The Bioarchaeology of
An Sơn and Hòa Diêm: Biosocial Insights
into Prehistoric Southern Vietnam

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Declaration

All work presented in this thesis is original unless otherwise referenced or acknowledged. This thesis has not been submitted, in whole or in part, for any previous qualifications from this or other academic institutions.

Anna Willis
Abstract

This thesis investigated the lifeways of two prehistoric Vietnamese communities, An Sơn from southern Vietnam and Hòa Diêm from the south central coast of Vietnam, representing two temporally distinct periods. Three themes were employed to assess and situate the health and behaviour of these people 1) health as an indicator of childhood stress 2) oral health and extramasticatory modifications and 3) palaeodiet. The interpretation of these key factors were undertaken with a consideration of the local natural and cultural environments, drawing comparisons and further contextualising the findings within the wider Southeast Asian bioarchaeological context.

Using standard bioarchaeological approaches the following results were obtained: childhood stress was generally worse during the Neolithic and improved over the Bronze and Iron Ages, oral health was significantly worse for females, particularly in the Neolithic and palaeodiet was consistent with the local zooarchaeological and environmental information available.

In interpreting the evidence for health as an indicator of childhood stress, oral health and extramasticatory modifications and palaeodiet, four metathemes of population history, connectivity, the Neolithic Demographic Transition and the osteological paradox were developed as a conceptual framework in which to explore these health indicators. The population affinities of both An Sơn and Hòa Diêm support the notion of genetic exchange between indigenous and migrating populations, albeit of different groups during different time periods. These observations play directly into what we know about connectivity and the complexity of regional mobility in the past. Large scale interaction spheres operating independently during the Neolithic and the Iron Age are supported by the evidence for the population history of the region.

Contextualising palaeodiet with other assemblages that were part of these interaction spheres suggests that diet was consistent with the expected outcomes from the local environmental information at a regional level. Consistent with the population history in the region and the migration of northeast Asians into Southeast Asia, the subsequent period presents the key characteristics of a Neolithic Demographic Transition. This period witnessed an explosion in population growth and fertility largely fuelled by factors such as the establishment of sedentary communities by those with a knowledge of agriculture and domestication, providing a constant and sustainable supply of food conducive to shorter birthing intervals.

Comparing oral health with other assemblages in Southeast Asia suggests that there was a decline in oral health during the Neolithic Demographic Transition, but this was largely
influenced by a decline in female oral health. The main reason for this decline in oral health was related to elevated levels of fertility and a clinically demonstrated predisposition to poor oral health exacerbated by pregnancy.

The significant degree of demic diffusion characterising the population history of the region, in addition to a complex but important degree of connectivity during both the Neolithic Demographic Transition and the Iron Age had implications for understanding childhood health as these were not necessarily biologically homogenous or stationary populations. Notwithstanding, this study found that childhood stress was generally worse during the Neolithic and improved over the Bronze and Iron Ages.
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Chapter One:

Introduction

The prehistory of Southeast Asia is complex and dynamic, and multidisciplinary research over the last few decades has greatly expanded our knowledge of the region. An essential key to understanding prehistory is understanding the people themselves, those who created the archaeological record and who spoke the languages, as a reflection of their ability to adapt to the changes within their natural and cultural environments.

A large amount of research has been focussed on various aspects of palaeohealth and bioarchaeology in Mainland Southeast Asia. Many different aspects of health have been analysed and presented using a range of different approaches (Clark 2014; Clark et al. 2014; Domett 2001, 2004; Domett and Oxenham 2011; Domett and Tayles 2006; Douglas 2006; Douglas and Pietrusewsky 2007; Halcrow 2006; Halcrow et al. 2013; Kirkland 2010; Oxenham 2000; Oxenham and Domett 2011; Oxenham et al. 2002a; Oxenham et al. 2006; Oxenham et al. 2002b; Oxenham and Tayles 2006; Pietrusewsky and Douglas 2002a; Pietrusewsky and Ikehara-Quebral 2007; Tayles 1999; Tayles et al. 2009; Tayles et al. 2000; Tayles et al. 2007), including using stable isotopes to examine residence, migration, marital customs and palaeodiet (Bentley et al. 2009; Bentley et al. 2005; Bentley et al. 2007; Bower et al. 2006; Cox 2009; Cox et al. 2011; Huffer 2012; King 2008; King and Norr 2006; King et al. 2013; King et al. 2015).

Historically, bioarchaeology in Vietnam has focussed mostly on cranial morphology, microevolutionary adaptation and population movement during the late Pleistocene and Holocene (Nguyễn 1990; Nguyẽn 1985, 1992, 1996b; Olivier 1966). However, recently there has been a move to explore more behavioural and health related aspects of ancient Vietnamese human skeletal assemblages (Huffer 2012; Oxenham 2000, 2006; Oxenham et al. 2011a; Oxenham et al. 2008c) and to understand how such approaches fit within the wider population history of Southeast Asia. Despite this move to incorporate Vietnam into a regional dialogue, no synthesis of the bioarchaeology of prehistoric Vietnam has been carried out to date, nor has a detailed comparative approach encompassing the wider Southeast Asian bioarchaeological discourse been undertaken.

This thesis investigates the lifeways of two prehistoric Vietnamese communities, An Sơn from southern Vietnam and Hòa Diêm from the south central coast of Vietnam, representing two temporally distinct periods. Three themes will be used to assess and situate the health and behaviour of these people 1) health as an indicator of childhood stress 2) oral health and extramasticatory modifications and 3) palaeodiet. The interpretation of these key factors takes into consideration the local natural and cultural environments,
drawing comparisons and further contextualising the findings within the wider Southeast Asian bioarchaeological context.

Southeast Asian populations, as we know them today, differ from one another in terms of their physical appearance, genetic makeup and heritage and language, the result of an enduring and complex interplay among migration, interaction and geography. The complementary nature of the three major subdisciplines of linguistics, archaeology and human biology can assist in an understanding of the prehistory of Southeast Asia and inform the complexities of bioarchaeological interpretation. In order to achieve this goal, several fundamental metathemes within Southeast Asia prehistory need to be outlined. The remainder of this chapter will first provide a discussion of the population history of the region in which to situate many of the subsequent health results, followed by a brief review of the relevant cultural periods under investigation, the Neolithic and Metal Periods. Then a discussion of the research approach informing this study is outlined, including a brief outline of the comparative sites used to contextualise the study. Finally, the specific study aims are outlined, followed by a brief outline of the thesis structure.

The population history of Southeast Asia

Any bioarchaeological study of Holocene Southeast Asia that ignores its multifarious and highly dynamic population history does so at some peril. The population history of Southeast Asia is complex and multifaceted. In East and Southeast Asia movements of people during the Neolithic Demographic Transition have been attributed to the dispersal of major language groups in association with rice farmers migrating throughout the region. The two layer, or immigration, model attempts to explain the peopling of Northeast and Southeast Asia with consideration of the human biological, archaeological and linguistic evidence.

The movement of anatomically modern humans out of eastern Africa can be traced back to between 200-150 thousand years ago, through southwestern Asia between 120-90 thousand years ago, and into Southeast Asia by about 60 thousand years ago (Demeter et al. 2012). Although the exact details and dates are not precise, the general chronology is accepted in the palaeoanthropological community. Craniofacially and dentally, signatures of the original colonisers of the region can be seen among past and living populations referred to as Australo-Melanesians (Matsumura and Oxenham 2014). These migrants are often referred to as the first layer, or migratory wave, in multiple migratory wave models.

For much of Southeast Asian prehistory, these first wave (layer) migrants seem to have operated as low density and somewhat scattered hunter gatherer bands spread throughout the landscape. At c. 7000BCE there is evidence that some of these groups developed into high density complex hunter gatherer communities in what is now southern China and
northern Vietnam. In general, these communities used coarse pottery and made hammer-dressed and edge-ground pebble axes, their subsistence practices included hunting and gathering from a range of terrestrial and riverine environments and they buried their dead in flexed or squatting positions (Chi and Hung 2012; Li et al. 2013; Oxenham and Buckley 2016b; Oxenham and Matsumura 2011; Rispoli 2007). From c. 3000BCE in southern China and c. 2000BCE in the rest of Southeast Asia, the population history of the region is characterised by the disappearance of these hunter gatherer communities and the emergence of agriculturalists (the second layer or migratory wave). The remainder of this section explores the evidence for this second wave, or layer, in the population history of Southeast Asia.

As noted, the two layer or immigration hypothesis (Jacob 1967) suggests that the first layer represents the initial colonisation of Southeast Asia by anatomically modern humans, their direct descendants being more or less morphologically similar to past and current Australo-Melanesians. The second layer represents the subsequent migration of Northeast Asians, along with farming, into the region from an immediate origin south of the Yangtze River basin, and subsequent genetic admixture with descendants of the original colonisers of Southeast Asia (Matsumura et al. 2011a; Matsumura et al. 2012; Matsumura and Oxenham 2014; Matsumura et al. 2008a; Matsumura et al. 2011b; Matsumura et al. 2015).

This model has been contested mainly due to the difficulty in distinguishing between morphological changes attributed to modernisation or genetics (Bulbeck 1982). The opposing model, the regional continuity or local evolution model, suggests that the modern Southeast Asian morphology is the direct result of rapid microevolutionary change or modernisation resulting in modifications in dentition, facial morphology and general robusticity, without significant admixture from the north (Hanihara 1994; Pietrusewsky 1994; Turner 1990). Two critical issues with the regional continuity model are that the data they use to support their model are derived from modern assemblages and there is a lack of assemblages dating prior to the Neolithic Demographic Transition (Matsumura and Oxenham 2014).

Notwithstanding, the two layer or immigration hypothesis is strongly supported by biological, archaeological and linguistic evidence, Mán Bạc in northern Vietnam (Oxenham et al. 2011a) is a particularly good example of demic diffusion in the early Neolithic. This population includes individuals of both Australo-Melanesian and modern Southeast Asian morphology living amongst one another. However, questions concerning the ultimate source, scale and timing of the second layer of migration still remain unanswered.

In a recent test of the model, Matsumura and Oxenham (2014) assessed 21 nonmetric dental traits in a sample consisting of early, middle and late Holocene assemblages from East and
Southeast Asia. Their results show a clear discontinuity between the earlier preNeolithic assemblages and later series from the Neolithic and Bronze Ages. The clearest example of this is seen within the Vietnamese samples, in particular between the preNeolithic series on the one hand and the Neolithic, Bronze and Iron Age assemblages on the other. This difference between the preNeolithic and later populations, and the close affinity among the later samples and modern Northeast Asian populations, corroborates the hypothesis of demic diffusion during the Neolithic originating from China and moving down and out into Southeast Asia. This view has also been evidenced in cranial morphometric studies on the same individuals (Matsumura et al. 2011b).

In comparison to the evidence of rapid diffusion into Vietnam, it would seem that it was slower and less extreme with increasing distance from China, in northeast Thailand for example. Matsumura and Oxenham (2014) suggest that this may be a reflection of the topography of the landscape, with mountainous ranges lying between China and northeast Thailand, potentially being a barrier in comparison to the ease of migration between China and northern Vietnam.

