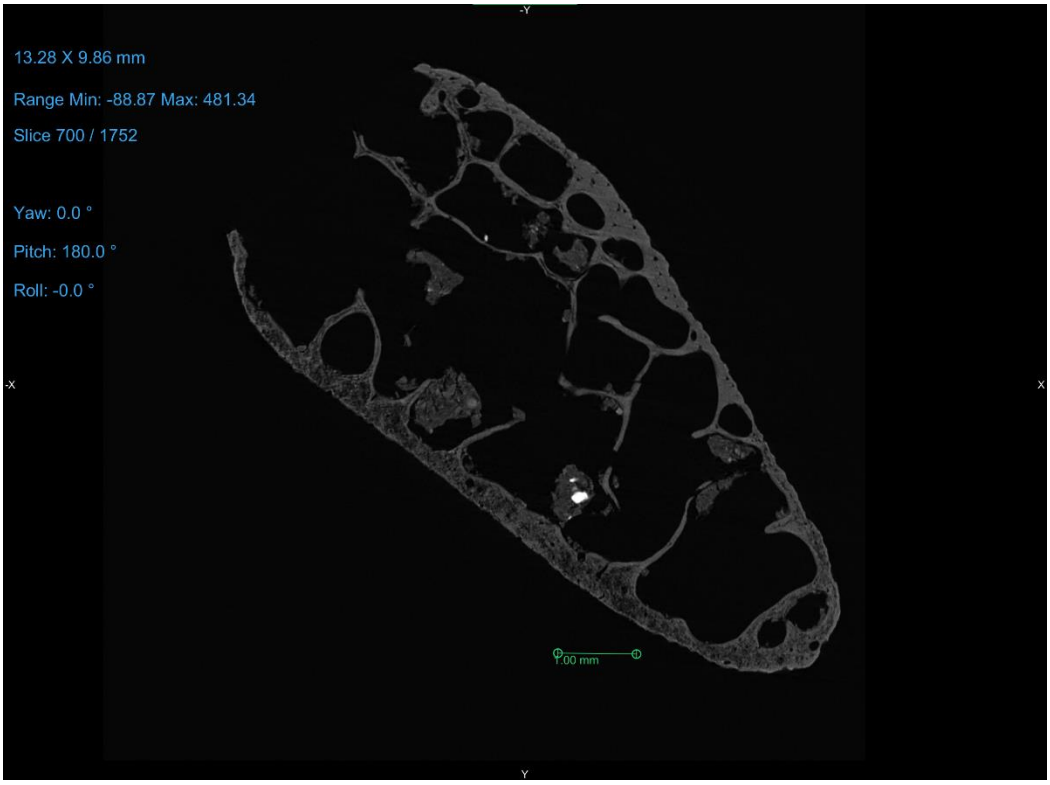

Figure F5.2. Micro-CT of individual 7A9-S46, slice 700

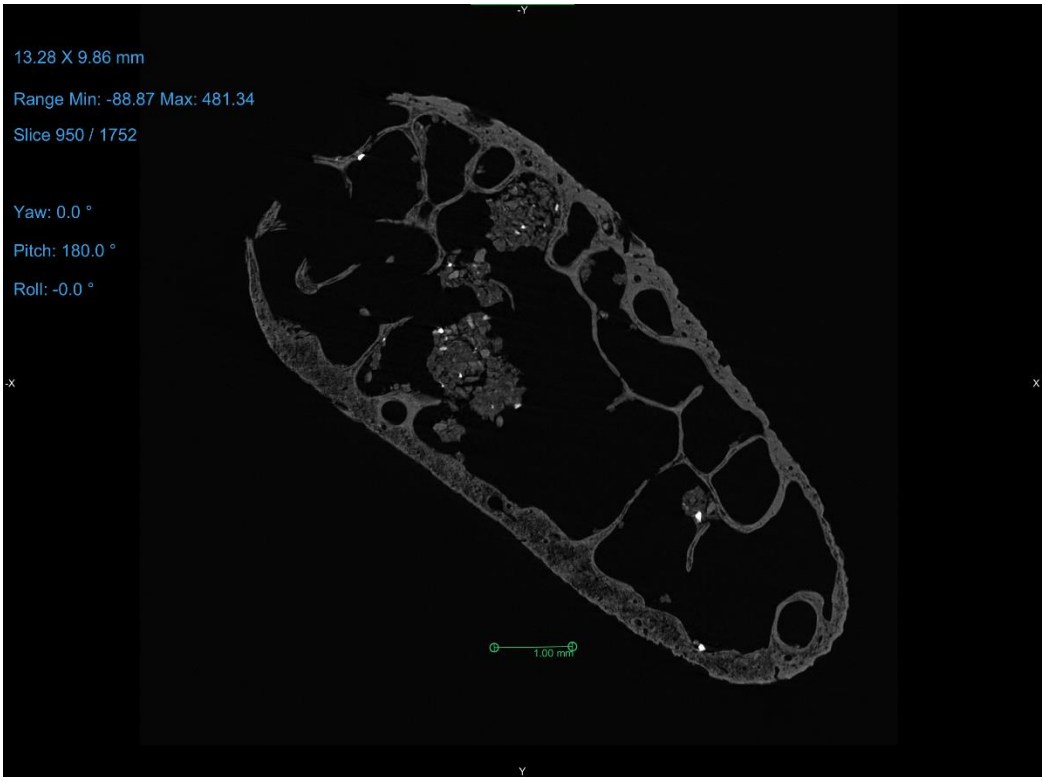

Figure F5.3. Micro-CT of individual 7A9-S46, slice 950

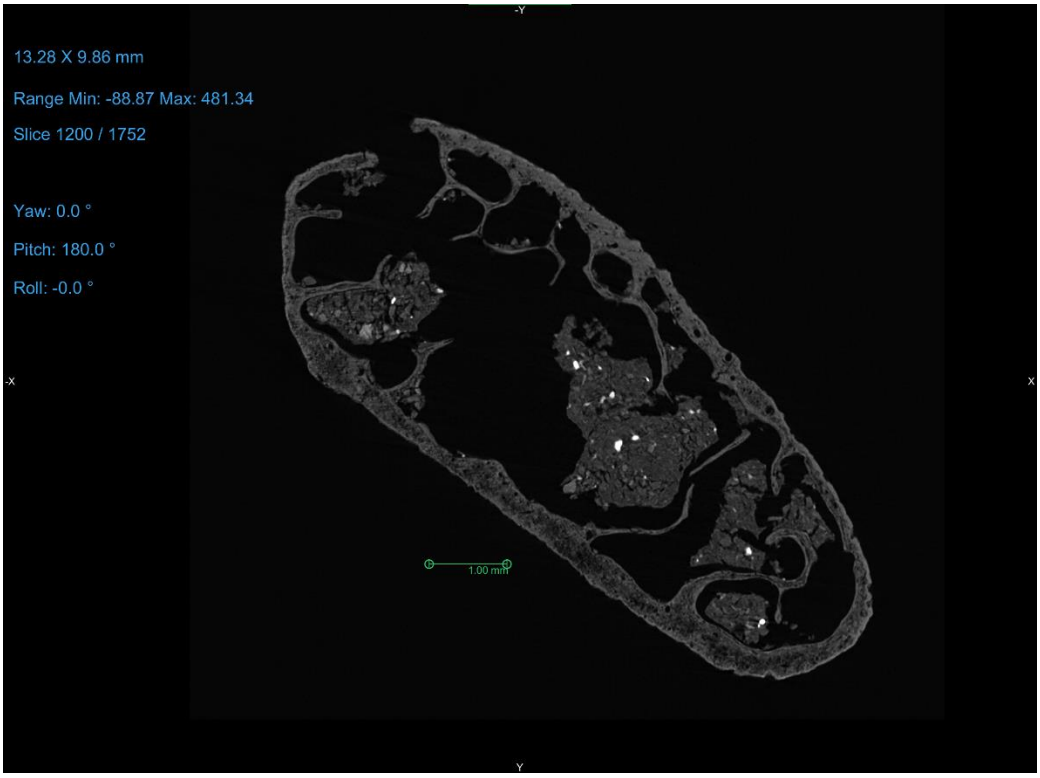

Figure F5.4. Micro-CT of individual 7A9-S46, slice 1200

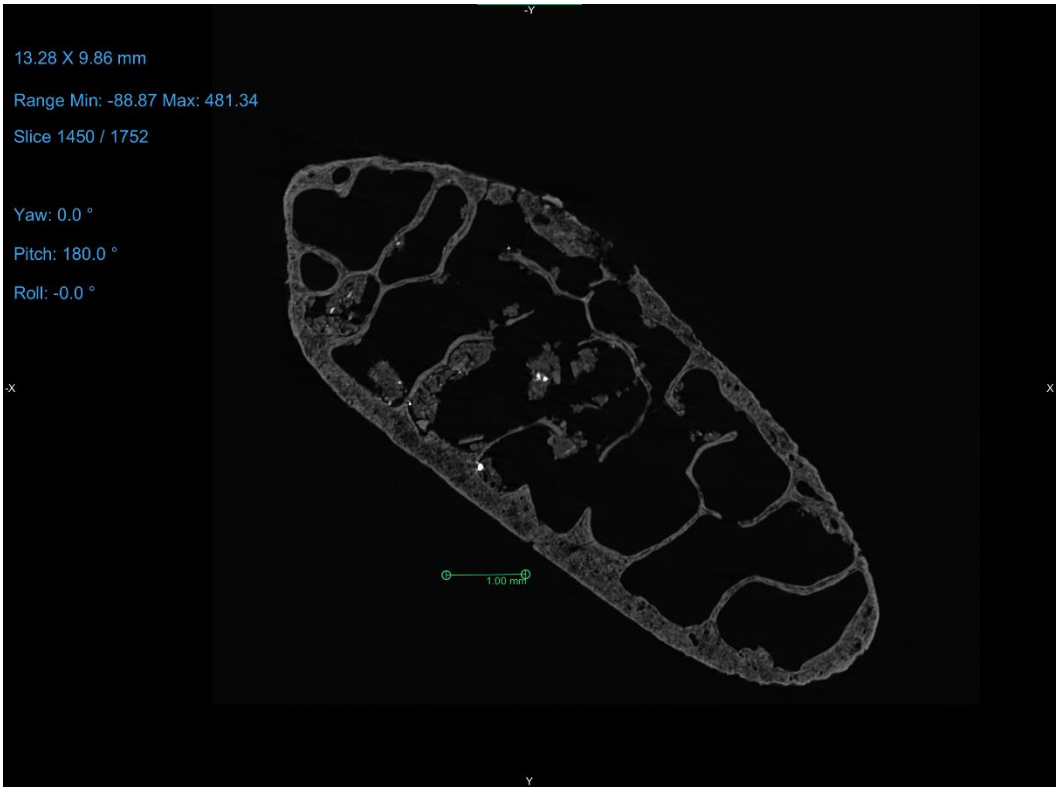

Figure F5.5. Micro-CT of individual 7A9-S46, slice 1450

F6: 7A11-S19 Scores and 5 Scan Slices

Table F6.1. Slice scores for individual 7A11-S19

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
650	2	0.5	2.5
900	3	0.5	3.5
1150	1	0.5	1.5
1400	2	0.5	2.5
1650	2	0.5	2.5
	10	2.5	12.5

