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RESEARCH ARTICLE

Dental disease reflects differential diets and changes in consumption over time at Knossos

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Abstract

Knossos was an important city on Crete and within Mediterranean networks during the Hellenistic, Roman, and Late Antique periods. However, there were significant social, cultural, and economic shifts that appear to have caused changes to daily lifeways, including diet. This paper sets out to explore dietary changes across these time periods by looking at dental caries, with reference also to antemortem tooth loss, calculus, and stable isotope data. This study also looks to contextualize these results using archaeological and textual information relating to diet. It presents a thorough methodological approach to the investigation and interpretation of caries and discusses some of the shortcomings of using a fragmentary and commingled skeletal assemblage. The Roman diet was more cariogenic than in the Hellenistic or Late Antique periods. The caries-zone analysis of the teeth suggests that there may have been a greater addition of sugars to the diet in the Roman period, though the increased caries could also be due to improved preparation techniques and technologies producing a more refined and sticky carbohydrate diet. Such changes could be due to either increased connectivity making certain foods more readily available, the cultural changes in food consumption or dental hygiene due to the influx of merchants, colonists, migrants, and other newcomers to the *Colonia Iulia Nobilis Cnosus* that was Roman Knossos, or increased prosperity at the site in this period. There was a significant difference detected between females and males for caries indicating differential dietary practices between the sexes, which was most notable for the Roman period.

KEYWORDS
colony, dental caries, dental disease, diet, dietary change, Knossos, loose teeth, Roman Crete

1 | INTRODUCTION

This paper sets out to explore why the prevalence of dental disease in the residents of Knossos changed between the Hellenistic (323–67 BCE), Roman (67 BCE–CE 400), and Late Antique (CE 400–700) periods. Although a series of endogenous, pathogenic, and environmental processes influence the manifestation of dental diseases, diet is a key influencer in its ability to affect the bacterial environment and saliva content in the mouth (Hillson, 1996; Larsen et al., 1991; Temple, 2015). As such, the study of dental diseases, and dental caries in particular, can be extremely informative for aspects of ancient diets, as well as changes and differences in those diets. This

study focuses on dental caries, though a comparison with the antemortem tooth loss, calculus, and stable isotope data (Moles et al., 2022; Moles, forthcoming-b) is also valuable for the investigation of dietary change and differentiation within the population.

The study of human skeletal remains is a fast growing discipline in Greece, and there are several overviews of its progress now published (Buikstra & Lagia, 2009; Eliopoulos et al., 2011; Lagia, 2015; Lagia et al., 2014; Mackinnon, 2007; Roberts et al., 2005; Schepartz et al., 2009). However, the study of human health, and dental health in particular, has been very little studied for the time periods represented by the present study. The only published studies of contemporary dental disease on Crete come from Hellenistic Chania (Bourbou, 2005), Roman Sfakaki (Bourbou, 2005), and Late Antique Eleutherna, Gortyn, and Kefali (Bourbou, 2010; Mallegni, 1988; Zygouri, 2005). These studies recovered teeth totaling 278 at Chania (36% of total possible teeth in adult individuals), 324 at Sfakaki (31%), 618 at Eleutherna (19%), 232 at Gortyn (25.0%), and 156 (9.9%) at Kefali with caries prevalences of 7.2%, 2.5%, 2.9%, 2.1%, and 8.3% of teeth, respectively. For these time periods in Greece, studies of dental health have also been conducted to greater and lesser extents at Roman Athens (Lagia, 2000), Roman Corinth (Fox, 2005; Fox Leonard, 1997), Roman and Late Antique Isthmia (Rife, 2012), Roman Pontokomi-Vrysi (Vergidou et al., 2021), Roman Amphipolis (Malama & Triantaphyllou, 2003), Late Antique Sourtara (Bourbou, 2009), Late Antique Pigi Athinas (Tritsaroli, 2014), and Late Antique Maroneia (Tritsaroli & Karadima, 2017), with limited possibilities for a comparative, integrated, or larger scale synthesis.

With its integral position within Mediterranean networks and as a site of long-term importance, having developed into the earliest urban center in Europe in the Bronze Age (Whitelaw et al., 2019), Knossos (Figure 1) is an interesting case study for the exploration of changing diet. The time period under study sees changing connectedness for the site within networks, in socioeconomic importance, and in agricultural productivity for trade. With a skeletal assemblage representing approximately 1000 years of occupation at the site, there is the opportunity to investigate how socioeconomic changes affected the daily lives of people at the fundamental level of their diet and dental health.

2 | HISTORICAL BACKGROUND

Knossos had been a leading city-state among the island's estimated 100 cities in the Hellenistic period (Perlman, 1992). It was the only Roman colony on Crete, the *Colonia Iulia Nobilis Cnosus* founded by 27 BCE, having put up a staunch resistance to the Roman invasion of the island in 69–67 BCE. Though the population became increasingly depleted from the 3rd century CE onwards, Knossos remained an important center into Late Antiquity.

Hellenistic Knossos was a large, complex urban center that, at least to some extent, had a centralized, administered food production and distribution system in the form of the *syssitia* (Chaniotis, 1999). This did not continue into the Roman period; therefore, it is possible

FIGURE 1 Map showing location of sites mentioned in the text where dental studies have been conducted for the Hellenistic, Roman, and Late Antique periods. Base map: d-maps.com [Colour figure can be viewed at wileyonlinelibrary.com]

that food types, preparation techniques, and technologies could have been somewhat different. Classical Greek and Roman written sources suggest a division of labor, with women doing the majority of food preparation and frequently eating separately but many sources also mention a division in male and female dining at banquets (Dalby, 1996, p. 6; Wilkins & Hill, 2006, p. 76).

There were many changes in the Roman period that could have impacted what foods were available (in general and to different groups in society) and how foods were prepared. The agricultural land to the south of Knossos was given to incomers from Capua in Campania (España-Chamorro, 2021), and soon after this, a colony was established at the site. With these changes, it is possible that there was a change in types of foods being produced and being desired by the resident population. This could include foodstuffs such as fruit, honey, and sweetened wine, which could account for the increase in caries in the Roman period, though there is evidence for fruit consumption and honey production from earlier periods too, though production, particularly of wine, appears to have increased in the Roman period.