Although the pattern of genetic influence from Northeast Asia through Southeast Asia would best be described as a clinal graduation reflecting the geographic spectrum of demic diffusion outward from Southern China, there are exceptions to this, notably at Neolithic Khok Phanom Di, which shows a strong Northeast Asian influence in dental morphology. Matsumura and Oxenham (2014) suggest that a likely reason for this is migration of Northeast Asians along the eastern seaboard of Mainland Southeast Asia down to the Gulf of Siam, where they settled and mixed with indigenous inhabitants. Two other exceptions are the populations from Iron Age Phum Snay in Cambodia and the Tanegashima Island Yayoi from Japan, where their dental morphology reflects the original indigenous morphology. These populations are explained in terms of their positions on the peripheries of the major routes of migration during and after the Neolithic Demographic Transition.

Those supporting the regional continuity or local evolution model seek to explain the considerable genetic heterogeneity among Southeast Asian populations as a consequence of regional variation, a protracted genetic history and microevolutionary change as a consequence of behavioural adaptation. The examples of rapid morphological change in some assemblages, for example, Khok Phanom Di and Mán Bạc which are both Neolithic sites, cannot be explained by the regional continuity or local evolution models. However, the two layer hypothesis, seeking an explanation that takes into consideration the speed and timing of the movement from Northeast Asia out into Southeast Asia by agricultural farmers, provides the most parsimonious explanation for the genetic heterogeneity witnessed in Southeast Asia. “The differential contribution, often clinal in nature, of East Asian genes into Southeast Asia is readily explained by the speed and direction of demic
diffusion, which in turn appears contingent on the nature of the geographic barriers and the
distance separating local Southeast Asian populations from the dispersing East/Northeast
Asian source populations. Such an observed pattern is not, and cannot be, accounted for
by the regional continuity model” (Matsumura and Oxenham 2014: 60).

Earliest farmers and complex hunter gatherers from China to Southeast Asia

The mid-Holocene in East and Southeast Asia is characterised by a number of fundamental
shifts in human adaptation which occurred as a direct response to the domestication of
cereals and animals in Central China, in turn facilitating major population growth and
catalysing subsequent developments in Southeast Asia. These developments are linked
to the genesis of many important language families including Sino-Tibetan, Altaic,
Austroasiatic, Austronesian and Tai (Bellwood 2013; Blust 2013; Higham 2013; Sagart
2008; Sidwell 2013). Pre-domestication began c. 7000BCE, arguably by individuals of
East Asian morphology (Brown 1999; Oxenham and Buckley 2016b), with the cultivation
of wild cereals between the Yellow and Huai Rivers and Middle Yangtze River valley
in China (Chi and Hung 2012). In the Yellow River Basin the cereals were broomcorn
and foxtail millets (*Panicum miliaceum* and *Setaria italica*) (Lee et al. 2007), while in
the Yangtze River basin it was short grained rice (*Oryza sativa japonica*) (Fuller et al.
2009). There is a high degree of similarity among the artefact assemblages of these early
agricultural cultures in both river basins in China. The main domesticated animal was
the pig in both areas. By c. 4500BCE successful adaptation of domesticated crops had
occurred. The millets of the Yellow River Basin tended to move north and west, while the
rice from the Yangtze River Basin tended to move south (Bellwood 2013).

The Neolithic millet communities that travelled up the Yellow River and southwest into
Sichuan and Tibet were likely early speakers of Sino-Tibetan. The cultural assemblages of
northeast China, however, are very different from those in the Yangtze, suggesting millet
agriculture was developed within an indigenous community, through communications
with regions in the south. These individuals were likely ancestral to the modern speakers
of Tungusic and Mongolian languages, which are unrelated to Sino-Tibetan (Bellwood
2013).

The spread southward of rice is more complicated than that of the northern transmission
both in terms of populations and linguistic development. It was carried through Mainland
Southeast Asia, Island Southeast Asia and the Himalayas by ancestral Tibeto-Burmese,
Austronesian, Austroasiatic, Tai and Hmong-Mien speaking populations. This occurred
in largely two major population migrations. One route was south and west into Mainland
Southeast Asia, Tibet and northeast India. The other route was through Taiwan, the
Philippines, and out into Island Southeast Asia and the Pacific (Bellwood 2013).
The agricultural systems in the Yangtze Valley became highly specialised offering domesticated and transportable crops and animals subsequently leading to population expansion and movement into southern China by c. 2500BCE and then out into Mainland Southeast Asia (Chi and Hung 2010). This occurred in two directions. The first was down the southern tributaries of the Middle Yangtze, down the Pearl River to Guangdong. The second went from the lower Yangtze down the Zhejiang coastline to Fujian and out to Taiwan (Bellwood 2013).

**Mainland Southeast Asian Neolithic cultures**

Our knowledge of Neolithic rice farming communities, all of which share to a greater or lesser degree a modern Southeast Asian craniofacial and dental morphology (see discussion of the population history of the region above), derives from a few key sites dating from c. 2100BCE. These sites are located in northern Vietnam, around the Red River delta (Oxenham et al. 2011a), in southern Vietnam around the Đồng Nai and Văm Cỏ River basins, just north of the Mekong Delta (Bellwood et al. 2011; Oxenham et al. 2015; Piper et al. 2014; Sarjeant 2012, 2014), on the Khorat Plateau in northeast Thailand (Higham and Kijngam 2011; Higham and Thosarat 2004a), and in the Chao Phraya River valley in central Thailand (Castillo 2011; Weber et al. 2010). The communities represented by these sites would all have been influenced by the Neolithic Demographic Transition, which saw significant increases in fertility as a result of sedentism, a reliable constant food source and decreased birthing intervals. There is a strong commonality among these sites in their farming subsistence orientation which includes agricultural crops of rice and millet, domesticates including pigs and dogs and consumption of a range of terrestrial and aquatic animals.

The mortuary practices of these Neolithic communities include the interment of individuals in an extended supine position while important aspects of their material culture include “uni-bevelled stone adzes with angular cross-sections and frequent hafting reduction, nephrite (in northern Southeast Asia at least), pottery spindle whorls, shell or bone fishhooks, shaped (rather than simply perforated) body ornaments, and evidence of deliberate settlement construction” (Oxenham and Buckley 2016a). There appears to be an extensive and enduring similarity in the surface decoration of pottery, especially on pedestals, with an emphasis on horizontal bands of geometric and curvilinear motifs filled with punctate or dentate stamping or fine combed incision (Rispoli 2007; Wiriyaromp 2010). There are regional similarities in some areas, especially in northern Vietnam and the Guangdong and Guangxi provinces of China, the inhabitants of which were likely ancestral Tai speakers, and then among the southern Vietnamese and northeast Thai sites (Sarjeant 2012, 2014), which are all in areas associated with rivers that feed into the Mekong, the inhabitants of which were likely ancestral Austroasiatic speakers (Bellwood 2013). However, because of the clear parallels among these areas, it has been described
as the Southeast Asian Interaction Sphere (Rispoli 2007: 280).

Mainland Southeast Asian Metal Period cultures

It was this Southeast Asian Interaction Sphere that saw, through interaction with southern China, the introduction of copper base metallurgy and the beginning of the Bronze Age from c. 1100BCE (Rispoli et al. 2013). This brought casting techniques, artefacts and raw materials that promoted a local innovation in mining and smelting, which contributed to increasing social, political and economic complexity, with a discernible increase in craft specialisation within the region (Pryce et al. 2014; Rispoli et al. 2013). While the polities that developed and interacted through this sphere continued, eventually during late first millennium complex historical events led to the destabilisation of this network (Rispoli et al. 2013). While the northern polities of Southeast Asia such as those of northern Vietnam, were influenced by relations with the Han empire, the southern polities were influenced more by the Indian subcontinent, in an arguably less conflicting exchange (Rispoli et al. 2013).

Although less is known about the origins of Iron metallurgy in Southeast Asia, c. 500BCE marks the beginning of the Iron Age, northern Vietnam was likely influenced from Southern China, while southern Southeast Asia was likely influenced by the Indian subcontinent. The manufacture of iron tools would have increased the rate of land clearance and agricultural intensification. Increasingly, new interaction spheres were developed in the Iron Age, including those of the Dông Sơn and Sa Huỳnh-Kalanay. These facilitated trade and exchange of new and exotic goods and knowledge; and no doubt contributed to the increased development of social complexity. The influence that these interaction spheres and routes of connectivity had on different communities would have been partially attributable to their access to these exchange networks and their interaction and complex social relationships with other communities (Higham 2015).

Research approach

Bioarchaeology studies disease dynamics in past human populations focussing on a skeletal population from a site or cemetery as the primary variable of analysis, grounded in the assumption that the cumulative prevalence and patterning of disease reflects health in the population (DeWitte and Stojanowski 2015). The ‘osteological paradox’ raises some fundamental issues with respect to using the dead to extrapolate inferences regarding the health of a population (DeWitte and Stojanowski 2015; Wood et al. 1992). Although the concept of the osteological paradox, published over twenty years ago, has provoked much engagement and discussion within the discipline of bioarchaeology and is often cited in academic publications, it is not commonly incorporated into bioarchaeological discussions of palaeohealth in any real substantive manner (DeWitte and Stojanowski 2015). Wood et al. (1992) identified three major issues that are important to consider in
any analysis and interpretation of human remains, those of demographic nonstationarity, selective mortality, and hidden heterogeneity.

Demographic nonstationarity refers to limitations of using the age at death distribution in reconstructing and understanding the demography of a population if that population was not stationary, for example, if it was undergoing increased fertility and growth, or increased mortality and decline (DeWitte and Stojanowski 2015). Using age at death as a proxy for the number of individuals dying within an age interval in a life table in order to extrapolate life expectancy and mortality at each age interval is problematic if the population is not stationary. Even if mortality remained constant, or if the population was growing or declining, the life expectancy will be under or overestimated respectively (DeWitte and Stojanowski 2015). If mortality remains stationary, the proportion of neonates and children within a growing population will increase, similarly within a declining population the proportion of neonates and children will decrease (DeWitte and Stojanowski 2015). The issue of demographic nonstationarity can be ameliorated to some extent by implementing methods using the proportion of subadults in a population as an indication of fertility and as a proxy for population growth (Bocquet-Appel 2011; Bocquet-Appel and Bar-Yosef 2008).

Selective mortality refers to the extrapolation of the health status of dead individuals on to the population that survived. A skeletal assemblage does not represent all the individuals that were at risk of disease or death at any given age. It only represents the portion of the population that died at that age, leaving us without knowledge of how many of them survived to a later age. Those who died from ill health are unlikely to accurately reflect those in the population who survived death in that age interval. Individuals with the highest frailty are the most susceptible to death and will likely die and be represented in the skeletal sample at that age, while their stronger peers would continue living and would eventually be represented in a different age interval. Due to selective mortality, using skeletal evidence of stress markers to indicate the health of the population will likely overestimate the prevalence of those conditions (DeWitte and Stojanowski 2015; Wood et al. 1992). However, only a low percentage of diseases that can manifest skeletally or dentally actually do so, which counteracts this problem, but to an unknown degree. This means that an individual with the disease must survive the initial, acute phase of the infection before the skeletal manifestations occur. This suggests a relatively good immune response as opposed to a person affected with the same disease dying before the disease manifested skeletally.