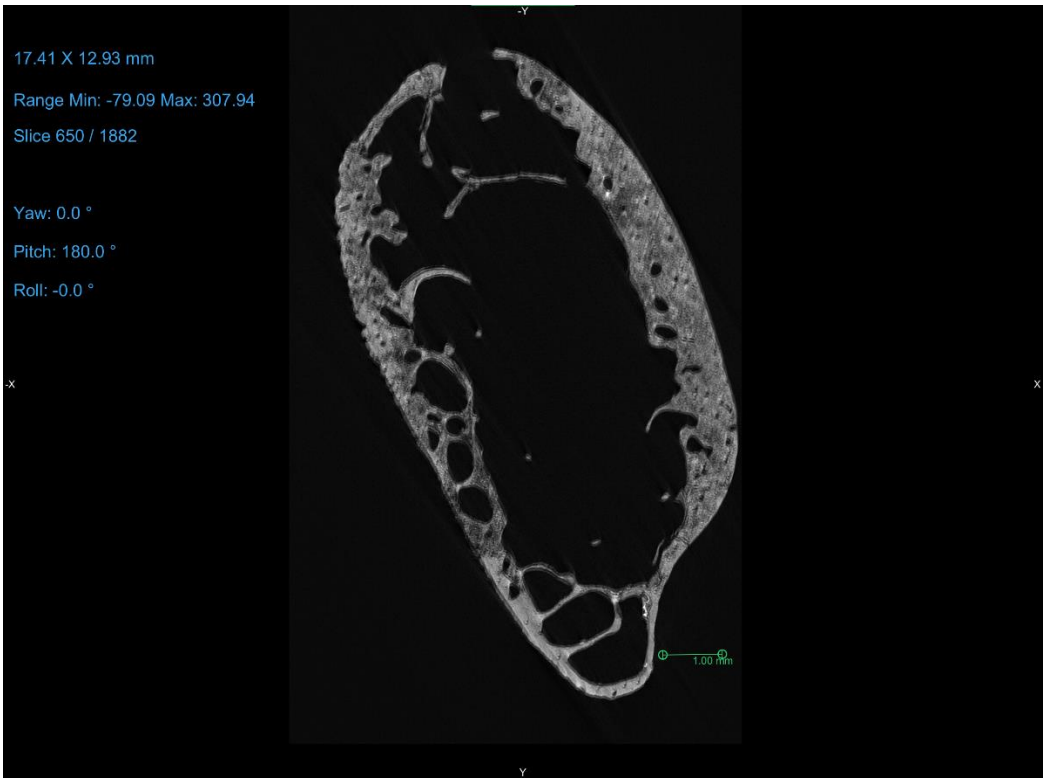

Figure F6.1. Micro-CT of individual 7A11-S19, slice 650

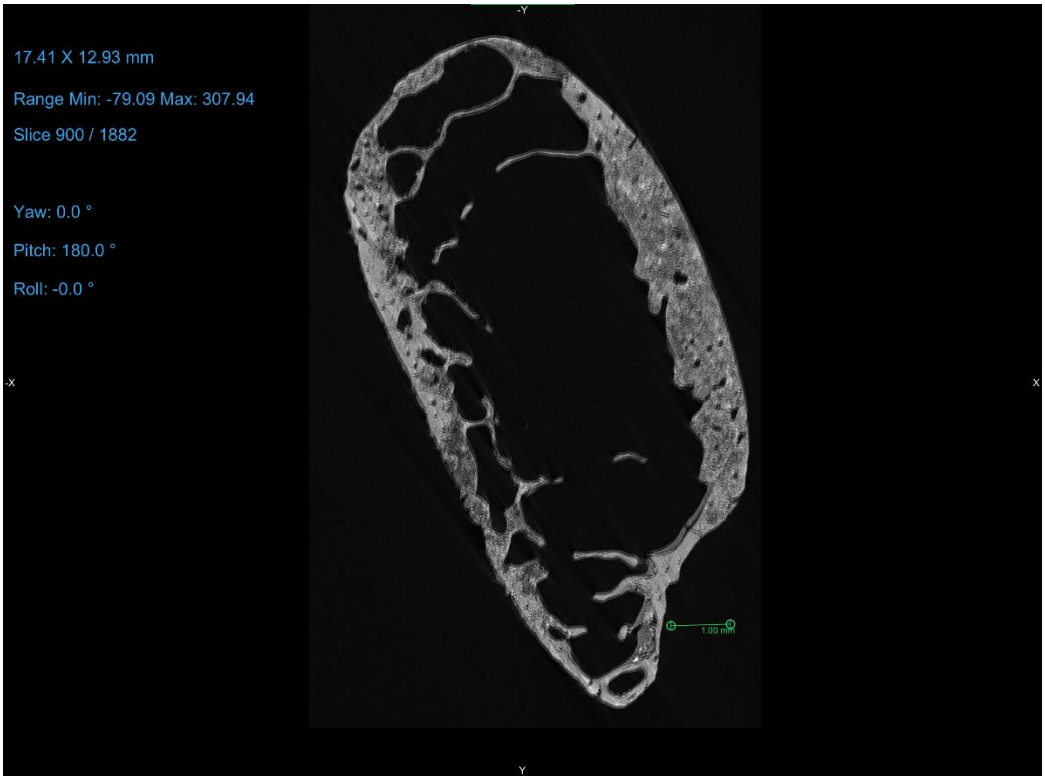

Figure F6.2. Micro-CT of individual 7A11-S19, slice 900

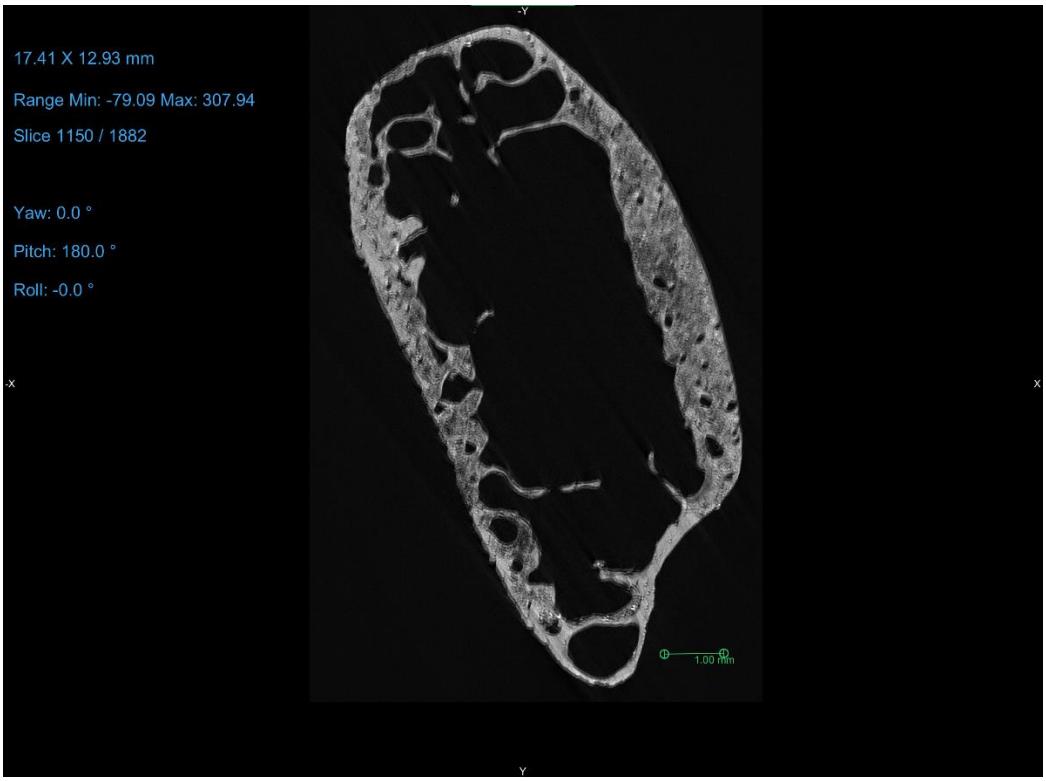

Figure F6.3. Micro-CT of individual 7A11-S19, slice 1150

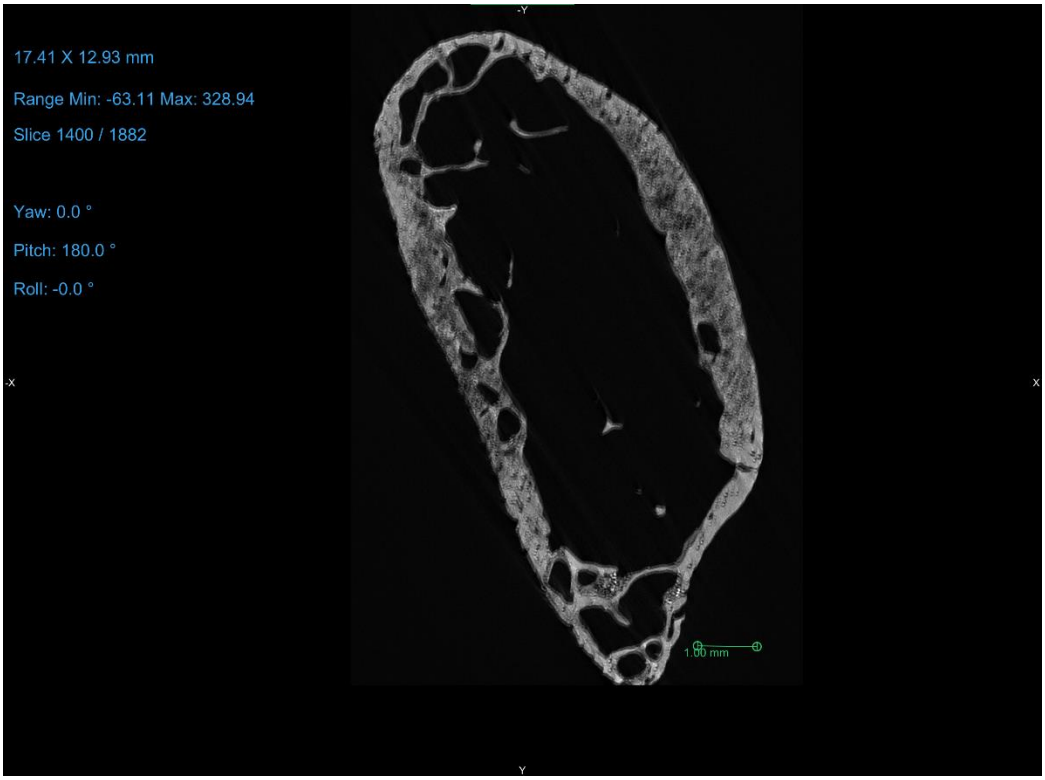

Figure F6.4. Micro-CT of individual 7A11-S19, slice 1400

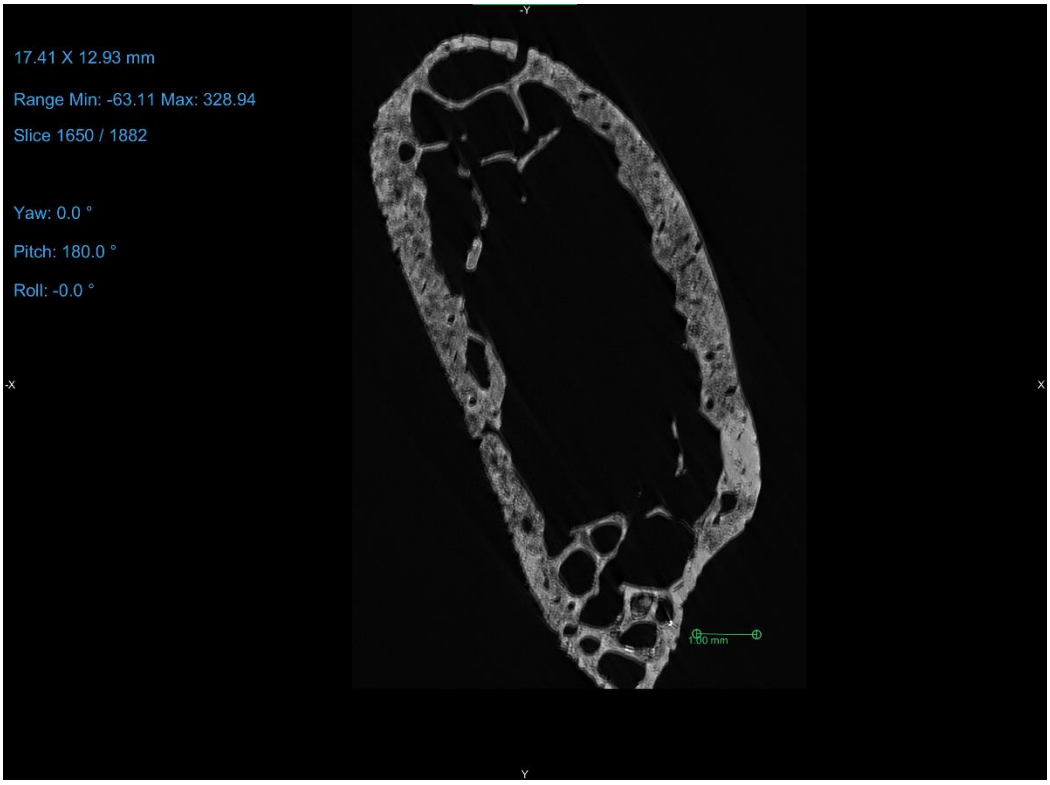

Figure F6.5. Micro-CT of individual 7A11-S19, slice 1650

F7: 7A11-S42 Scores and 5 Scan Slices

Table F7.1. Slice scores for individual 7A11-S42

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
550	1	0	1.0
800	1	0	1.0
1050	1	0.5	1.5
1300	1	0	1.0
1550	0	0	0.0
	4	0.5	4.5