Large quantities of Cretan wine amphorae are found throughout the Roman Empire, and by the mid-second century CE, excavations of sites in Campania and Rome have produced evidence suggesting up to 20% of wine amphorae were coming from Crete (Carandini & Panella, 1977, p. 225; Casaramona et al., 2010, p. 113; Rizzo, 2003). The export trade would have required a significant increase in production of items such as wine and honey, which may have resulted in these items being more readily available locally as well as for export. The change in the economy of Crete at this transition meant that a great deal more food could have been accessed through trade (Chaniotis, 1999, p. 211).

There is evidence at Knossos—and elsewhere on Crete—for a change in cookware ceramics. The casseroles of local or regional fabrics in the Hellenistic period were replaced by cook pots of a different variety of shapes, including more imports, in the Roman period (Gallimore, 2015, pp. 180–185; Hayes, 1971, p. 274, 1983, p. 106; Sackett, 1992, pp. 168–170). However, it cannot be determined from shape alone whether the contents of such pots would have changed significantly. Evidence for Roman ceramic beehives is abundant on Crete, particularly in the west and center of the island, though it was unclear whether this was on a scale for mass export or if the honey and wax was produced on a subsistence level (Francis, 2016, p. 84). There is sparse evidence for Hellenistic beekeeping at Knossos, but such evidence tends to be late Hellenistic and is generally uncommon throughout Crete until the Roman period, though it is possible non-ceramic hives were used (Eiring, 2001, p. 129; Francis, 2016, p. 87; Homann-Wedeking, 1950, p. 185). A small number of examples from Gortyn, Eleutherna, and Sphakia demonstrate change in ceramic beehive shape in the Late Antique period and attest to continued honey production on Crete in this time period, though ceramic beehives are not known beyond the Early Byzantine period (Francis, 2016, p. 89).

Changes in prosperity, for at least an aspect of society, can be observed with more conspicuous consumption in grave goods in the 1st–2nd century CE and public building works and mosaics in public and private settings particularly in the 2nd and 3rd centuries CE. A shift of spending to the public sphere in the 4th–6th centuries is evident in the construction of basilica churches with mosaics (Sweetman, 2013).

The urban occupation in the Late Antique period was steadily contracting in extent, and the settlement would have had a significantly smaller population than in the Hellenistic and Roman periods. A centralized food production system and mass crop production (e.g., vines) for overseas trade may no longer have existed to the same extent. The amphora dumps at Knossos in the north (imports) and the south (local) appear to essentially be Early Roman (Trainor, 2019). The large-scale production and exportation of wine seems to have come to an end by c. CE 300 (Marangou, 1999, p. 278), though amphora production did continue at Knossos (as well as at Gortyn and Eleutherna) into the Late Antique period (Frend & Johnston, 1962, p. 229; Gallimore, 2015, p. 209; Hayes, 2001, p. 434). A return to a family or household level of food production and small-scale, local trade may have enabled a more diverse diet to be accessible and affordable.

3 | MATERIAL

The human skeletal remains from approximately 1000 years of habitation at Knossos were studied. A total of 1572 permanent teeth (14% of total possible teeth in adult individuals) were recorded. Of these teeth, 667 were maxillary teeth, while 905 were mandibular. These came from a variety of contexts, including individual graves and communal commingled tombs, and were scored by tooth either within complete or partial dentitions or as isolated loose teeth. The skeletal remains come from legacy rescue excavations of the British School at Athens at Knossos, which would not always have included retrieval methods such as sieving during excavation; therefore, small elements would sometimes have been missed.

4 | METHODS

Dental caries is a disease process, which progresses from slight enamel opacities to extensive cavities involving the partial or complete destruction of the crown and roots of teeth (Hillson, 2008), as the dental hard tissues are demineralized by organic acids produced by bacterial fermentation of carbohydrates in the diet (Larsen, 2015; Temple, 2015).

Caries was scored using the Hillson (2001) method of scoring each surface of the crown and root on an 8-point scale of caries progression. Scores 1–2 represent opacity and roughening of the tooth surface, scores 3–6 represent a small, medium, and large cavity, respectively, limited to a single surface of the tooth, while scores 7–8 are gross caries lesions affecting multiple surfaces of the tooth. Results are presented for caries (any: scores 1–8) but for the purposes of comparability as some studies do not score early-stage caries (i.e., scores 1–2), prior to the appearance of a cavity, results are also presented for caries (cavities: scores 3–8).

Caries was observed visually with the aid of a magnifying lamp. It can be easily scored on both loose teeth and in the jaws. This method enables the complete range of caries with different forms and etiologies to be recorded for the assessment of the progressive nature of the disease. It also records the presence of approximal attrition facets, which allows some insight into dental crowding—as a possible contributing factor to caries—even in loose teeth. This allows for better interpretation of the disease than less comprehensive scoring systems.

A caries score for an individual tooth was calculated by adding the Hillson (2001) scores for each surface of the tooth together to assess the severity of caries. These scores were then added together for all teeth within a category being investigated and divided by the number of carious teeth in that category.

Sex estimations were made using the standard methods of the skull and pelvis morphology (Buikstra & Ubelaker, 1994). However, in many cases, particularly with commingled and isolated teeth, it was not possible to estimate sex. The teeth that had no sex estimation were excluded from the comparison of caries between the sexes, though it was possible to include these teeth in the other comparisons (by time period, age group, and tomb type). This was the case for all loose teeth that were not associated with an individual, as no attempt was made to estimate sex for isolated teeth.

Age-at-death for both loose teeth and those in the jaws were estimated using dental wear, following Smith (1984), and cross-referencing Miles (1963), Lovejoy (1985), and Brothwell (1989). Using this combination of techniques allowed for age estimations for all loose teeth and not just molars or complete dentitions. Estimating age-at-death by dental wear is highly variable and population specific; therefore, steps were taken to check the reliability for this population.

As well as the combination of the four different dental wear techniques, the individual burials (where both dental wear and other skeletal ageing methods could be employed) were used as a control to judge whether the age categories from the Smith (1984) wear stages were appropriately assigned. In the case of individual non-commingled burials, it was also possible to employ standard methods of age estimation from the pubic symphysis (Brooks & Suchey, 1990) and auricular surface (Lovejoy et al., 1985). These methods were used to assign individuals to an age group, which, while acknowledging the difficulties of adult age-at-death determination (Moles, forthcoming-b), can be broadly equated to the following age ranges: infant 0–3 years, child >3–12 years, adolescent >12–20 years, young adult >20–30 years, middle adult >30–45 years, and old adult >45 years.

