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Diversity in pig husbandry from the Classical-Hellenistic to the Byzantine periods: an integrated dental analysis of Düzen Tepe and Sagalassos assemblages (Turkey)

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Highlights

An integrated dental analysis was performed to document pig husbandry

It shows an evolution in pig husbandry from Classical-Hellenistic to Byzantine times

A great diversity in Early Byzantine pig management at Sagalassos is highlighted

Pig management scale ranged from close confinement to extensive rearing

Sequential $\delta^{18}\text{O}$ analysis in teeth reveals the existence of two birth seasons

Abstract

Ethnographical, historical and archaeological evidence suggests that a great diversity in pig husbandry may have existed in the past. However, such diversity remains difficult to document from traditional zooarchaeological methods and its study may necessitate the implementation of combined methodological approaches. An integrated dental analysis, combining kill-off patterns, traditional and geometric morphometrics, linear enamel hypoplasia (LEH), microwear and stable isotope ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$) data, has been performed on assemblages from the neighbouring sites of Düzen Tepe and Sagalassos (SW Turkey) dated to Classical-Hellenistic to Byzantine time periods. Results indicate a diachronic evolution in slaughter practices, and a gradual decrease in pig mean size from the Early-Middle Imperial to the Byzantine. The seasonality of physiological stressing events remains the same, although their intensity varies through time. During the Early Byzantine period (AD 450-700), pig demographic management is characterized by two birth seasons, and a great diversity in diet and scale of management occurred, from free-ranging pigs – whether or not given food supplement – to closely confined well-watered and more omnivorous pigs.

Keywords

Pig husbandry; kill-off patterns; hypoplasia; $\delta^{18}\text{O}$; $\delta^{13}\text{C}$; $\delta^{15}\text{N}$; geometric morphometrics

1. Introduction

Since the beginning of its domestication and up to the Seljuk conquest, pig has played an important role in Anatolian human subsistence systems as an efficient provider of meat and fat. Recent ethnographic studies have highlighted the existence of a great diversity in pig husbandry practices, ranging from free-living populations to intensive farming (Albarella et al. 2007, 2011; Hadjikoumis 2012; Halstead and Isaakidou 2011). This diversity reflects the adaptation by modern herders of domestic pig breeds' physiological characteristics to local socio-economic and environmental contexts. Some of these characteristics, notably the ability to give birth twice a year or to digest a wide variety of food resources, are also observed in the wild ancestor, the wild boar (e.g. Etienne 2003). It is therefore very likely that an important diversity in pig husbandry already existed in the past, as suggested by the distinct domestic morphotypes mentioned in ancient texts (Columella De Re Rustica 7.9.2, Foster and Heffner 1968). These different practices do not imply the same labour input (Redding 2015), the same scale of herding (Balasse et al. 2015) or degree of specialisation (Sapir-Hen et al. 2014), and the study of pig husbandry practices can therefore document the socio-economic organisation of past societies.

Relatively newly developed methods, and their combined use (Balasse et al. 2016; Mainland et al. 2015), allow a better understanding of the past diversity of pig husbandry. Such new methods include dental microwear (Clavel and Sicard 2007; Ward and Mainland 1999; Wilkie et al. 2007), linear enamel hypoplasia (LEH) analysis (Clavel and Sicard 2007; Dobney and Ervynck 2000; Wang et al. 2012; Teegen 2013), stable isotope analysis (e.g. Ervynck et al. 2007; Guiry et al. 2012; Hamilton et al. 2009; Hammond and O'Connor 2013; Minagawa et al. 2005; Zavodny et al. 2014), geometric morphometrics (GMM; Cucchi et al. 2011; Duval et al. 2015; Evin 2015) and the analysis of dental calculus (Weber and Price 2015). So far, a limited number of sites have been subject to a combination of several of these approaches (e.g. Levroux Les Arènes – Duval et al. 2015; Frémondeau 2012; medieval sites in Flanders (Belgium) – Ervynck et al. 2007; or Romanian Gumelnița sites – Balasse et al. 2016).

From the early 1990s onwards, excavations at the ancient town of Sagalassos and the nearby settlement of Düzen Tepe (ancient Pisidia, SW Turkey, Fig.1) have unearthed a faunal assemblage exceptional in its size (more than a million studied remains) and by its broad chronological coverage (from Classical-Hellenistic to Middle Byzantine periods), allowing documentation of pig husbandry practices at a local scale over more than a millennium. Over this broad timeframe, Pisidia has been integrated into several consecutive broader political entities: the Persian Empire (until 333 BC), Hellenic kingdoms (333 – 25 BC), and Roman and Byzantine Empires (from 25 BC onwards) (Waelkens 1993).

The Classical Hellenistic site of Düzen Tepe (5th - 2nd c. BC) was a large fortified settlement located just 1.8 km southwest from Sagalassos (Vanhaverbeke and Waelkens 2009; Vanhaverbeke et al. 2010). Excavations and geophysical survey brought to light both single and multi-roomed buildings distributed between a fortified acropolis and lower agora. The overall picture of Düzen Tepe's economy is one of a rural community herding mainly sheep and goat, and producing its pottery and metal (Vanhaverbeke et al. 2010; Poblome et al. 2013; Vyncke et al. 2014; De Cupere et al., in press). Sporadic evidence testifies to the site integration into wider trade networks. The exact relationship of Düzen Tepe with the ancient town of Sagalassos is still under investigation, but whereas the former settlement dwindled from the 2nd c. BC onwards, the latter continued to develop.

Sagalassos underwent a rapid Hellenisation, and had already acquired the status of *polis* by the beginning of the 3rd c. BC (Poblome et al. 2013; Waelkens 2011). The town was a major population

centre from 25 BC to the beginning of the 6th c. AD, and played the administrative and religious role of provincial capital during the 2nd and 3rd c. AD (Waelkens 2011). The place was also a mass production centre of terra sigillata pottery (Sagalassos red-slip-ware), exporting artefacts in Anatolia and beyond up to the 7th c. AD (Poblome 2011). The integration of Sagalassos into long-distance trade networks is further attested by among others the import of preserved fish from Egypt in Roman and Early Byzantine times (Arndt et al. 2003). After a major earthquake around AD 500, the structure of the town gradually changed with the developing encroachment of public spaces, and a subsequent ruralisation. In the mid-7th c. AD, a devastating earthquake led to the almost complete abandonment of the town, although archaeological evidence testifies to a residual occupation during the 10th - 13th c. AD (Baeten et al. 2012; Kaptijn et al. 2013; Vanhaverbeke and Waelkens 2003; Vanhaverbeke et al. 2004, 2009; Waelkens 2006).

The territory of Sagalassos is spread over ca. 1200 km² and is composed of fertile inter-mountain valleys between 350 and 1100 m a.s.l. and of several peaks, the highest of which - the Akdağ, 2275 m a.s.l. - towers over Sagalassos itself (De Cupere et al. 2015, Degryse et al. 2008; Kint et al. 2014; Vanhaverbeke and Waelkens 2003). The local area is characterized by an Oro-Mediterranean climate: precipitation falls mostly during winter in the form of snow, while the dry season lasts from July to September; the coldest and warmest months are January and July, respectively (Kint et al. 2014; Paulissen et al. 1993; Sensoy 2004; IAEA/WMO). The natural vegetation is characteristic of the Oro-Mediterranean zone (Paulissen et al. 1993), and was estimated to be evergreen needle-leaved forest above 1000/1200m a.s.l., and mixed evergreen forest, including deciduous oak trees, at lower altitudes. The most humid valley bottoms were occupied by marshes and wetlands (Bakker et al. 2012, 2013; Paulissen et al. 1993).

The period spanning from the Classical-Hellenistic to the Early Byzantine is marked by the so-called Beyşehir Occupation Phase and its subsequent gradual decline around AD 300/650. This phase was characterized in pollen records by an increase in anthropogenic impact and cereal cultivation, increased values of local wetland indicators in the valley bottoms and the expansion or recovery of deciduous and evergreen oak woodlands. The subsequent decrease of these indicators has been correlated with a gradual shift in animal husbandry practices towards pastoralism, coinciding with an evolution towards a relatively drier and more open environment (Bakker et al. 2012). The settlement pattern also evolved through time, with mainly fortified sites on top of mountains during the Classical period (500-333 BC). This changed during Hellenistic times, with the creation of new sites on the edge of valleys and the development of an intensive farming of the valley plains, which reached a climax during the Roman period (De Cupere et al. 2015).

At both Düzen Tepe and Sagalassos, domestic mammals, represented by goat, sheep, cattle and pig, largely dominate the faunal assemblage (De Cupere 2001; De Cupere et al. 2015). Wild mammals are poorly represented, and wild boar remains are even almost completely absent in all contexts. The share of domestic pig fluctuates between 8.5 and 26.2 %, with a minimum in the Classical-Hellenistic and a maximum in the Late Roman periods (relative number of identified specimens - NISP- compared to cattle and sheep/goat, De Cupere et al. 2015, Fig.2). The importance of pig in the local palaeoeconomy has led to several analytical studies to unravel pig management strategies (De Cupere 2001; Fuller et al. 2012; Ottoni et al. 2013; Vanpoucke et al. 2007a; Vanpoucke 2008; Vanpoucke et al. 2009).

An interpretation of the Sagalassos pig mortality profiles based on eruption and wear of mandibular teeth, indicated the existence of a seasonal slaughter, and suggested the occurrence of two farrowings a year, an assertion that was not supported by the analysis of the linear enamel

hypoplasia (LEH) (De Cupere 2001; Vanpoucke et al. 2007a). This apparent contradiction led the authors to the conclusion that pig demographic management at Sagalassos was based on a main spring farrowing season and a regular slaughter to ensure a regular pork supply to the town (Vanpoucke et al. 2007a). The LEH record also revealed that pigs were raised in free-range (presumably in the forest), benefiting from quite good living conditions, while microwear analysis found evidence that pigs consumed at Sagalassos were fattened on a soft diet prior to slaughter (Vanpoucke et al. 2009). In accordance with these last results, bone collagen stable isotope analysis revealed that, while pigs had an herbivorous diet during Classical-Hellenistic times, during later periods they had a significantly higher intake of animal protein (Fuller et al. 2012). These data, which provide apparently conflicting evidence, suggest the implementation of complex pig husbandry strategies.