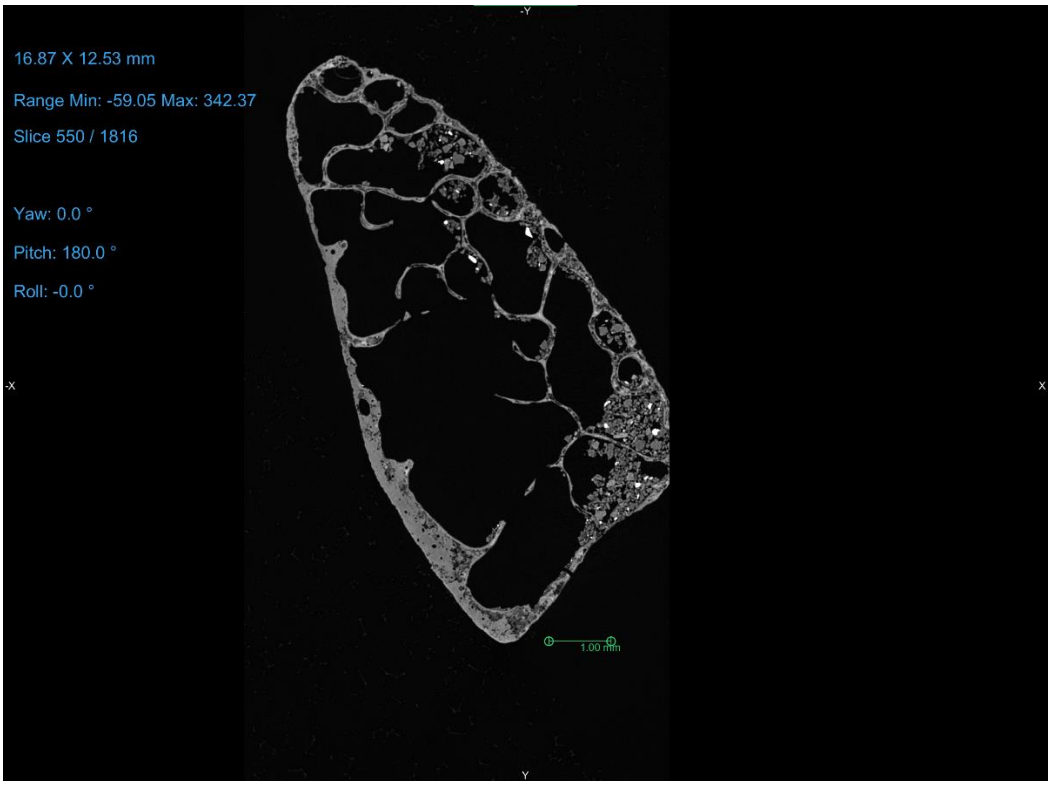

Figure F7.1. Micro-CT of individual 7A11-S42, slice 550

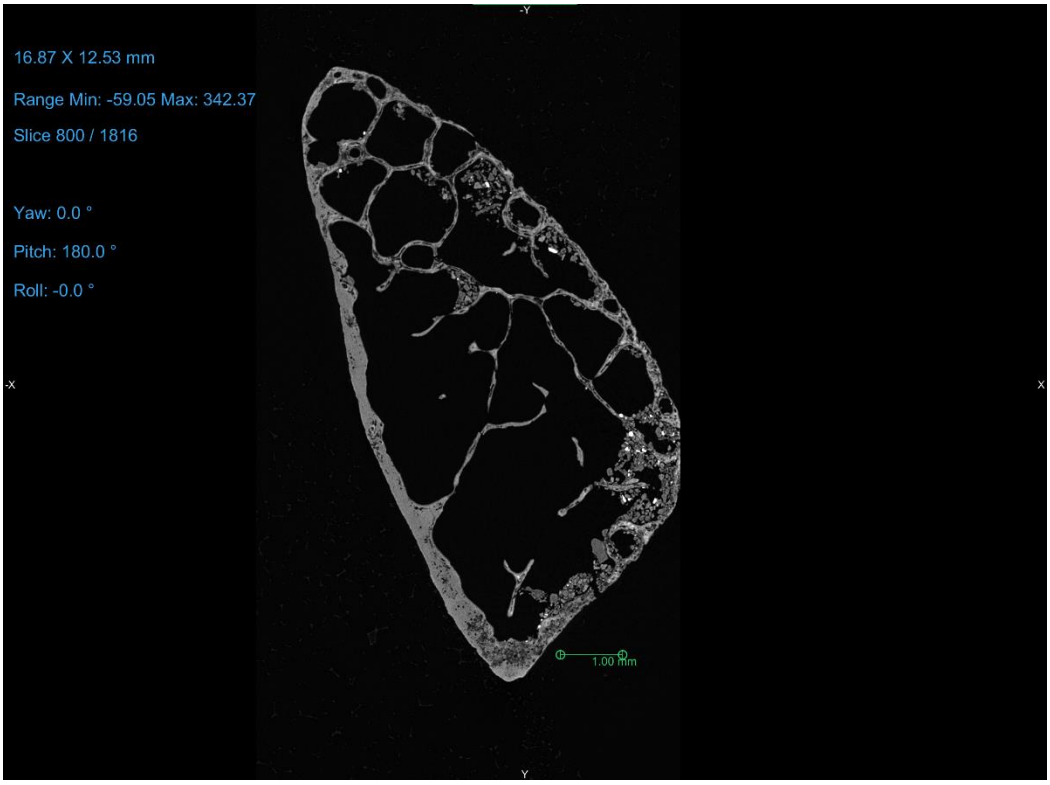

Figure F7.2. Micro-CT of individual 7A11-S42, slice 800

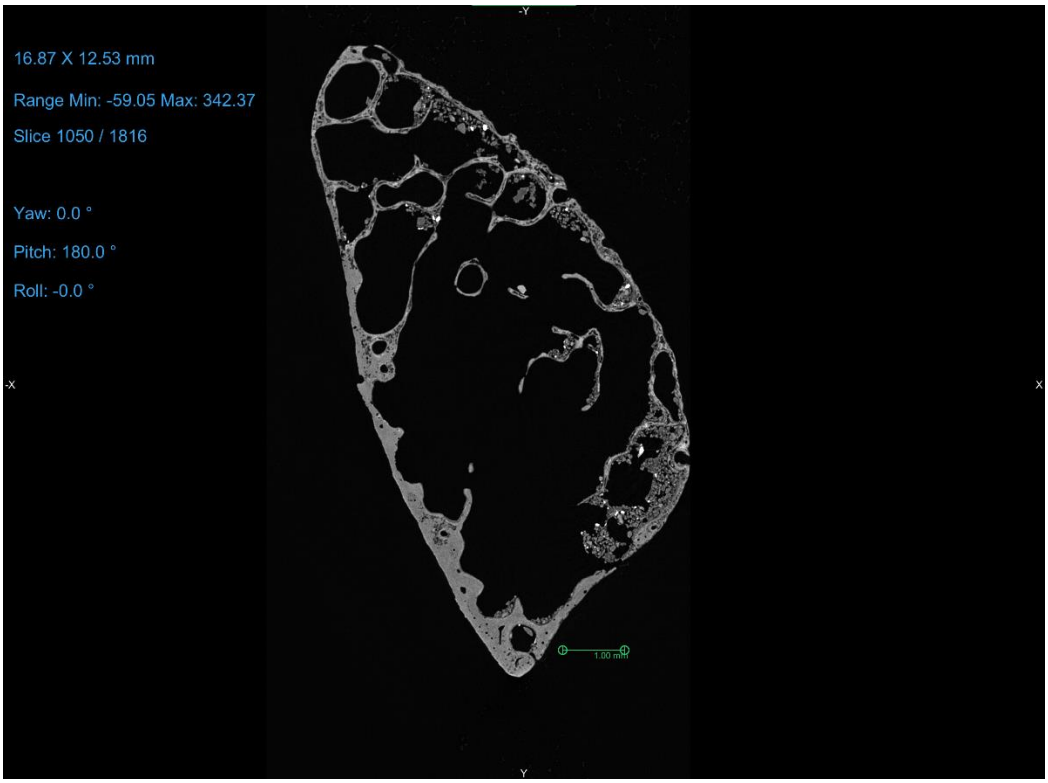

Figure F7.3. Micro-CT of individual 7A11-S42, slice 1050

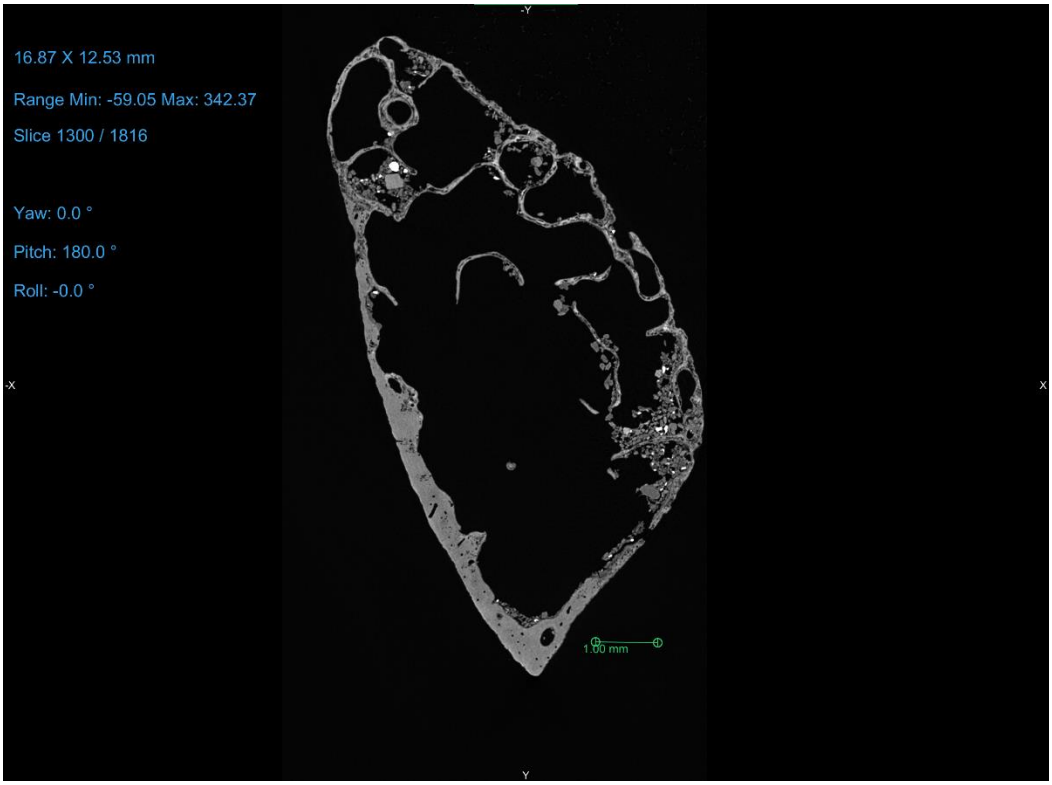