The statistical significance of differences between the different groups being assessed for caries was calculated using a Pearson's chi-square test (χ^2) and by applying 95% confidence interval error bars to the bar graphs (overlapping bars suggest the difference is not statistically significant).

5 | RESULTS

There was a total of 274 (17.4%) carious teeth and a total of 151 (9.6%) teeth with more severe caries, when a cavitous lesion has formed (i.e., caries score 3–8). The average cumulative caries score for carious teeth was 6. Approximal attrition facets were always limited to the enamel. Caries is more common in certain areas of the mouth, tooth types, zones of the teeth, and in older individuals. Therefore, before considering the main variables of the study, it is important to consider the tooth types, tooth zones, and age distribution of the assemblage.

5.1 | Tooth types

A comparison of the maxillary and mandibular teeth showed no significant difference between the upper and low jaws in caries prevalence, with 19.2% of maxillary teeth and 16.1% of mandibular teeth manifesting caries (Table 1 and Figure 2).

Caries was most common in the molars, followed by the premolars (Table 1), as was expected due to the fissure systems on their occlusal surfaces (Hillson, 2008, p. 117). Both had significantly higher caries levels than the canines and incisors (see non-overlapping confidence intervals for caries prevalence in Figure 3). Figure 4 demonstrates the expected (or ideal) proportions of each tooth type based

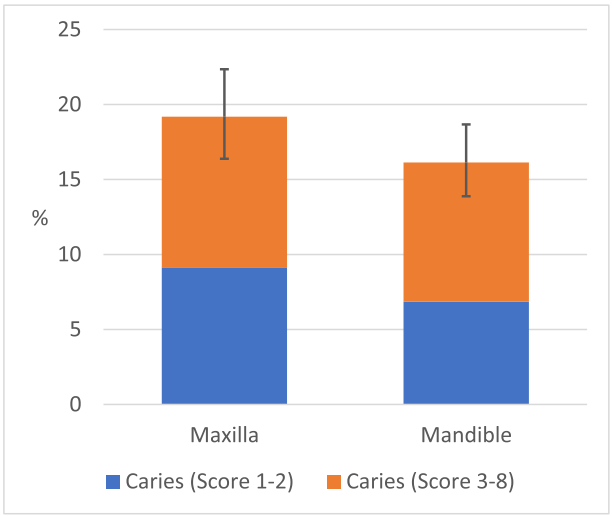

FIGURE 2 Caries prevalence for maxillary and mandibular teeth with 95% confidence interval error bars demonstrating no significant difference between the upper and lower teeth [Colour figure can be viewed at wileyonlinelibrary.com]

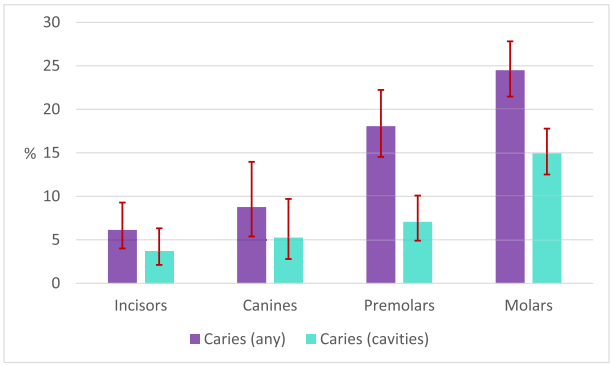

FIGURE 3 Prevalence of caries (any: score 1–8) and caries (cavities: score 3–8) by tooth for each tooth type with 95% confidence interval error bars [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Caries counts and scores by tooth for each tooth type

	Teeth with caries (any: score 1–8)	Teeth with caries (cavities: score 3–8)	Average caries score
Maxilla	19.2% (128/667)	10.0% (67/667)	6.5
Mandible	16.1% (146/905)	9.3% (84/905)	5.5
Incisors	6.1% (20/326)	3.7% (12/326)	4.3
Canines	8.8% (15/171)	5.3% (9/171)	6.1
Premolars	18.1% (69/382)	7.1% (27/382)	6.4
Molars	24.5% (172/702)	15.0% (105/702)	6.1

