Dental microwear study of pigs from the classical site of Sagalassos (SW Turkey) as an aid for the reconstruction of husbandry practices in ancient times

Sofie Vanpoucke, Ingrid Mainland, Bea De Cupere and Marc Waelkens

Microwear analysis of pig teeth from the classical site of Sagalassos (SW Turkey) is undertaken to obtain insight into pig management strategies in this region from the 1st to 7th centuries AD. Earlier research on modern pigs revealed significant differences in microwear patterns between stall-fed and free-ranging, rooting individuals. A comparison of the microwear data of the Sagalassos pig with those from archaeological and modern pigs with a known or presumed type of management shows that the microwear of the Sagalassos pigs is very different. It is suggested that the Sagalassos pigs had a very soft, non-abrasive diet, that in the first instance cannot be attributed to either management type. Therefore, the nature of the substrate on which the animals were foraging and its impact on microwear are considered and the microwear data are compared with the results of previous archaeozoological research carried out at the site. Further, diachronic changes in microwear patterns are investigated.

Keywords: pig, microwear, Sagalassos, Turkey, Roman, Early Byzantine, husbandry practices

Introduction

The ruins of Sagalassos, a Roman-Early Byzantine city, are located approximately 7 km north of the village of Ağlasun in the province of Burdur, and 110 km to the north of Antalya (Fig. 1) (Waelkens 1993). Excavations within this city have yielded large faunal assemblages primarily dating to between the 1st and 7th centuries AD (De Cupere 2001). These indicate that provisioning of the city with animal products was largely based on domesticates, and that hunting and fishing played only a minor role. Variation in the representation of domesticates is evident through time, with an increase in cattle at the expense of sheep and goat in the 4th century, the most prosperous period of the town. Afterwards, the city fell into decline as a consequence of increased instability in the region, together with earthquakes, diseases and natural disasters; the city was gradually abandoned during the 6th and 7th centuries (Waelkens 1993, 2002). In samples dating to that period, cattle numbers drop and sheep and goat become more frequent again. The proportion of pig does not show a clear diachronic trend, but remains more or less constant through time.

Pig husbandry practices during the Roman and Early Byzantine periods at Sagalassos have been explored using a combination of conventional and more novel zooarchaeological approaches, including tooth eruption/wear, biometry, trace elements and analyses of hypoplasia (De Cupere 2001; Vanhaverbeke *et al.* in prep.; Vanpoucke *et al.* 2007). This paper represents a further such novel study, namely the analysis of dental microwear patterning in the Sagalassos pigs. Dental microwear has been widely applied as a palaeodietary technique for ungulates within Tertiary contexts but has only recently begun to be applied to the question of domestic animal diet and management within the Holocene (Mainland 2006; 2007; Mainland and

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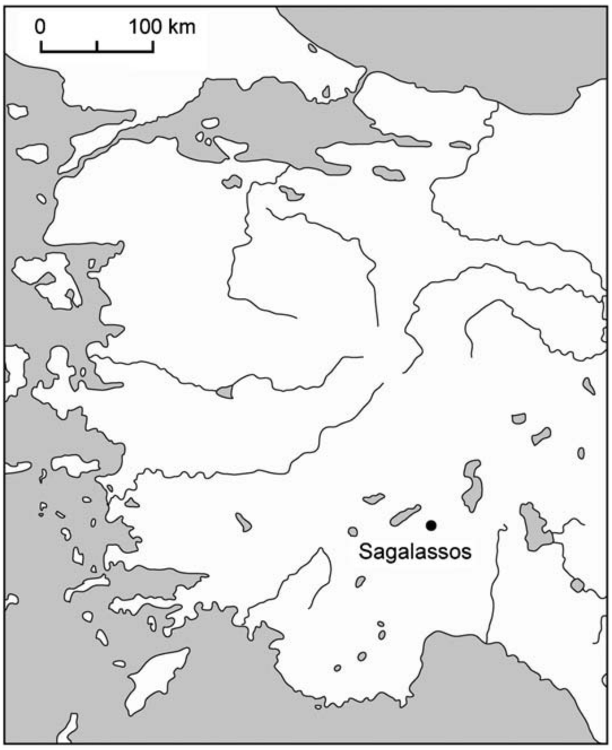

Figure 1 Map of western Turkey with indication of Sagalassos

Halstead 2004; Beuls 2004). In suids, it has been suggested that microwear can be used to distinguish level of dietary abrasiveness, dietary texture and that it may differentiate stall-fed and free ranging/rooting individuals (Wilkie *et al.* 2007; Ward and Mainland 1999). Microwear will reflect diet over a short period of time prior to death and as such is potentially a useful adjunct to approaches such as hypoplasia and isotopic or trace element analyses of bone collagen which allow insight into diet/management over the lifetime of an individual (Mainland 1998; Thomas and Mainland 2005).

Pig husbandry practices at Sagalassos

Slaughter ages of pig were reconstructed using tooth eruption and wear in the mandibular teeth. In general, from the 1st to the 7th centuries AD, pigs were slaughtered at a young age, before they were two years old, and probably mainly during winter months when fodder was scarce (De Cupere 2001; Vanpoucke *et al.* 2007). However, while the survival curve for the Imperial (25 BC–AD 300) and the Early Byzantine period (AD 450–650) is similar, a larger percentage of pigs were slaughtered during their second year in the Late Roman period (AD 300–450). Measurements on pig bones also show significantly higher values for the Late Roman period, suggesting that the animals — as they could become somewhat older during this time — also became larger and, as a consequence, were yielding more meat (De Cupere 2001, 82). Dental measurements suggest a larger type of pigs during the Imperial and Late Roman period than during the subsequent Early Byzantine period, a phenomenon that is also observed in European sites (Vanpoucke 2008, fig 4.2, 92). Pig bones showed high contents of heavy metals during the whole occupation period of Sagalassos, indicating that these animals were mainly being herded in, or, fed with fodder from polluted areas, i.e. in the vicinity of the city (Vanhaverbeke *et al.* in prep.).

Linear enamel hypoplasia LEH is a deficiency in enamel thickness occurring during tooth crown formation, visible as lines or depressions on the enamel surface, and caused by stress of infectious or nutritional nature (food availability and quality), or by physiological stress at birth or weaning (Goodman and Rose 1990). Dobney and Ervynck (2000) have established that in domestic pigs and wild boar, depressions found on the second and third molar can be assigned to food shortage during the winter period, while lines are more likely to reflect random stress events (e.g. diseases) (Dobney *et al.* 2002).

At Sagalassos, winter depressions are frequently found on pig second molars, but are much less common on their third molars (Vanpoucke *et al.* 2007; Vanpoucke 2008). Almost half of the population may thus have had feeding shortages in their first winter, a period during which the second molar is formed, but only few animals during their second winter, when the third molar is formed. Assuming that all pigs would have been fed equally well if kept in sties, the discrepancy between the second and third molars suggests that they were not kept in enclosures but rather were free-ranging. Further, the hypoplasia-index, which evaluates overall rates of occurrence for a population (Dobney *et al.* 2007; Ervynck and Dobney 1999), of the Sagalassos pigs was found to be similar to that of recent Asian wild boars (Vanpoucke *et al.* 2007). Therefore, it was concluded that the pigs of Sagalassos were most probably free-ranging. Older pigs (aged more than one year) may be able to forage more effectively during times of scarcer food availability in winter

Material and methods

Microwear was sampled and recorded following the protocol used in previous studies of pig teeth (Dobney *et al.* 2005; Wilkie *et al.* 2007; Mainland *et al.* in prep.). Analysis focused on facet 9 (bucco-posterior cusp) of the mandibular second molar (M2), a crushing facet which is widely used in microwear analysis (e.g. Teaford 1994). The suitability of this facet for analysis is affected by the degree of wear: in pigs optimal results are obtained when the tooth exhibits a Grant's wear stage between 'a' and 'e'; at greater wear stages the facet is obliterated (Grant 1982). Teeth with wear stages greater than 'e' were thus not used. The total number of pig teeth from Sagalassos that were retained for microwear analysis is 60. These were grouped into three chronological periods: the Imperial (n=17), the Late Roman (n=20), and the Early Byzantine (n=23). Molar wear stages of the studied teeth are given in Table 1.

Dental replicas (negative=Coltène President Plus Jet, Regular Body; positive=Araldite (MY753-KG/HY956-KG were examined for microwear using an environmental scanning electron microscope (FEI Quanta 400 ESEM). Images of the enamel surface on facet 9 were captured at 500x and all visible microwear defects were counted and measured for orientation, maximum length and breadth using Microware 4·02 (Ungar 2002). Features were classified into different feature types using the length to breadth ratios outlined in Wilkie *et al.* (2007).