Figure F7.4. Micro-CT of individual 7A11-S42, slice 1300

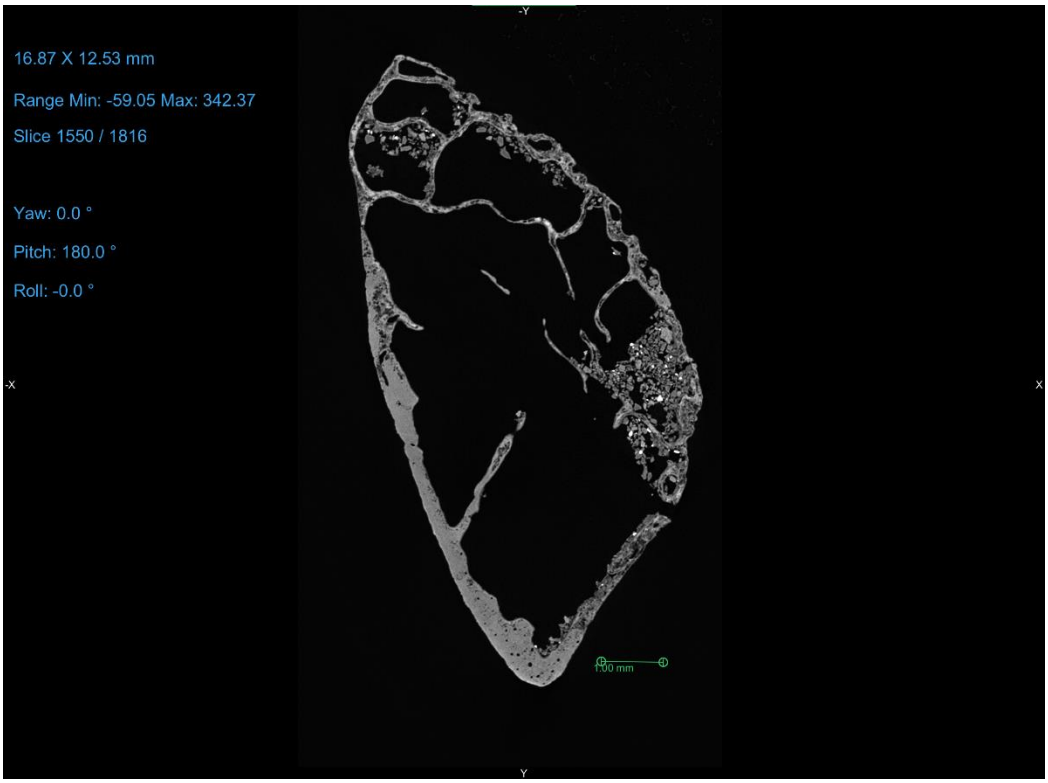

Figure F7.5. Micro-CT of individual 7A11-S42, slice 1550

F8: 2B9 Scores and 5 Scan Slices

Table F8.1. Slice scores for individual 2B9

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
300	0	0	0.0
550	0	0	0.0
800	0	0	0.0
1050	0	0	0.0
1300	1	0	1.0
	1	0	1.0