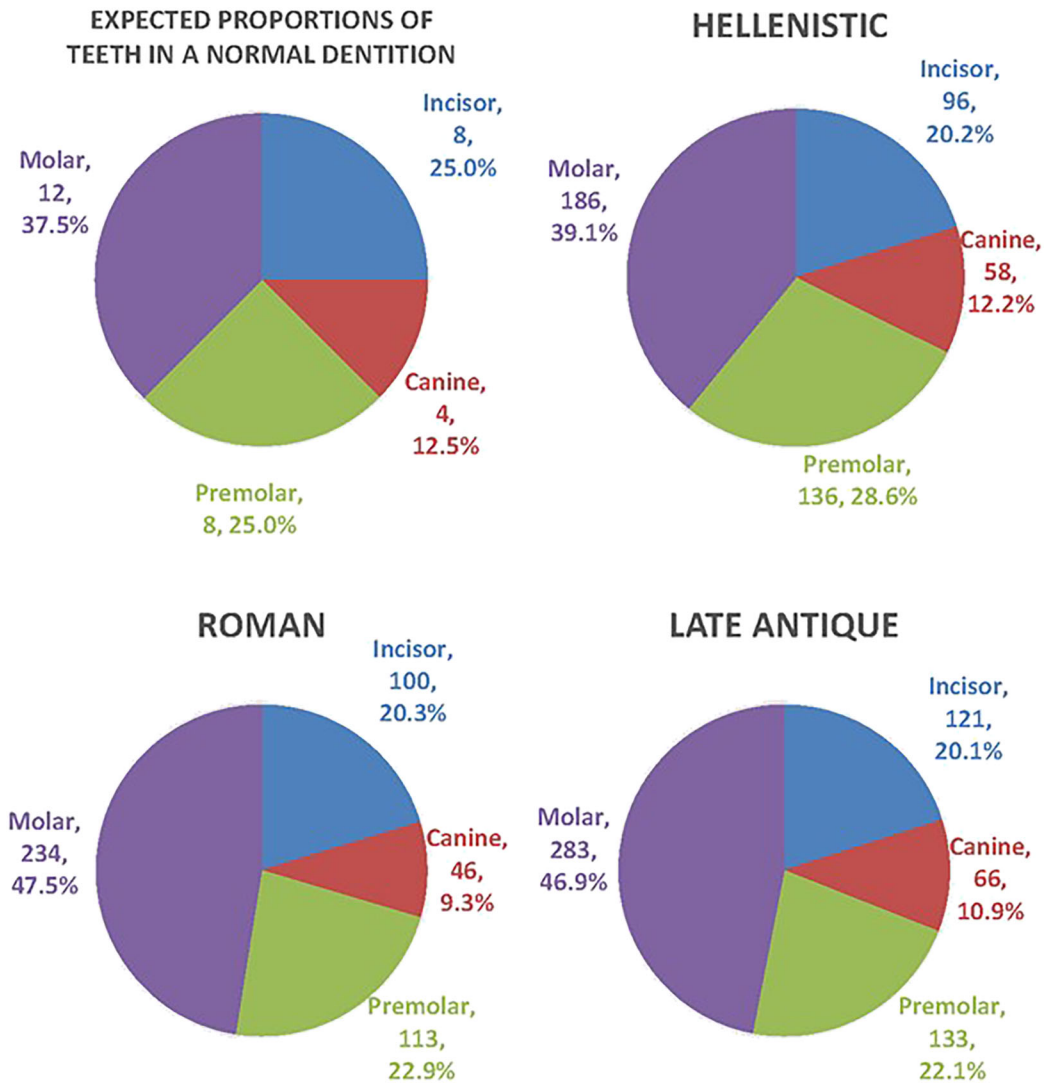

FIGURE 4 Pie charts demonstrating expected proportions of each tooth type in a normal dentition (assuming third molars are present) and the proportions of each tooth type present in the assemblage for each time period [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Proportions and numbers of each tooth type for each of the main variables within the main categories under study

	Incisor	Canine	Premolar	Molar
Expected values	**25.0% (8)**	**12.5% (4)**	**25.0% (8)**	**37.5% (12)**
Time periods				
Hellenistic	20.2% (96)	12.2% (58)	28.6% (136)	39.1% (186)
Roman	20.3% (100)	9.3% (46)	22.9% (113)	47.5% (234)
Late Antique	20.1% (121)	10.9% (66)	22.1% (133)	46.9% (283)
Sexes				
Female	21.4% (134)	12.0% (75)	26.2% (164)	40.4% (253)
Male	22.7% (100)	12.0% (53)	26.1% (115)	39.2% (173)
Age groups				
Child	27.9% (24)	8.1% (7)	9.3% (8)	54.7% (47)
Adolescent	21.5% (29)	11.9% (16)	26.7% (36)	40.0% (54)
Young adult	21.3% (211)	10.4% (103)	25.0% (248)	43.3% (429)
Middle adult	17.3% (56)	12.4% (40)	23.8% (77)	46.4% (150)
Old adult	9.8% (4)	9.8% (4)	31.7% (13)	48.8% (20)

on a complete, normal dentition, including the third molars, and the proportions of each tooth type for each of the time periods.

Table 2 displays the numbers and proportions of each tooth type for all of the main variables being studied to provide a control for the following results. The most commonly underrepresented tooth type is the incisor, followed by the canine. Molars are nearly always overrepresented due to more often being preserved within the jaws and potentially due to their being larger and therefore more visible even when loose for collection during excavation. However, if these under- and over-representations are similar for each of the variables being compared, then it will not bias the comparison. Considering the assemblage by time periods, for example, the molars and premolars are over-represented in each case, and the incisors and canines are under-represented (Figure 4). The Roman and Late Antique distributions are very similar, while the Hellenistic distribution is closer to the "expected" proportions but this is unlikely to be a significant enough difference to bias the results.

5.2 | Tooth zone

Caries was scored by the sites or zones of the tooth, with the results presented by tooth type and for all the teeth combined in Table 3. Figure 5 groups the tooth zones together into similar types to get a better overall picture of the zones of the teeth most affected by caries.

The most common sites for caries on the molars and premolars were the mesial and distal contact areas and the occlusal surfaces (fissures). Caries was less common in the incisors and canines but was most common in the attrition facets (where wear had exposed dentine on the occlusal surface) and on the buccal enamel and root surface/cemento-enamel junction (CEJ). The tendency of attrition facets and root surfaces to be the most common sites for caries has been found to be a familiar pattern amongst archaeological agriculturalist groups that were typified by high attrition rates alongside a high starch, low sugar diet (Hillson, 2008, p. 125). The high wear rates (and the resultant continued eruption) cause the more vulnerable surfaces at the CEJ and enamel-dentine junction (EDJ) to be exposed.

However, with caries being more common in the molars and premolars, the overall pattern has the highest caries rates in the occlusal surfaces and mesial/distal (interproximal) contact areas, and these were significantly higher rates than for the attrition facets or roots surfaces, as demonstrated by the non-overlapping 95% confidence intervals (Figure 5). This could be due to the low wear rates or young

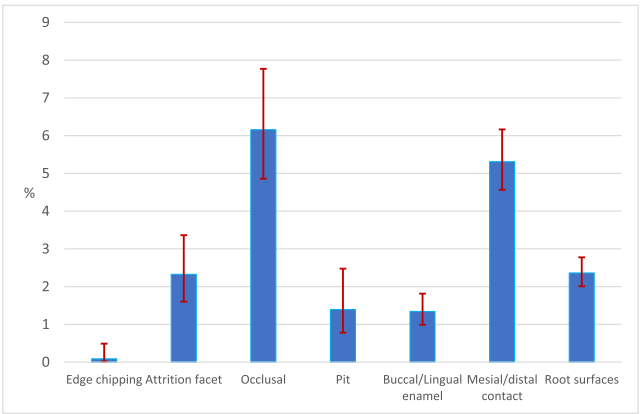

FIGURE 5 Caries prevalence for the tooth zones grouped into similar types for all teeth with 95% confidence interval error bars [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Numbers of caries, counts of zones scored, and percentage of caries for each tooth zone, presented for each tooth type and for all the teeth combined