The stable isotope analysis of bone collagen conducted by Fuller et al. (2012) has provided $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values that represent isotopic ratios averaged over a pig's life (Hedges et al. 2007). To address pig husbandry practices with a more precise temporal resolution, two additional samplings were performed on pig incisors dated to the Early Byzantine period: a sequential stable isotope analysis ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$) of enamel to document the seasonality of husbandry practices; and a bulk stable isotope analysis ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) of root dentine to assess pig trophic position over a shorter time span (a few months, see section 2.4.1.). Thus, the aim of this paper is threefold: 1) to document, at the seasonal scale, the diversity of pig demographic and diet management strategies during the Early Byzantine, 2) to produce a synthesis of pig husbandry at Düzen Tepe and Sagalassos from Classical-Hellenistic to Byzantine time periods, by integrating of kill-off patterns, traditional and geometric morphometrics, hypoplasia (LEH), microwear and stable isotope ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$) data, all obtained from dental remains and 3) to propose tentative interpretations in the light of the broader socioeconomic and political changes occurring in the study area over the timeframe considered.

2. Material and Methods

At Sagalassos, excavations were largely carried out in the centre of the city and to a smaller extent in the eastern *suburbium*. Faunal remains were recovered from dumps, destruction layers and layers related to the building and alterations of the (monumental) edifices and other infrastructures. Altogether, the main part of the faunal remains represent consumption refuse from the city's inhabitants, dates being principally supplied by the ceramic evidence. Similarly, excavations at Düzen Tepe yielded predominantly consumption refuse from layers, dated using both the ceramic assemblages and AMS dating.

Over the years, pig assemblages of Düzen Tepe and Sagalassos have been the subject of several studies based on different methods, chronological periods or available material, and addressing different aspects of pig husbandry. Table 1 provides a summary of available data. Due to the small size of its datasets, the Middle Byzantine period is not discussed in this paper.

2.1. Age at death estimates and mortality profiles

Age at death assessment and mortality profiles are based on the recording of eruption and wear stages on mandibular premolars (Pd4 and P4) and molars (M1 to M3) using Grant's Tooth Wear Stages (TWS) (1982). Following Horard-Herbin's methodology (1997: 140; see also Frémondeau et al. 2015: 217), specimens ($n = 1119$) were further attributed to one of 17 development stages (from A to Q), each corresponding to a precise estimated age in months. When more than one age class was possible for one specimen, it was evenly distributed between the various classes. Specimens

attributed to five or more likely age classes (n = 27) were excluded. Age at death frequency distributions are represented using histograms.

Changes in slaughter practices were tested with Chi-square tests. To ensure a sufficient number of observations, the data have been clustered into five age-class groups, associated with pork production categories inferred from historical and ethnographic records (Albarella 2004; Dutertre et al. 2007; Maestrini pers. com. 2012; Molénat and Casabianca 1979): 0-2 months (perinatal mortality); 2-6 months (interpreted as suckling/weaning pigs); 6-14 months (fresh pork); 14-20 months (high yield fresh pork / processed pork?); 20-30 months (processed pork / high yield fresh pork?); >30 months (culled of the breeding stock).

Apart from pork production categories, pig management strategies themselves may influence slaughter practices by inducing different weight gains: the household stall-fed pig, whose diet is integrally and abundantly provided by its owner and whose movement are often restricted, is generally slaughtered at the age of one year at the latest. In contrast, the pig reared in extensive conditions, eating only available environmental resources, shows an overall slower, season-dependant weight gain, resulting in a later slaughter (Halstead and Isaakidou, 2011; Molénat and Casabianca 1979). Diet complementation can accelerate pig's weight gain, accordingly bringing forward slaughter (Molénat and Casabianca 1979). The herder's ability to provide his livestock with fodder may depend on herd size, the opportunity to acquire fodder, and labour/time availability. Whether a specific slaughter strategy is market-driven or depending on herding conditions, is, however, a difficult question to infer from kill-off patterns only and necessitates the comparison with other zooarchaeological and archaeological pieces of evidence.

2.2. Geometric Morphometrics (GMM)

Differences in tooth morphology were assessed using a GMM analysis performed on 41 mandibular third molars (M3) originating from three time periods (Early-Middle Imperial (n=9), Late Roman (n=13) and Early Byzantine (n=19)). The 2D landmark and sliding semi-landmark based approach was performed following the protocol detailed in Evin et al. (2013). Differences in molar shape were tested using multivariate analyses of variance (MANOVA) based on a reduced number of variables (following Evin et al. 2013). Differences in size (corresponding to the log transformed centroid size) between periods were tested with Kruskal-Wallis and Wilcoxon tests and visualised using boxplots.

2.3. The analysis of Linear Enamel Hypoplasia

LEH is a deficiency in the formation of the enamel matrix resulting from physiological – especially nutritional and infectious – stress (Dobney and Ervynck 1998). The comparison of LEH frequencies between domestic pig populations has revealed that low stress occurrences could be evidence for herding in forested areas with sufficient food resources (Dobney et al. 2007; Ervynck et al. 2007; Vanpoucke et al. 2007b). The distribution of LEH over the crown height of the mandibular fourth premolar (Pd4) and three molars (M1, M2, M3) has been associated with seasonal stressing events (such as weaning, first and second winter stress), the occurrence of which has been used to detect birth seasonality and the possible presence of double farrowing per year (Clavel and Sicard 2007; Dobney and Ervynck 2000).

LEH analysis was already performed on Sagalassos assemblages (Vanpoucke 2008; Vanpoucke et al. 2007a), using the methodology developed in Dobney and Ervynck (1998), Ervynck and Dobney (1999) and Dobney et al. (2002). The material comprised both mandibles and isolated mandibular

teeth (Pd4, M1-M3), totalling 1341 specimens dated from the Early-Middle Imperial to the Early Byzantine time periods; at the time of research no Classical-Hellenistic or Middle Byzantine material was available. Since then, the chronological attribution of some archaeological features has been changed. This necessity of re-analysing the Sagalassos LEH record offered the opportunity to apply a new approach for interpreting LEH frequency over crown height (Frémondeau, 2012), based on a detailed chronology of wild boar tooth development (Carter and Magnell 2007), and which consists in displaying LEH relative frequencies against months of pig life (from 1 to 3 months for M1, 3 to 9 months for M2 and 9 to 18 months for M3). Further explanation on the calculation of the classes in months is available in sup. data 1.

2.4. Isotopic analysis of pig teeth

The stable isotope analysis targets the chronological period that provided the richest faunal assemblage, namely the Early Byzantine period. Twelve unworn or slightly worn mandibular first incisors (I1) belonging to different animals were selected (sup. data 2A). On each one of them, two different samplings were performed: 1) sequential $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analysis of enamel carbonates, to address the seasonality of birth and diet; 2) bulk $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ analysis of dentine collagen in the root, to check for the trophic position of the specimens. The protocols for these analyses are described in sup. data 2B.

2.4.1. Integration of the isotopic signal in first incisor (I1) dental tissues

The isotope signals measured in pig I1 crown enamel and root dentine do not represent the same lifespan. In enamel, this signal spans approximately the last three quarters of the first year of life (3-12 m; Frémondeau et al. 2012). The pig I1 root forms from 12 to 20 months (Tonge and McCance 1973; sup. data 2C). The sampled I1, however, displayed a largely open root (sup. data 2C), indicating that the specimens were killed before the completion of root formation. They were also characterized by an almost unworn (no dentine was visible) but fully mineralized crown - which means that the teeth had begun to erupt but had not yet reached occlusion by the time the pigs were killed. In wild boar, I1 breaks through the gum at approximately 14 months and reaches occlusion at 18 months (Heck and Raschke 1980; Matschke 1967; Varin 1977). The Early Byzantine specimens were therefore probably killed at an age between 14 and 18 months, and the isotopic signal measured in the root represents most likely a lifespan comprised between 12 and 18 months.

2.4.2. Stable isotope analysis principles

In mammals, the carbonate oxygen isotope composition of tooth enamel bioapatite indirectly reflects that of ingested water, which in turn may track seasonal variations of precipitation $\delta^{18}\text{O}$ signal at mid and high latitudes (Flanagan and Ehleringer 1991; Iacumin et al. 1996; Land et al. 1980; Longinelli 1984; Luz et al. 1984). As the timing of tooth development is fixed within a species, it is possible to estimate birth seasonality from the assessment of the inter-individual variability in the position of $\delta^{18}\text{O}$ optima measured in a same tooth (Balasse 2003; Balasse et al. 2012a; Blaise and Balasse 2011; Bryant et al. 1996; Buchan et al. 2015; Tornero et al. 2013). This assessment, however, may be hampered by tooth size inter-individual variability. To overcome this problem, two methods were used: 1) the normalization of the sample positions from the Enamel-Root Junction (ERJ) to an averaged maximum crown height calculated from all sampled specimens; 2) the normalization of the $\delta^{18}\text{O}$ max position (x_0) to the period (X, the height of crown over which an annual cycle is recorded) using a mathematical model (Balasse et al. 2012b).

In terrestrial environments, the main factor influencing $\delta^{13}\text{C}$ values is the plant photosynthetic pathway: modern C_3 and C_4 plants display $\delta^{13}\text{C}$ values ranging from -37 to -20 ‰ (average: -27 ‰) and -21 to -9 ‰ (average: -12 ‰), respectively (Kohn 2010; Tieszen 1991; Tieszen and Boutton 1989). Plant $\delta^{13}\text{C}$ values may be affected to a lesser extent by altitude, aridity, forest cover, or the plant part analysed (Badeck et al. 2005; Bonafini et al. 2013; Cernusak et al. 2009; Heaton 1999). Plant nitrogen isotope composition depends on their ability to fix atmospheric N_2 (as in legumes) and is impacted by abiotic factors such as temperature, water availability, soil type, etc., or anthropogenic factors such as manuring (Ambrose 1991; Commisso and Nelson 2006, 2007; Fraser et al. 2011; Pardo and Nadelhoffer 2010; Peterson and Fry 1987).