A comparison was made between the microwear of the Sagalassos pigs and the pigs previously examined by Mainland and colleagues (Wilkie *et al.* 2007; Mainland *et al.* in prep.). The latter material is from various European archaeological sites spanning the Mesolithic (Noyen-sur-Seine – France, Sludegard – Denmark and Bloksbjerg – Denmark), Neolithic (Bercy – France, Villeneuve-Tolosane-Cugnaux – France, Troldebjerg – Denmark, Makriyalos – Greece and Arbon – Switzerland), Roman (Elm's farm – UK) and medieval periods (Coppergate – UK and Fishergate – UK), from modern rooting pigs, i.e. farmed wild boar reared in paddocks (Northumberland – UK and Yorkshire – UK) and free-ranging wild boar and domestic pigs living in forest environments (Eberswalde – Germany and Inverness – UK, respectively).

The data of all samples were subjected to descriptive statistics, which were visualised in boxplots, and tested for normality using the Kolmogorov-Smirnov test with Liliefors Significance Correction (Norušis 1990). A parametric ANOVA test, followed by Scheffé post-hoc test and a non-parametric Kruskal-Wallis test, was then carried out to identify statistical significant differences between the different samples. These univariate statistical tests were all performed in SPSS 12·0. The data were next subjected to multivariate analyses, i.e. principal component analysis (PCA) and cluster analysis, which consider the influence of all examined variables at the same time. For the intra-site comparison of the three Sagalassos samples, all variables were included in these multivariate analyses. When the Sagalassos data were compared with the other samples, three variables (slov, % rp and % ns) had to be omitted from the analysis because these data were not available for all groups studied (Wilkie *et al.* 2007). PCA and cluster analysis were undertaken using Microsoft XLStat.

Results

Comparison of Sagalassos with other archaeological and modern material

Data from each period at Sagalassos was compared to the archaeological and modern material outlined above using descriptive statistics (Table 2; Fig. 2). All three chronological groups from Sagalassos exhibit pits and striations that are smaller, in terms of both length and breadth, than the other archaeological and modern material. In addition, considerably less variation is exhibited by the Sagalassos samples. The means of these variables in the Sagalassos pigs are most similar to those of the modern rooting pigs (both paddocked and from forest environments) but differ greatly from the Roman and medieval pigs. A similar trend is observed for density, although here the variation in the three Sagalassos samples is somewhat larger. Another variable, the percentage of pits, shows mean values for the Sagalassos groups intermediate between the modern pigs and, Roman and medieval pigs. Three variables (the percentage of rounded pits, the percentage of narrow striations and the standard deviation of striation orientation) have not been considered here, since data are not available for the Roman and medieval sites.

Table 1 Grant wear stages of the studied molar pig teeth of Sagalassos

Tooth Wear Stage according to Grant (1982)	Imperial	Late Roman	Early Byzantine
a	5	6	6
b	2	6	5
c	5	3	7
d	2	2	4
e	3	3	1

Table 2 Summary of the descriptive statistics and normality tests of the microwear data obtained from modern and archaeological pig teeth samples (slov: standard deviation for striation orientation)

							Kolmogorov-Smirnov		
		N	**mean**	**median**	**variance**	**SD**	**Stat**	**df**	**Sig.**
pit length	Mesolithic	4	7·2	6·4	11·291	3·36015	.269	4	.
	Neolithic	41	6·0	5·8	2·468	1·57094	.126	41	.100
	Roman	8	7·2	6·8	4·053	2·01331	.191	8	.200
	Medieval	14	7·9	7·5	5·980	2·44538	.188	14	.193
	Modern forest	13	5·1	5·0	.533	.73027	.109	13	.200
	Modern paddocked	10	7·9	6·7	17·617	4·19723	.322	10	.004
	Sagalassos Imperial	17	3·3	3·1	.183	.42790	.159	17	.200
	Sagalassos Late Roman	20	3·5	3·5	.227	.47658	.201	20	.033
	Sagalassos Early Byzantine	23	3·5	3·3	.397	.62975	.199	23	.019
pit breadth	Mesolithic	4	3·6	3·9	.485	.69622	.349	4	.
	Neolithic	41	2·7	2·5	.381	.61739	.149	41	.022
	Roman	8	3·9	3·7	1·129	1·06262	.233	8	.200
	Medieval	14	4·7	4·6	1·498	1·22408	.178	14	.200
	Modern forest	13	2·7	2·5	.269	.51862	.337	13	.000
	Modern paddocked	10	3·4	2·8	2·654	1·62918	.259	10	.057
	Sagalassos Imperial	17	1·6	1·6	.028	.16596	.174	17	.184
	Sagalassos Late Roman	20	1·7	1·7	.030	.17282	.116	20	.200
	Sagalassos Early Byzantine	23	1·7	1·6	.096	.30953	.178	23	.056
striation length	Mesolithic	4	25·8	25·8	35·815	5·98459	.229	4	.
	Neolithic	41	22·6	21·4	52·440	7·24153	.124	41	.114
	Roman	8	26·6	25·8	28·788	5·36543	.195	8	.200
	Medieval	14	26·0	28·5	67·097	8·19130	.204	14	.119
	Modern forest	13	20·0	19·3	10·769	3·28168	.118	13	.200
	Modern paddocked	10	21·1	21·1	37·865	6·15343	.202	10	.200
	Sagalassos Imperial	17	5·4	5·5	.536	.73196	.147	17	.200
	Sagalassos Late Roman	20	6·4	6·1	2·101	1·44957	.131	20	.200
	Sagalassos Early Byzantine	23	5·9	5·8	1·082	1·03998	.099	23	.200
striation breadth	Mesolithic	4	2·7	2·7	.542	.73605	.258	4	.
	Neolithic	41	1·7	1·7	.196	.44236	.167	41	.005
	Roman	8	2·5	2·5	.168	.41022	.182	8	.200
	Medieval	14	3·3	3·2	.982	.99072	.118	14	.200
	Modern forest	13	1·8	1·7	.106	.32547	.210	13	.121
	Modern paddocked	10	1·7	1·7	.068	.26136	.217	10	.200
	Sagalassos Imperial	17	.7	.6	.016	.12804	.233	17	.015
	Sagalassos Late Roman	20	.9	.9	.032	.17888	.164	20	.165
	Sagalassos Early Byzantine	23	.6	.6	.018	.13319	.208	23	.011
% pits	Mesolithic	4	30·9	18·3	1266·782	35·59188	.382	4	.
	Neolithic	41	21·2	15·8	393·113	19·82707	.175	41	.003
	Roman	8	60·8	59·9	222·773	14·92558	.179	8	.200
	Medieval	14	81·0	78·8	113·232	10·64104	.142	14	.200
	Modern forest	13	34·2	34·5	225·685	15·02283	.138	13	.200
	Modern paddocked	10	25·7	25·3	284·332	16·86215	.126	10	.200
	Sagalassos Imperial	17	49·3	49·4	314·122	17·72349	.086	17	.200
	Sagalassos Late Roman	20	59·2	61·4	111·465	10·55769	.130	20	.200
	Sagalassos Early Byzantine	23	42·9	48·2	193·794	13·92098	.169	23	.086
density	Mesolithic	4	878·8	955·8	136014·92	368·80200	.210	4	.
	Neolithic	41	1664·1	1464·3	1178054·5	1085·3822	.136	41	.053
	Roman	8	3792·1	3773·4	1070567·7	1034·6824	.178	8	.200
	Medieval	14	3497·1	3454·2	686168·41	828·35283	.106	14	.200
	Modern forest	13	1725·6	1576·9	1221012·4	1104·9943	.201	13	.158
	Modern paddocked	10	1843·7	1518·4	2356118·0	1534·965	.333	10	.002
	Sagalassos Imperial	17	837·4	772·1	136873·86	369·96467	.127	17	.200
	Sagalassos Late Roman	20	589·3	521·8	140721·97	375·12927	.159	20	.199
	Sagalassos Early Byzantine	23	691·2	698·3	129668·56	360·09520	.099	23	.200

PCA identifies three clusters of data points (i.e. of individual tooth samples) (Fig. 3). A first cluster comprises the Sagalassos teeth in the outer left-hand-side of the graph. On the opposite side (upper right), the Roman and medieval pig teeth tend to group together, while the modern material and the Mesolithic and Neolithic samples are plotted mainly in the lower right quadrant of the diagram. Cluster analysis of all data resulted in the same groups as given by the PCA and is therefore not included here.