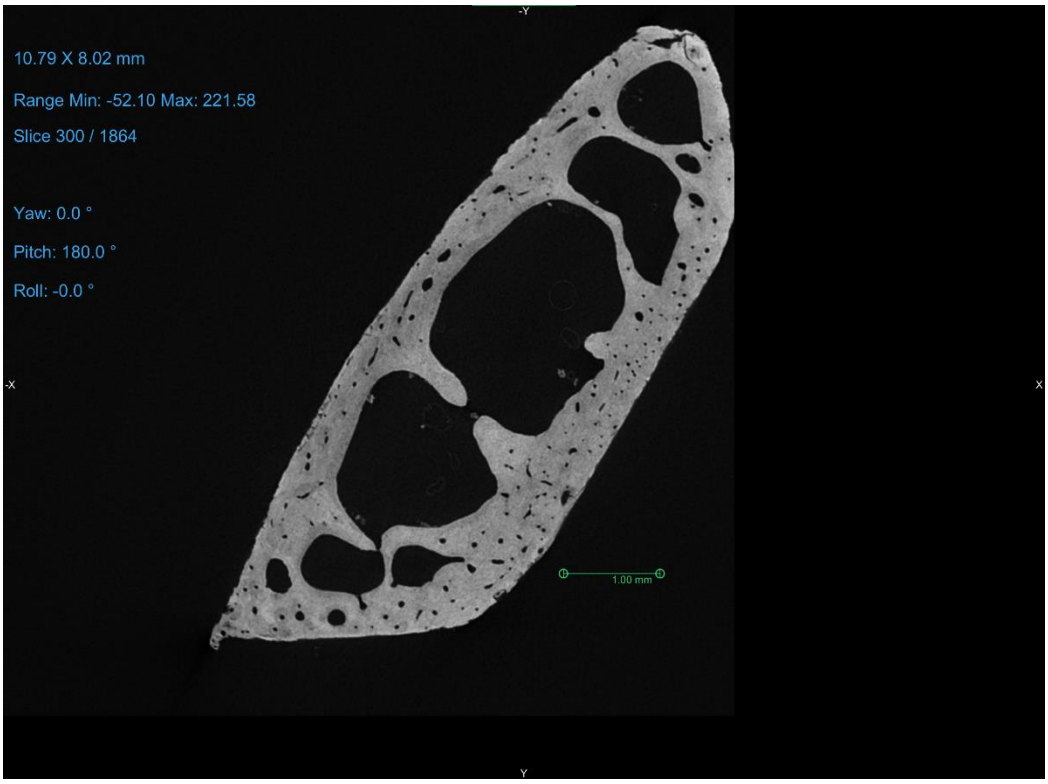

Figure F8.1. Micro-CT of individual 2B9, slice 300

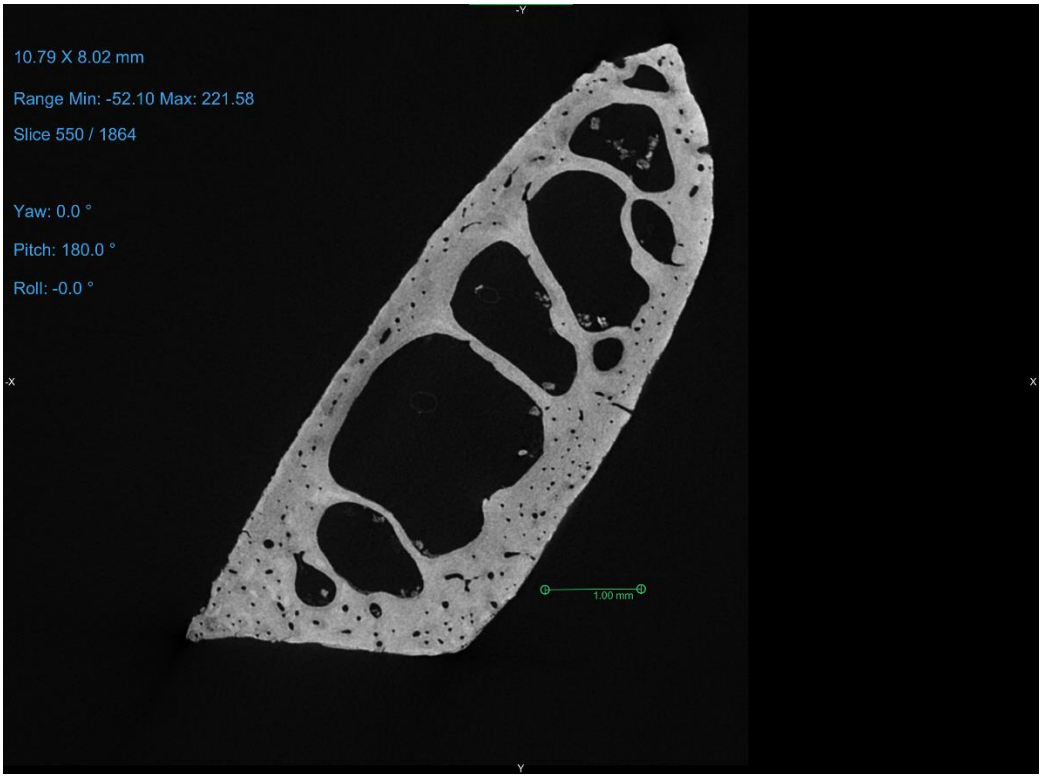

Figure F8.2. Micro-CT of individual 2B9, slice 550

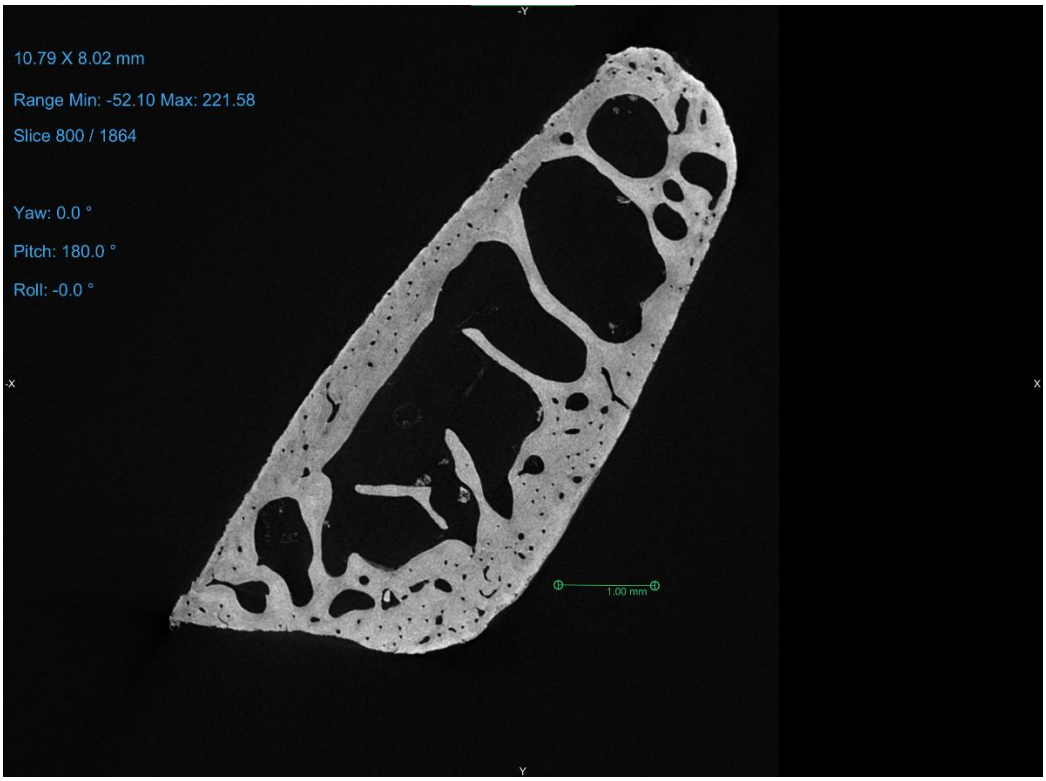

Figure F8.3. Micro-CT of individual 2B9, slice 800

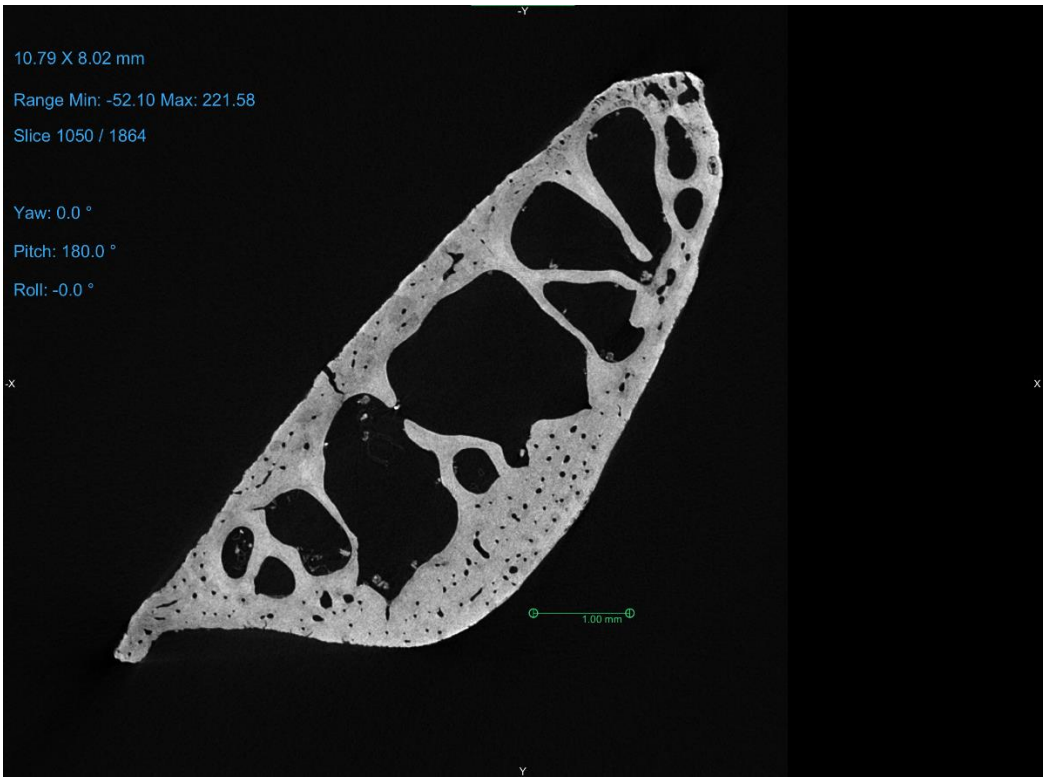

Figure F8.4. Micro-CT of individual 2B9, slice 1050

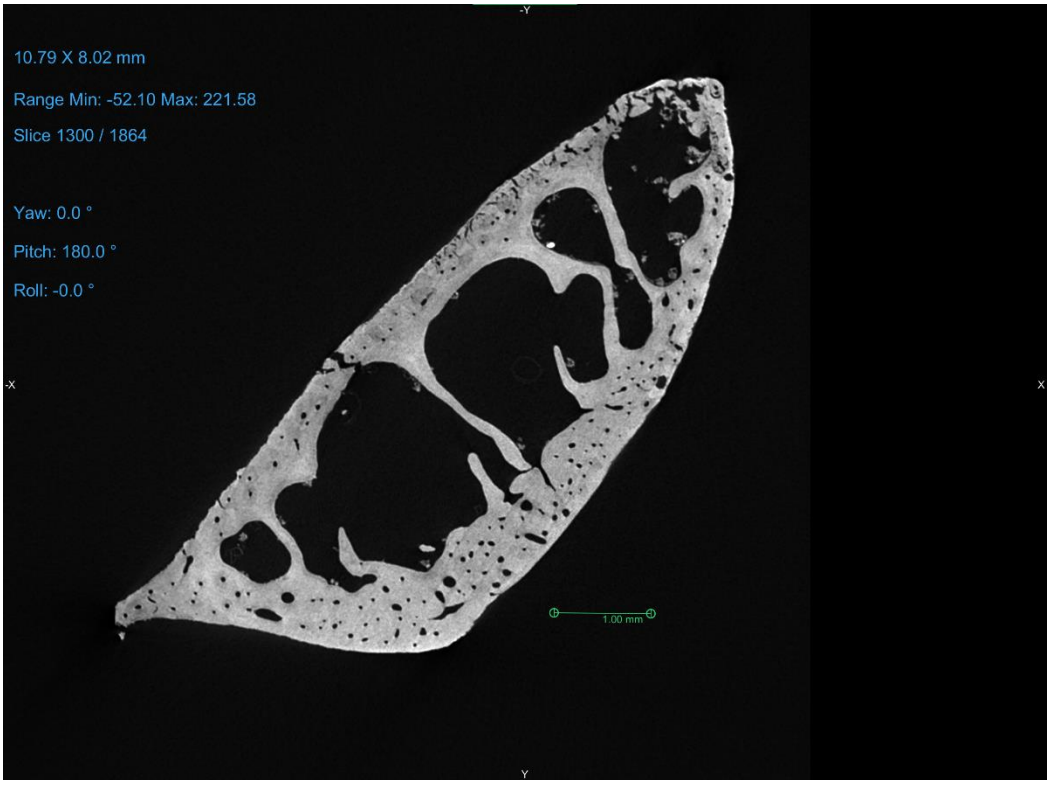

Figure F8.5. Micro-CT of individual 2B9, slice 1300

F9: 2E13 Scores and 5 Scan Slices

Table F9.1. Slice scores for individual 2E13

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
800	2	0.5	2.5
1050	2	0.5	2.5
1300	3	0.5	3.5
1550	2	0.5	2.5
1800	3	0.5	3.5
	12	2.5	14.5