3. Results

3.1. Exploitation of *Sagalassos* kill-off patterns

The mortality profiles are displayed in Fig. 3. For Classical-Hellenistic Düzen Tepe, a clear peak can be observed at the age of 2-4 months (20.0 %), and to a lesser extent at the age of 22-24 months (15.3 %) and 36-60 months (15.5 %). This slaughter pattern differs significantly from those of *Sagalassos* (Table 2a). For the Early-Middle Imperial to the Early Byzantine periods, four slaughter peaks can be identified around age classes: 2-6 months, 8-10 months, 16-20 months, and 22-24 months. However, the intensity of these peaks varies between periods. The Early-Middle Imperial period is characterised by a well-defined peak at 16-20 months (38.6 %), followed by a clear peak at 8-10 months (11.4 %), while the two other peaks are less pronounced. The Late Roman period displays peaks of more homogeneous intensity (2-6 months: 19.2 %, 8-10 months: 12.3 %; 16-20 months: 23.7 %, 22-24 months: 10.8 %). Early Byzantine slaughter targets primarily 16-20 month old pigs (26.9 %), then 8-10 month and 2-6 month old pigs (18.4 % and 18.2 % respectively), whereas the fourth peak at age class 22-24 months is almost completely absent. The proportion of pigs killed during their first year increases with time, while that of pigs slaughtered during their second year decreases (30.4 %, 42.5 %, 48.0 % and 60.4 %, 45.5 %, 43.9 %, respectively), although the difference is only statistically significant between the Early-Middle Imperial and the Early Byzantine periods (chi-square test, p-value = 0.00041; Table 2b). In addition, there seems to be a slight preference during the Late Roman period for pigs aged 0-6 months (22.1 %) compared to 6-12 months (20.4 %), while in Early Byzantine the opposite is observed (19.3 % and 28.6 % respectively).

3.2. Geometric Morphometrics

No differences in *Sagalassos* molar shape were detected between the periods ($F_{10,70}=1.677$, $p=0.103$, based on the 5 first components of a principal component analysis; Table 3). Nevertheless, molars from the three periods (from Early-Middle Imperial to Early Byzantine) differ significantly in size (Kruskal-Wallis : $X^2=9.33$, $p=0.0094$) with a trend towards a decrease of size through time (Fig.4). The only significant pairwise comparison, however, was between the two extreme periods (Early-Middle Imperial and Early Byzantine) (Table 3). This size decrease seems paired with an increase in size variability during the Late Roman and Early Byzantine periods.

3.3. LEH analysis

Few LEH are observed on Pd4s, and only in the Late Roman (7 %, $n = 15$) and Early Byzantine (2 %, $n = 96$) assemblages (Fig. 5). Considering molars, LEH frequencies in the M1 are similarly the lowest

during all periods (Fig. 5 and Table 4). The M2 (especially M2b cusps) is the most affected tooth during both Late Roman and Early Byzantine periods, whereas the Early-Middle Imperial period stands out with a higher LEH proportion in the M3 (particularly on M3a and M3b cusps) (Fig. 5). These differences are partially visible when taking into account multiple LEH occurrences per tooth cusp (Table 4). The M3 is the only, strongly affected tooth during the Early-Middle Imperial period. In the Late Roman period, the M2 is strongly affected, while during the Early Byzantine period both M2 and M3 are affected but to a smaller extent.

In the M1, LEH occurrence coincides mainly with the second month after birth for the Early-Middle Imperial and Late Roman periods (Fig.6), equally between the second and third months for the Early Byzantine period. In the M2, the occurrence of LEH in the seventh month after birth is noticeable. Smaller peaks of line occurrence occur at 4, 5 and 5-6 months for the Early-Middle Imperial, Late Roman and Early Byzantine periods, respectively. In the M3, LEH distribution is marked by a main peak of occurrences coinciding with the 11th-12th months after birth, and a smaller one at 15-16 months.

3.4. Stable isotope analysis

3.4.1. Oxygen and carbon isotope ratios measured in dental enamel

The $\delta^{18}\text{O}$ values range globally from -5.8 to -0.9 ‰ (Fig.7, Table 5 and Sup data 2D). Among the 13 specimens analysed, five (**SAG 13, 35, 39, 44, 48**) display little to no intra-tooth variation (between 0.7 and 1.3 ‰) and $\delta^{18}\text{O}$ values lower than -4 ‰, whereas the seven remaining specimens display cyclical variations. When both $\delta^{18}\text{O}$ optima are identifiable in a same sequence, the amplitude of intra-tooth variation varies from 1.9 to 3.5 ‰, and the in-between distance is graphically estimated to range from 15 to 25 mm.

Overall, $\delta^{13}\text{C}$ values measured in tooth enamel range from -13.2 to -8.3 ‰. Half of the pigs (**SAG 6, 13, 39, 44** and **48**, four of which also show no variation in the $\delta^{18}\text{O}$ signal as mentioned above) are characterized by $\delta^{13}\text{C}$ sequences showing no or very little intra-tooth amplitude variation (from 0.2 to 1.1 ‰). **SAG 35** and **36** stand out with increasing $\delta^{13}\text{C}$ sequences from the tip to the bottom of the crown. **SAG 14** displays an abrupt drop in $\delta^{13}\text{C}$ values at around 24 mm from the Enamel-Root Junction (ERJ). Three specimens (**SAG 5, 8** and **38**) display a sinusoidal pattern of $\delta^{13}\text{C}$ variations characterized by lower values when $\delta^{18}\text{O}$ values are the highest, and higher $\delta^{13}\text{C}$ values coinciding with decreasing $\delta^{18}\text{O}$ values.

3.4.2. Carbon and nitrogen isotope ratios measured in root dentine collagen

Results from bulk dentine collagen $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ analysis are shown in Fig.8 and Table 6. Extraction yields vary from 62 to 143 mg/g. Atomic C:N ratios range from 3.0 to 3.1, while nitrogen and carbon content was between 13.9 and 16.2 % and 37.1 and 43.1 %, respectively; values that fall within the accepted range for well preserved collagen (Ambrose, 1993; Van Klinken, 1999). Carbon isotope ratios range from -21.0 to -19.3 ‰ and average -20.1 ± 0.5 ‰. Nitrogen isotope ratios vary from 5.9 to 9.6 ‰ and average 8.0 ± 1.3 ‰.

4. Discussion

4.1. Diachronic evolution of pig demographic management at Sagalassos

The Classical-Hellenistic kill-off pattern is characterized by the highest relative proportions of very young piglets (0-2 months: 6.7 %) and old animals (>30 months: 22.8 %). The former age class could represent natural perinatal deaths, while the latter could correspond to culled breeders. As it is very

likely that the meat obtained from old animals would have been consumed by the herders, this mortality pattern, together with other evidence such as the results from the bone collagen stable isotope analysis (Fuller et al. 2012), argues for the local raising of pigs by Düzen Tepe dwellers, an hypothesis that matches the acknowledged rural nature of the settlement. The very low occurrence of dental remains from intermediate aged pigs might further reflect the consumption of some of these animals outside the settlement walls, although strong evidence for production of food and goods above subsistence level is still lacking (Vanhaverbeke et al. 2010).

In contrast, Sagalassos kill-off patterns correspond to a consumer-site profile, which is further evidenced by a male overrepresentation (sex ratio: 7.7:1) in the faunal assemblages, suggesting that the breeding of pigs took place outside the town and animals were brought in (De Cupere 2001). Early-Middle Imperial slaughter preferentially targets yearling pigs, suggesting the search for high yield animals. The Early-Middle Imperial period coincides with the building boom of the town, as well as its nomination as provincial capital, which brought the Imperial courts and magistrates (Kaptijn et al. 2013). Additionally, Sagalassos was in charge of the Imperial Cult, which dragged annually several thousands of people from the whole province (Waelkens 2011). All this resulted in a significant increase in the town size and of the number of its inhabitants, inducing in turn an increasing meat demand that was met by the raising of high yield animals (Vanpoucke 2008).

Late Roman assemblages display the highest proportion of pig remains (ca. 26 %, Fig.2), as well as cattle remains (ca. 48 %, Fig.2), reflecting a further increase in meat demand. The fact that no conspicuous slaughter peak characterizes the Late Roman kill-off pattern while pork supply gains in importance may suggest a diversification of the supplied products, including more suckling/weaning pigs (2-6 months) and perhaps processed pork (20-30 months). Interestingly, the Late Roman period is also characterized by the highest relative proportion of fruits and naked wheat and barley (Marinova Unpublished results). Both trends might reflect an increase in luxury food item consumption (Bakels and Jacomet 2003), especially as the years 300-450 AD are known as a period of great economic prosperity for Sagalassos, fostering the emergence of a small but powerful provincial aristocratic elite (the *proteuntes*), and evidenced by among others the construction of a palace building on the Upper Agora (Waelkens 2011). Finally, the increase in suckling pigs could fit the description made by Columella of a cost-effective pig herd management in the vicinity of towns, which involved selling some of the piglets as suckling pigs in the nearby city markets, thus allowing sows to be serviced twice a year (De Re Rustica 7.9.3-4, Forster and Heffner 1968).

In the Early Byzantine period, the relative proportion of pig remains decreases to ca. 20% (Fig.2). The overall decrease in pig size during this period (see section 4.2.), the concomitant fall in the proportion of cattle remains (to ca. 26 %, Fig.2.) and the consumption of younger pigs (see section 3.1.) might represent a decline in meat demand as a consequence of the decrease in population size of Sagalassos and the ruralisation process that took place in the town.

4.2. Evolution of pig size from Early-Middle Imperial to Early Byzantine periods

A previous comparative analysis of mandibular tooth size (Pd4 – M3) revealed a decreasing trend of size between the Early-Middle Imperial and the Early Byzantine periods (Vanpoucke 2008), which is confirmed by the GMM analysis. Ongoing research on the evolution of long bone size (Log Size Index method) has further shown that pigs were the smallest during the Classical-Hellenistic period (De Cupere unpublished data). As the phenotype of an individual depends both on its genotype and on the environmental conditions where it has grown up (Via and Lande 1985; West-Eberhard 1989), pig size changes might be explained either by a renewal of pig populations or a change in farming

conditions. The absence of differences in molar shape from Early-Middle Imperial to Early Byzantine periods, which may suggest that the genetic pool of pig populations did not dramatically change, and the apparent increasing diversity in pig size during Late Roman and Early Byzantine periods, might argue in favour of the latter. This change in pig farming could be related to pig diet or breeding selection and the scale of management (for example free-ranging vs. close confinement). For instance, size increase during the Early-Middle Imperial period could have resulted from the selection of bigger and more robust animals to meet the town's increasing meat requirements (Vanpoucke 2008).