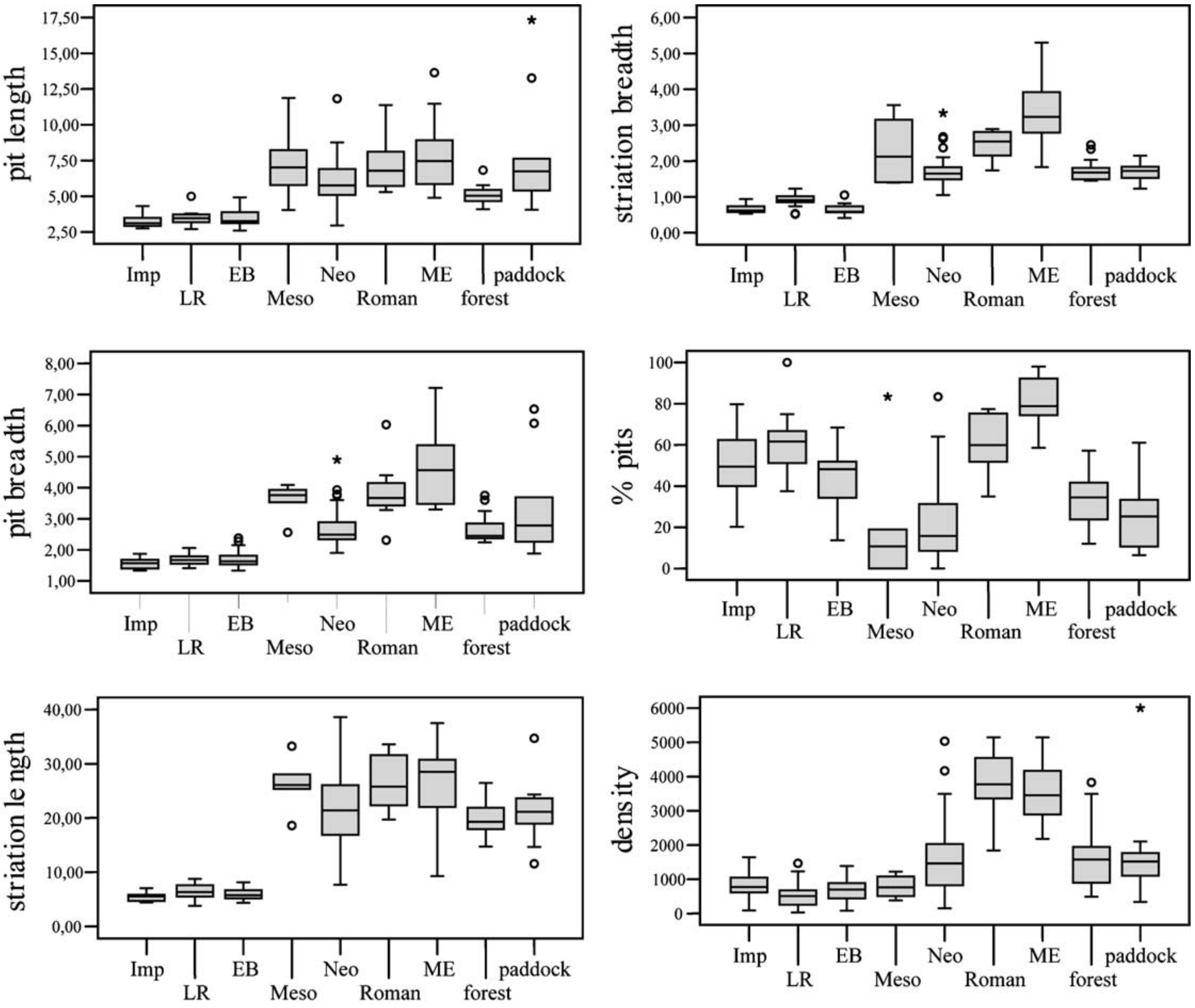

Figure 2 Box-plots summarizing the descriptive statistics of the microwear data obtained from archaeological and modern samples (*Sagalassos*: Imp: Imperial – LR: Late: Roman – EB: Early Byzantine; *other archaeological*: Meso: Mesolithic – Neo: Neolithic – Roman – ME: Medieval; *modern*: forest: forest free-ranging wild boar and domestic pigs – paddock: paddocked but rooting wild boar)

Sagalassos

The results of the descriptive statistics and the univariate tests for the three Sagalassos samples are given in Tables 3–6. Significant differences are found between the Imperial and the Late Roman period on striation length (sl), striation breadth (sb) and the percentage of narrow striations (% ns), with teeth from the latter period having longer and broader striations, and a lower percentage of narrow striations (Fig. 4). The teeth from the Late Roman period exhibit not only broader striations and a lower percentage of narrow striations compared to those from the Early Byzantine period, but also show a higher percentage of pits (% pits). Significant differences between the Imperial and the Early Byzantine period were only found in the percentage of narrow striations (% ns). The length and breadth of the pits do not appear to change significantly through time, nor do the percentage of rounded pits (% rp), the striation orientation (slov) and the density of features (Table 5). However, visual appreciation of the box-plots in Fig. 4 suggests a lower density of features during the Late Roman period.

The PCA-graph shows that most of the Late Roman data cluster together in the lower half of the graph, while the observations of the Imperial and Early Byzantine samples overlap largely in the left part of the graph (Fig. 5). The separation of the late Roman observations is caused by the second principal component, which is mainly determined by three variables, i.e. striation breadth (sb), percentage narrow striations (% ns) and percentage pits (% pits), as was already evident from the univariate statistics.

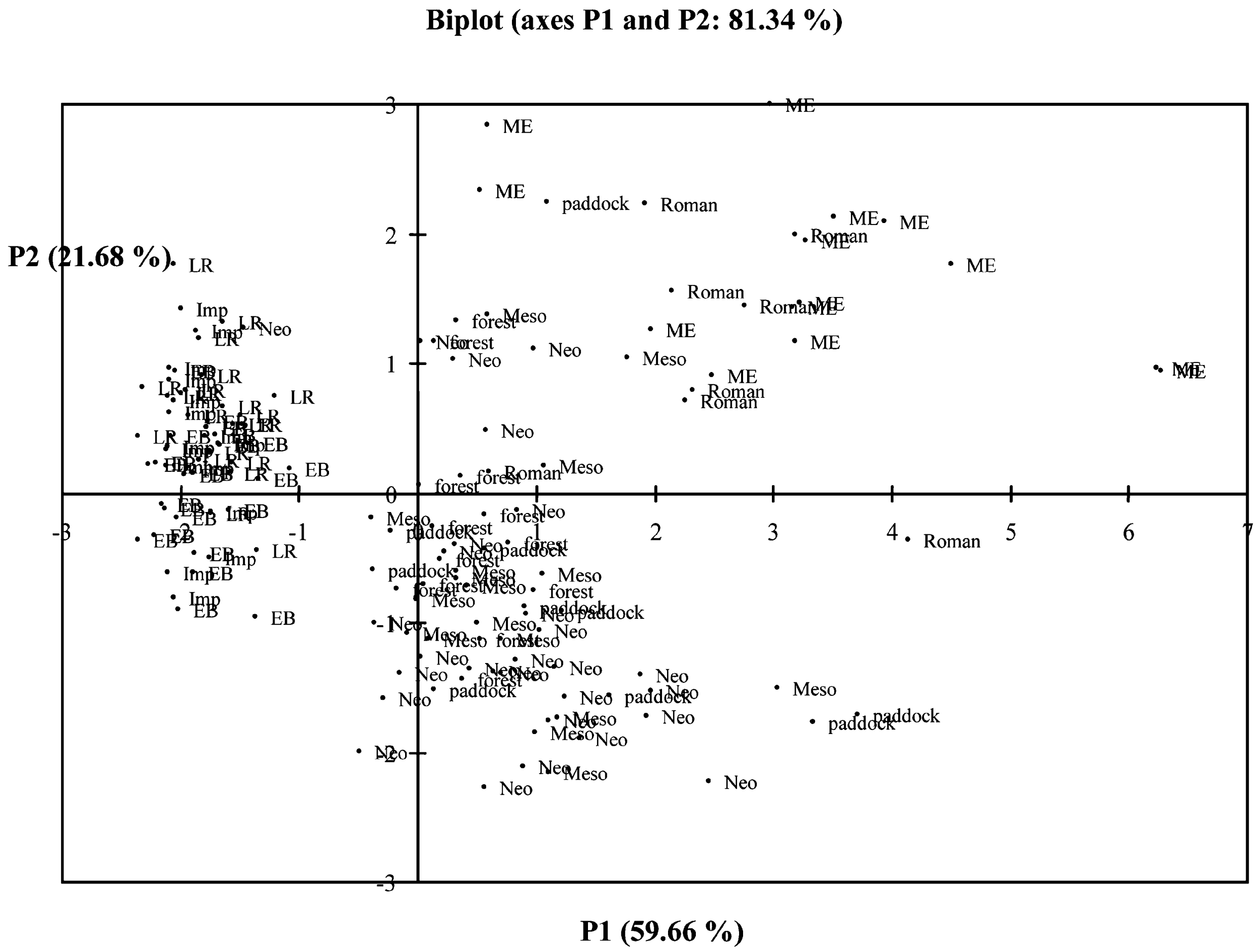

Figure 3 PCA-graph based on the microwear data obtained from archaeological and modern samples (for abbreviations see Figure 2)

A similar clustering is given by the cluster analysis (Fig. 6): a first group mainly consists of Late Roman material (Fig. 6: cluster B), while a second group comprises most of the Imperial and Early Byzantine material (Fig. 6: cluster A). The dendrogram, however, shows the presence of a third, small group, represented by six Early Byzantine specimens and one Late Roman specimen (Fig. 6: cluster C). These teeth are also represented by the points in the right upper part of the PCA plot (Fig. 5) but were not initially recognised as a separate cluster. The separation of this cluster, on the first principal component, is determined by the dimensions of the features (pit breadth and length, striation breadth and length). Qualitative examination of the teeth indicated that five of the six Early Byzantine specimens exhibited an eroded surface.