	Edge chip.	Attrit. facet	Buccal enamel	Bucc. root	Distal contact	Dist. root	Lingual enamel	Ling. root	Mesial contact	Mes. root	Occlus. surface	Pit
Incisor caries	0	5	7	7	3	1	1	1	2	5	0	1
Zones scored	290	293	326	316	314	315	322	316	318	316	0	129
% caries	0.0	1.7	2.1	2.2	1.0	0.3	0.3	0.3	0.6	1.6		0.8
Canine caries	0	3	3	3	3	4	2	2	2	0	0	0
Zones scored	156	156	169	163	166	164	167	162	162	164	0	0
% caries	0.0	1.9	1.8	1.8	1.8	2.4	1.2	1.2	1.2	0.0		
Premolar caries	0	5	6	11	20	12	0	5	19	4	13	0
Zones scored	242	250	330	368	367	354	374	371	366	372	367	0
% caries	0.0	2.0	1.8	3.0	5.4	3.4	0.0	1.3	5.2	1.1	3.5	
Molar caries	1	14	15	21	45	23	7	13	67	31	52	10
Zones scored	467	462	687	675	668	667	683	670	672	662	689	661
% caries	0.2	3.0	2.2	3.1	6.7	3.4	1.0	1.9	10.0	4.7	7.5	1.5
Total caries	1	27	31	42	71	40	10	21	90	40	65	11
Zones scored	1155	1161	1512	1522	1515	1500	1546	1519	1518	1514	1056	790
% caries	0.1	2.3	2.1	2.8	4.7	2.7	0.6	1.4	5.9	2.6	6.2	1.4

ages-at-death (most ages were determined by dental wear) not exposing the CEJ or EDJ for as long or in as many teeth as in other agricultural communities with starch staples in their diets. Although the prevalence of caries is much lower, the pattern of higher caries on the occlusal and interproximal surfaces is more comparable to modern western caries patterns which have been attributed to the high sugar and starch diets and high frequency of snacking during childhood (Hillson, 2008, p. 120). This could be indicative of a higher sugar content in the diets at Knossos than was customary in agricultural populations, meaning that caries often occurred in a tooth prior to the exposure of dentine from wear, or the CEJ from continual eruption.

5.3 | Age group

Caries was expected to be highly age progressive, though factors such as antemortem tooth loss and wear can mask this to a degree in the results (Hillson, 1996, p. 284). Additionally, small sample sizes, particularly in the Old Adult category, may produce unrepresentative results. The results are displayed in Table 4. The overall trend for caries was that it increased with increasing age, other than the Adolescent result being slightly elevated above the Young Adult one, likely due to the relatively small sample size for Adolescents.

5.4 | Time period

The overall caries results and the breakdown by time period are displayed in Table 5. The results by time period are displayed in Figure 6 and demonstrate a peak in the prevalence of caries in the Roman period, occurring in 25.2% (124/493) of teeth compared with only 8.4% (40/476) in the Hellenistic period and 18.2% (110/603) in the Late Antique period. The difference between caries prevalence for the three time periods was statistically highly significant ($X^2 = 47.7$, $p = 0.00$), as can also be seen from the confidence intervals in Figure 6, which do not cross over for caries. Although there is less difference for caries (cavities: score 3–8) prevalence, the same pattern can be observed, with 6.3% (30/476) for the Hellenistic period, 12.8% (63/493) for the Roman period, and 9.6% (58/603) for the Late Antique period.

The average caries score reflects the average severity of lesions and demonstrates a different pattern across the time periods, with 6.9 for the Hellenistic period, 5.9 for the Roman period, and 5.7 for the Late Antique period. This indicates that the severity of carious lesions was greatest in the Hellenistic period; that is, there is the smallest difference between the occurrence of early-stage caries (any: score 1–2) versus more advanced caries (cavities: score 3–8). This means that there are relatively few occurrences of caries in the initial stages and a greater number of severe lesions (i.e., larger and penetrating deeper

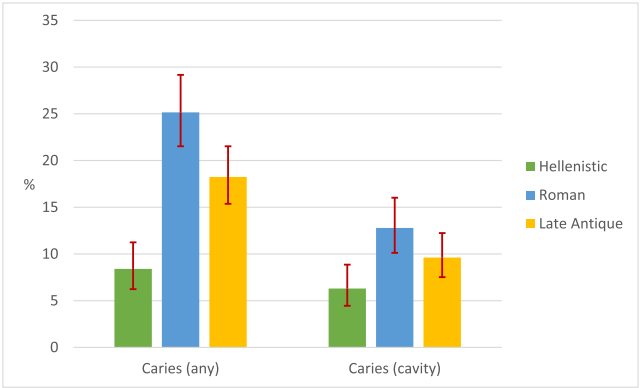

FIGURE 6 Prevalence of any caries (any: score 1–8) and caries (cavities: score 3–8) by tooth for each time period with 95% confidence interval error bars. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 4 Prevalence of caries, cavities and carious scores for the age groups

	Teeth with caries (any: score 1–8)	Teeth with caries (cavities: score 3–8)	Average caries score
Child	8.1% (7/86)	1.2% (1/86)	2.3
Adolescent	17.8% (24/135)	6.7% (9/135)	2.8
Young adult	16.8% (166/991)	8.9% (88/991)	5.5
Middle adult	20.7% (67/323)	15.2% (49/323)	9.0
Old adult	29.3% (12/41)	14.6% (6/41)	5.6

TABLE 5 Caries counts and scores by tooth for each time period

	Caries (any)		Caries (cavity)		Caries score (total)	Average caries score	Total teeth
Hellenistic	40	8.4%	30	6.3%	277	6.9	476
Roman	124	25.2%	63	12.8%	731	5.9	493
Late Antique	110	18.2%	58	9.6%	623	5.7	603
Total (all periods)	274		151		1631	6.0	1572

into the tooth, through the enamel and into the dentine and pulp chamber, or in the case of the root, through the cementum and into the root canal).

The results by age group for each time period (Table 6) affirm the overall caries results. These results also indicate that caries was lowest in the Hellenistic period and highest in the Roman period and shows that the overall time period results have not been skewed by the demographics of the groups. It also enables a comparison of a single age group across the time periods. The largest sample size was for the Young Adults, and it is clear from the caries results that this group follows the pattern of a peak in caries in the Roman period.

5.5 | Sex

As shown by Figure 7, males have higher frequencies of caries than females, with 18.1% (80/441) of male teeth having caries, compared with 12.5% (78/626) of female teeth. This was a statistically significant difference according to a chi-square test ($X^2 = 6.6$, $p = 0.01$), though there is a slight overlap of the 95% confidence intervals. This pattern prevails with the early-stage caries excluded, with 9.8% (43/441) of male teeth displaying cavities compared with 7.2% (45/626) of female teeth.