4.3. Animal health and environmental stress from Early-Middle Imperial to Middle Byzantine periods

LEH occurrence on Late Roman (7 %, n = 15) and Early Byzantine (2 %, n = 96) Pd4s indicates that during both periods, some of the reproductive sows suffered from physiological stress during gestation. This deterioration of the gestating sows' health status or well-being could be explained by insufficient feeding, earlier breeding (Deniz and Payne 1982), social stress (Couret et al. 2009), or, perhaps, the implementation of a two-farrowing season per year breeding system as described by Columella (see section 4.1.). Whatever its origin, maternal stress during gestation is known to negatively impact the subsequent development of the offspring, notably affecting growth weight and immune system development (Couret et al. 2009; Kapoor and Matthews 2005), and might have played a role in the pig size decrease from the mid-Late Roman period. Looking at the lower molars, the tooth displaying relative higher LEH frequency changes through time: M3 (9-18 months) in the Early-Middle Imperial period, M2 (3-9 months) and to a lesser extent M1 (0-3 months) in later periods. This trend suggests a change in pig husbandry.

Different plausible causes may explain LEH occurrence peaks over molar crown height (Dobney and Ervynck 2000): weaning could explain the peak at 2-3 months. Castration, especially for the males, should also be considered for both piglets aged between 1 and 4 months (Berthoud 1884; Frémondeau 2012; Hadjikoumis 2012; Lequertier 1929;) or later on between six and twelve months of age (Columella *De Re Rustica* 7.9. 4, Forster and Heffner 1968; Varro *De Re Rustica* 2.4.21, Guiraud 2003; Cucchi pers. com. 2009). The seventh month peak remains difficult to interpret, since it has been observed in both wild and domestic pigs born during different seasons, and might be linked to the environment (Frémondeau 2012). Besides castration of the males for the 11-12 month peak, likely explanations for the pattern of LEH distribution over M3 may be periods of undernutrition. In a Mediterranean mountainous area, such periods may happen during summer or when there is snow cover, at the end of winter-beginning of spring (Frémondeau 2012).

In brief, there is no significant diachronic change in the seasonality of LEH occurrence, and we can assume that the seasonality of stresses remained similar from the Early-Middle Imperial to the Early Byzantine periods. In contrast, the variations observed in relative LEH frequencies between teeth and periods argue for a diachronic evolution in the physiological stress endured by pigs. This apparent contradiction suggests changes in the intensity of the same seasonal stresses, which means either a greater degree of human manipulation of a targeted age group (Hadjikoumis 2010) or a deterioration of the farming conditions of the concerned age groups, such as an increased inter-individual competition and/or a decrease in food availability.

4.4. Early Byzantine pig herd management inferred from stable isotope analyses

4.4.1. The $\delta^{18}\text{O}$ signature of local water and the interpretation of the $\delta^{18}\text{O}$ sequences

In the territory of Sagalassos and its close vicinity, several water sources – characterized by different $\delta^{18}\text{O}$ signals - were available to water the pigs: ^{18}O -enriched lake water from Gölçük, located ca. 6 km north from Sagalassos; small spring and aqueduct water with lower $\delta^{18}\text{O}$ compositions varying seasonally; large springs and well water with low and constant $\delta^{18}\text{O}$ values (Dufour et al. 2007; Gunyakti et al. 1993; Steegen et al. 1993). According to this review, the six pigs displaying little or no intra-tooth variation (**SAG 13, 35, 39, 44, 48** and **SAG 14** at the beginning of its life) would likely have been watered either from groundwater (taken from wells), or from a spring with a large discharge. One possibility could have been Ağlasun Çay River, which irrigated Ağlasun Valley (Waelkens et al. 1999).

In contrast, the seven specimens displaying a sinusoidal pattern of $\delta^{18}\text{O}$ variations (**SAG 5, 6, 8, 34, 36** and **48**, as well as **SAG 14** in a second time), could have been watered from small springs, aqueducts or small ponds, the $\delta^{18}\text{O}$ values of which would have tracked the seasonal $\delta^{18}\text{O}$ variation of temperatures. This is further supported by the distances measured between the minimal and maximal $\delta^{18}\text{O}$ values in the sequences of these pigs (15 – 25 mm), which match the length of half an annual cycle measured in modern Corsican pigs (20 - 30 mm; Frémondeau 2012). The seasonal variation of temperatures was in all probability the main factor affecting the $\delta^{18}\text{O}$ signal measured in these seven pigs. The time span that these sequences would represent, would therefore correspond to approximately 9-10 months.

In **SAG 14** I1, however, the time span would be more than 12 months, a hypothesis which is not compatible with I1 mineralization process timing (Frémondeau et al. 2012). Actually, this specimen displays a mixed pattern, the upper 12 mm of the sequence resembling that of the first five specimens, and the lower 24 mm to the second group of specimens, suggesting a change in husbandry regime in its early life.

4.4.2. Assessment of pig birth seasonality and season

The mathematical model described by Balasse et al. (2012b) could be applied to **SAG 5, 6, 8, 14, 34, 38** sequences to assess birth seasonality (**SAG 36** was excluded due to a too short sequence). Modelled $\delta^{18}\text{O}$ sequences are shown as grey lines in Fig.7 and results are displayed in Table 7 and Fig.9. Values range from 0.16 (**SAG 5**) to 0.84 (**SAG 34**), suggesting that births would have been spread over 10 months. Although the sample size is small, a mixture analysis allowed the identification of two groups: one composed of four specimens (**SAG 5, 6, 8** and **38**; mean x_0/X value: 0.23 ± 0.04 , $p(\text{normal}) = 0.81$), the other including **SAG 14** and **SAG 34** (mean x_0/X value: 0.80 ± 0.05 , $p(\text{normal}) = 0.85$); which suggests the existence of two birth seasons.

The normalization of **SAG 5, 6, 8, 14, 34, 36** and **38** $\delta^{18}\text{O}$ sequences to an averaged maximum crown height (36.2 mm, Fig.10) revealed the same two groups: **SAG 5, 6, 8** and **38** on the one hand, and **SAG 14** and **34** on the other hand, while the **SAG 36** $\delta^{18}\text{O}$ sequence is in-between. As the start of the isotope record is known to coincide with the third month after birth (Frémondeau *et al.*, 2012; Frémondeau, 2012), it is possible to estimate the season of birth of these specimens. For **SAG 34** (and by deduction for **SAG 14**), whose sequence begins with high (summer) $\delta^{18}\text{O}$ values, this would be end of winter – spring. For **SAG 5, 6, 8** and **38**, whose sequences begin with low (winter) $\delta^{18}\text{O}$ values, this would be end of summer – autumn. The apparent under-occurrence of animals born in late winter-spring, which is the natural birth season in wild boar (Etienne 2003), is quite unexpected and contradicts the previous interpretation suggesting a main farrowing season in spring (Vanpoucke et al. 2007). Although this result can stem from the small sample size, another plausible explanation

could be linked to the seasonality of slaughter and the specific age-at-death of the sampled specimens.

4.4.3. Assessment of slaughter seasonality

The age-at-death of the sampled pigs was estimated to be between 14 and 18 months (section 2.6.). Interestingly, a slaughter peak targeting the age-class 16-20 months has been recorded in the Early Byzantine mortality profile (Fig.3). The sampled incisors most probably belonged to pigs from this age-class and were consequently killed at the same age. As they were born during different seasons of the year, these pigs would also have been slaughtered at different seasons of the year. **SAG 34**, likely born at the end of winter – spring, would have been killed at the end of spring – summer of the following year, whereas **SAG 5, 6, 8 and 38**, born at the end of summer – autumn, would have been killed in the winter of the following year. Due to meat preservation issues, the warmest months of the year are generally avoided for pig slaughter (Hadjikoumis 2012), which probably explains why most of these *ca.* 16-18 month-old pigs were not born in the expected farrowing season (late winter-spring). In any case, the sequence measured in **SAG 36** suggests that pig births may have been more staggered over the year, which would imply a more spread out slaughter ensuring a regular pork supply to the inhabitants (Vanpoucke et al. 2007a).

4.4.4. A C₄ component in pig diet?

The lower $\delta^{13}\text{C}$ range value measured in pig enamel (-13.2 ‰) corresponds to an estimated diet $\delta^{13}\text{C}$ value -26.2 ‰ (using an isotopic fractionation ϵ^* of $+13.3 \pm 0.3$ ‰; Passey et al. 2005), testifying to a C₃ terrestrial diet. The threshold $\delta^{13}\text{C}$ value that would reflect increasing amounts of C₄ inputs in pig's diet (-23 ‰; Kohn 2010; Francey et al. 1999; Mutlu et al. 2011; Pearson et al. 2007), corresponds to a $\delta^{13}\text{C}_{\text{enamel}}$ value of -10.0 ‰. According to this estimation, seven specimens would have had a C₃ terrestrial diet (**SAG 5, 34, 36, 38, 39, 44 and 48**). Two specimens (**SAG 6 and 14**) display $\delta^{13}\text{C}$ values well above -10.0 ‰, indicating the presence of a C₄ component in their diet. Three others (**SAG 8, 13 and 35**) have maximum $\delta^{13}\text{C}$ values around -10.0 ‰, which does not allow the exclusion of a small C₄-plant based contribution to their diet.

The dentine $\delta^{13}\text{C}$ values, however, indicate a C₃ terrestrial diet for all pigs (estimated using a ¹³C-enrichment Δ of + 5 ‰; Ambrose and Norr 1993; Hare et al. 1991; Hedges et al. 2005; Howland et al. 2003; Lee-Thorp et al. 1989), which contradicts enamel $\delta^{13}\text{C}$ results in spite of a good correlation between the two measured signals (Fig.11). This discrepancy could be explained by the fact that the two carbon isotope signals do not represent the same life span, nor the same diet fraction. I1 crown enamel is mineralized approximately during the first year of life while root dentine $\delta^{13}\text{C}$ value represents an average over the second year of life, and enamel carbonates $\delta^{13}\text{C}$ reflects the carbon isotope composition of global diet, while collagen $\delta^{13}\text{C}$ reflects rather that of the protein fraction (Ambrose and Norr 1993; Tieszen and Fagre 1993).