Discussion

Inter-observer error

There is growing appreciation amongst microwear researchers that how microwear features are recorded can vary between observers and that this can affect the comparability of results between researchers (Grine *et al.* 2002; Galbany *et al.* 2005). This raises the possibility that the differences observed, especially in feature size, between the Sagalassos samples and the material previously studied by Mainland and colleagues, could have been biased by the observers themselves. Although the same methodology was used by all researchers, it is possible that the differences in pit size and frequency reflect a difference in feature recognition between researchers, more precisely by using a smaller visual cut-off point for recording features (Grine *et al.* 2002). To test this possibility, a between groups analysis was undertaken in which very small pits (breadth $<1\ \mu m$) and small striations (breadth $<0{\cdot}5\ \mu m$) — the size range over which inter-observer discrepancy was considered most likely — were excluded. For this purpose 20 cases were randomly chosen from both the Sagalassos material and the database composed by Mainland and colleagues. A Mann-Whitney-U test on this data after removal of the smaller features indicates that

Table 3 Descriptive statistics and normality tests of the microwear data obtained from the Sagalassos samples (slov: standard deviation for striation orientation)

							Kolmogorov-Smirnov		
	Period	N	mean	median	variance	SD	Stat	df	Sig.
pit length	Imperial	17	3·3	3·1	.183	.42790	.159	17	.200
	Late Roman	20	3·5	3·5	.227	.47658	.201	20	.033
	Early Byzantine	23	3·5	3·3	.397	.62975	.199	23	.019
pit breadth	Imperial	17	1·6	1·6	.028	.16596	.174	17	.184
	Late Roman	20	1·7	1·7	.030	.17282	.116	20	.200
	Early Byzantine	23	1·7	1·6	.096	.30953	.178	23	.056
striation length	Imperial	17	5·4	5·5	.536	.73196	.147	17	.200
	Late Roman	20	6·4	6·1	2·101	1·44957	.131	20	.200
	Early Byzantine	23	5·9	5·8	1·082	1·03998	.099	23	.200
striation breadth	Imperial	17	.7	.6	.016	.12804	.233	17	.015
	Late Roman	20	.9	.9	.032	.17888	.164	20	.165
	Early Byzantine	23	.6	.6	.018	.13319	.208	23	.011
slov	Imperial	17	41·5	41·1	231·826	15·22584	.100	17	.200
	Late Roman	20	47·0	52·7	367·912	19·18102	.150	20	.200
	Early Byzantine	23	43·2	44·2	180·777	13·44534	.136	23	.200
% rounded pits	Imperial	17	47·1	45·3	75·773	8·70477	.164	17	.200
	Late Roman	20	48·2	48·9	171·258	13·08656	.180	20	.200
	Early Byzantine	23	44·6	47·3	105·170	10·25524	.134	23	.200
% narrow striations	Imperial	17	31·2	30·3	177·873	13·33690	.101	17	.200
	Late Roman	20	18·1	16·3	68·060	8·24983	.141	20	.200
	Early Byzantine	23	41·5	42·6	149·010	12·20697	.146	23	.200
% pits	Imperial	17	49·3	49·4	314·122	17·72349	.086	17	.200
	Late Roman	20	59·2	61·4	111·465	10·55769	.130	20	.200
	Early Byzantine	23	42·9	48·2	193·794	13·92098	.169	23	.086
density	Imperial	17	837·4	772·1	136873·86	369·96467	.127	17	.200
	Late Roman	20	589·3	521·8	140721·97	375·12927	.159	20	.199
	Early Byzantine	23	691·2	698·3	129668·56	360·09520	.099	23	.200

Table 4 Summary of the ANOVA test of the microwear data obtained from the Sagalassos samples (slov:: standard deviation for striation orientation)

		Sum of Squares	df	Mean Square	F	Sig.
pit length	Between Groups	.872	2	.436	1·534	.224
	Within Groups	16·491	58	.284		
	Total	17·364	60			
pit breadth	Between Groups	.266	2	.133	2·477	.093
	Within Groups	3·116	58	.054		
	Total	3·382	60			
striation length	Between Groups	9·327	2	4·663	3·741	* .030
	Within Groups	72·291	58	1·246		
	Total	81·618	60			
striation breadth	Between Groups	.855	2	.428	19·681	* .000
	Within Groups	1·261	58	.022		
	Total	2·116	60			
slov	Between Groups	311·236	2	155·618	.615	.544
	Within Groups	14676·639	58	253·046		
	Total	14987·875	60			
% rounded pits	Between Groups	238·425	2	119·213	.948	.393
	Within Groups	7294·698	58	125·771		
	Total	7533·123	60			
% narrow striations	Between Groups	5868·646	2	2934·323	22·549	* .000
	Within Groups	7417·323	57	130·128		
	Total	13285·969	59			
% pits	Between Groups	3726·961	2	1863·480	8·320	* .001
	Within Groups	12990·676	58	223·977		
	Total	16717·637	60			
density	Between Groups	709790·859	2	354895·430	2·568	.085
	Within Groups	8016396·968	58	138213·741		
	Total	8726187·827	60			

Table 5 Scheffé post-hoc test of the microwear data obtained from the Sagalassos samples; * indicates significant differences at the 0·05 level (slov: standard deviation for striation orientation)

	Imperial *vs* Late Roman	Imperial *vs* Early Byzantine	Late Roman *vs* Early Byzantine
pit length	0·576	0·225	0·776
pit breadth	0·262	0·106	0·883
striation length	* 0·030	0·411	0·321
striation breadth	* 0·000	0·829	* 0·000
slov	0·571	0·944	0·734
% rounded pits	0·836	0·791	0·395
% narrow striations	* 0·004	* 0·023	* 0·000
% pits	0·059	0·420	* 0·001
density	0·086	0·474	0·522

significant differences are still evident between the Sagalassos material and comparative data (Table 7). Furthermore, box-plots show that the variation in feature size at Sagalassos is very small and that larger features, which cannot be overlooked by the observer, were not noted at all, in contrast to the pig teeth studied by Mainland and colleagues (Fig. 2). This suggests that the smaller features observed in the Sagalassos pigs are most probably not a reflection of differences in feature recognition. Therefore, other factors must be responsible for the observed differences in microwear patterns.

Free-ranging versus stall-fed

The pit to striation ratio, or percentage pits, is central for microwear interpretation and forms the basic characteristic for distinguishing, among others, browsers and grazers (Walker *et al.* 1978; Solounias and Semprebon 2002), primate folivores and frugivores (Teaford and Walker 1984) and primate grazers, folivores and rooters (Daegling and Grine 1999). This is primarily because the ratio of pits and striations is thought to reflect a combination of the biomechanics of mastication (masticatory movements and force of mastication), food texture (hard *versus* soft diet) and abrasiveness (size and quantity of consumed abrasives, such as phytoliths and soil particles). Further, feature dimensions, in particular pit size have been related to food texture (e.g. Walker 1984; Teaford and Oyen 1989; Rose and Ungar 1998). While large pits originate during the consumption of hard food, as a consequence of the high vertical compressive forces required to break it into pieces and chew it, small pitted features are thought to form during the consumption of a soft diet. A soft diet allows more tooth–ooth contact and small, prism-size enamel fragments are plucked from the enamel surface by adhesive forces.

In pigs, it has been argued that pit relative frequency (percentage pits) is indicative of the level of abrasives consumed and in particular the amount of soil ingested, such that high levels of soil ingestion are associated with few pits and many striations (Ward and Mainland 1999; Wilkie *et al.* 2007). A similar association between striations and soil ingestion has been documented in other species (Teaford and Lytle 1996; Ungar and Teaford 1996; Teaford *et al.* 2001; Silcox and Teaford 2002; Mainland 2003). This association has led to the suggestion that pit relative frequency can be used to distinguish stall-fed and free-ranging/rooting pigs and has enabled identification of stall-fed animals in Roman and medieval archaeological contexts in the UK (Wilkie *et al.* 2007, tables 13·2 and 13·3). The interpretation of feature dimensions in pigs is, however, more difficult, partly because no data on food texture was available for the modern pigs studied by Ward and Mainland (1999).