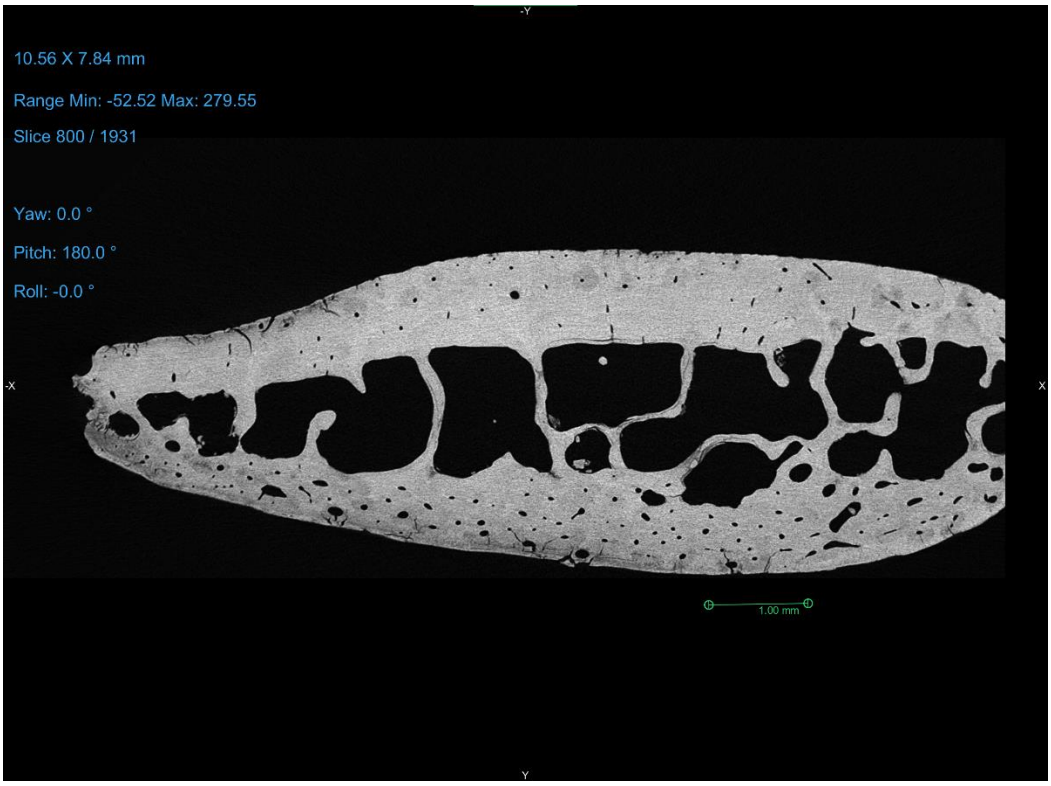

Figure F9.1. Micro-CT of individual 2E13, slice 800

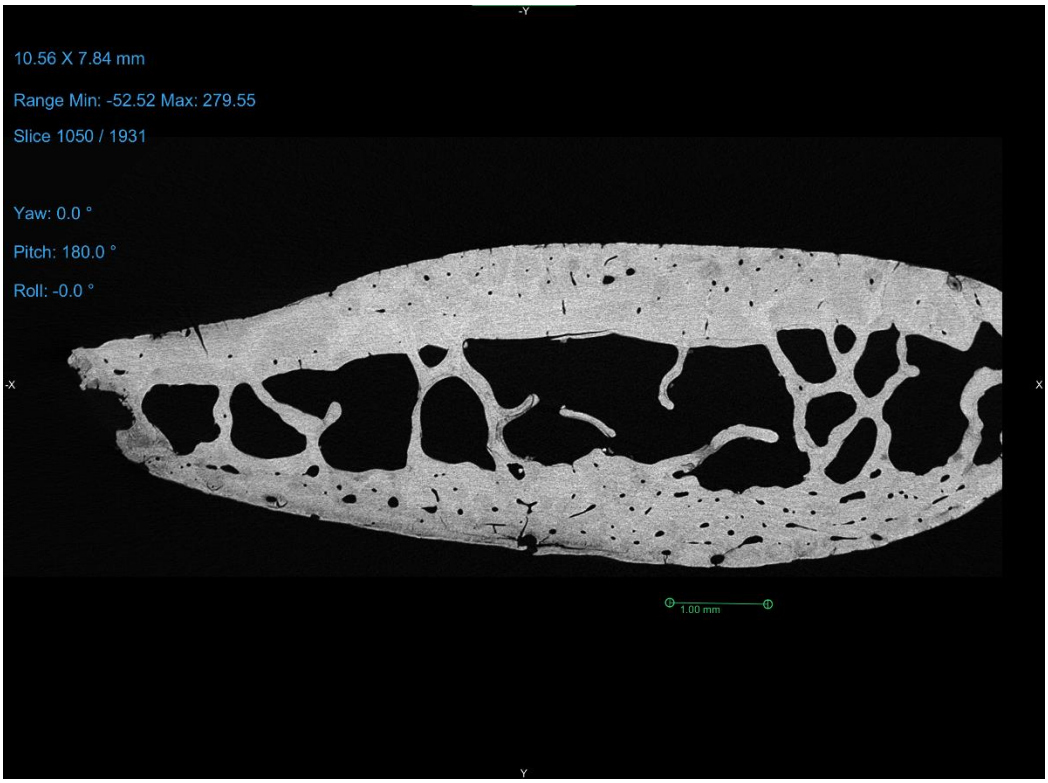

Figure F9.2. Micro-CT of individual 2E13, slice 1050

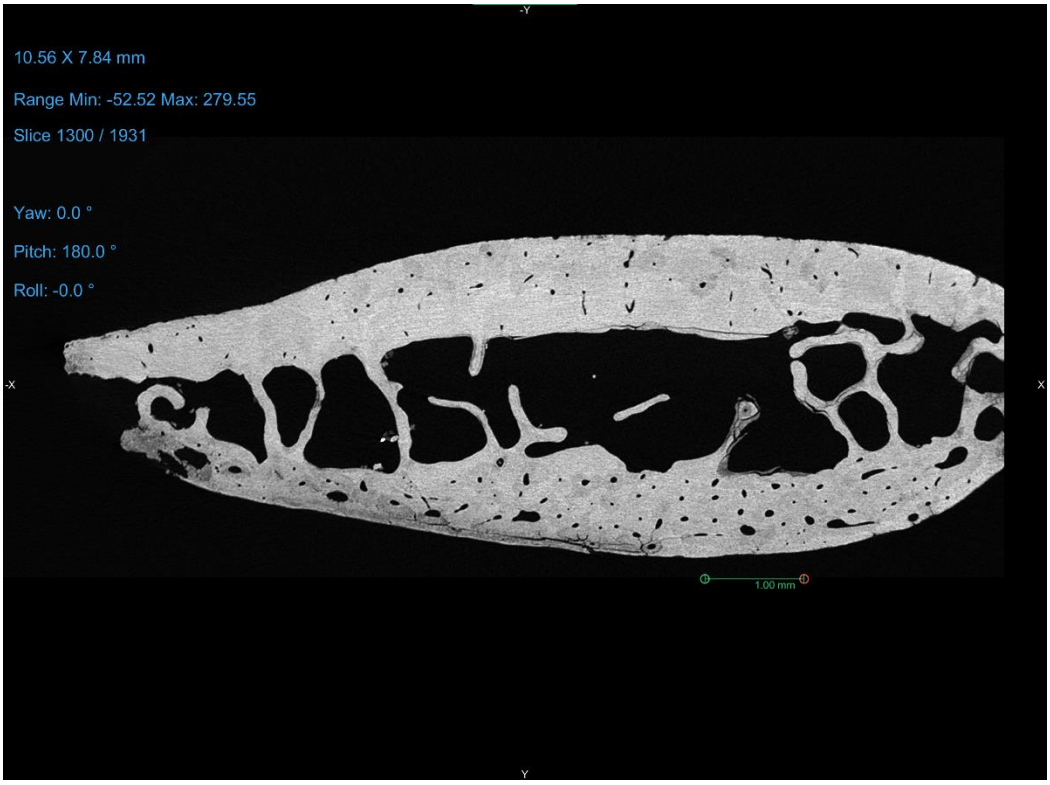

Figure F9.3. Micro-CT of individual 2E13, slice 1300

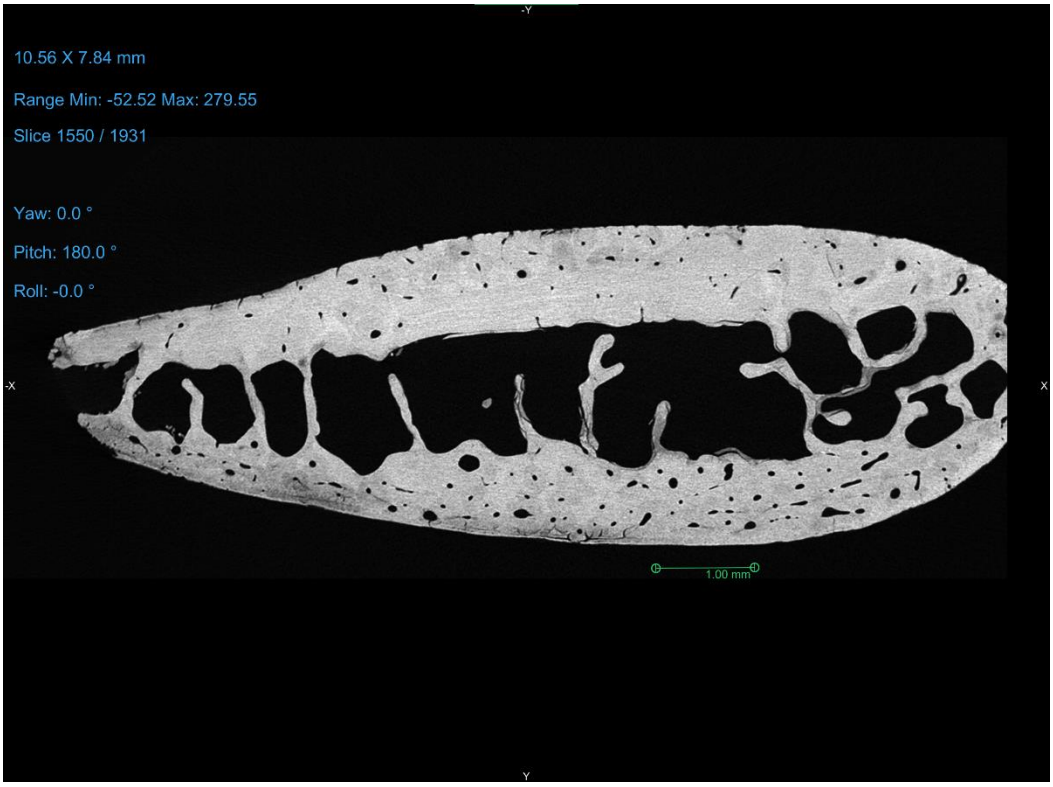