For **SAG 6 and 14**, this apparent discrepancy in $\delta^{13}\text{C}$ values could stem either from a change in diet (from mixed C₃-C₄ plant based to pure C₃) between the first and second year of life, or from the fact that the C₄ component did not contribute significantly to collagen synthesis, as it may be the case with plants in an omnivorous diet (Fernandes et al. 2012) – although this second alternative is less likely for **SAG 14** (see below section 4.5.6.). Several non-exclusive hypotheses can be proposed as C₄ plant sources: millet in the form of stubble field, agricultural threshold remains or human meal food waste; C₄ plants foraged or gathered in the marshy areas of the territory; or C₄ plants foraged in

trampled mixed grasslands (Fuller et al. 2012; Marinova unpublished data; Čarni and Mucina 1998; Wang 2002).

4.4.5. Seasonality of pig diet

The flat $\delta^{13}\text{C}$ sequences observed in half of the pigs (**SAG 6, 13, 34, 39, 44** and **48**) suggest the consumption of a rather isotopically homogenous C_3 terrestrial diet during the first year of pig life (except for **SAG 6** who had a small C_4 plant based contribution to its diet). The gradual increase in $\delta^{13}\text{C}$ values over crown height observed in **SAG 35**, and in the lowest 15 mm of the crown in **SAG 36** and **48** may suggest a fodder-supplied diet during their first year of life (Frémondeau 2012). **SAG 14** display an abrupt change of diet, from a C_4 -plant based contribution (crown upper 12 mm), to a rather C_3 terrestrial diet (lower 24 mm). Three specimens (**SAG 5, 8** and **38**) display a seasonal pattern of $\delta^{13}\text{C}$ variations characterized by lower values in summer and higher values measured in autumn and winter. Similar patterns have already been observed for modern Corsican wild pigs (Frémondeau et al. 2012), as well as for Iron Age domestic pigs (Frémondeau 2012; Frémondeau et al. 2012), and were interpreted as pigs foraging under the forest canopy and eating forest fruits during the mast period. Notably, acorns are starch-rich non-photosynthetic organs that ripen during the warmest and most arid months of the year, all factors that can result in a ^{13}C -enrichment as high as 3 ‰ compared to leaves (Cernusak et al. 2009; Heaton 1999; Tieszen 1991; Tieszen and Boutton 1989). Hence, a high proportion of acorns in **SAG 8**'s diet might explain the higher $\delta^{13}\text{C}$ values measured in its incisor. Ecological and palynological studies testify to the presence of oak (*Quercus cerris* and *Q. coccifera*) woodlands in Sagalassos territory and in the close vicinity of the town, which may have been exploited as foraging areas for the pigs at least seasonally (Baeten et al. 2012; Bakker et al. 2012, 2013; Kint et al. 2014; Vanpoucke et al. 2009; Vermoere et al. 2003).

4.4.6. The trophic status of the pigs

The dentine collagen $\delta^{15}\text{N}$ values falls within the 4.9-11.0 ‰-range of bone collagen $\delta^{15}\text{N}$ values obtained by Fuller et al. (2012), and on average the two datasets do not significantly differ (t-test, $p = 0.72$). The 3.7 ‰ - range in dentine $\delta^{15}\text{N}$ values (from 5.9 to 9.6 ‰) exceeds the + 3 ‰ average stepwise enrichment considered to reflect an increase in trophic position (Ambrose and DeNiro 1986; Post 2002; Schoeninger and DeNiro 1984). This broad range likely reflects a gradual gradient from almost none to increasing proportions of animal protein in pig's diet. In this respect, it is interesting to note that the two pigs that display the lowest dentine $\delta^{15}\text{N}$ values, namely **SAG 34** and **14**, are also those which were likely born at the end of winter/beginning of spring. The herbivorous diet and spring birth season of these two specimens might therefore correspond to a more extensive husbandry regime.

4.5. Inferences on Early Byzantine husbandry regimes

4.5.1. Pig husbandry in historical sources and ethnographic studies

Traditionally, the scale of pig management may vary from the family who buys one piglet to be fattened for household consumption, to the specialised herder who owns more than a hundred pigs, a number of which at least is raised in free-range. Indeed, the bigger the herd, the more difficult it becomes to supplement pig diet when food is scarce or to boost pig growth. The "household pig" is a practice quite common and widespread in time and place, aiming at sustaining the local community and maintaining local social interaction, and it can therefore hardly be associated with specific socio-

economic conditions. In contrast, large herds management implies society specialization and the production of surpluses aiming at either a market economy or a centralized power.

The control over animal movement varies from close confinement to free-range and includes tethering, holding pens or daily move to pastures under the pig-keeper's conduct (Albarella et al. 2007, 2011; Hadjikoumis 2012; Halstead and Isaakidou 2011; Hide 2003). Columella (*On agriculture* 7.9.6-10, Forster and Heffner 1968) describes three different categories of pastures exploited for pig feeding: 1) oak forests preferentially composed of a diversity of trees and shrubs that provide fruits at different seasons of the year; 2) non-cultivated pastures, and especially wetlands and marshlands, in which pigs feed on roots of aquatic plant and worms; 3) cultivated pastures or orchards.

In free-range conditions, pig growth depends on the seasonal availability of natural food resources. The time of plenty is autumn, when acorns, chestnuts or beechnuts, and mushrooms are available, and can extend to winter. Outside this period, pigs may feed on plants (either under- or above-ground parts), fruits, worms, snails or small vertebrates. In times of food shortage (especially in winter/beginning of spring and in summer in dry climates) or for fattening, both historical (Aristotle *History of animals* 7.6, Gotthelf and Peck 2006; Varro *Economie rurale* 2.2., Guiraud 2003; Columella *On agriculture* 7.9.6-10, Forster and Heffner 1968; Palladius *The work of farming* 2.26, Fitch 2013) and ethnographic sources mention the supplementation of pig diet with stored acorns, fruits such as figs or prickly pears, legumes, vegetables or cereals (notably barley, rye, or triticale). Alternatively, pig herds may be moved seasonally, for example to stubble fields in plains or valleys (Albarella et al. 2011), or on the contrary to high altitude grasslands (Frémondeau 2012).

Pig husbandry may also be integrated to other activities, such as the breeding of other livestock providing whey for pigs, vine or olive cultivation, bakery, butchery or tannery (Columella *De Re Rustica* 7.9.2, Forster and Heffner 1968; Varro *Economie rurale* 2.2., Guiraud 2003; Palladius *The work of farming* 2.26, Fitch 2013; Albarella et al. 2011; Laurans 1976). To conclude, slaughter seasonality is determined by several factors, including the seasonality of birth and the growth rate - which depends in turn on the quality and quantity of food and the seasonal availability of natural resources-, the existence of a demand for specific products (such as processed pork; Frémondeau et al. 2015) or at a specific time of year (e.g. for religious/ceremonial practices; Cato *De agri cultura*, Goujard 2002), and climatic conditions (especially temperature).

4.5.2. Integration of tooth isotopic data

The variability observed in the different isotope signals suggests the existence of a high diversity in Early Byzantine pig management. Three of the pigs with an omnivorous diet (**SAG 35**, **39** and **48**) were likely watered from wells and had either an isotopically homogenous diet or display a gradual increase in $\delta^{13}\text{C}$ values that may indicate a fodder-supplied diet. All this suggests these three specimens were kept in close confinement.

For **SAG 6**, the occurrence of a $\delta^{18}\text{O}$ seasonal pattern combined with a C_4 contribution to diet during the first year of life suggests rather herding in the open air with a C_4 -signal complementation, or in the marshy areas (as mentioned in Columella *De Re Rustica* 7.9.6-10; Forster and Heffner 1968) of the humid valley bottoms of Sagalassos territory such as the area of Burdur lake, where C_4 plants characteristic of these wet environments were available (Fuller et al. 2012).

Interestingly, the diet switch observed in **SAG 14** between 30 and 25 mm from I1 ERJ coincides with a change in drinking water source, from likely well-watered and C_4 -foddered diet to spring-watered and a C_3 -terrestrial diet. This suggests a move from pigsty in the earliest months of life to

free-range later on. The extensive herding conditions for both **SAG 14** and **34** are further supported by low $\delta^{15}\text{N}$ dentine values and a spring birth season.

Both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ seasonal variations in **SAG 5**, **8** and **38** support their free-range in a forested area during the first year. That said, **SAG 38** is also one of the specimens fed an omnivorous diet during the second year. Either **SAG 38** was raised in free-range but had its diet supplemented, or its herding conditions changed from free-range to close confinement sometime between its first and second year of life. This last hypothesis would be in accordance with previous research combining micro-wear and LEH analyses (Vanpoucke et al. 2009).

From the integration of all isotope data, it appears that different scales of pig management existed, including extensive herding and close confinement (if household rearing, the latter could correspond to pig raising within the town), but also intermediate systems implying notably seasonal foddering. Furthermore, the identified dietary patterns strongly suggest the exploitation of several different environments, such as the forest or marshy areas, which entails that several pig herds of different sizes were raised in different places – likely by different owners – within the territory of Sagalassos.

5. Conclusions

Through an integrated dental analysis including kill-off pattern, traditional and geometric morphometric, linear enamel hypoplasia and stable isotope analysis, this paper has shed new light on the long-term evolution at Düzen Tepe and Sagalassos (ancient Pisidia, 500 BC – 700 AD), of pig husbandry practices and animal economy. It revealed the occurrence of a major change between the Classical-Hellenistic period on the one hand and the Early-Middle Imperial to Early Byzantine periods on the other hand. The picture that emerges from the Classical-Hellenistic data is one of a quite rural community raising pigs for its own consumption, and where pigs probably played a minor role in animal protein supply compared to cattle and caprines. In Roman times, animal husbandry turned to a diversified farming system, where pigs played an increasingly important role in order to feed Sagalassos urban market, which subsequently declined in the Early Byzantine.