Considering Teaford and Oyen's (1989) model for small pit formation, it can be assumed — and that this model has been shown to be applicable in species other than primates lends some support to this assumption (e.g. Mainland and Halstead 2004) — that the prevalence of small microwear features in the Sagalassos material is indicative of a soft, non-abrasive diet. Further, pit percentages for the Sagalassos teeth

Table 6 Non parametrical Kruskal-Wallis analysis of the microwear data obtained from the Sagalassos samples (slov: standard deviation for striation orientation)

	pit length	pit breadth	striation length	striation breadth	slov	% rounded pits	% narrow striations	% pits	density
Chi-Square	2·789	4·204	5·689	20·135	1·755	1·151	27·259	13·532	5·007
df	2	2	2	2	2	2	2	2	2
Asymp. Sig.	0·248	0·122	0·058	0·000*	0·416	0·562	0·000*	0·001*	0·082

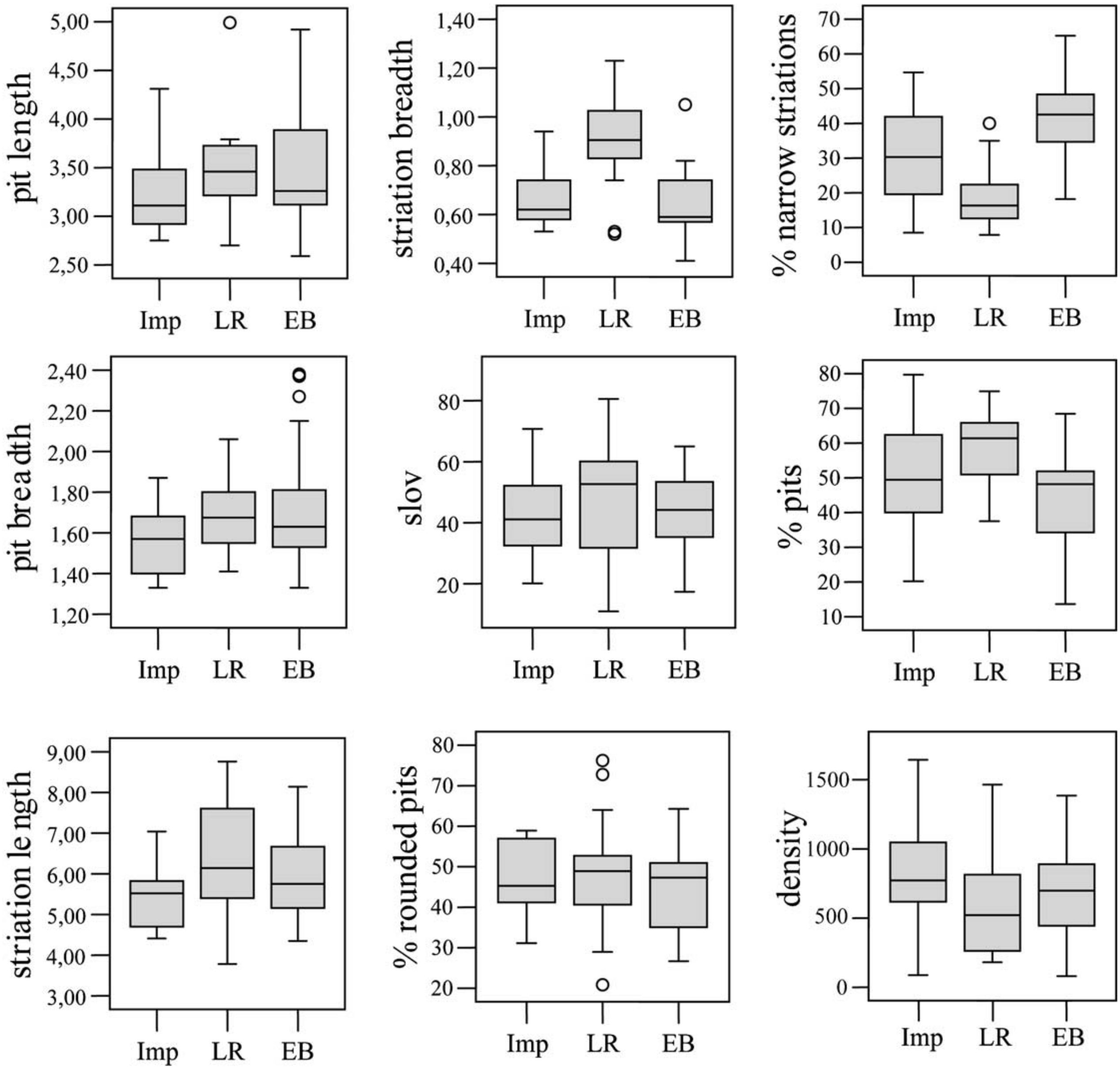

Figure 4 **Box-plots summarizing the descriptive statistics of the microwear data obtained from the Sagalassos samples (Imp: Imperial; LR: Late Roman; EB: Early Byzantine; slov: standard deviation for striation orientation)**

fall between values observed for the modern rooting pigs and the archaeological Roman/medieval pigs, which have been interpreted as stall-fed pigs (Ward and Mainland 1999; Wilkie *et al.* 2007). Together this may be suggestive of stall-fed animals at Sagalassos. This conclusion, however, would seem to contradict other data on pig husbandry from Sagalassos, namely that derived from linear enamel hypoplasia (see above) which indicates that the Sagalassos pigs were free-ranging. Further, both the univariate (Table 2; Fig. 2) and the multivariate statistics (Fig. 3) indicate that the Sagalassos pigs have a rather distinctive microwear pattern in comparison to the modern and archaeological samples examined by Mainland *et al.* (Ward and Mainland 1999; Wilkie *et al.* 2007), and may thus have a different etiology.

Influence of the substrate

An explanation for the distinctive microwear of the Sagalassos pigs may lie in the geology of the Sagalassos region. Substrate will have an impact on microwear through the hardness and morphology of mineral particles ingested with soil during foraging. This is particularly relevant for pigs which are known to ingest significant quantities of soil when rooting (Fries *et al.* 1982). The territory of Sagalassos is about 1800 km^2 and is mainly characterised by limestones, flysch deposits and ophiolites (Waelkens