Figure F9.4. Micro-CT of individual 2E13, slice 1550

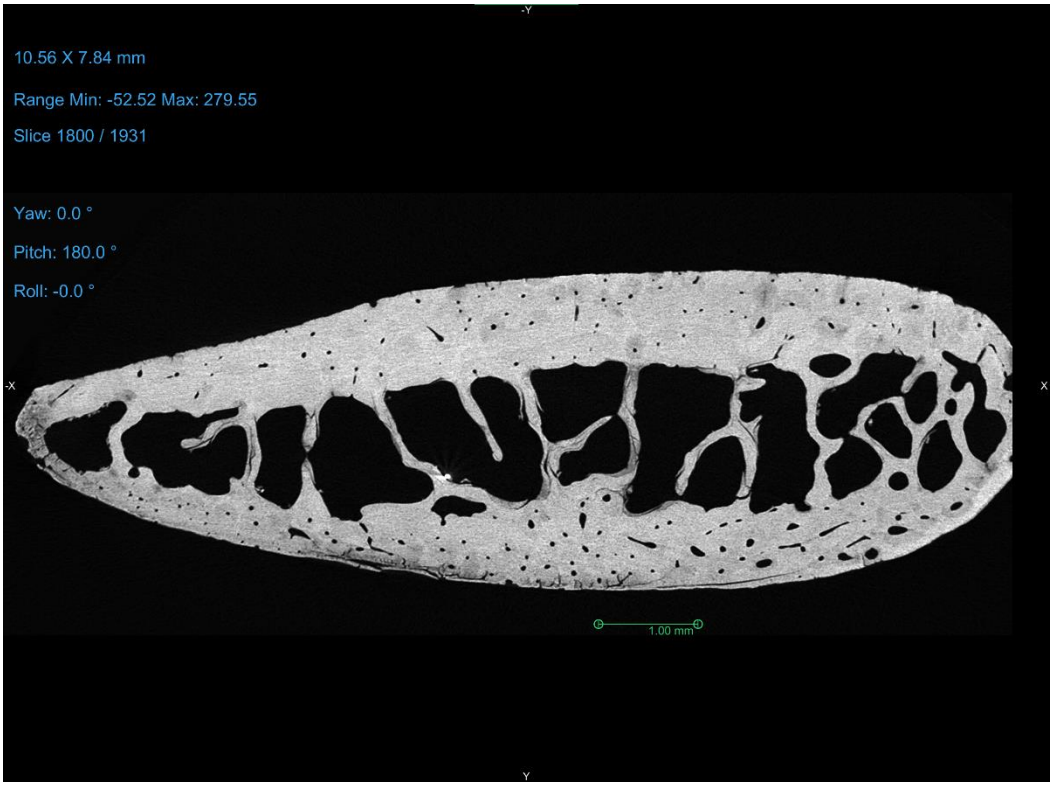

Figure F9.5. Micro-CT of individual 2E13, slice 1800

F10: 2G4 Scores and 5 Scan Slices

Table F10.1. Slice scores for individual 2G4

Slice Number	DCL Score	Incomplete Mineralization(+0.5)	Total Score
450	0	0	0.0
700	1	0	1.0
950	1	0	1.0
1200	0	0	0.0
1450	0	0	0.0
	2	0	2.0