This major shift between the Classical-Hellenistic and subsequent periods might originate from several factors: the intrinsic nature of both sites (rural settlement vs. provincial capital with a urban market and a high meat demand), a cultural change (the Pisidian Düzen Tepe vs. the Hellenized and subsequently Romanized Sagalassos), or a reorganisation of the settlement pattern and the production system in the countryside (hill sites and slope exploitation vs. intensive farming in the valleys). From the Early-Middle Imperial period onwards, pig management strategies may have been triggered by the economic welfare of Sagalassos and its elite.

This paper has also highlighted several methodological issues, among which the fact that pig demographic management study necessitates the direct assessment of birth seasonality, which proved to be feasible from the sequential $\delta^{18}\text{O}$ analysis in loose incisors. Moreover, the sampling of almost unworn but fully mineralized lower I1 allowed comparing diet and herding management between the first and second year of life, by analysing both the enamel layer and the root.

Despite the use of a new methodology, the interpretation of Sagalassos LEH record in terms of birth seasonality proved to be difficult. Nevertheless, the analysis of LEH relative frequencies per tooth and the consideration of multiple LEH occurrences highlighted the existence of subtle diachronic changes in husbandry practices and/or farming conditions, testifying to the usefulness of LEH analysis.

This paper has also shown that the more methods are combined, the more complex the picture becomes on husbandry practices. More specifically, stable isotope analysis in pig teeth constitutes a promising tool to address husbandry practices at an unprecedented level of details. For the Early Byzantine Sagalassos assemblage, this method enabled the identification of birth and slaughter over the year, probably to ensure regular pork supply; as well as a diversity in pig management systems implying different scales of management and the probable co-existence of several herds raised in different areas within Sagalassos hinterland.

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Figure 11: Correlation between the $\delta^{13}\text{C}$ values measured in the enamel carbonates and the dentine collagen of the twelve pig first mandibular incisors from Early Byzantine Sagalassos. Each gray square represents one specimen. The straight line figures the linear regression (equation and correlation coefficient R^2 displayed on chart).

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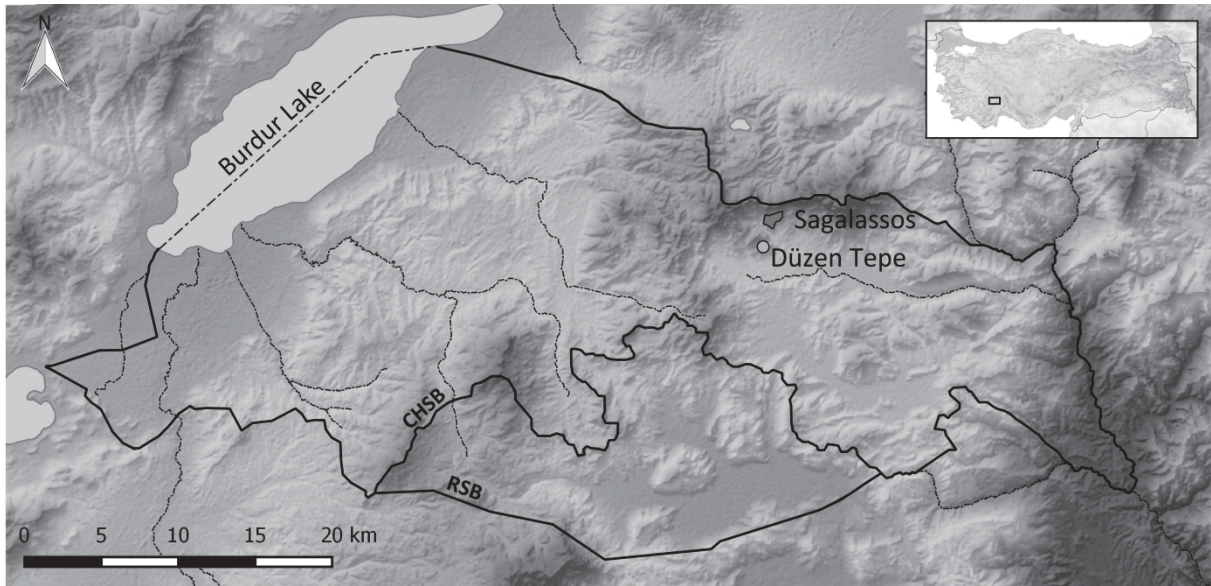


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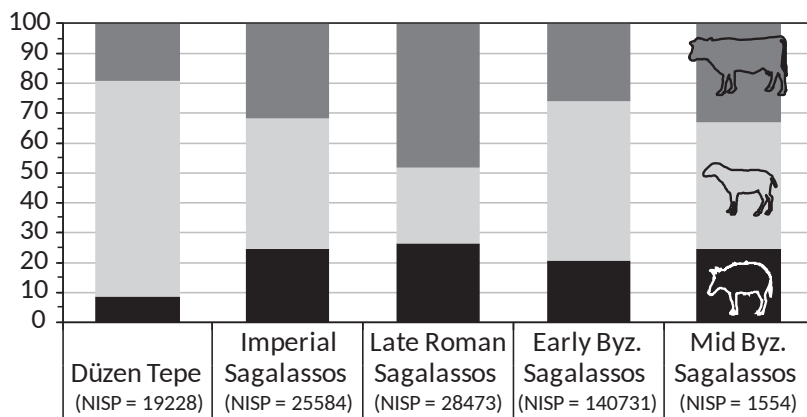


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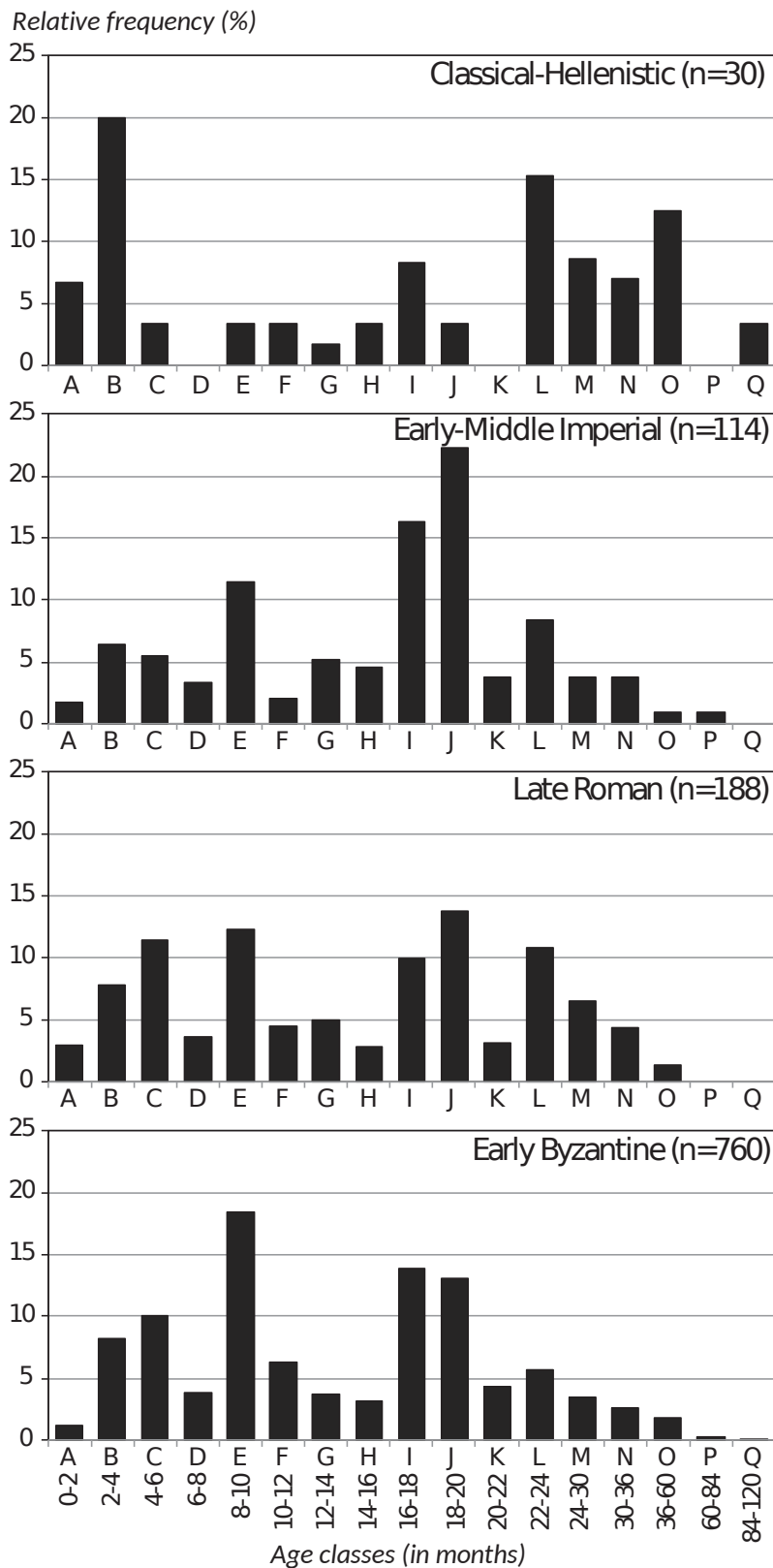