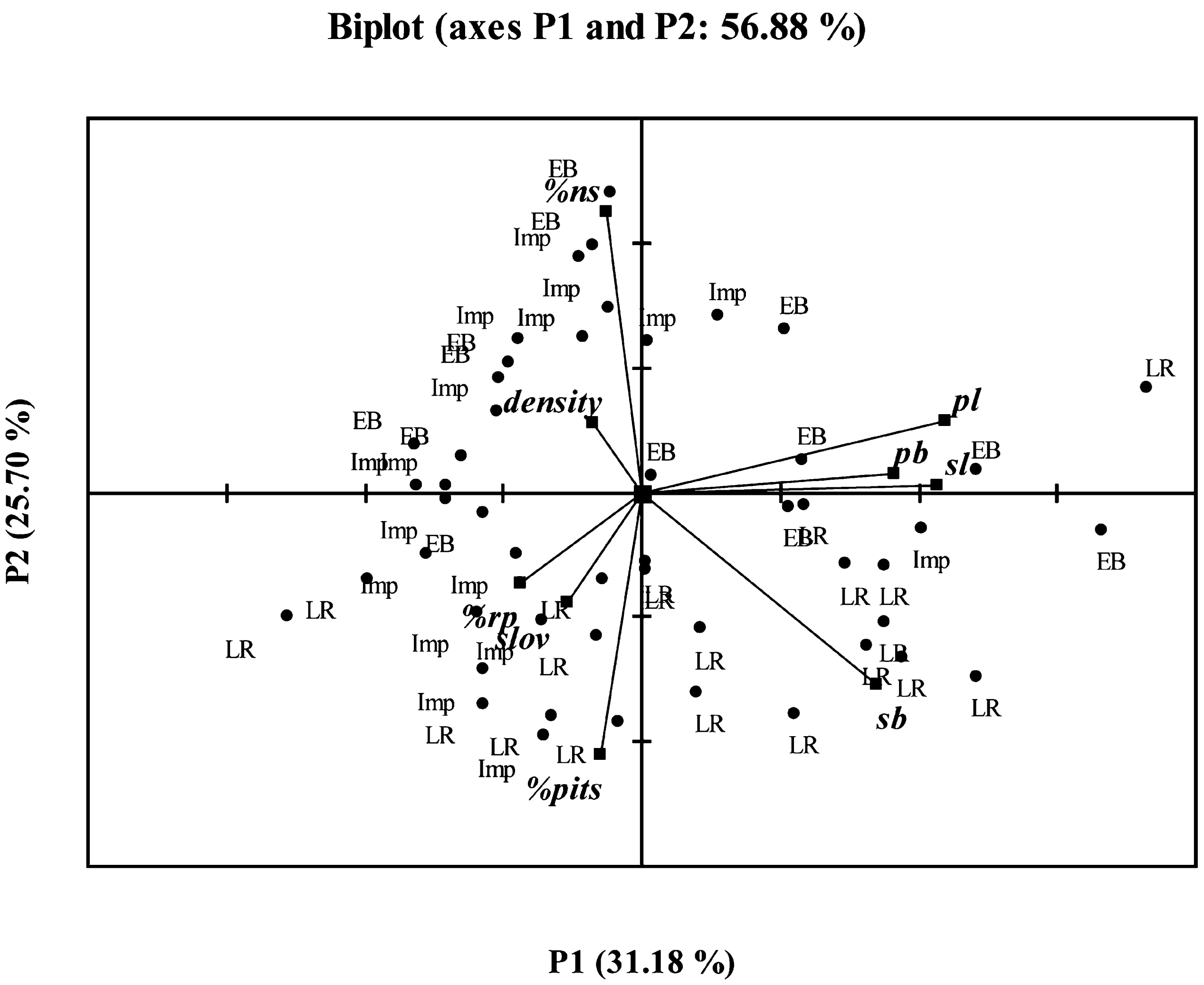

Figure 5 PCA-graph based on the microwear data obtained from the Sagalassos samples (Imp: Imperial; LR: Late Roman; EB: Early Byzantine; pl: pit length; pb: pit breadth; sl: striation length; sb: striation breadth; slov: standard deviation for striation orientation; %rp: % rounded pits; %ns: % narrow striations)

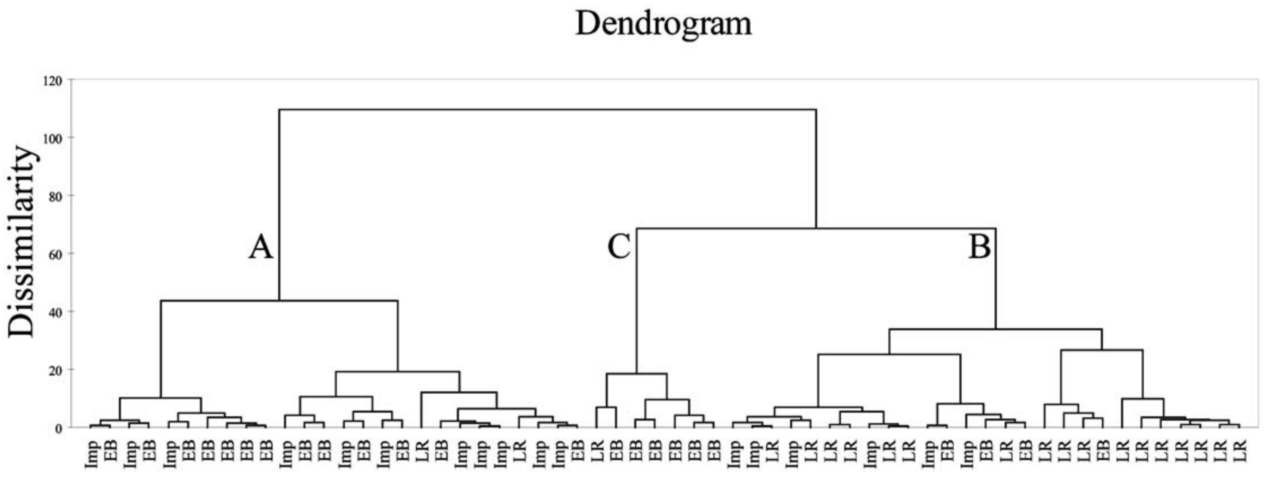

Figure 6 Dendrogram representing the cluster analysis of the microwear data obtained from the Sagalassos samples (Imp: Imperial; LR: Late Roman; EB: Early Byzantine)

Table 7 Mann-Whitney-U test on random cases of two observers, after removal of the smaller features; * indicates significant differences between both samples at the 0·05 level (IM: observers I. Mainland and colleagues; SVP: observer S. Vanpoucke)

Ranks

	subsample	N	Mean Rank	Sum of Ranks
	IM	20	26·98	539·50
pit length	SVP	20	14·03	280·50
	Total	40		
	IM	20	27·55	551·00
pit breadth	SVP	20	13·45	269·00
	Total	40		
	IM	20	29·55	591·00
striation length	SVP	20	11·45	229·00
	Total	40		
	IM	20	29·65	593·00
striation breadth	SVP	20	11·35	227·00
	Total	40		

Test statistics

	pit length	pit breadth	striation length	striation breadth
Mann-Whitney-U	70·500	59·000	19·000	17·000
Wilcoxon W	280·500	269·000	229·000	227·000
Z	−3·503	−3·815	−4·896	−4·951
Asymp. Sig. (2-tailed)	.000*	.000*	.000*	.000*

and Degryse 2003; Waelkens *et al.* 2003a; Degryse and Poblome 2008; Degryse *et al.* 2008). The main component of limestones are carbonates (3 on Mohs' hardness scale) which are not hard enough to scratch tooth enamel (5 on Mohs' hardness scale). The flysch deposits, on the contrary, contain a lot of quartz (7 on Mohs' scale) and are therefore capable of producing microwear features on the enamel surface. The ophiolites within the territory of Sagalassos are mainly composed of serpentine, clay and some weathered feldspars; only the feldspars are able to scratch enamel (P. Degryse, pers. comm.). When the modern suid material is considered, the Inverness pigs come from a quartz rich geological area, and quartz minerals were present in dung samples from the Yorkshire pigs. No information on the geological background of the pigs from Eberswalde is available. The Roman and medieval material, the so-called stall-fed pigs, was collected from sites in the UK. Coppergate and Fishergate (York) are both located in an area of sandstone but there are calcareous areas close by. Elms Farm is situated on the Essex gravels but again is close to areas of calcareous soils. Thus, although there might be a carbonate component, both the modern rooting pigs and the archaeological 'stall-fed pigs' originate from areas with a quartz-based geology; this is in contrast to the Sagalassos pigs which had been living on a more pronounced calcareous substrate. The small dimensions of the microwear features in the Sagalassos material, in comparison to the modern rooting pigs and the stall-fed pigs considered here, may therefore be the result of their different geological background.

Some of the archaeological sites studied by Mainland and colleagues are also located in areas in which the bedrock is calcareous, e.g. Neolithic Arbon, or mainly calcareous, e.g. Neolithic Makriyalos (Mainland *et al.* in prep.) but microwear patterns from these sites are again different to that evident at Sagalassos. Feature dimensions (pl, pb, sl, sb) on the Sagalassos teeth are significantly smaller than those of both Neolithic sites (Table 8; Fig. 7), and are thus not what might be anticipated if the pigs of all three locations consumed soil particles with a similar hardness. Microwear patterns of sheep and goat teeth have also been investigated for Makriyalos (Mainland and Halstead 2004, fig. 5) and Sagalassos (Beuls 2004, calculated from table V.16). When considering, e.g. the sheep, similar values of the feature dimensions were found for the Makriyalos sheep and modern sheep that had been herded on a calcareous substrate near Sagalassos, while sheep that were herded on both calcareous and flysch soils near the latter site exhibited larger microwear features (Table 9). This is in accordance with Solounias and Semprebon (2002) who associated heavier striations and larger pits with a more abrasive diet consisting of bigger abrasive particles. When the pit percentage (% pits) of microwear in pigs is then considered, the Makriyalos values are significantly lower than those in the Sagalassos material (Table 8, Fig. 7). The low values of the pit percentage suggest that the pigs at these Neolithic sites were more likely to be free-ranging than enclosed in sties. And, indeed, in the PCA-plot their data points cluster together with the modern rooting pigs (Fig. 3). Therefore, it is quite unlikely that the small dimensions of the microwear features observed in the Sagalassos pig teeth, when compared to the rooting pigs and the stall-fed pigs, can (solely) be explained by differences in geological background; they are more likely to be the result of a soft diet with an almost complete lack of abrasive soil particles.