Hidden heterogeneity in frailty highlights the fact that all individuals in a population have an inherent variability in susceptibility to death and the reasons for this are multifactorial; both intrinsic and extrinsic factors including age, sex, biological differences in immunocompetence, differences in behaviour, and differences in environmental factors.
Selective mortality and hidden heterogeneity work in combination to obscure the identification or relevance of palaeoepidemiological trends in past populations (DeWitte and Stojanowski 2015).

Wood et al. (1992) made four recommendations for future bioarchaeological interpretations of stress, many of which are now being addressed, and which are reviewed in detail in DeWitte and Stojanowski (2015). As Wood et al. (1992) predicated, advances in the fields of human biology, demography, epidemiology and genetics have significantly contributed to our understanding of the complex nature of variation in frailty and susceptibility in hidden heterogeneity and selective mortality (DeWitte and Stojanowski 2015).

Modern clinical research has contributed to bioarchaeology in the understanding of health and frailty and lesion formation processes in living populations. Although the focus of clinicians is often to understand diseases that are not relevant to bioarchaeologists, some relevant examples include research on oral health (Boggess 2008; Gajendra and Kumar 2004; Prodan et al. 2015; Russell and Mayberry 2008; Silk et al. 2008), enamel hypoplasia (Gravina et al. 2013; Salanitri and Seow 2013) and cribra orbitalia (Exner et al. 2004; Smith-Guzmán 2015). Metaanalyses also contribute to our understanding of age and sex patterns in mortality due to disease (Lozano et al. 2012).

There has been an increasing focus on the genetic determinants of disease and immunocompetence; and epigenetics and the developmental origins of disease. Recent research has identified genes associated with differential susceptibility to different diseases and the genetic source of particular pathologies, illuminating the risks of morbidity and mortality from various diseases (Hill 2012). Research has also centred on sex differences in immunocompetence (Fischer et al. 2015; Garenne 2015; Giefing-Kröll et al. 2015; Muenchhoff and Boulder 2014). Several lines of research into epigenetics and the adaptability of humans in response to intergenerational maternal environmental, physiological or psychosocial stress have increased our understanding of the sensitive and innate plasticity of the developmental period (Barker 1990; Kuzawa and Bragg 2012; Kuzawa and Quinn 2009). In particular, epigenetic mechanisms, which are heritable and can switch on or off genes, without modifying the genetic code, can have transgenerational effects which influence the foetal and infant health outcomes later in life but are neither explicitly biological or social outcomes.

The recommendation which Wood et al. (1992) felt was within the ambit of bioarchaeologists was to use ‘simple’ assemblages representing egalitarian communities, which were biologically and culturally homogenous, representing generations of inhabitants, rather than time averaged assemblages spanning several temporal periods (DeWitte and Stojanowski 2015). They argued that these minimise the impact of hidden heterogeneity and demographic nonstationarity. Studies using assemblages that match these criteria
provide an opportunity to understand lesion formation processes and their association with age, sex and variability in susceptibility to death without the compounding effects of temporal changes in the cultural or natural environment. Identification of burial clusters in cemeteries is also important as they may represent familial groupings, or aggregates related to social class which may have different levels of heterogeneous frailty (DeWitte and Stojanowski 2015; Wood et al. 1992).

The evolution of our understanding and incorporation of these processes and their importance has been reflected in the modification and refinement of biocultural models for interpreting stress in populations (Goodman and Martin 2002; Goodman et al. 1984; Huss-Ashmore et al. 1982; Klaus 2012; Larsen 2015). Imposed at a population level, the model considers the extrinsic effects of the natural and cultural environments and also the intrinsic mechanisms such as host resistance and developmental plasticity in epigenetics and the physiological response to these factors. The effect that these then have at a population level and how they may be ameliorated with behavioural or biological adaptation and the subsequent circularity in the process can then be better understood.

Comparative sites

The development of a regional and wider Southeast Asian synthesis requires the use of comparative assemblages from Vietnam and Thailand through which to contextualise An Sơn and Hòa Diệm. There is a paucity of well dated skeletal material available for analysis in Vietnam and little bioarchaeological data has been published in English aside from Oxenham and colleagues’ work (Oxenham 2000, 2006; Oxenham et al. 2011a; Oxenham et al. 2005; Oxenham et al. 2006; Oxenham et al. 2002b). Thailand, however, presents several reliably dated, well researched and published assemblages that each span one temporal period (Domett 2001, 2004; Tayles 1992; Tayles 1999; Tayles et al. 2007).

Comparative assemblages that span more than one temporal period or with contentious dates were omitted from comparison in an attempt to mitigate issues associated with time averaging (DeWitte and Stojanowski 2015; Wood et al. 1992). The selected comparative assemblages include the Vietnamese sites of Cồn Cổ Ngựa (a preNeolithic series) and Mán Bạc (a Neolithic series) and the Thai sites Khok Phanom Di (Neolithic), Ban Lum Khao and Ban Na Di (both Bronze Age) and Noen U-Loke (an Iron Age series) (Figure 1.1 and Table 1.1).

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Period</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>preNeolithic</td>
<td>c. 4000-3000BCE</td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>Neolithic</td>
<td>c. 2000–1500BCE</td>
</tr>
<tr>
<td>Man Bac</td>
<td>Neolithic</td>
<td>c. 2000-1775BCE</td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>Bronze Age</td>
<td>c. 1400-500BCE</td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>Bronze Age</td>
<td>c. 600-200BCE</td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>Iron Age</td>
<td>c. 400BCE-500CE</td>
</tr>
</tbody>
</table>

This suite of comparative assemblages are used throughout this work to contextualise general health, oral health and palaeodiet. However, in the palaeodietary reconstruction several other sites were incorporated to further expand and contextualise dietary findings. These sites and relevant references and sources are presented and further discussed throughout the thesis.

**Overall aim**

An Sơn in the south and Hòa Diêm on the south central coast represent two temporally distinct periods in Vietnam: An Sơn representing a site influenced by the Neolithic Demographic Transition and Hòa Diêm representing the Iron Age. Both of these sites provide evidence for complex patterns of connectivity within the larger Southeast Asian Interaction Spheres: An Sơn in the Southeast Asian Interaction Sphere and Hòa Diêm in the Sa Huỳnh-Kalanay Interaction Sphere. The complex population history and the timing of the Neolithic Demographic Transition must be considered in an interpretation of the health and life styles of the inhabitants of Southeast Asia. During the Neolithic Demographic Transition population size, fertility, adaptability and population success would no doubt have differed among different populations depending largely on whether the processes involved colonisation or immigration and demic diffusion. Similarly, during the Iron Age Hòa Diêm would have been involved in a complex interplay of regional and interregional social interaction across the South China Sea. Four metathemes of population history, connectivity, the Neolithic Demographic Transition and the osteological paradox will be developed in the next few chapters as a conceptual framework for the interpretation of the physiological heath, oral health and extramasticatory behaviours and palaeodiet of An Sơn and Hòa Diêm to determine if their patterns of health and behaviour can be broadly attributed to temporal changes in the natural and cultural environment.

**Thesis structure**

Chapter Two will provide an introduction to the natural and cultural environment of Vietnam, and an exploration of the archaeology of the region, providing a foundation on which to introduce the background of An Sơn and Hòa Diêm. Chapter Three will present the demographic profile of An Sơn and Hòa Diêm and the relevant comparative assemblages used throughout the thesis, providing the age and sex distribution of individuals at the sites, which will facilitate an understanding of palaeohealth with reference to the age progressive nature of these and any differences related to other factors, for example, sex or behaviour. The $^{15}P_3$ values are also presented as an indication of potential population growth and fertility at the sites.
Figure 1.1. Map of Southeast Asia
Chapter Four will present the physiological health at An Sơn and Hòa Diểm using three indicators of childhood stress including stature, linear enamel hypoplasia and cribra orbitalia, which will then be contextualised in a regional comparison. Chapter Five will present evidence for the oral health and extramasticatory behaviour at An Sơn and Hòa Diểm. The oral health section will include caries, pulp chamber exposure, alveolar lesions and antemortem tooth loss which will then be contextualised in a regional comparison. The extramasticatory modifications section will include interproximal grooves, chipping and staining.

Chapter Six will present the palaeodietary reconstruction at An Sơn and Hòa Diểm which will then be contextualised in a regional comparison. Chapter Seven will present a concluding synthesis and future directions.
Chapter Two:

Vietnam, its Environment and Archaeology: Contextualising An Sơn and Hòa Diêm

This chapter will begin by introducing the natural environment of Vietnam in general and central coastal and southern Vietnam in particular. Following that an outline of the archaeology of Vietnam, particularly the Neolithic through to the Iron Age, is provided as a context in which to introduce the two sites examined in detail in this thesis, Neolithic An Sơn and Iron Age Hòa Diêm.

CLIMATE AND ENVIRONMENT

Vietnam is a species-rich and ecologically diverse country with some of the world’s most unique natural features, including spectacular deltas, mosaic forested areas, vast limestone caves, picturesque cloud forests, red sand dunes and associated rock formations and savannah type grasslands (Sterling et al. 2006). Vietnam covers an area of 330,591 km$^2$, the majority of the country is a thin strip 50km wide at the narrowest point, curving along the east coast of continental Southeast Asia, widening in the northern and southern regions (Sterling et al. 2006). The country features a diverse topography. A quarter of the landmass is of an altitude above 625m, which includes the Hoàng Liên Sơn mountain range in the northwest of the country running parallel to the Red River and the Trường Sơn mountain range which runs along the western border with Laos. A quarter of the landmass is below 20m in the Red River Delta in the north, the Mekong River Delta in the south and along the coastal plains. The final half of the landmass features hills at an intermediate elevation (Sterling et al. 2006).

Vietnam is largely affected by the tropical monsoon system and is characterised by a dry cool winter and warm wet summer with short transitional periods between the two, although there are variations depending on latitude and elevation within the country. Northern Vietnam is subtropical while the south is tropical and less seasonal (Phạm 1996; Sterling et al. 2006). Northern Vietnam is ecologically complex; it features limestone and granite outcrops, uplands and lowlands, and the Red River Delta. Vietnam’s Red River Delta includes Hà Nội, Vĩnh Phúc, Bắc Ninh, Hải Dương, Hải Phòng, Hưng Yên, Thái Bình, Hà Nam, Nam Định and Ninh Bình provinces (Figure 2.1 and Figure 2.2). Northwest Vietnam (Tây Bắc) includes Lai Châu, Điện Biên, Sơn La and Hòa Bình provinces. Northeast Vietnam (Đông Bắc) includes Quảng Ninh, Hà Giang, Cao Bằng, Bắc Kan, Tuyên Quang, Lào Cai, Yên Bái, Thái Nguyên, Lạng Sơn, Bắc Giang and Phú Thọ provinces (Figure 2.1 and Figure 2.2).