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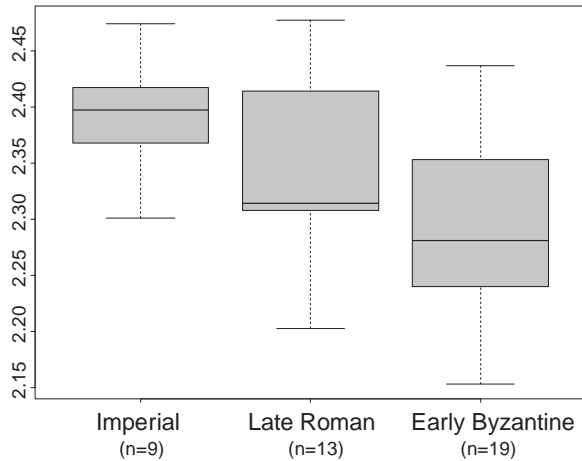
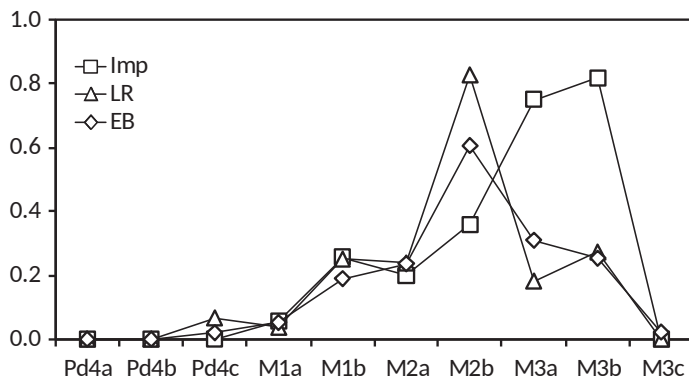


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sample size:

Imp	16	16	14	35	35	30	25	12	11	8
LR	15	16	15	27	24	21	23	11	11	8
EB	100	100	96	170	163	135	132	58	55	45

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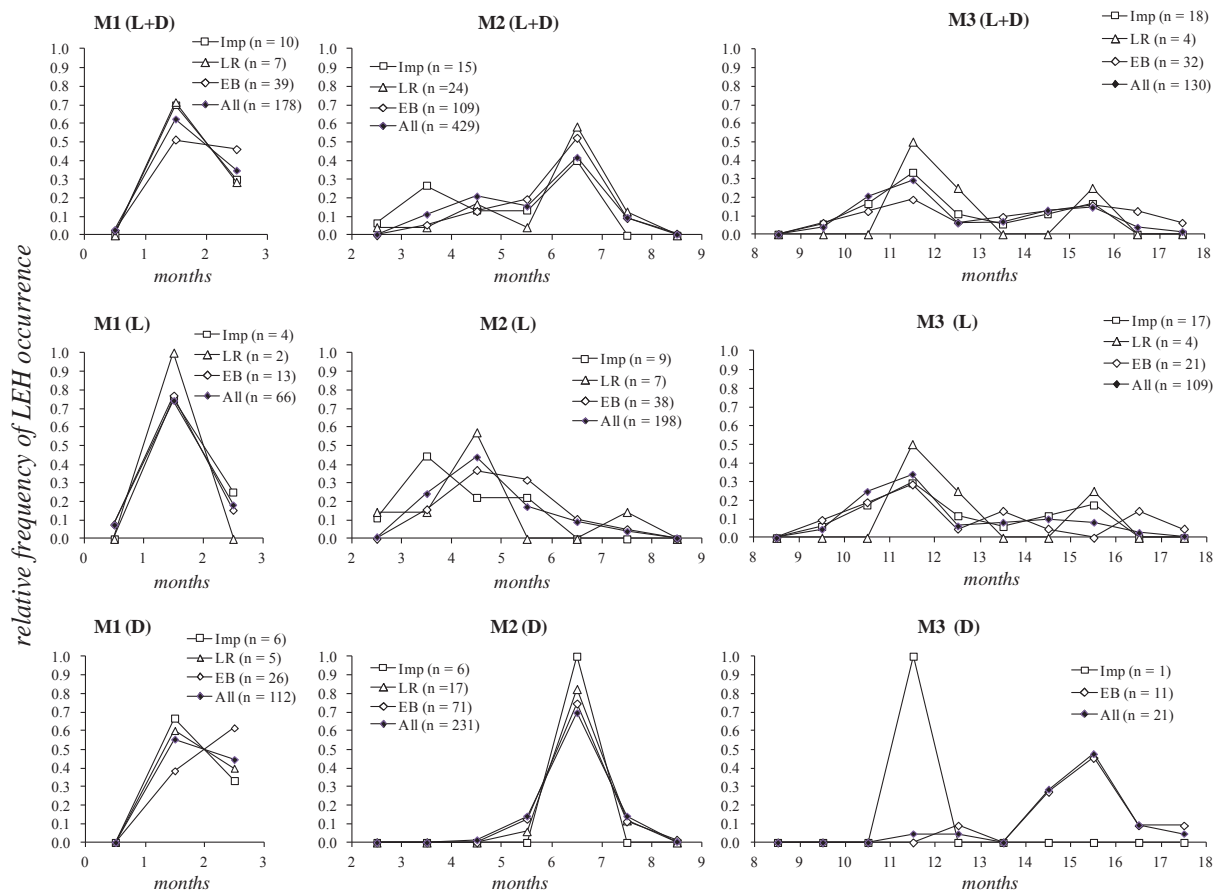


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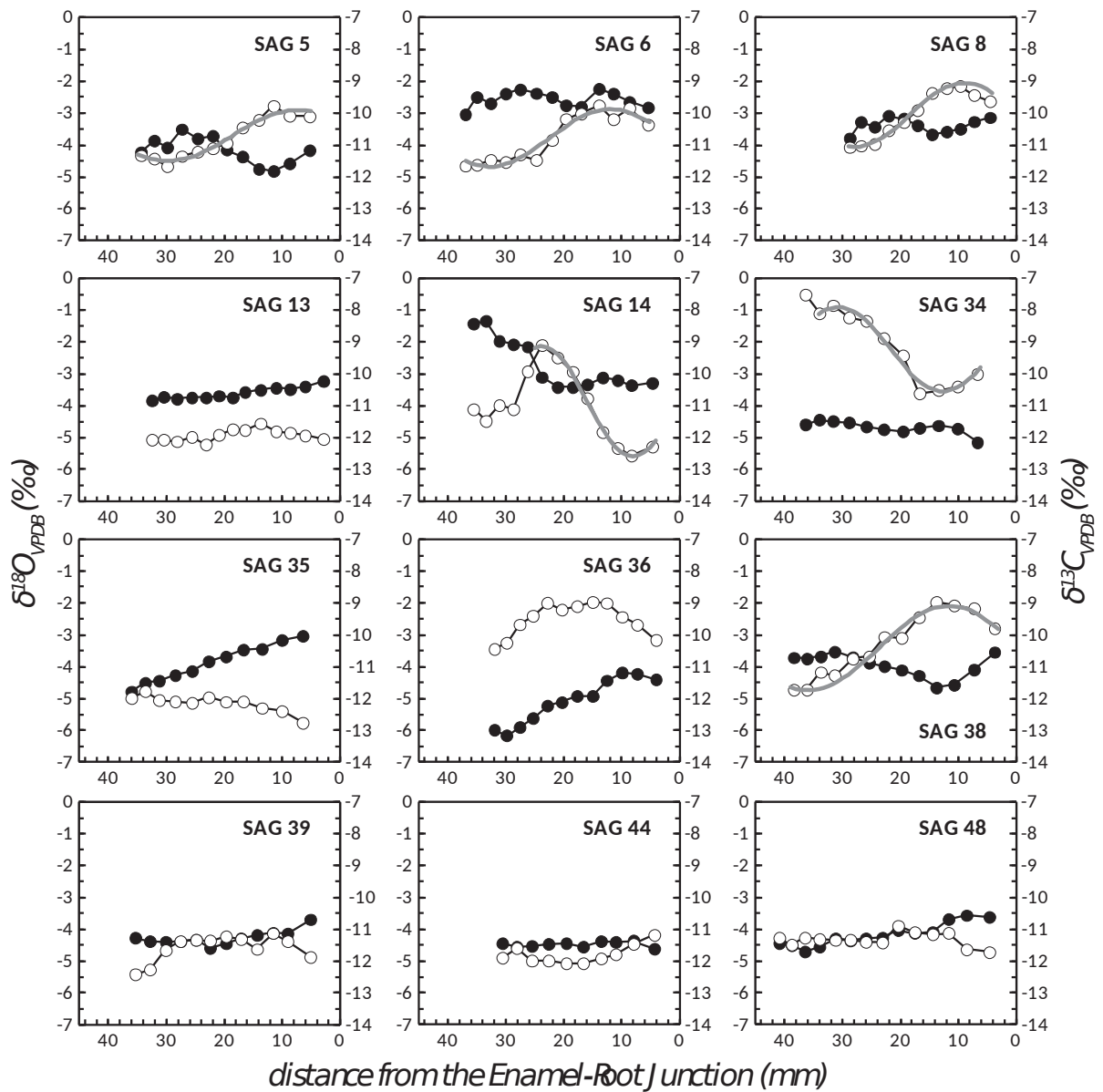


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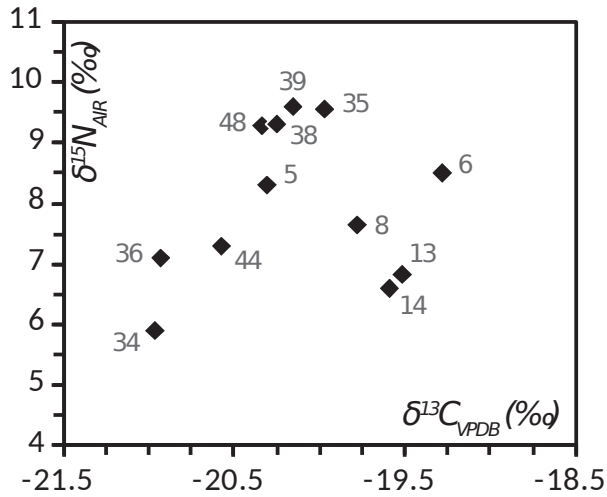


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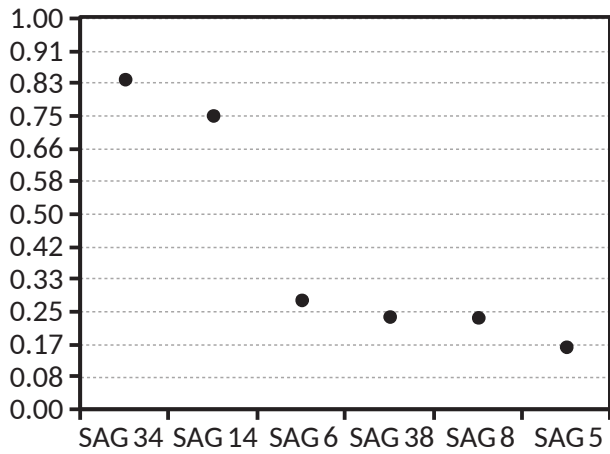