Variation of microwear features

Little variation in feature dimensions is observed among the modern rooting pigs, and especially the

Table 8 Summary of the ANOVA and Scheffé post-hoc test of the microwear data, obtained from the pig teeth of Sagalassos and, of Neolithic Arbon and Makriyalos (Imp: Imperial; LR: Late Roman; EB: Early Byzantine)

	ANOVA					
		Sum of Squares	df	Mean Square	F	Sig.
pit length	Between Groups	98·126	4	24·532	40·546	.000*
	Within Groups	50·217	83	.605		
	Total	148·344	87			
pit breadth	Between Groups	13·558	4	3·390	32·459	.000*
	Within Groups	8·667	83	.104		
	Total	22·226	87			
striation length	Between Groups	5053·442	4	1263·361	73·152	.000*
	Within Groups	1433·442	83	17·270		
	Total	6486·885	87			
striation breadth	Between Groups	15·003	4	3·751	75·206	.000*
	Within Groups	4·139	83	.050		
	Total	19·142	87			
% pits	Between Groups	17609·023	4	4402·256	16·222	.000*
	Within Groups	22524·520	83	271·380		
	Total	40133·542	87			
density	Between Groups	26967246·981	4	6741811·745	13·177	.000*
	Within Groups	42465032·528	83	511626·898		
	Total	69432279·509	87			

	Scheffé					
		Arbon	Makriyalos	Sagalassos Imp	Sagalassos LR	Sagalassos EB
pit length	Arbon	/				
	Makriyalos	.996	/			
	Sagalassos Imp	.000*	.000*	/		
	Sagalassos LR	.000*	.000*	.971	/	
	Sagalassos EB	.000*	.000*	.837	.993	/
pit breadth	Arbon	/				
	Makriyalos	.992	/			
	Sagalassos Imp	.000*	.000*	/		
	Sagalassos LR	.000*	.000*	.841	/	
	Sagalassos EB	.000*	.000*	.663	.998	/
striation length	Arbon	/				
	Makriyalos	.999	/			
	Sagalassos Imp	.000*	.000*	/		
	Sagalassos LR	.000*	.000*	.969	/	
	Sagalassos EB	.000*	.000*	.998	.997	/
striation breadth	Arbon	/				
	Makriyalos	.762	/			
	Sagalassos Imp	.000*	.000*	/		
	Sagalassos LR	.000*	.000*	.047*	/	
	Sagalassos EB	.000*	.000*	.997	.008*	/
% pits	Arbon	/				
	Makriyalos	.977	/			
	Sagalassos Imp	.001*	.012*	/		
	Sagalassos LR	.000*	.000*	.306	/	
	Sagalassos EB	.008*	.099	.834	.013*	/
density	Arbon	/				
	Makriyalos	.997	/			
	Sagalassos Imp	.007*	.004*	/		
	Sagalassos LR	.000*	.000*	.846	/	
	Sagalassos EB	.000*	.000*	.981	.986	/

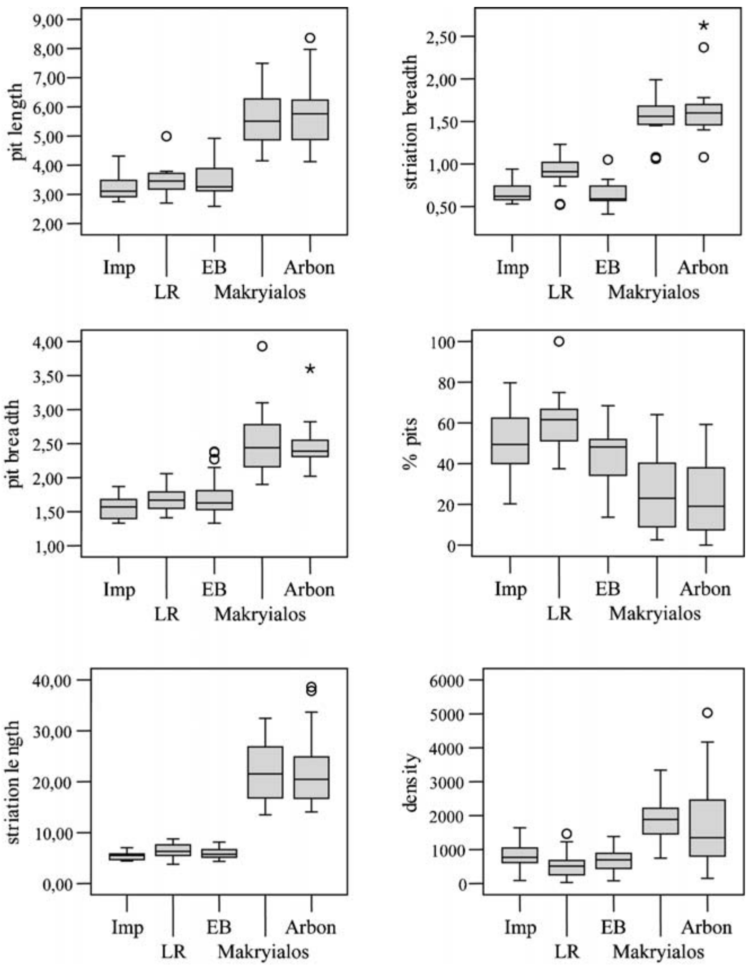

Figure 7 Box-plots summarizing the descriptive statistics of the microwear data obtained from the Sagalassos samples and two Neolithic sites (Imp: Imperial; LR: Late Roman; EB: Early Byzantine)

free-ranging pigs in forests (Fig. 2), even though the latter sample is drawn from two distinct areas (Germany and UK). The Roman and, especially, medieval samples show much greater variation, even though the material is derived from only one and two sites respectively. Although the diet of wild boar (Heptner *et al.* 1989) and presumably also of free-ranging pigs, includes a great variety of items, they are free to feed selectively. Such behaviour can result, depending on availability, in a diet composed of a more limited number of food items, which in turn could cause a less diversified microwear pattern and thus explain the low variation in feature dimensions among free-ranging pigs. The very low variation in feature dimensions among the Sagalassos pigs suggests that, beside its soft nature, the composition must have been rather homogeneous, favouring the idea that they were stall-fed. On the other hand, as indicated in the PCA-plot (Fig. 3), the microwear of the Sagalassos pigs is also very different from that observed in the Roman and medieval pigs. The latter had previously been identified as 'stall-fed', but being of archaeological origin are of course strictly of unknown diet.

Microwear and LEH

As indicated above, analysis of LEH suggests that the Sagalassos pigs were most probably free-ranging

Table 9 Microwear data obtained from sheep of Neolithic Makriyalos and modern sheep from the territory of Sagalassos

	substrate	season	pit length	pit breadth	striation length	striation breadth	% pits
Makriyalos	Calcareous	–	5·42	2·78	17·94	1·33	20·65
	Calcareous	summer	4·81	2·31	20·00	1·53	35·11
Sagalassos	Flysh & calcareous	spring	9·92	5·60	51·98	1·83	24·86
	Flysh & calcareous	summer	10·03	5·54	66·07	1·99	33·52

(Vanpouke *et al.* 2007). The microwear analysis, on the other hand, indicates that the pigs were consuming soft fodder during at least a short time period prior to slaughtering. It is known that dental microwear shows a rapid turnover rate which may even be as fast as 2–3 days for highly abrasive diets (Teaford and Oyen 1989). The microwear results thus do not exclude the possibility that the pigs were eating other (harder) food, as would be expected from free-ranging/rooting populations, except for during the final phase of their lives. LEH and microwear together thus suggest that during most of their lives the pigs were herded in the environment surrounding the city of Sagalasso, but that just before slaughtering they were fattened, on soft food and in enclosures. This would be of no surprise considering that the city of Sagalassos was a typical consumer site, supplied with young, mainly male pigs (De Cupere 2001; Vanpoucke *et al.* 2007). Classical writers provide little information on the feeding of pigs, but Varro mentions mast as fodder — which suggests herding in woods — as well as beans, barley and other grains. Columella, on the other hand, lists a variety of foods but recommends a well-grassed orchard to fatten pigs for the table, as well as foods such as fruits, nuts and figs (White 1970, 318–19).

Diachronic changes at Sagalassos

Microwear patterning within the Sagalassos pigs varies through time with the Late Roman pigs in particular showing significant differences from the earlier (Imperial) and later (Early Byzantine) assemblages. Late Roman pigs have broader and longer striations (sb, sl and % ns) than in other periods and in addition exhibit a higher frequency of pitted features (% pits), though this variable is significant only between the Early Byzantine and Late Roman period. As already mentioned above, these changes could potentially be attributed to several factors both dietary and non-dietary, including variation in dietary hardness (e.g. Teaford and Walker 1984), the sise or quantity of abrasives consumed (Solounias and Semprebon 2002), and the biomechanics of mastication (Gordon 1982, 1984).

Gordon (1982; 1984), for example, has suggested that pit frequency (% pits) increases posteriorally along the molar row reflecting higher potential levels of compression at the back and a greater degree of lateral movement at the front of the mandible. As the microwear analysis of the entire sample from Sagalassos (and the other sites) was carried out on the same facet of the same tooth, the influence of such biomechanical factors can, however, be eliminated as a possible factor in the changes observed through time at Sagalassos.