Vietnam’s curving central region (Trung Bộ) is a diverse area encompassing forest
2. Vietnam, its Environment and Archaeology: Contextualising An Sơn and Hòa Diệm

Figure 2.1. Regions in modern Vietnam. Data from General Statistics Office of Vietnam (2015)
Figure 2.2. Provinces in modern Vietnam. Data from General Statistics Office of Vietnam (2015)
covered mountains, lowlands and coastal plains, and it includes the wettest and driest regions of the country. The north central coast (Bắc Trung Bộ) includes Thanh Hóa, Nghệ An, Hà Tĩnh, Quảng Bình, Quảng Trị, and Thừa Thiên–Huế provinces. The south central coast (Nam Trung Bộ) includes Đà Nẵng, Quảng Nam, Quảng Ngãi, Bình Định, Phú Yên, Khánh Hòa, Ninh Thuận and Bình Thuận provinces. The Central Highlands include Kon Tum, Gia Lai, Đắk Lắk, Đắk Nông and Lâm Đồng provinces (Figure 2.1 and Figure 2.2). The Trường Sơn Mountains are dominated by forests, with a mix of tropical and subtropical species, the composition of which change with latitude and elevation (Sterling et al. 2006). The northern Trường Sơn Mountains are characterised by semi evergreen and endemic species, while evergreen forests grow at all elevations. The southern Trường Sơn Mountains are characterised by drier semi evergreen and deciduous forests. The coastal plains situated between the lowlands and the South China Sea feature thorny vegetation, including cycad forests. A unique dry coastal sand forest, including dipterocarps, grows among the red sands around Cam Ranh Bay. The coast is dominated by sand dunes, lagoons and estuarine outlets for the many rivers running from the Trường Sơn Mountains to the coast. Along the shallow continental Sunda Shelf lie diverse marine habitats including coral reefs and sea grass beds (Sterling et al. 2006).

Southeast Vietnam (Đông Nam Bộ) includes Tây Ninh, Bình Phước, Bình Dương, Đồng Nai and Bà Rịa - Vũng Tàu provinces and Hồ Chí Minh City (Figure 2.1 and Figure 2.2). There is a general incline from north-northeast to west-southwest; the region is characterised by distinctive ecological environments, which include a hilly stone and basalt terrain, which gets gradually flatter with inland wetlands and alluvial soil nearer the Mekong, and the lowland mangrove area forming the coast (Phạm 1996). The area is covered in tropical and semitropical forests which offer an abundance of native flora and fauna. The region features a number of river systems, including the Vàm Cỏ Đông and Vàm Cỏ Tây, Là Ngà, Bé, Sài Gòn, and the Thị Tính Rivers which feed into the Mekong (Bùi et al. 2010; Phạm 1996). This environment provided a rich and diverse area for the establishment of ancient communities. This is demonstrated in a system of interconnected archaeological sites of various different temporal periods along these river banks.

Southern Vietnam is dominated by the Mekong Delta, one of the largest in Asia, and includes Long An, Tiền Giang, Bến Tre, Trà Vinh, Vĩnh Long, Đồng Tháp, An Giang, Kiên Giang, Cà Mau, Hậu Giang, Sóc Trăng, Bạc Liêu and Ca Mau provinces (Figure 2.1 and Figure 2.2). The delta plain is about 62,520 km², 52,100 km² of which is in Vietnam, the remainder being in Cambodia (Nguyễn et al. 2000). The lower river courses are tide-dominated from the South China Sea and the Gulf of Thailand which have deposited silts, clays and sands into the basin. The Mekong River is about 4300km long, descending from the Tibetan plateau in China through Myanmar, Laos, Thailand and Cambodia, where it splits into the Mekong and Bassac Rivers which then flow into southern Vietnam to form the delta. The topography of the Mekong delta is made up of an upper inner delta plain
characterised by fluvial processes and a lower outer delta plain composed of a beach ridge system (Tạ et al. 2002b).

The vegetation of the northern area of southern Vietnam includes lowland evergreen trees dominating the upper canopy and semi-evergreen and deciduous trees situated in the understory, quite similar to the lower elevation forests of south central Vietnam (Sterling et al. 2006). Freshwater swamp forests, including paperbark, grow in the wetland areas where salinity is low, while mangrove forests dominate along the coastlines and estuaries where salinity is higher. Grasslands dominated by sedges and grasses, and bamboo forests, grow throughout the delta area supporting diverse plant and animal species (Sterling et al. 2006).

ARCHAEOLOGICAL OVERVIEW

New dates and recent finds in Southeast Asia indicate that modern humans had inhabited the region by about 60 thousand years ago (Demeter et al. 2012), although the oldest directly dated anatomically modern human remains in Vietnam occur at 10 thousand years ago at Hang Chổ Cave (Matsumura et al. 2008b), and 12 thousand years ago at Hang Muối (Bulbeck et al. 2007). In terms of material culture, Vietnamese archaeologists recognise the Sơn Vi lithic assemblage of pebble tools and flakes, dated around 30 thousand years ago (Nguyễn 1996a), as the earliest in Vietnam, followed by the Hòa Bình, which is generally believed to have existed between 18 and 6 thousand years ago. A series of subsequent mid-Holocene cultures are recognised in Vietnam (e.g. Bắc Sơn, Soi Nhụ), that for the most part represent dispersed and low density hunter gatherer communities. The earliest evidence for relatively dense and potentially sedentary communities in Vietnam is seen with the establishment of the Đa Bút culture in northern Vietnam, c. 4000BCE (Oxenham 2001).

The archaeology of south Vietnam

The Neolithic in southern Vietnam

In the Vietnamese language literature the term Neolithic is used to describe sites with evidence for pottery and/or polished or edge-ground stone tools. Three phases are used to categorise the Neolithic, early, middle and late. Each phase includes various regional ‘cultures’ which often include several sites, named after one site which typifies the ‘culture’. In this particular scheme the early Neolithic comprises the Hoabinhian, Bắc Sơn and Soi Nhụ. The middle Neolithic includes the Đa Bút, Quỳnh Văn and Cái Bèo cultures. The late Neolithic encompasses Hà Giang, Mai Pha, Hạ Long and Bà Tró in the north, Biên Hồ, Lung Leng, Buôn Triết in the central highlands, and sites in southern Vietnam that are not designated by a culture (Nguyễn 2003).
To date, there are no sites belonging to the early or middle Neolithic phases in southern Vietnam, and because early and middle ‘Neolithic’ sites in the rest of Vietnam do not provide any evidence for farming (neither domesticated crops nor animals), they are not considered Neolithic by other Mainland Southeast Asian archaeologists (Higham 2004b; Oxenham and Matsumura 2011). Indeed, the Neolithic in general is not seen to have emerged in Mainland Southeast Asia (including Vietnam) until c. 2100BCE (Bellwood 2013; Higham 2013; Oxenham et al. 2015).

The chronological framework for southern Vietnam is still not fully understood, particularly the transition from the Neolithic through to the Bronze and Iron periods. However, recent work on this and on the Neolithic in particular is helping clarify this issue (Bellwood et al. 2011; Bùi et al. 2010; Oxenham et al. 2015; Sarjeant 2014a). Indeed, there is also very little convincing archaeological evidence for early hunter gatherer communities existing in southern Vietnam prior to the Neolithic, which ushered in the first recorded evidence for modern human occupation in the region.

An Sơn is representative of one of the first Neolithic sites representing human activity in this region, while there are several recently excavated sites in the Vàm Cỏ Đông River valley that provide further insight into the Neolithic (Table 2.1 and Figure 2.3). These sites are all mounded sites positioned beside rivers on the alluvial floodplain, and include Dinh Ông, Gò Canh Nông, Lộc Giang, An Sơn and Gò Cau Su, although Gò Cau Su is a lot farther from a river than the others, and Rạch Núi lies in the lowland mangroves of the coast.

There are also Metal Period sites located in the inland wetland of Đồng Tháp Mười (plain of reeds) around the Vàm Cỏ Tây River, including Cổ Sơn Tự, Gò Ô Chùa and Rạch Rừng (see below for a discussion of Metal Period sites in this region). It appears that the Neolithic sites are located along the Vàm Cỏ Đông River, while the Metal Period sites are located along the Vàm Cỏ Tây River, which may be related to the trajectory of the Holocene marine transgression and the unsuitability of the more inland wetlands earlier in the temporal sequence.

In the east of southern Vietnam, in modern day Bình Dương and Đồng Nai provinces, around the Đồng Nai, Sài Gòn, Thị Tính and Bé rivers, there are several clusters of Neolithic sites (Table 2.1 and Figure 2.3). Vịnh Bà Kỳ is located on the Thị Tính River and Bà Lụa on the Sài Gòn River. Mỹ Lộc, Cù Lao Rùa, Gò Me and Bình Đa are located along the Đồng Nai River, and Phước Tân is located on one of its tributaries. Hàng Ông Dũng, Hàng Ông Đại and Suối Linh are located along the Bé River. The Neolithic sites of Cù Lao Rùa and Mỹ Lộc continued into the Metal Period, alongside a number of other sites such as Đốc Chúa along the Đồng Nai River and Phú Chánh along the Cái stream (suối) in Bình Dương Province, and the sites of Suối Chồn, Phú Hòa, Đâu Giấy and Hàng
## Table 2.1. Neolithic archaeological sites in southeast Vietnam

<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Province</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gò Cá Sỏi</td>
<td>Tân Phước commune, Tân Thành district</td>
<td>Bà Rịa Vũng Tàu</td>
<td>10° 33' 39&quot;</td>
<td>107° 3' 37&quot;</td>
<td>Bùi 1998</td>
</tr>
<tr>
<td>Gò Cây Me</td>
<td>Long Tâm commune, Bà Rịa city</td>
<td>Bà Rịa Vũng Tàu</td>
<td>10° 30' 44&quot;</td>
<td>107° 11' 36&quot;</td>
<td>Nguyễn et al. 2005</td>
</tr>
<tr>
<td>Bà Lụa</td>
<td>Chánh Nghĩa ward, Thủ Dầu Một city</td>
<td>Bình Dương</td>
<td>10° 57' 12&quot;</td>
<td>106° 39' 32&quot;</td>
<td>Bùi et al. 2010</td>
</tr>
<tr>
<td>Cư Lao Rủa</td>
<td>Thành Phước commune, Tân Uyên district</td>
<td>Bình Dương</td>
<td>10° 58' 56&quot;</td>
<td>106° 47' 3&quot;</td>
<td>Nguyễn 2008b, 2011; Nguyễn et al. 2004b</td>
</tr>
<tr>
<td>Hàng Ông Đại</td>
<td>Tân Định commune, Tân Uyên district</td>
<td>Bình Dương</td>
<td>11° 15' 6&quot;</td>
<td>106° 51' 40&quot;</td>
<td>Bùi et al. 2010</td>
</tr>
<tr>
<td>Hàng Ông Đụng</td>
<td>Tam Lập commune, Phú Giáo district</td>
<td>Bình Dương</td>
<td>11° 15' 15&quot;</td>
<td>106° 51' 31&quot;</td>
<td>Bùi et al. 2010</td>
</tr>
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<td>106° 50' 36&quot;</td>
<td>Nguyễn 2008a; Nguyễn et al. 2006a</td>
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<td>Bình Dương</td>
<td>11° 3' 24&quot;</td>
<td>106° 37' 0&quot;</td>
<td>Nguyễn and Phạm 1983</td>
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<td>Bình Đa</td>
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<td>106° 51' 36&quot;</td>
<td>Nguyễn 1981; Phạm et al. 1994</td>
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<td>107° 13' 50&quot;</td>
<td>Hoàng and Nguyễn 1977; Hoàng et al. 1978</td>
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<td>107° 13' 46&quot;</td>
<td>Phạm and Luu 1997; Phạm 2008b</td>
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<td>Bùi et al. 1997a</td>
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<td>Đặng et al. 2008; Văn et al. 2008</td>
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<td>Trần et al. 2001</td>
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<td>Quang and Ngò 1994; Quang et al. 1994</td>
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</tr>
</tbody>
</table>

*1 Site spans Neolithic and Metal Period
Coordinates calculated by the author or sourced from references
2. Vietnam, its Environment and Archaeology: Contextualising An Sơn and Hòa Diêm

Gòn 9 in Đong Nai Province.