When observing the difference in caries prevalence between the sexes within each time period, there is a mixed picture (Table 7). If cavity-level caries (score 3–8) is observed, the pattern of males having a higher occurrence of cavities prevails, though only marginally so for the Late Antique teeth and the confidence intervals for males and females within each time period have substantial overlap, suggesting no significant difference (Figure 8). However, with large numbers of Roman Female and Late Antique Male teeth having early-stage caries (score 1–2), the results for the complete range of caries are very mixed with males having higher caries prevalence in the Hellenistic and Late Antique periods but the females having the greater caries prevalence in the Roman period and the highest overall occurrence of caries with 23.7%. The only significant difference between the sexes was for caries (any) in the Late Antique period.

The large numbers of Roman Female and Late Antique Male teeth with early-stage caries are conversely reflected in the highest average caries scores being for the Roman Male and Late Antique Female groups (Table 7). Though cavities are a more reliable measure

TABLE 6 Caries (any: score 1–8) and caries (cavities: score 3–8) counts and prevalences (%) and total tooth counts for each age group by time period

		Hellenistic	Roman	Late Antique
Child	Caries (any)	0	0	7
	%		0.0	9.6
	Caries (cavity)	0	0	1
	%		0.0	1.4
	Total teeth	0	15	73
Adolescent	Caries (any)	1	20	3
	%	3.3	28.6	8.8
	Caries (cavity)	1	7	1
	%	3.3	10.0	2.9
	Total teeth	30	70	34
Young adult	Caries (any)	20	69	80
	%	6.3	24.4	20.3
	Caries (cavity)	15	32	43
	%	4.7	11.3	10.9
	Total teeth	318	283	394
Middle adult	Caries (any)	21	33	13
	%	17.5	29.5	14.3
	Caries (cavity)	16	23	10
	%	13.3	20.5	11.0
	Total teeth	120	112	91
Old adult	Caries (any)	0	5	7
	%	0.0	35.7	70.0
	Caries (cavity)	0	3	3
	%	0.0	21.4	30.0
	Total teeth	17	14	10

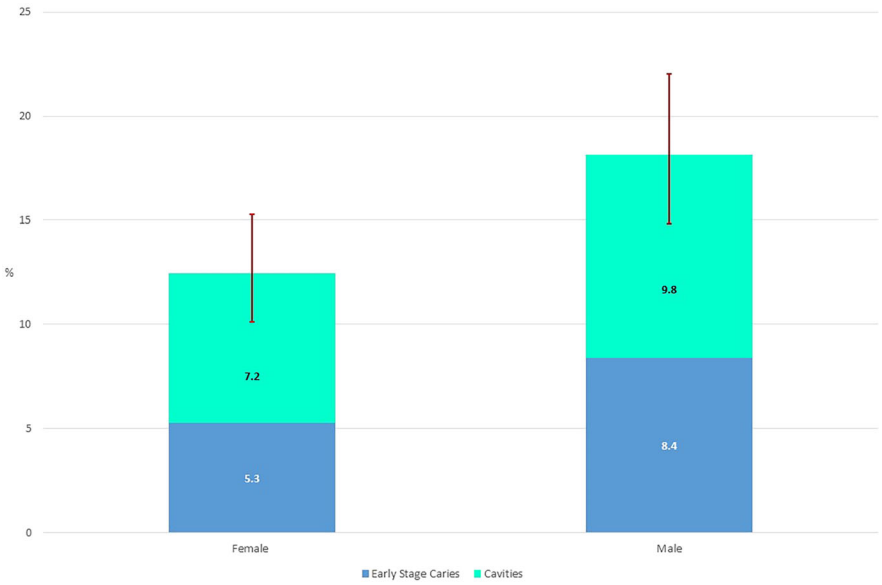

FIGURE 7 Prevalence of early-stage caries (score 1–2) and cavities (caries score 3–8) by tooth for the sexes, stacked to show total caries prevalence with 95% confidence interval error bars. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 7 Prevalence of caries (any: score 1–8) and caries (cavities: score 3–8) and carious scores for the sexes by time period and combined

	Teeth with caries (any: score 1–8)	Teeth with caries (cavities: score 3–8)	Average caries score
Hellenistic female	6.0% (16/268)	4.5% (12/268)	6.8
Hellenistic male	9.5% (10/105)	6.7% (7/105)	3.8
Roman female	23.7% (46/194)	10.3% (20/194)	3.8
Roman male	21.2% (25/118)	16.1% (19/118)	13.6
Late Antique female	9.9% (16/162)	8.0% (13/162)	13.3
Late Antique male	21.5% (45/209)	8.6% (18/209)	4.0
All time periods			
Female	12.5% (78/626)	7.2% (45/626)	6.4
Indeterminate	25.0% (7/28)	17.9% (5/28)	3.9
Male	18.1% (80/441)	9.8% (43/441)	6.9

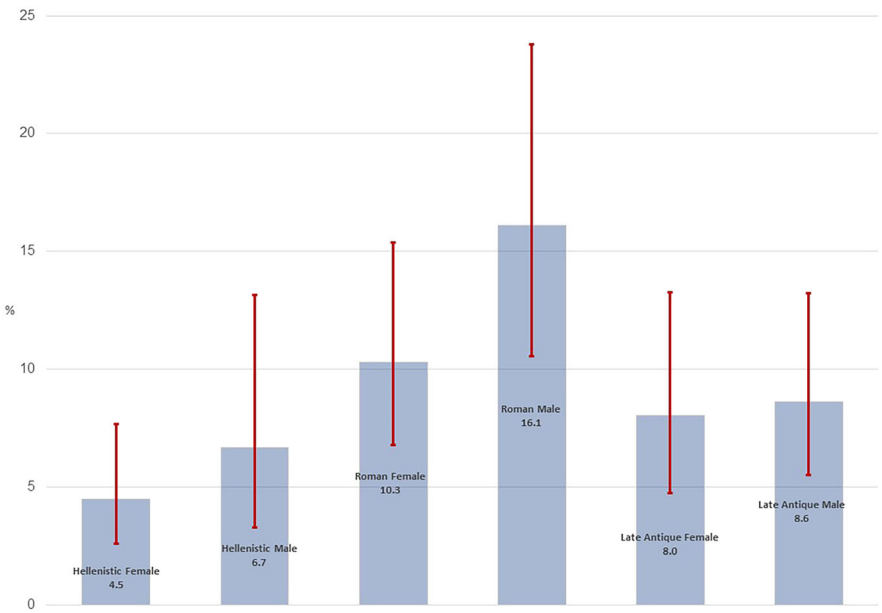

FIGURE 8 Prevalence of caries (cavities: score 3–8) for the sexes by time period, with 95% confidence interval error bars [Colour figure can be viewed at wileyonlinelibrary.com]