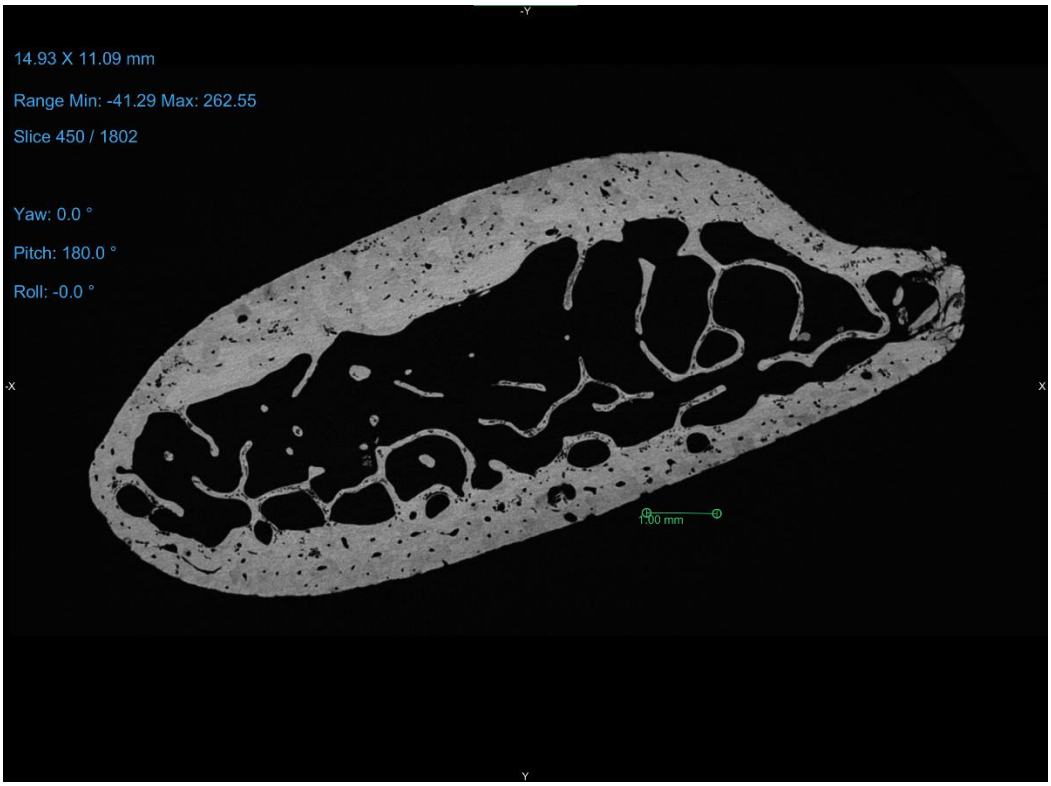

Figure F10.1. Micro-CT of individual 2G4, slice 450

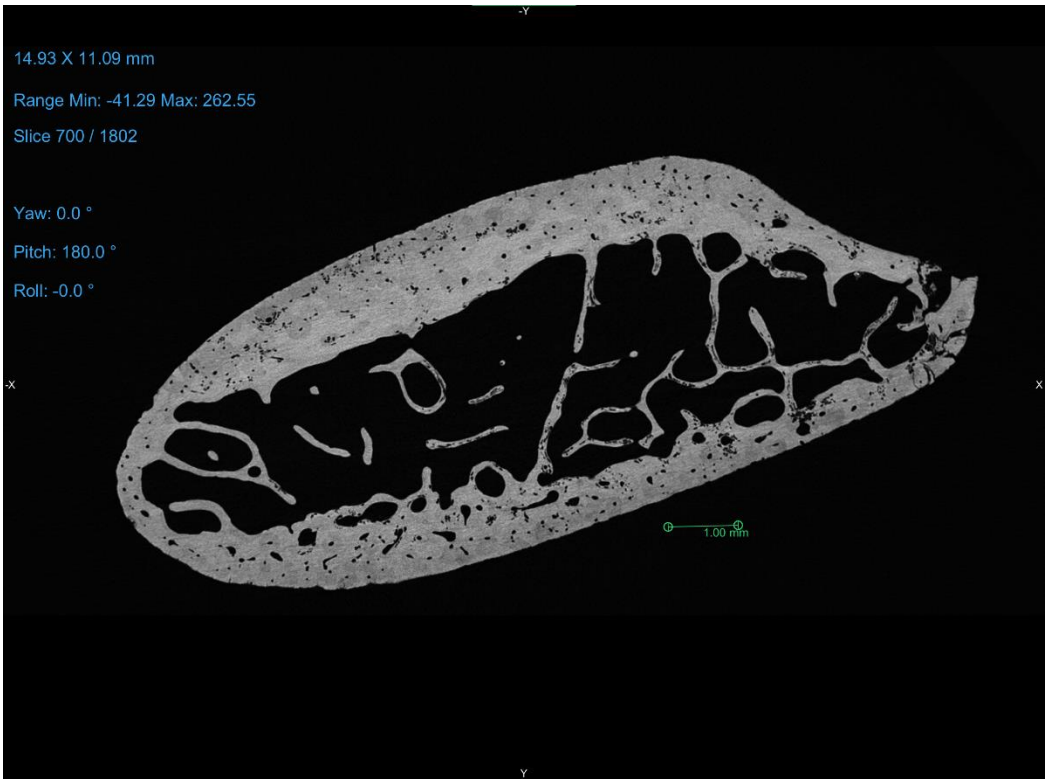

Figure F10.2. Micro-CT of individual 2G4, slice 700

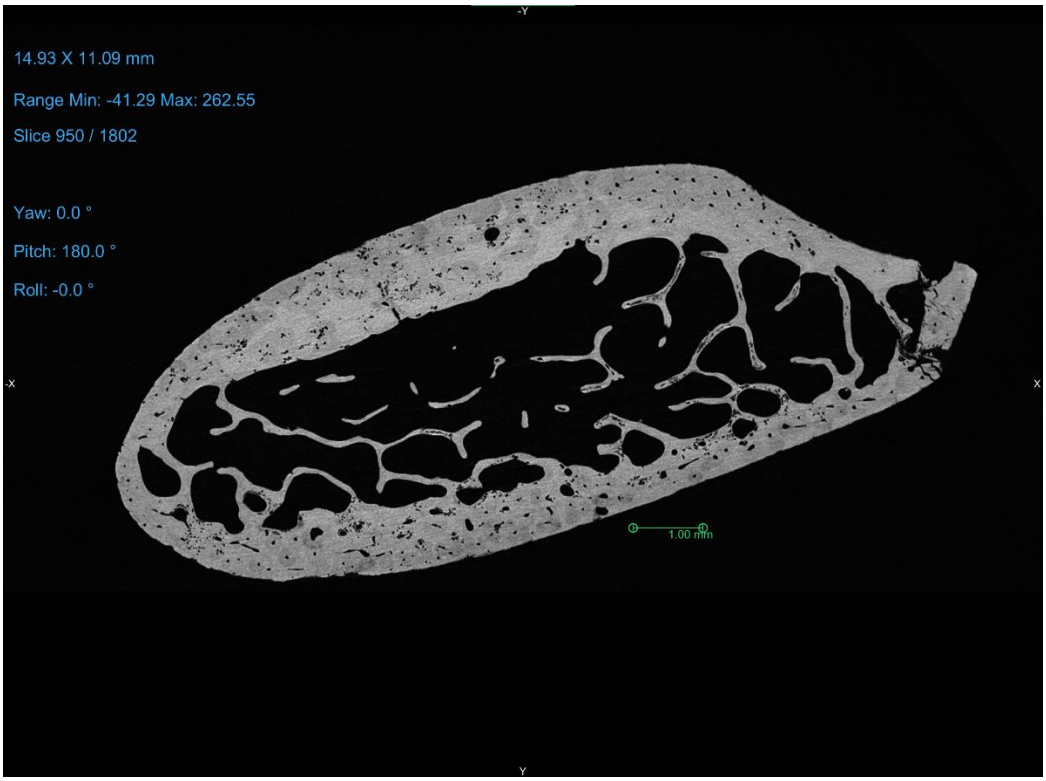

Figure F10.3. Micro-CT of individual 2G4, slice 950

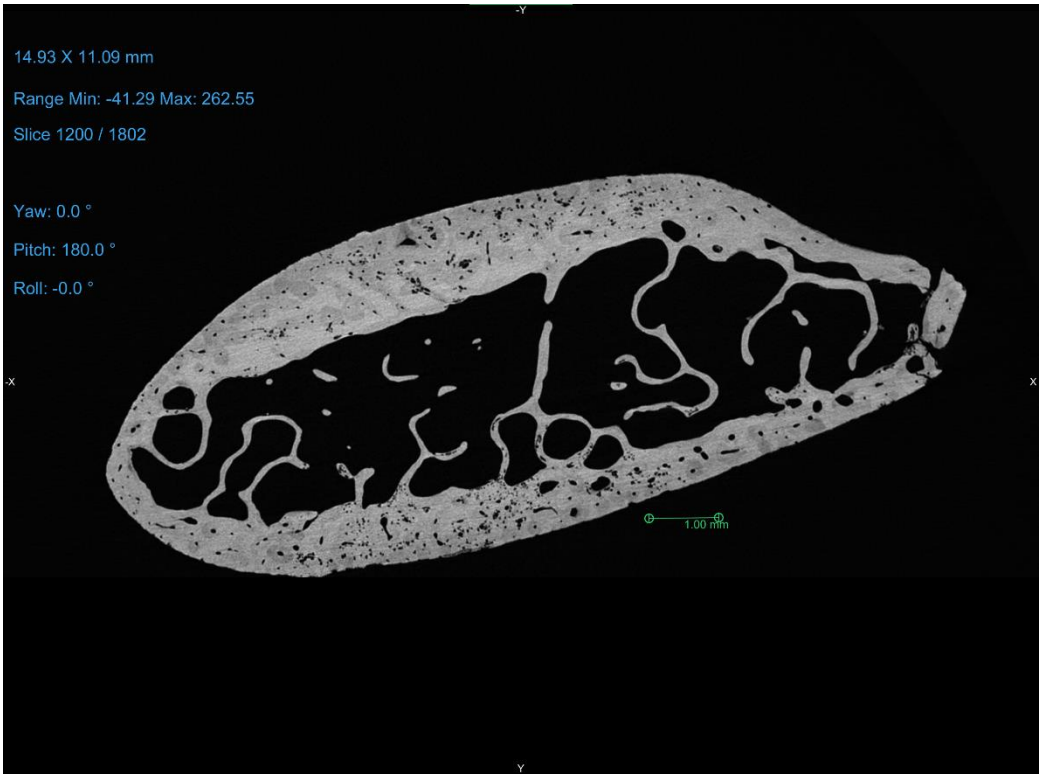

Figure F10.4. Micro-CT of individual 2G4, slice 1200

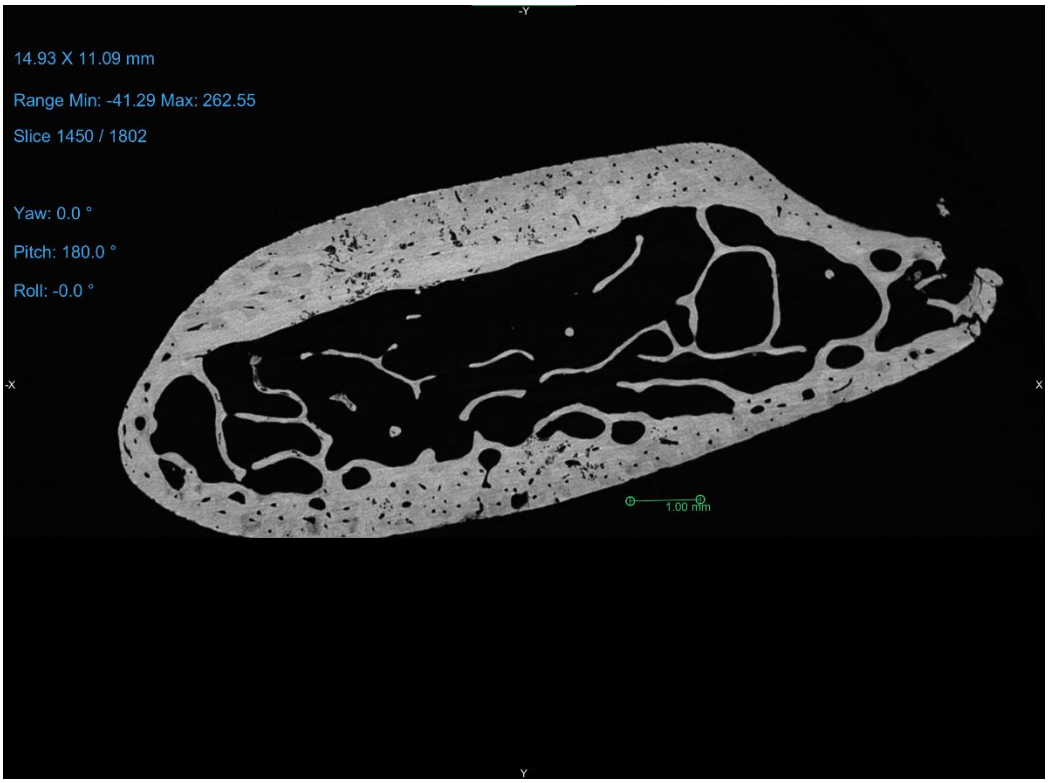

Figure F10.5. Micro-CT of individual 2G4, slice 1450