Human skeletal remains have been found at Rạch Rừng along the Vàm Cỏ Tay River and ‘burials’ have been found at Cù Lao Rùa, Độc Chùa and Gò Me located along the Đồng Nai River (Figure 2.3). However, the soils were inimical to bone preservation, and only clusters of pottery and artefacts assumed to be grave goods were found.

Bronze and Iron Age sites in southern Vietnam

Jar burials have been found in the sites of Suối Chồn, Phú Hòa, Dầu Giây and Hàng Gòn in Đong Nai Province and Giồng Cá Vồ and Giồng Phệt in the mangroves of Cần Giờ district (rừng ngập mặn Cần Giờ) of Hồ Chí Minh City (Figure 2.3). Penannular nephrite lingling-o and bicephalous pendants/earrings, a characteristic features of Sa Huỳnh burials, have been recovered at Suối Chồn and Phú Hòa in Đong Nai (Phạm 1996) and from Giồng Cá Vồ (Nguyễn 1995). The significance of these particular items will be discussed below. Phú Chánh, located near the Cái stream, is one of the most remarkable
sites recently excavated in southeast Vietnam. It was located in a swamp, the waterlogged conditions of which preserved an impressive set of botanical remains, wooden artefacts, and carved wooden and bamboo clay covered burials jars, some associated with Đông Sơn drums and one with a bronze Han Dynasty mirror. One of the carved wooden jars was fitted with a Đông Sơn drum for a lid. Phú Chánh serves as a reminder that knowledge from the archaeological record is limited by what is preserved, and that it is only in remarkable circumstances of preservation that a glimpse of what is not normally preserved sometimes occurs.

There is a commonality among these sites in southeast Vietnam that continues from the late Neolithic period through to the Iron Age. There are subtle regional differences mostly associated with availability of raw materials contributing to variations in specialisations which are expressed in localised stylistic differences in certain goods. These communities had a common repertoire of material culture and skills which evolved and developed with the introduction of new ideas, raw materials, techniques and technology. Good quality clay is abundant in the area and the pottery vessels found in association with these sites reflect the knowledge and skill of the local people and their personal and community identity. The lithic workshops of Bình Dương province attest to a sophisticated level of communication and shared vested interest in stone tool production and distribution among the sites in the area, with evidence for different stages of manufacture ranging from simple export of raw materials through varying levels of processing and production represented at the different sites.

In the later sites of southeastern Vietnam, bronze and iron implements and their sandstone casting moulds, particularly at Đốc Chúa and Cù Lao Rùa, are evidence for the adoption of metallurgy and accomplishment in the manipulation of new raw materials. Although there is no evidence for a presence of copper ore in southern Vietnam, suggesting that the raw materials were imported and smelting knowledge was adopted from surrounding regions, there is iron ore available locally (Phạm 1996). Large numbers of spindle whorls were also found in Đốc Chúa and Cù Lao Rùa, indicating an early and specialised textile industry which continued to develop, with wooden weaving tools being preserved at Phú Chánh. Evidence for jar burial practices characteristic of the Sa Huỳnh of central Vietnam and a range of associated imported artefacts indicates that by this stage southeast Vietnam was in constant interaction with other areas.

The archaeology of central coastal Vietnam

Unlike northern Vietnam (not dealt with here) and southern Vietnam (see above), central coastal Vietnam, *sensu stricto*, has limited evidence for a Neolithic occupation phase, although some argue that the Sa Huỳnh developed directly from the Neolithic and these sites are referred to as pre Sa Huỳnh and discussed below. The rich and widespread
archaeological sites dominating this landscape can be, for the most part, traced back to the Iron Age with the iconic culture representative of this period termed the Sa Huỳnh.

**Defining and contextualising the Sa Huỳnh**

The Sa Huỳnh culture is named after the coastal town of Sa Huỳnh in Quảng Ngãi province, Vietnam. This was the location where the first sequence of jar burials ever discovered in Vietnam was originally reported in 1909 by a French customs official named Vinet, and later described by Henri Parmentier in 1924 (Southworth 2004). Most information regarding the Sa Huỳnh culture, which extends from Thừa Thiên–Huế to the southern Đồng Nai Delta (Figure 2.2), has come from jar burial sites in large coastal sand dunes, although sites have also been found along the alluvial plains of rivers and in the mountainous highland areas (Bellwood 2007; Bùi 2005; Lâm 2011; Southworth 2004; Yamagata 2006) Table 2.2 and Figure 2.4.

The burial jars of the Sa Huỳnh culture are large, thin, earthenware vessels that are frequently found in clusters. The size and form, which varies between different sites, includes ovoid, spherical or cylindrical, the latter can be over 1m high with many of them being lidded (Glover et al. 1996; Yamagata 2006). The method for interring individuals in jars varies, some contain primary burials and others incomplete secondary interments. Some of the jars contain single individuals, while others contain multiple individuals. As well as jar burials there are also occasional primary inhumations. Examples of Sa Huỳnh sites where individuals were both interred in jars and inhumed in the ground as primary burials include Tiên Lãnh (Bùi 2008), Thạch Bích, Gò Mả Vôi (Yamagata 2006) Lai Nghi (Reinecke 2007), Xóm Ốc (Phạm 2005) and Hòa Diêm (Yamagata 2008a; Yamagata et al. 2012b) see Figure 2.4.

The grave goods that have been found in association with the jar burials include impressed and incised earthenware pots, bronze and iron artefacts, carnelian and agate beads, and nephrite and glass penannular earrings (lingling-o) and bicephalous animal pendants/earrings (Bellina and Glover 2004; Bellwood 2007; Southworth 2004). The practice of interring individuals in jars contrasts with the widespread and enduring mortuary tradition of inhumation seen in the rest of Mainland Southeast Asia (Higham 2004b) and in the north of Vietnam, for example, at Mán Bạc (Huffer and Trịnh 2011) and in the Đồng Sơn culture. However, jar burials are widely dispersed in Island Southeast Asia and parts of Thailand (Bellina and Glover 2004). The inclusion of stone beads in the mortuary assemblages of the Sa Huỳnh period, the diffusion of a jar burial tradition in Taiwan and the Philippines, northern Indonesia and parts of Thailand, and the finding of lingling-o and bicephalous pendants/earrings made of Taiwan (Fengtian) nephrite in Mainland and Island Southeast Asia suggest that the people of the Sa Huỳnh culture were involved in extensive overseas trade during this period (Bellina and Glover 2004; Hung et al. 2007;
<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Province</th>
<th>Period</th>
</tr>
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<td>Bình Định</td>
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Data from Lâm Thị Mỹ Dzung (2008; pers. comm.)
Hung et al. (2013); the concept and significance of interaction and the implications of this will be discussed below.

Although the term ‘Sa Huỳnh’ has developed into a synonym for generalised jar burial practices in Vietnam, elusive issues relating to the chronological development of the Sa Huỳnh culture, the range of regional variation and stylistic variation among its sites, and potential sources of influence upon it, have recently been synthesised by Lâm Thị Mỹ Dzung (2008, 2011). In central Vietnam the cultural sequence, as defined archaeologically, forms three phases; the pre Sa Huỳnh, the typical Sa Huỳnh and the Early Chăm. Although each of these phases can be designated to a general time period, the fluidity and interaction among them cannot be rigidly defined (Lâm 2011).

The pre Sa Huỳnh period is represented by several sites that belong to the Xóm Cồn, Long Thành and Bình Châu cultures, dating to c. 1550-550BCE. These independent cultural traditions eventually coalesced to form the typical Sa Huỳnh culture (Lâm 2011). The typical Sa Huỳnh cultural period is dated to c. 500BCE-100CE. Sa Huỳnh sites are prevalent from Thừa Thiên-Huế down to the Đồng Nai delta but represent two local groups or traditions. The northern group, located in the provinces Quảng Trị, Thừa Thiên–Huế, Quảng Nam, Quảng Ngãi, Bình Định and Đà Nẵng City (see Figure 2.2), is characterised by jar burials, secondary burials and cremations. The burial jars are ovoid and cylindrical, often with flat topped conical lids. The southern group, located in the provinces Khánh Hòa, Ninh Thuận and Bình Thuận, down to the Đồng Nai Delta (see Figure 2.2), is characterised by jar burials, primary and secondary burials, inhumations and cremations. The burial jars are spherical, often with semicircular lids (Lâm 2011).

Following the Sa Huỳnh, the Early Chăm reflects the state formation period which

<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Province</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bình Châu</td>
<td>Bình Châu commune, Bình Sơn district</td>
<td>Quảng Ngãi</td>
<td>pre Sa Huỳnh</td>
</tr>
<tr>
<td>Bình Châu II</td>
<td>Bình Châu commune, Bình Sơn district</td>
<td>Quảng Ngãi</td>
<td>pre Sa Huỳnh</td>
</tr>
<tr>
<td>Gò Kim</td>
<td>Bình Chướng commune, Bình Sơn district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Gò Quế</td>
<td>Bình Đông commune, Bình Sơn district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Long Thành</td>
<td>Phố Thành commune, Đức Phớ district</td>
<td>Quảng Ngãi</td>
<td>pre Sa Huỳnh</td>
</tr>
<tr>
<td>Núi Sutura</td>
<td>Tịnh An commune, Sơn Tịnh district</td>
<td>Quảng Ngãi</td>
<td>pre Sa Huỳnh</td>
</tr>
<tr>
<td>Phú Khương</td>
<td>Phố Thánh commune, Đức Phớ district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Sa Huỳnh</td>
<td>Phố Thánh commune, Đức Phớ district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Sự Chinh</td>
<td>Lý Hải commune, Lý Sơn district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh-Champa</td>
</tr>
<tr>
<td>Thanh Đức</td>
<td>Phố Thành commune, Đức Phờ district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Trảng Quỳnh</td>
<td>Bình Châu commune, Bình Sơn district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Xóm Òc</td>
<td>Lý Vinh commune, Lý Sơn district</td>
<td>Quảng Ngãi</td>
<td>pre Sa Huỳnh - Sa Huỳnh</td>
</tr>
<tr>
<td>Xuân Phố</td>
<td>Nghĩa Kỳ commune, Tư Nghĩa district</td>
<td>Quảng Ngãi</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Cảnh Dài</td>
<td>Hương Chủ commune, Hương Trà district</td>
<td>Thừa Thiên Huế</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Cảnh Ràng</td>
<td>Hương Chủ commune, Hương Trà district</td>
<td>Thừa Thiên Huế</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Vườn Cửa Thiền</td>
<td>Tứ Hạ town, Hương Trà district</td>
<td>Thừa Thiên Huế</td>
<td>Sa Huỳnh</td>
</tr>
<tr>
<td>Vườn Nhà Anh Phan Văn Nhơn</td>
<td>Hương Chủ commune, Hương Trà district</td>
<td>Thừa Thiên Huế</td>
<td>Sa Huỳnh</td>
</tr>
</tbody>
</table>

Data from Lâm Thị Mỹ Dzung (2008; pers. comm.)
witnesses the Jinan phase from 100-200CE and the establishment of Linyi polities from 200-500CE. Linyi was independent of the development of the Chămpa Kingdom and defines a period before the term Chămpa appeared in ancient Chinese texts (Yamagata 1998).