(compared with including the early-caries stages), as poor surface condition can lead to missing the early manifestations, there is no reason why the teeth from the same contexts (e.g., Roman male and female) should have different surface preservation. This does not adequately explain the dramatic difference in early-stage caries between females and males in either the Roman or Late Antique periods. Nor can age differences be held accountable for this difference as there was not a dramatic difference in the age profiles of males and females in these time periods.

6 | DISCUSSION

It can be observed in the dental data that there are changes in diet from Hellenistic to Roman times and again between the Roman and Late Antique periods. There is no close dating for some of the tombs in this study (Moles, forthcoming-b). This makes it difficult to discern exactly when the changes in diet occurred, whether in the Late Hellenistic period, around the time of the Roman conquest, or if they were associated with the establishment of a colony at the site, or its stabilization later in the 1st century AD.

The results for all time periods are higher than for any of the comparative studies conducted on contemporary skeletal assemblages on Crete. Looking at comparative studies from Greece more broadly there are some comparably high results, though the Roman Knossos result was higher than any of these comparative studies (Figure 9). Even using the more severe caries (cavities: score 3–8) as a comparative measure, the Knossos results were still higher than for the other Cretan studies. This indicates a more cariogenic diet in the population at Knossos in comparison to a range of different sites, from another Roman colony at Corinth (5.0%) to a rural farming community at Pigi Athinas (21.9%). This demonstrates that there does not appear to be any strong connection between the site type or status and caries prevalence or diet.

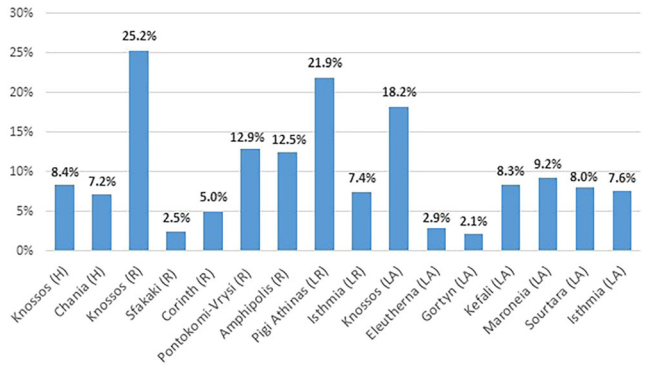

FIGURE 9 Prevalence of caries per tooth for contemporary sites in Greece. Hellenistic Chania (Bourbou, 2005), Roman Sfakaki (Bourbou, 2005), Roman Corinth (Fox, 2005; Fox Leonard, 1997), Roman Pontokomi-Vrysi (Vergidou et al., 2021), Roman Amphipolis (Malama & Triantaphyllou, 2003), Late Roman Pigi Athinas (Tritsaroli, 2014), Late Roman and Late Antique Isthmia (Rife, 2012), Late Antique Eleutherna, Gortyn, and Kefali (Bourbou, 2010; Mallegni, 1988; Zygouri, 2005), Late Antique Maroneia (Tritsaroli & Karadima, 2017), and Late Antique Sourtara (Bourbou, 2009) [Colour figure can be viewed at wileyonlinelibrary.com]

6.1 | Hellenistic

The Hellenistic period had remarkably low levels of caries compared with the later time periods. However, it should be noted that the surface condition of the Hellenistic teeth was often observed to be more degraded on account of the grave type. It is possible that this result is affected by a difficulty in observing the early manifestations of caries in some teeth. However, if the destruction of enamel was deemed to have reached an unscorable extent, these teeth were not recorded. Additionally, this preservation phenomenon was not exclusive to Hellenistic graves and was noted from several other graves. Nevertheless, there is a suspicious lack of early-stage caries for Hellenistic teeth which may in part be due to preservation issues (e.g., Figure 10).

The difference in caries prevalence may also be due to groups of differing social status being represented in the Hellenistic and Roman graves. The Hellenistic assemblage was heavily dominated by females and the tomb forms were simpler than in the later periods, representing a potentially lower social class. However, very few more elaborate tomb types are known from Hellenistic Crete, indicating a lack of social differentiation being expressed in the burial sphere (Moles, forthcoming-a). Females (overall and for the Hellenistic period specifically) had lower caries rates than males.

6.2 | Roman

Dental health was at its worst in the Roman period with the prevalence of both caries and antemortem tooth loss (Moles, forthcoming-b) at their highest. This suggests that the Roman diet was more cariogenic than in the Hellenistic or Late Antique

FIGURE 10 Poor enamel surface preservation of Hellenistic teeth. Unit 12, Individual 1. KMF/78 Tomb 39 [Colour figure can be viewed at wileyonlinelibrary.com]

periods and indicates a high carbohydrate diet of starchy foods such as wheat. Wheat is likely to have been a staple food source across all these time periods. The difference in the Roman period may have been a greater addition of sugars to the diet, in the form of fruit or honey, which is supported by the caries-zone analysis of the teeth. Increased caries could also be due to improved preparation techniques and technologies producing a more refined and sticky carbohydrate diet. The distribution of caries by zones of the teeth suggests a higher level of sugar in the diet than in many archaeological agricultural societies, as caries often occurred in teeth prior to the exposure of dentine from wear or of the root from continual eruption.

Such changes could be due to either increased connectivity making certain foods more readily available or the cultural changes in food consumption or dental hygiene due to the influx of merchants, colonists, migrants and other newcomers to Roman Knossos. Combining this information with further studies of contemporary ceramics, other food preparation apparatus, and residue and archaeobotanical evidence could help to create a clearer picture of dietary change and in particular the apparent increase in the consumption of sugars in the Roman period.