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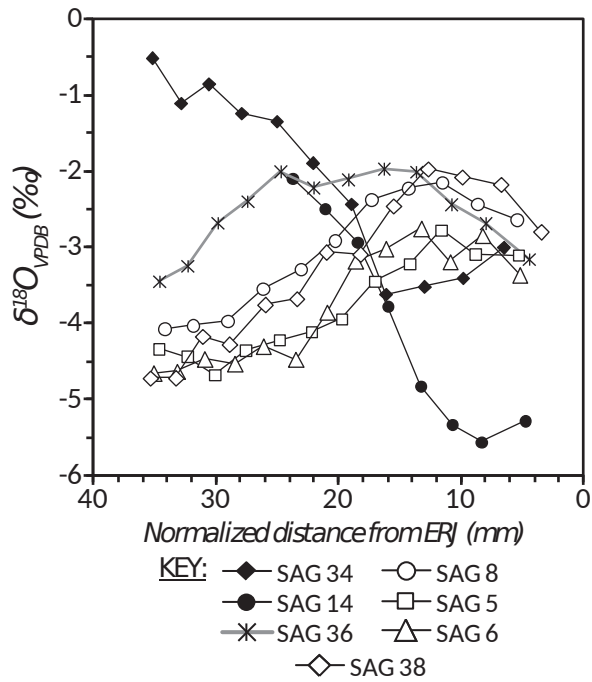


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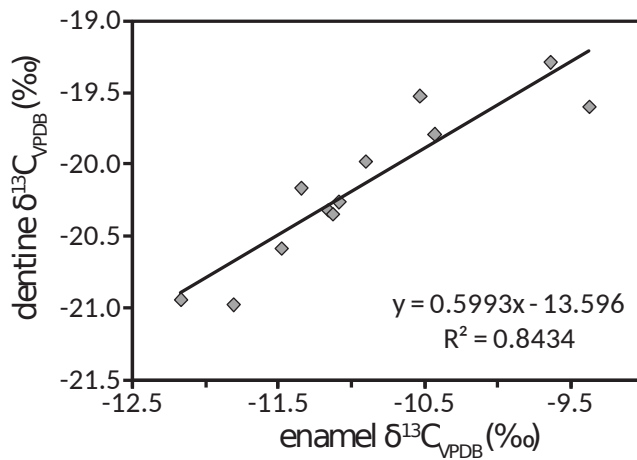


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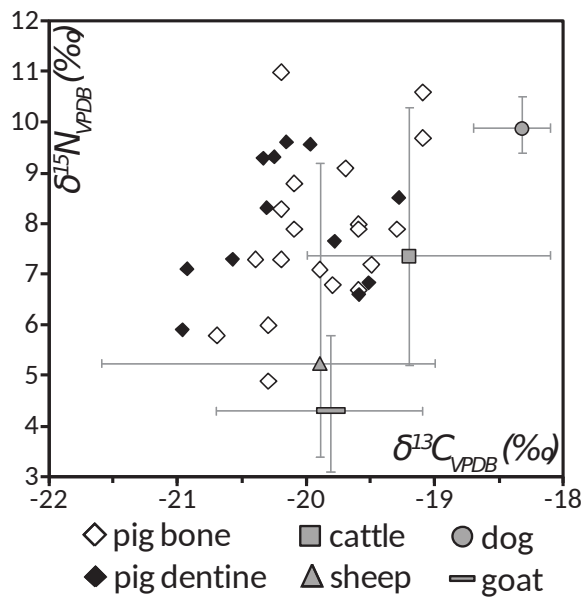


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SITE	PERIOD		METHOD				
			mortality profiles (demographic management)	GMM, morphometry (pig size and morphology)	LEH analysis (farming conditions and pig welfare)	microwear (diet)	stable isotope analysis (birth and diet seasonality, trophic status)
Düzen Tepe	Classical-Hellenistic	5 th - 2 nd BC	✓				
Sagalassos	Early-Middle Imperial	25 BC - 300 AD	✓	✓	✓	✓	
	Late Roman	300 - 450 AD	✓	✓	✓	✓	
	Early Byzantine	450 - 700 AD	✓	✓	✓	✓	✓
	Middle Byzantine	10 th - 13 th AD	(✓)		(✓)		
References			De Cupere 2001 Vanpoucke et al. 2009 this paper	Vanpoucke 2008 this paper	Vanpoucke et al. 2007 this paper	Vanpoucke et al. 2009	this paper

Table 2: Pairwise differences between four different chronological periods in the number of specimens per age class considering a) five age groups as defined in section 2.1., and b) pigs aged 0-12 m and 12-24 m. Significant results of the Chi-Square tests are in bold.

a	Early-Middle Imperial	Late Roman	Early Byzantine
Classical-Hellenistic	1.92E-07	1.74E-04	2.71E-07
Early-Middle Imperial	-	0.29053	0.32275
Late Roman		-	0.67006

b	Early-Middle Imperial	Late Roman	Early Byzantine
Classical-Hellenistic	0.10456	0.71751	0.98867
Early-Middle Imperial	-	0.01872	0.00041
Late Roman		-	0.35036

Table 3 : Pairwise differences between three different chronological periods in molar size (lower diagonal, results of wilcoxon tests) and shape (upper diagonal, results of MANOVAs). Results in bold are significant.

Size \ Shape	Imperial	Late Roman - Phase 7	Early Byzantine
Early-Middle Imperial	-	F _(5, 16) =1.51, p=0.24	F _(5, 22) =2.44, p=0.06
Late Roman - Phase 7	W=76, p=0.26	-	F _(6, 26) =1.52, p=0.22
Early Byzantine	W=148, p=0.001	W=166, p=0.11	-

Table 4: Relative frequencies of the cusps (a: anterior; b: posterior or mesial; c: posterior) of the first (M1), second (M2) and third (M3) mandibular molars displaying more than one LEH, per chronological period.

	M1a	M1b	M2a	M2b	M3a	M3b	M3c
Early-Middle Imperial	0	0	0	0	16.7	18.2	0
Late Roman	3.7	0	0	13	0	0	0
Early Byzantine	0	0	0.7	2.3	6.9	3.6	0

Table 5: Results from sequential oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) stable isotope analysis in the enamel of pig first mandibular incisor from Early Byzantine Sagalassos. For each specimen, minimum, maximum ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$) and mean ($\delta^{13}\text{C}$) values, and intra-tooth amplitudes are indicated.

Specimen	$\delta^{18}\text{O}$ (‰)			$\delta^{13}\text{C}$ (‰)			
	min	max	amplitude	min	max	amplitude	mean
SAG 5	-4.7	-2.8	1.9	-11.8	-10.5	1.3	-11.2
SAG 6	-4.7	-2.8	1.9	-10.0	-9.2	0.8	-9.6
SAG 8	-4.1	-2.1	1.9	-10.8	-10.1	0.7	-10.4
SAG 13	-5.2	-4.6	0.7	-10.8	-10.2	0.6	-10.5
SAG 14	-5.6	-2.1	3.5	-10.4	-8.3	2.1	-9.4
SAG 34	-3.6	-0.9	3.1	-12.1	-11.5	0.7	-11.8
SAG 35	-5.8	-4.8	1.0	-11.8	-10.0	1.7	-10.9
SAG 36	-3.4	-2.0	1.5	-13.2	-11.2	2.0	-12.2
SAG 38	-4.7	-2.0	2.7	-11.7	-10.5	1.1	-11.1
SAG 39	-5.4	-4.1	1.3	-11.6	-11.1	0.5	-11.3
SAG 44	-5.1	-4.2	0.9	-11.6	-11.4	0.2	-11.5
SAG 48	-4.7	-3.9	0.8	-11.7	-10.6	1.1	-11.1

Table 6: Results from the bulk collagen stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope analysis in the root dentine of the Early Byzantine pig first mandibular incisors. For each specimen, initial sample weight, collagen extraction yield, collagen carbon - % C- and nitrogen - % N- contents, atomic C:N ratio are also indicated.

Specimen	Init. Wt. (mg)	yield (mg/g)	%N	%C	C:N	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	sd $\delta^{13}\text{C}$	sd $\delta^{15}\text{N}$
SAG 5	194	71	14.3	37.1	3.0	-20.3	8.3	0.03	0.01
SAG 6	244	62	14.2	37.1	3.0	-19.3	8.5	0.00	0.02
SAG 8	238	123	16.0	42.8	3.1	-19.8	7.7	0.01	0.05
SAG 13	232	80	14.4	38.9	3.1	-19.5	6.8	0.05	0.07
SAG 14	138	108	14.6	39.0	3.1	-19.6	6.6	0.07	0.03
SAG 34	250	133	16.0	42.9	3.1	-21.0	5.9	0.03	0.11
SAG 35	193	136	16.2	43.1	3.1	-20.0	9.6	0.03	0.04
SAG 36	287	100	15.6	42.0	3.1	-20.9	7.1	0.01	0.00
SAG 38	261	131	15.9	41.8	3.1	-20.3	9.3	0.02	0.14
SAG 39	252	143	15.8	41.7	3.1	-20.2	9.6	0.01	0.07
SAG 44	236	103	15.7	42.1	3.1	-20.6	7.3	0.01	0.14
SAG 48	152	71	13.9	37.1	3.1	-20.3	9.3	0.02	0.06

Table 7: Results from the calculation of the best fit (least squares method) for combined variation of the period (X), the amplitude of variation (A), the delay (x_0) and the mean (M) for the measured values in the first mandibular incisor (r is the Pearson coefficient value).

	SAG 34	SAG 14	SAG 6	SAG 38	SAG 8	SAG 5
X	36.4	31.7	42.1	48.7	37.9	45.1
A	1.3	1.7	0.9	1.3	1.0	0.8
x_0	30.7	23.8	11.8	11.6	8.9	7.3
M	-2.3	-3.9	-3.8	-3.4	-3.1	-3.7
r	0.986	0.999	0.965	0.998	0.990	0.984
x_0/X	0.84	0.75	0.28	0.24	0.24	0.16