One of the defining features of the Sa Huỳnh culture is the interment of an individual in a jar with associated artefacts reflective of the temporal period. However, there are subtle regional differences within these general mortuary practices. Lâm Thị Mỹ Dzung (2011) has identified three successive phases within the typical Sa Huỳnh cultural period. Phase I is characterised by sites such as Gò Mả Vổi, Bình Châu II, Bình Yên (Trench 1), Thạch
2. Vietnam, its Environment and Archaeology: Contextualising An Sơn and Hòa Diêm

Bích and Gò Quê. In this phase, jar burials and extended inhumations are present, and associated burial artefacts include bronze and iron items and a few glass beads. There are no bronze containers or bronze mirrors characteristic of Han Dynasty Chinese influence. The burial practices and associated artefacts demonstrate a strong commonality with the northern Đông Sơn culture.

Phase II is characterised by sites such as Gò Dừa, Lai Nghi, Bình Yên (Trench 2), An Bang, Đại Lãnh, Động Cườm, Sa Huỳnh and Diên Khánh. This phase represents the peak of the Sa Huỳnh culture. Burial artefacts include iron implements, agate, carnelian and glass beads and earrings, and some gold jewellery. Imported artefacts include bronze vessels, Han Dynasty bronze mirrors and alkaline etched beads. The pottery is poorly decorated in comparison to that of Phase I. The burial practices and associated artefacts demonstrate a strong commonality with the northern Han.

Phase III is characterised by sites such as Lai Nghi, Hậu Xá II, the burials of Xóm Ôc, Suối Chình, Rừng Long Thuỷ, the burials of Hóa Diêm, Giồng Cá Vồ and Giồng Phết. In this phase, jar burials and extended inhumations are still present, but burial practices and associated artefacts demonstrate influence from China, India and other Southeast Asian islands.

There are variations in jar shape and style identified by Lâm (2011) as traditions I and II, which can be broadly defined geographically as a northern style and a southern style. In the northern sites, from Long Thạnh to Sa Huỳnh, the burial jars are ovoid or cylindrical. In the southern sites, from Bàu Trám to Suối Chình and including Hóa Diêm and Giồng Cá Vồ, the burial jars are spherical (Figure 2.5). Although there is a broad geographic trend in the style of jar burial it is again not rigid. For example, in Khánh Hòa Province, Hóa Diêm demonstrates tradition II in jar shape, while at Diên Khánh it is tradition I (Lâm 2011). Yamagata (2006; 2008b) argues against including sites from the south, such as Suối Chình, Hóa Diêm, Giồng Cá Vồ and Giồng Phết as Sa Huỳnh, based on differences in mortuary practices and characteristics of pottery and burial jars. Having defined and contextualised the Sa Huỳnh, the following section will trace the development of this

Figure 2.5. Jar burials from An Bang, Quảng Nam (Tradition I, left) and Suối Chình, Quảng Ngãi (Tradition II, right) (not to scale)
The development of the Sa Huỳnh culture

In order to understand the origins and nature of the Sa Huỳnh jar burial tradition an examination of the regional distribution and chronology of jar burial practices is required. The practice of interring individuals in jar burials is a longstanding tradition in Asia and has been observed in archaeological sites all over the region; in Northeast Asia in China, Taiwan, Korea and Japan; in Island Southeast Asia in Taiwan, the Philippines, Indonesia and Malaysia; in Mainland Southeast Asia in Thailand and Vietnam, and in India and Sri Lanka. The sites presented and discussed are those from Taiwan, Island Southeast Asia and Mainland Southeast Asia, as they are most relevant to the Sa Huỳnh (see Table 2.3 and Figure 2.6). This review is not exhaustive as many reports remain as relatively inaccessible ‘grey literature’, however, they will provide an indication of the geographic coverage and distribution of jar burial practices. The range of variation in this practice is diverse and the question as to whether the practice spread through human migration with subsequent localised variations or whether it has developed independently in many different areas is still one that remains unanswered.

Many Vietnamese scholars believe that the Sa Huỳnh culture developed locally, within Vietnam (Hà 1988), with several Neolithic cultures including Bàu Tró, Hòa Lộc, Xóm Cồn and Đồng Nai associated with the formation of the Long Thạnh culture through to the Bình Châu culture and eventually coalescing into the early Sa Huỳnh. However, others argue that there are too many distinctions in pottery form, and that they must represent independent distinctive cultures that are neither continuous nor successive (Bùi and Yamagata 2005). Hung et al. (2013) suggest that the stylistic differences of the pottery traditions may be attributed to differential influences, the Long Thạnh pottery influenced by the northern Phùng Nguyên culture and the Bình Châu pottery influenced by the Neolithic tradition of red-slipped pottery that developed in southern Taiwan and the Philippines.

It has been suggested that the Sa Huỳnh people, or at least those who inhabited sites dating to after 500BCE, were Malayo-Chamic (Austronesian) speakers who originated from Island Southeast Asia (Hung et al. 2013). The ancestral Malayo-Chamic language was introduced into Vietnam from northwestern Borneo about 2000 years ago, before large numbers of Sanskrit loan words became integral to the Southeast Asia vocabulary, but after the cognate term besi for iron was incorporated into the Malayic and Chamic languages (Blust 2005). The Chamic migration from Island Southeast Asia to Vietnam must have included a large number of individuals; otherwise the language would not have taken hold and successfully replaced the native Mon-Khmer languages in the central coastal area (Bellwood 2005; Hung et al. 2013).
Table 2.3. Neolithic and Metal Age Jar burial sites in Southeast Asia

<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Country</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anjar</td>
<td>Anjar District, north Banten, west Java</td>
<td>Indonesia</td>
<td>van Heekeren 1956</td>
</tr>
<tr>
<td>Buwawansi</td>
<td>Gebe Island</td>
<td>Indonesia</td>
<td>Bellwood 2007</td>
</tr>
<tr>
<td>Gilimanuk</td>
<td>Melaya, Jembrana district, western Bali</td>
<td>Indonesia</td>
<td>Soejono 1979</td>
</tr>
<tr>
<td>Gua Siti Nafisah</td>
<td>Nusilko, Helmahera island</td>
<td>Indonesia</td>
<td>Bellwood et al. 1993</td>
</tr>
<tr>
<td>Leang Buidane Cave</td>
<td>Lirung district, Salebabu Island</td>
<td>Indonesia</td>
<td>Bellwood 1978</td>
</tr>
<tr>
<td>Melolo</td>
<td>Sumba Island, Nusa Tenggara</td>
<td>Indonesia</td>
<td>Bintarti 1986</td>
</tr>
<tr>
<td>Plawangan</td>
<td>Plawangan, Rembang district, north central Java</td>
<td>Indonesia</td>
<td>Sukendar and Awe 1981</td>
</tr>
<tr>
<td>Tanjung Pinang rock shelter</td>
<td>Morotai Island</td>
<td>Indonesia</td>
<td>Bellwood et al. 1993</td>
</tr>
<tr>
<td>Tebingtinggi</td>
<td>Lesungbatu village, Muara Danau, Tebingtinggi, south west Sumatra</td>
<td>Indonesia</td>
<td>van Heekeren 1958</td>
</tr>
<tr>
<td>Uattamdi Cave</td>
<td>Guruapin, Helmahera district, Kayoa Island</td>
<td>Indonesia</td>
<td>Bellwood et al. 1993</td>
</tr>
<tr>
<td>Niah Cave</td>
<td>Niah, Sarawak</td>
<td>Malaysia</td>
<td>Harrison 1967</td>
</tr>
<tr>
<td>Pusu Samang Tas Cave</td>
<td>Madai complex, Sabah</td>
<td>Malaysia</td>
<td>Harrison and Harrison 1971</td>
</tr>
<tr>
<td>Arku Cave</td>
<td>Peñablanca, Cagayan Province, northern Luzon</td>
<td>Philippines</td>
<td>Thiel 1990</td>
</tr>
<tr>
<td>Ayub Cave</td>
<td>Maitum, Sarangani Province, Mindanao</td>
<td>Philippines</td>
<td>Dizon 1993</td>
</tr>
<tr>
<td>Bato Caves</td>
<td>Bacon, Sorsogon</td>
<td>Philippines</td>
<td>Fox and Evangelista 1957a</td>
</tr>
<tr>
<td>Behia</td>
<td>Magallanes, Sorsogon</td>
<td>Philippines</td>
<td>Cuevas 1992, Legaspi 1968</td>
</tr>
<tr>
<td>Binisitan, Boton</td>
<td>Casiguran, Sorsogon</td>
<td>Philippines</td>
<td>Dizon 1979a</td>
</tr>
<tr>
<td>Cagraray Caves</td>
<td>Albay, Sorsogon</td>
<td>Philippines</td>
<td>Fox and Evangelista 1957b</td>
</tr>
<tr>
<td>Calatagan</td>
<td>Batangas</td>
<td>Philippines</td>
<td>De La Torre 2003</td>
</tr>
<tr>
<td>Carrangalan</td>
<td>Nueva Ecija</td>
<td>Philippines</td>
<td>Evangelista 1957</td>
</tr>
<tr>
<td>Catanauan</td>
<td>Catanauan, Bondoc Peninsula, Quezon</td>
<td>Philippines</td>
<td>Paz et al. 2008</td>
</tr>
<tr>
<td>Chamber A at Tabon Caves</td>
<td>Quezon, Palawan</td>
<td>Philippines</td>
<td>Fox 1970</td>
</tr>
<tr>
<td>Chamber B at Tabon Caves</td>
<td>Quezon, Palawan</td>
<td>Philippines</td>
<td>Fox 1970</td>
</tr>
<tr>
<td>Chuhangin</td>
<td>Ibuhos Island</td>
<td>Philippines</td>
<td>Dizon 2000</td>
</tr>
<tr>
<td>Dipnay Supuan</td>
<td>Batan Island</td>
<td>Philippines</td>
<td>Faylona 2003</td>
</tr>
<tr>
<td>Diptan</td>
<td>Batan Island</td>
<td>Philippines</td>
<td>Dizon 2000</td>
</tr>
<tr>
<td>Jupi</td>
<td>Gubat, Sorsogon</td>
<td>Philippines</td>
<td>Legaspi 1973</td>
</tr>
<tr>
<td>Maguhot</td>
<td>Bacong, Negros Island</td>
<td>Philippines</td>
<td>Tenazas 1974</td>
</tr>
<tr>
<td>Makabog</td>
<td>Aroroy, Masbate Island</td>
<td>Philippines</td>
<td>Solheim II 1953, 1954</td>
</tr>
<tr>
<td>Pilar</td>
<td>Pilar, Sorsogon</td>
<td>Philippines</td>
<td>Beyer and De Veyra 1947, Dizon 1978</td>
</tr>
<tr>
<td>Recudo</td>
<td>San Narsico, Bondoc Peninsula, Quezon</td>
<td>Philippines</td>
<td>Solheim II 1951</td>
</tr>
<tr>
<td>San Juan, Bacon</td>
<td>Casiguran, Sorsogon</td>
<td>Philippines</td>
<td>Dizon 1979b</td>
</tr>
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</table>
Table 2.3. Neolithic and Metal Age Jar burial sites in Southeast Asia continued