When considering the influence of the abrasive particle size, it is generally held in the microwear literature that larger abrasive particles (exogenous or indigenous) will be reflected by larger features, whether striations or pits (e.g. Solounias and Semprebon 2002). If the pigs of Sagalassos were rooting pigs, they would presumably, like modern sheep (*cf.* Beuls 2004), exhibit more heavy striations and larger pits when herded on the gritty soils of the flysch deposits than on the limestones and ophiolites. Even the larger and longer striations on the tooth enamel of the Late Roman pigs, however, are too small to be caused by the influence of this abrasive flysch substratum. Changes of foraging areas with a different geological substrate can, therefore, be excluded as a cause for the observed differences in microwear. Diet variation, therefore, seems to be the most plausible explanation for the microwear differences observed between the three Sagalassos samples.

The diet of the pigs may have changed in the Late Roman period as a consequence of environmental change. Palynological research on two cores from the territory of Sagalassos showed the presence of vegetation assemblages that are indicative of a global trend towards aridification: the driest episodes were recorded between cal. AD 130 and 350 and this period corresponds with the so-called Roman Warming Period, characterised by a gradual decrease of rainfall and a progressive increase of temperature. During this period moister cultivated species disappeared or strongly decreased and led to a progressive arboricultural degradation. Olive trees which were, due to these favorable climatic conditions, introduced above 1400 m a.s.l., disappeared again from the pollen record around cal. AD 300. Further, wettest conditions were testified at cal. AD 400. These indications of climatic change during the Late Roman period are in agreement with global and Middle Eastern climatic studies which show increased precipitation levels around AD 400. After cal. AD 450 vegetation assemblages suggest a moister climate with slightly lower temperatures compared to the Roman era and a regeneration of alluvial woodland and pine forest with a dense undergrowth of deciduous oak (Kaniewski *et al.* 2007, with references therein). The observed environmental changes from the Imperial (25 BC–AD 300) to the Late Roman period (AD 300–450) may have brought about a diet that was tougher and/or higher in abrasives (e.g. Solounias and Semprebon 2002), resulting in larger features and a lower percentage of narrow striations in the Late Roman period.

Diet change may also have been the result of a changing economy through time. This observation is echoed in other aspects of the archaeozoological record. In the case of the pigs, mortality profiles indicate an older slaughtering age in the first half of the 4th century (De Cupere 2001; Vanpoucke *et al.* 2007) while metrical data demonstrate the presence of significantly larger individuals (Vanpoucke 2008). This indicates the breeding of larger animals that were rendering more meat, most possibly at a time when demand was higher. Indeed, there is evidence for a general agricultural intensification during the Late Roman period (Vanhaverbeke *et al.* in prep.). Rougher or marginal areas may have been exploited, and it is possible that pig breeders were using fodders of another kind (i.e. other grains, plants) or quality (i.e. tougher, drier). It should, however, be noted that the differences observed between the subsequent periods are not related to the differences in slaughter age *per se*, as the second molars that were used for this microwear study all show a Grant wear stage ranging from a to e, in about equal proportions (Table 1). The microwear study is thus based on pigs of similar ontogenetic ages.

A final remark has to be made about seven teeth from the Early Byzantine period which display an eroded surface. These teeth derive from different loci and are not biased towards particular parts of the site. None of the soils in the territory have an acid pH: Sagalassos is situated within a very carbonate rich environment and the pH of all the soils are considered neutral to alkaline (S. Deckers, pers. comm.) and hence an acid pH can be ruled out as a possible cause for the erosion. Furthermore, as alkaline soil types cause no alteration of microwear features, any influence of the soil itself can be excluded (King *et al.* 1999). A possible explanation for the eroded enamel surface is the acidity of the diet. Puech (1984) stated that mastication of fibrous acidic food items, such as unripe fruits, can cause an etching of the tooth enamel. This same pattern was found in orangutans feeding on acidic fruit flesh (Lucas 1989). Teaford (1988) also indicated that dietary acidity affects the rate of enamel wear as well as the overall appearance of microwear. As the appearance of the eroded enamel surfaces (Fig. 8) resembles closely the eroded surfaces examined by Puech (1984) and King *et al.* (1999), an acidic substance in the diet may explain the occurrence of these surfaces. In the territory of Sagalassos there is palynological evidence for grapevines, which have a very acid pH (Waelkens *et al.* 2003b), and macrobotanical remains evidence the presence of many different fruits and nuts, e.g. grape, fig, apple, elderberry and cherry at the site (E. Marinova, pers. comm.), both of which strongly support this interpretation. It can be concluded that the erosion of some teeth in the Early Byzantine period is most probably the result of the consumption of unripe acidic fruit by some individuals. Whether this reflects chance consumption of fruits by pigs foraging freely through the territory or the feeding of fruit garbage to stalled pigs cannot be ascertained from the microwear evidence alone.

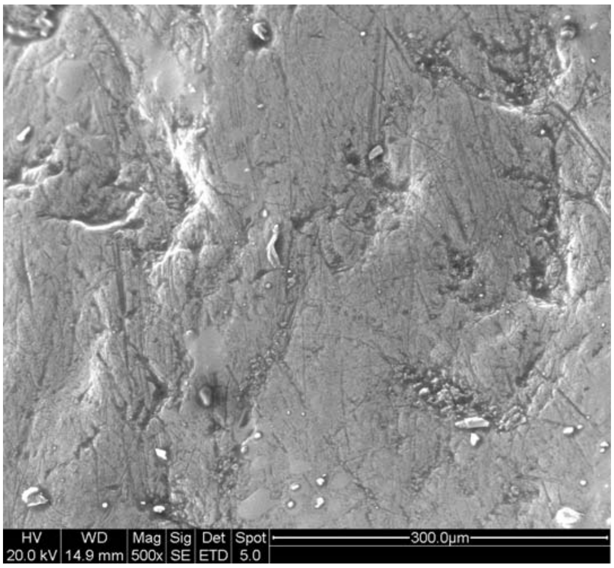

Figure 8 **Eroded dental enamel surface of a pig second molar (SA 95 UAN 216) of Sagalassos dated to the Early Byzantine period**

Conclusions

Microwear in the Sagalassos pig teeth is characterised by very small features and an intermediate percentage of pits. Previous research on modern suids has equated an emphasis on pitting with a ‘soft’ diet, lacking in abrasives such as exogenous soil particles, and has suggested that this kind of microwear patterning may be indicative of stall-fed animals (Ward and Mainland 1999; Wilkie *et al.* 2007). Nevertheless, the microwear in the Sagalassos pigs is not comparable with the archaeological pigs previously identified as stall-fed; nor indeed is it comparable with that found in modern free-ranging, rooting pigs. The substrate on which pigs forage has an impact on microwear formation because of the enormous intake of soil particles during foraging (Fries *et al.* 1982). The substrate in the territory of

Sagalassos consists largely of limestone and ophiolites, which are softer than enamel, and to a lesser extent of abrasive flysch deposits; the distinctive microwear might thus reflect aspects of geology rather than diet. Comparison between the data from Sagalassos and two Neolithic sites, which are also dominated by a calcareous geology, however, has indicated that the non-abrasive substrate cannot explain the etiology of the distinctive microwear patterns observed at Sagalassos. Hence, it is concluded that the microwear in the Sagalassos pigs reflects a soft, non-abrasive diet, and is likely to be represent stall-fed pigs. Differences between the Sagalassos pigs and the Roman and Medieval pigs previously identified as stall-fed can be attributed to variability in the size/hardness of dietary items and/or abrasive particles consumed.

The identification of stall-fed animals at Sagalassos would appear initially to contradict the results of the LEH analysis which suggested that pigs were likely to have been free-herded during most of their lives (Vanpouke *et al.* 2007). Ethnographic and historic accounts of pig husbandry within the Mediterranean area demonstrate that in the recent past it was common practice to stall and fatten-up prior to slaughter pigs that had been herded within the wider landscape (Halstead and Isaakidou in press). Moreover, classical writers indicate that fattening of pigs was practiced during the Roman period (White 1970). LEH and microwear suggest similar practices may have been evident at Sagalassos during classical times, while trace element analyses indicate that herding and/or the collection of fodder for pigs occurred in the proximity of the city.

The microwear patterns of the Sagalassos pigs also showed changes through time: pig teeth dated to the Late Roman period have a microwear pattern that points towards a (slightly) more abrasive diet than in the Imperial and the Early Byzantine period. Both environmental and economical reasons have to be considered as a possible reason. Palynological research indicated climatic changes which may have provoked a diet that was tougher and/or higher in abrasives during the Late Roman period. Furthermore, previous archaeozoological research on the slaughtering ages and size reconstruction of pigs indicated a different management during the same period.

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