6.3 | Late Antique

The Late Antique period sees a fall in caries rates compared with the Roman period though the prevalence is still higher than it was in the Hellenistic period. Stable isotope analysis indicated a higher marine animal protein component in Late Antique diets (Moles et al., 2022), which could partially explain this change in dental disease from the Roman period. Cariogenic cereals are likely to have remained the staple food in this time period but the higher caries rates in the Late Antique period compared with either the Hellenistic period or comparative Late Antique Cretan assemblages (Bourbou, 2010, p. 47) may be explained by higher levels of sugars in the diet. If the Roman colonists, other sorts of migrants, or merchants introduced higher levels of fruit or honey into the diets, these foods may have remained part of the diet into the Late Antique period. It may also be the case that the groups represented in the Knossos graves were of slightly higher status than those represented elsewhere in Crete.

Stable isotope results indicated a slight increase in marine animal sources of protein in the later Roman and Late Antique periods (Moles et al., 2022) and the associated dental data, with decreased caries, decreased antemortem tooth loss and increased calculus (Moles, forthcoming-b), may support this suggestion. A decrease in population in Late Antiquity may have resulted in a reduction in pressure on food resources, with a greater number of people living above basic subsistence levels. However, the movement of some Knossian residents to nearby Heraklion may have meant the pressure on resources in the wider region did not change. Dietary change could also be due to increased prosperity, which would have suffered considerable set-backs for some time following the Roman conquest. Meat production in the Roman world was associated with prosperity as it requires more land than arable farming and involves the wasteful conversion of plant calories into animals (Jongman, 2007). Therefore, whether due to decreased pressure on resources or increased prosperity, an increased diversity of food types in the diet is apparent.

6.4 | Age and sex

Dental conditions generally followed the expected trend of being age progressive with the exception of the Old Adult category which was generally explicable by the effects of high wear, tooth loss, and the sample size being small and potentially unrepresentative.

There was a significant difference detected between females and males for caries, with males having a higher prevalence of caries. The same pattern has been observed for calculus and antemortem tooth loss (Moles, forthcoming-b). No significant difference was detected for male and female diets from the stable isotope analysis (Moles et al., 2022), but this demonstrates the value of using multiple methods for the determination of aspects of ancient diets.

The pattern of males having worse dental health generally prevails within each time period. The dental results indicate some differences in diet between males and females. The severity levels of carious lesions in particular suggest that the nature of this difference varied within each time period. These differences could have taken the form of differential access to foodstuffs (such as the more cariogenic sugary foods), or in food preparation (more or less refined foods). The differences may also reflect different eating habits, in terms of frequency of meals, as more frequent consumption of carbohydrates is linked to higher caries rates (Arcella et al., 2002; Punitha et al., 2015). The *syssitia*, which would have entailed males and females eating separately during the Hellenistic period, did not endure into the Roman period.

Males had a higher prevalence of caries demonstrating poorer dental hygiene and access to more cariogenic foods and potentially different dietary habits, in terms of eating more frequently than females. The different diets of females and males, indicated by the dental disease results, suggest that meals adhered to social rules even after the dissolution of the Archaic to Hellenistic *syssitia*.

7 | LIMITATIONS OF THE STUDY

Without a larger and more intact dental assemblage it is hard to be certain that the patterns and trends observed are fully representative. Ideally, complete dentitions with a typical ratio of lip and cheek teeth would be used rather than partial dentitions and loose teeth where the incisors and canines are underrepresented. Scoring each side of the tooth and considering the severity of lesions can help circumvent under- or over-representation problems to a certain extent, but when it comes to comparing different assemblages, there is little that can be done to overcome the shortcomings of poor excavation and preservation, such as a lack of representation for anterior teeth.

Although analyzing exclusively complete dentitions would make the results more easily comparable across different studies and

populations, it is rarely the case that this exists for any archaeological assemblage and it would dramatically decrease sample sizes. The caries results had quite large sample sizes of scorable teeth for the variables under investigation, allowing the comparisons by time period, age, sex and social status to be considered valid within the Knossos assemblage.

Due to the large number of commingled and isolated loose teeth, age-at-death estimations were often limited to the use of dental wear, which can be affected by a range of factors and can be highly varied within a single individual. Sex estimation was not possible for the isolated loose teeth, limiting the sample size for the comparison of the sexes.

The lack of clarity in studies regarding exact methods of scoring caries can cause problems for comparability. Some studies score dental diseases by individual which is problematic, particularly for caries, as it does not distinguish between an individual with a single mild lesion and one with many severe lesions. Scoring by tooth gives a more representative picture of caries prevalence across an assemblage (Steckel et al., 2002, p. 70). However, statistical evaluation of caries rates for epidemiological purposes is problematic in fragmented archaeological material. The DMF index records the number of decayed, missing or filled teeth for each individual to express the mean per individual across the assemblage. This does not account for having more than one lesion per tooth or for teeth lost by periodontal disease or post-mortem (Hillson, 1996, pp. 279–280; Temple, 2015, p. 443). Scoring by tooth with highly fragmented material (often with poor retrieval of elements) can result in over-representing better preserved individuals while other individuals may be represented by a single tooth. Molars are more prone to caries than anterior teeth, and molars are less likely to be lost post-mortem, so assemblages with poor anterior tooth preservation will have artificially inflated caries rates (Hillson, 1996, p. 280).

8 | CONCLUSIONS

Integrating the archaeological evidence (whether biological, environmental, or material) with the textual and iconographical records enables us to push interpretations beyond what any individual line of evidence can say about daily life and enables those interpretations to be more representative of the entire population rather than an elite group. This study has contextualized the dental data using the available historical and archaeological sources to demonstrate aspects of lifestyle (in this case diet), in relation to the better documented large-scale political and social changes at Knossos and on Crete.

Changes in caries prevalence over time demonstrate how the social changes that occurred during these time periods were substantial enough to have a significant impact on the lives, physical wellbeing, and health of the inhabitants of Knossos. Greater connectivity, new peoples and potentially increased prosperity in the Roman period resulted in changes in diet and poorer dental health. The cariogenic foods that were widely consumed in the Roman period at Knossos, did not disappear in Late Antiquity, when the caries results for Knossos remain higher than for most comparative studies in Greece. Although greater resolution on the details of these impacts is not possible from the stable isotopic and dental data, this evidence can supplement other studies of daily life from the material culture.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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