<table>
<thead>
<tr>
<th>Site name</th>
<th>Location</th>
<th>Country</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Savidug</td>
<td>Sabtang Island</td>
<td>Philippines</td>
<td>Bellwood and Dizon 2013b</td>
</tr>
<tr>
<td>Tigkiw na Saday</td>
<td>Casiguran, Sorsogon</td>
<td>Philippines</td>
<td>Dizon 1979c</td>
</tr>
<tr>
<td>Tumagudtud</td>
<td>San Narsico, Bondoc Peninsula, Quezon</td>
<td>Philippines</td>
<td>Solheim II 1951</td>
</tr>
<tr>
<td>Huangangshan</td>
<td>Hualian</td>
<td>Taiwan</td>
<td>Bellwood and Dizon 2013a; Ye 2001</td>
</tr>
<tr>
<td>Lanyu</td>
<td>Lanyu Island, Taitung County</td>
<td>Taiwan</td>
<td>Tsang 2005</td>
</tr>
<tr>
<td>Wanshan</td>
<td>Yilan County</td>
<td>Taiwan</td>
<td>Tsang 2005</td>
</tr>
<tr>
<td>Yanliao</td>
<td>Hualian</td>
<td>Taiwan</td>
<td>Bellwood and Dizon 2013a; Ye 2001</td>
</tr>
<tr>
<td>Ban Kan Luang</td>
<td>Muang District, Ubon Ratchathani province</td>
<td>Thailand</td>
<td>Indrawooth 1997</td>
</tr>
<tr>
<td>Ban Krabuang Nok</td>
<td>Chum Phuang District, Nakhon Ratchasima province</td>
<td>Thailand</td>
<td>Indrawooth 1997</td>
</tr>
<tr>
<td>Ban Non Wat</td>
<td>Non Sung district, Nakhon Ratchasima</td>
<td>Thailand</td>
<td>Higham and Kjngam 2011</td>
</tr>
<tr>
<td>Muang Fa Daed Song Yang</td>
<td>Kamalasai District, Karasin Province</td>
<td>Thailand</td>
<td>Indrawooth 1997</td>
</tr>
<tr>
<td>Làng Vac</td>
<td>Nghị hà Hòa commune, Thái Hòa town, Nghệ An province</td>
<td>Vietnam</td>
<td>Hà 1980</td>
</tr>
<tr>
<td>Long Thanh</td>
<td>Phú Thành commune, Đức Phú district, Quảng Ngãi</td>
<td>Vietnam</td>
<td>Chữ 1997; Chữ and Đào 1978; Hà 1988</td>
</tr>
</tbody>
</table>
The oldest evidence for jar burial practices in the region occurs in the Neolithic. In Vietnam these sites are referred to as pre Sa Huỳnh (c. 1550-550BCE) and thus presumably predate the arrival of Malayo-Chamic immigrants into the coastal region of Vietnam, which suggests that the Sa Huỳnh developed in Vietnam before any Malayo-Chamic influence. The following section will discuss the earliest examples of jar burials in the region.

Two examples of archaeological sites with jar burials argued to be from the Neolithic are Lung Leng and Long Thành (Nguyễn 2005b; Trần 2005; Yamagata 1998). Lung Leng is located in Sa Binh commune, Sa Thầy District, Kon Tum Province in the central highlands (Tây Nguyên). There were two distinct layers at the site, a lower lateritic layer and an alluvial layer dated from c. 2100BCE-100CE (Bùi 2005; Nguyễn 2005b; Yamagata 1998). There were 209 burials excavated at Lung Leng. Fourteen were inhumations and 185 were jar burials. Of the jar burials, 79 were large ovoid jars, 74 were spherical jars and 32 were smaller spherical jars positioned mouth to mouth. Three radiocarbon dates from burial contexts ranged from 1740-1390BCE (Nguyễn 2010). The inhumations are argued to date earlier than the jar burials and the spherical jars earlier than the large ovoid
Jars and small spherical jars that were placed mouth to mouth (Nguyễn 2010; Trần 2005). There is a reference to a bicephalous earring found at the site, however, the temporal context in which it was found is not stated (Lê 2012).

Jar burials have also been recovered at Long Thành, in Phố Thành commune, Đức Phổ District, Quảng Ngãi Province. The site has two distinctive occupation phases according to the archaeology, with a thin sterile layer separating the two, the jar burials belonging to the later one. Radiocarbon dates for the site situate it at c. 1500-1000BCE (Chử 1997; Chử and Đào 1978; Hà 1988). It is unclear where in the stratigraphic profile the radiocarbon dates were sourced, however, no metal objects have been recovered from any of the jar burials, so it probably represents a transitional site dating from the Neolithic. The stylistic similarity between some of the jars at Lung Leng and Long Thành attest to the degree of interaction between these sites (Figures 2.7).

**Beyond Vietnam**

It is important to look beyond Vietnam in order to better understand the development of the Sa Huỳnh and the jar burial tradition in the region in general. In Northeast Thailand two adult jar burials have been recovered from Ban Non Wat (Figure 1.1), Burials 28 and 292, both dating to the Neolithic. Radiocarbon dates taken from charcoal and a bivalve shell within the jar of Burial 28 were 2150-1936BCE and 1499-1407BCE respectively (Higham and Kijngam 2011), so of a similar temporal period to the pre Sa Huỳnh sites in Vietnam. Both jar burials were spherical in form. The most interesting point about these burials was that the individuals were primary burials within the jars and very well preserved.

In the Philippines two cave sites with jar burials are argued to date from the Neolithic. The deposit in Chamber A in the Tabon Caves on Palawan Island (Table 2.3 and Figure 2.6), from which the Manunggul jar was recovered, was radiocarbon dated 890 and 710BCE (Fox 1970). There were no metal implements recovered from this cave, which supports the assertion that the assemblage is at least preMetal, however, metal was recovered from chamber B, so either the chambers represent different temporal periods, or there was just no metal included in the jars in chamber A. Arku Cave, in Peñablanca, Cagayan Province in northeast Luzon (Table 2.3 and Figure 2.6), was radiocarbon dated to c. 2200-50BCE (Thiel 1990), however, this is questionable. Penannular lingling-o earrings were recovered from both sites (Fox 1970; Thiel 1990). In Malaysia, jar burials have also been recovered from Niah Cave in Sarawak (Table 2.3 and Figure 2.6) radiocarbon dated to 1500-200BCE (Lloyd-Smith et al. 2016). The stylistic discontinuity between Vietnam and the Philippines in the Neolithic supports the idea that Austronesians (Malayo-Polynesians) did not reach Vietnam until the Iron Age (Bellwood 2007). But if this was the case one is left wondering about the origins of the jar burial tradition during the pre
Many scholars over the years have observed the close parallels between Iron Age assemblages at various different sites around the South China Sea (Bellwood 2007; Fox 1970; Glover 1996; Loofs-Wissowa 1982). Solheim originally suggested the concept of a maritime trading network across the region. Working in Kalanay cave on the northwest of Masbate Island, in the Bicol region of the central Philippines, and on the Guthe pottery collection curated at the Museum of Anthropology (University of Michigan), he noted that the mortuary practices, the pottery and other artefacts including jade penannular lingling-o and bicephalous earrings/pendants were very similar to those in Sa Huỳnh sites in central Vietnam, and coined the term the Sa Huỳnh-Kalanay pottery tradition. Although he suggested that the network may have been fuelled by population movements or trade (Solheim II 1959a, 1959b) amongst Malayo-Polynesian (Austronesian) speakers (Solheim II 1964, 2006), subsequent research suggests that the Austronesians moved out into Island Southeast Asia from an origin in Taiwan at least 1000 years earlier than the emergence of the typical Sa Huỳnh Culture (Hung et al. 2013).

Solheim (2002) created a list of diagnostic decorative features of the pottery complex of Kalanay cave, including paired diagonal borders, curvilinear and rectangular scrolls and triangles, punctate stamping within incised lines, crenulated shell impressions, scalloped shell impressions and cutouts in pedestals, suggesting the scalloped shell impressions to be the most diagnostic feature. Yamagata (2012b) argues punctate stamping within incised lines and crenulated shell impressions are common features among Sa Huỳnh pottery, however, scalloped shell impressions are not, and cordmarking, which is very common among Sa Huỳnh pottery, does not appear on the Kalanay pottery. What led Solheim to associate the Kalanay pottery with the Sa Huỳnh pottery was the striking similarity he observed in the use of the incised spiral motif (Yamagata 2012b). While these occasionally feature on the burial lids in Sa Huỳnh sites, they are not common on the accessory mortuary vessels (Yamagata 2012b). There are, however, very strong resemblances between the Kalanay pottery, that of Ko Din in Thailand and that of Hòa Diêm in Khánh Hòa Province (Favereau 2015; Lâm 2008; Yamagata 2008b, 2012b).

Figure 2.7. Jar burials from Long Thạnh (left) and Lung Leng (right) (not to scale)
Fox (1970) argued that the Tabon pottery complex, from Tabon Cave on Palawan Island in the Philippines (Table 2.3 and Figure 2.6), was very different from the Kalanay pottery complex as cordmarking and paddle impressed pottery were the norms in Tabon. However, the burial jars from Tabon featured burial lids similar to the Sa Huỳnh burial lids. There has been a long history of connections inferred between the Philippines and the Sa Huỳnh of Vietnam. Palawan, in particular, was likely a key player in the exchange of goods and ideas due to its geographic position near Vietnam (Yamagata 2012b).

In the Bicol region of the Philippines, at the southern tip of Luzon Island, several jar burial sites have been found in Sorsogon province and Masbate Island and to the northwest on the nearby Bondoc Peninsular (part of modern day Quezon province) (Table 2.3 and Figure 2.6). These have a commonality in the style of the jars, the arrangement of the jars and the associated artefacts (Ragragio 2012). The jars are plain, low fired earthenware, with little decoration other than cordmarking, and are ovoid in shape. They have caps of volcanic tuff, limestone or coral which have intentionally carved circular impressions on the underside to fit over the jars. The lids that have been uncovered from secure archaeological contexts are undecorated. These jars were buried with their mouths above ground, rather than put into caves as observed elsewhere in the Philippines. Accessory vessels included in the burial jars are characteristic of the Sa Huỳnh-Kalanay style. Although there are variations among these sites and in their locations, either inland or on coastal beaches, together with variations in the material of the capping lids or the amount of manipulation of them, there is an underlying theme of commonality in the area, which is very different to the comparable contemporaneous jar burials of Palawan in the west, Mindanao in the south or others to the north (Ragragio 2012). This similarity in jar burial practices in the Bicol region of the central Philippines could suggest that the Sa Huỳnh-Kalanay is more relevant to the southern tradition of the Sa Huỳnh culture, including sites such as Suối Chình, Hòa Diêm, Giòng Cả Vò and Giòng Phệt (Table 2.2 and Figure 2.4). There are very few secure dates for these sites, unfortunately, so the question of which way the influence went cannot be answered at this stage, but it is worth exploring. Is there any other evidence for interaction between the Bicol region of the Philippines and the southern Sa Huỳnh sites in Vietnam?

Although interaction among sites situated around the South China Sea has long been mooted, interest in the Sa Huỳnh-Kalanay Interaction Sphere is beginning to gain momentum again, with more research and more evidence for interaction. The chronological framework for the region is also being tightened (Hung et al. 2013). Evidence for the Sa Huỳnh-Kalanay Interaction Sphere comes from a number of different sources, including archaeological continuity in stylistic themes seen in pottery, jewellery and mortuary practices. Linguistically, all of these interconnected regions were populated by Malayo-Polynesian speaking people (Hung et al. 2013).
Evidence suggests there were two large exchange networks operating across the South China Sea. The first involved the movement of large bronze Dôn Son drums into Mainland Southeast Asia and Sumatra, Java, Bali, Kalimantan and Nusa Tenggara (Bellwood 2007). These drums were not present in the northern reaches of the South China Sea, Taiwan, the Philippines, or the northern regions of Borneo. The second large network involved the Sa Huỳnh-Kalanay pottery complex which did, however, reach these areas and is argued to have been a key component in their transition to metallurgy.

The development of metallurgy in Island Southeast Asia was introduced on to a Neolithic background, and there was no independent metallurgical development or gradual transition from the Neolithic through to a Bronze and then Iron Age as was the case in China and Mainland Southeast Asia. Between 500-300BCE, in Taiwan and the Philippines for example, there was a rapid incursion of new raw materials, new technology and new artefacts onto a cultural background that lacked any prior knowledge of Bronze (Bellina and Glover 2004; Glover 1996; Hung and Bellwood 2010). These included Iron, Copper and Bronze, casting moulds, siliceous stone beads and Indo-Pacific glass beads. Between 500BCE-100CE there is evidence of interaction through two very distinctive items made from Fengtian nephrite from Taiwan, the lingling-o penannular earring and the bicephalous animal earring/pendant. Despite the fact that the earrings were often manufactured locally from imported Taiwanese nephrite blanks, the consistency in the size and shapes of the objects suggests a continuity of knowledge among the artisans. Similarly, Mindoro jade from Mindoro Island in the central Philippines has been utilised throughout the region to manufacture beads, earrings, pendants and lingling-o. While these are relatively recent items, Hung et al. (2013) suggest that the baked clay earrings found at Neolithic Thạch Lạc and pre Sa Huỳnh site Bình Châu, Gò Mả Vô and possibly Bến Đò in central Vietnam and Savidug and Nagsabaran in the Philippines (Hung et al. 2013; Lâm 2008; Reinecke 2002), are possible precursors to the lingling-o; dating from 1500BCE they are a testament to the antiquity of this interaction sphere operating in the South China Sea.

Examining a potential background for this interconnectivity, the early Neolithic and pre Sa Huỳnh assemblages from coastal Vietnam show evidence of interaction with Island Southeast Asia and Austronesian speaking populations from around 1500-1000BCE. This connection between regions around the South China Sea suggests an interaction between Malayo-Polynesian speakers and residents of the central Vietnamese coast that dates significantly earlier than the arrival of Malayo-Chamic speakers from Borneo. This indicates that there was interaction among sites around the South China Sea well before the Malayo-Chamic speakers influenced the typical Sa Huỳnh culture.

These connections serve as a reminder that interactions among different regions, cultures and people are not necessarily always visible archaeologically or linguistically (Hung
et al. 2013). These older trade routes across the South China Sea were likely the same that were travelled in the Iron Age. The number of new, noticeable and non-perishable items that were manufactured and traded during the Iron Age leaves a relatively clear archaeological signature that should not blind us to the likelihood that the well sailed trading routes of this period were more than likely travelled many centuries before, from Neolithic times at least (Hung et al. 2013). The communication and contact probably became more prevalent over the last few centuries BCE, visible in the archaeological record in the widespread distribution of lingling-o, bicephalous nephrite earrings/pendants, glass beads, iron artefacts and pottery. What this obscures, however, is the deeper cultural affinity among these groups of people (Hung et al. 2013).

The Sa Huỳnh culture of central Vietnam shows a large amount of variation stylistically and geographically which is not surprising given the range of influences and the number of interactions between Vietnam and other areas around the South China Sea. This is a product of the diffusion of ideas through interaction. The extension of the Sa Huỳnh culture into the Thu Bon River Valley and at Lung Leng in the central highlands shows that it was not simply a feature of coastal sand dunes or a practice undertaken solely by Malayo-Chamic speakers, it was also part of the Mon-Khmer tradition (Hung et al. 2013). Was the Neolithic jar burial practice a tradition that left southern China with Austroasiatic speaking people, moving down the river systems, and somehow came through northeast Thailand, as observed at Ban Non Wat, and then moving down the tributaries of the Mekong, through the highlands of Vietnam as observed at Lung Leng, and eventually down the Mekong to southern Vietnam and then over to the Bicol region of the Philippines? Or did the jar burial tradition come the other way, out through Taiwan with Austronesian speakers, through the Batanes and then into the Bikol region and over to coastal Vietnam, particularly the southern region? The strong similarities in the jar burial traditions suggest some form of communication, but which way it went is a question that cannot be answered at this stage. Perhaps as Hung et al. (2013) suggest the interaction should be viewed as reciprocal.

THE SITES

So far the discussion has focussed on the environment and climate of Vietnam in addition to surveying the relevant archaeology with respect to the development of the Neolithic and Metal Periods. In the following section the two sites forming the focus of this thesis are examined in some detail. First, Neolithic An Sơn is reviewed, followed by Iron Age Hòa Diệm.

An Sơn

This section will introduce the Neolithic site of An Sơn, one of the key sites examined in this thesis. The archaeological history of the site will be presented, followed by an
interpretation of the construction of the site from the stratigraphy, the chronology of the site, the flora, fauna and evidence for subsistence, the material culture, the burials and finally the genetic affinities of the individuals from An Sơn.

An Sơn is in Sơn Lợi, An Ninh Tây commune, Đức Hòa district, Long An province in southern Vietnam. In the present day it is located on the verge of an active floodplain about 300m east of the Vàm Cỏ Đông River (10° 59’ 19” N, 106° 17’ 41” E) (Figure 1.1). The Vàm Cỏ River system runs through Long An Province and comprises two main rivers, the Vàm Cỏ Đông in the east and the Vàm Cỏ Tây in the west. The Vàm Cỏ Đông River is linked to the Saigon and Đồng Nai River by small streams, while the Vàm Cỏ Tây is similarly linked to the Mekong River (Bùi et al. 1997b). The Vàm Cỏ Đông and Vàm Cỏ Tây intersect in the east of the province, flowing to the sea in the northern region of the Mekong Delta.

Several significant sites dating from the Neolithic to the Iron Age have been discovered in this region, particularly along the Vàm Cỏ River system and the Đồng Nai and Saigon River valleys. An Sơn is among a concentration of Neolithic sites along the Vàm Cỏ Đông River (Figure 2.3). An Sơn is presently about 75km from the sea, situated on a raised quaternary alluvial terrace that during the mid-Holocene marine transgression was quite close to the coast, with the sea level highstand 2.5-4.5m above present sea level occurring between 4000-3000BCE (Nguyễn et al. 2000; Proske et al. 2011; Tạ et al. 2002a; Tạ et al. 2002b).

In 1997 the mound at An Sơn was more than 5m high and 170m in maximum diameter (Nishimura and Nguyễ́n 2002). However, in the intervening years the edges of the mound have been increasingly cut away, while the top of the mound was levelled to rebuild the Phước Trườ́ng pagoda and plant perennial trees. The west of the mound was terraced from the road to the top of the mound, creating a steep 5m high slope. The south of the mound was terraced as a vertical face. The east of the mound was mined for soil to use for house construction and agriculture. The mound currently stands at about 4m in height with an area of 90x65m (Bellwood et al. 2011).

**Archaeological history of the site**

The early years

The ancient remains of An Sơn were first discovered by the local people in 1938. Later that year two French archaeologists, Louis Malleret and Paul Levy, surveyed the area and dug two test pits to a little over 2m in depth, in which they discovered prehistoric stone tools and pottery sherds as well as historic bricks (Dăng et al. 2008; Malleret 1963; Phạm et al. 2006). Malleret (1963: 95) reported a local had said one of his relatives had dug a
trench in 1910 on the north side of the mound next to the pagoda and discovered bricks at a depth of about 3 metres. It was suggested that the remains from An Sơn represented two periods of past occupation, Neolithic and historic Khmer (Malleret 1963).

1978 season

In 1977, two years after the complete liberation of Vietnam, archaeologists from the Institute of Social Sciences in Hồ Chí Minh City and the Department of Culture and Information in Long An province investigated An Sơn again. The following year, in 1978, Lê Xuân Diêm in collaboration with these same institutions conducted the first official excavation at An Sơn. The total excavation area was 144m² and comprised three trenches (Lê 1978c). Trench 2 (78ASH2) was on the mound top (9x6m), and Trench 1 (78ASH1 - 10x5m) and Trench 3 (78ASH3 - 10x4m) were located at the base of the mound to the east with a 1m baulk between them (Figure 2.8 and Figure 2.9) (Lê 1978b).

1997 season

An Sơn was excavated a second time in 1997, under the directorship of Bùi Phát Diệm, the Long An provincial museum, the Institute of Social Sciences in Hồ Chí Minh City, the Institute of Archaeology in Hanoi and a number of researchers from Japan led by Masanari Nishimura. The excavation consisted of three test pits, two 1x1m (97ASTS1 and 97ASTS2) and the third 2x2m (97ASTS3), and the main trench, Trench 1 (97ASH1 - 8x4m), which were all located on the top of the mound (Figure 2.8 and Figure 2.9) (Phạm et al. 2006).

2004 season

The third excavation was directed by Dr. Phạm Quang Sơn in collaboration with the Long An provincial museum and the Southern Institute of Social Sciences in 2004. Three large trenches and five test pits were excavated with a total area of 313m². The trenches were divided into small squares (2x2m), numbered according to their order 1,2,3,4 north to south and A, B, C, D west to east (Phạm et al. 2006).

Trench 1 (04ASH1) was located on the east side of the mound (6x4m). Trench 2 (04ASH2), 8x12m, was positioned 9.7m west of Trench 1 (04ASH1) and 15m east of the west wall of the 1997 Trench 1 (97ASH1). Trench 3 (04ASH3) was located 17m south of Trench 2 and was 17x10m. It was divided into two equal parts, with a 1m strip left unexcavated in the middle. The trench was extended in the northeast (5m²) and northwest corners (18m²) during the duration of the excavation.

The test pits (TS) were each 2x1m. 04ASTS1 was positioned south of Trench 1 (04ASH1),
in order to examine the current state of the cultural layer. 04ASTS2 was positioned 1m north of Trench 2 (04ASH2), in order to locate the south wall of 1978 Trench 3 (78ASH3). Test squares 3, 4 and 5 (04ASTS3, 04ASTS4 and 04ASTS5) were positioned on a transect between Trench 2 (04ASH2) and Trench 3 (04ASH3) to assist correlation of stratigraphy across the area (Figure 2.8 and Figure 2.9).

2007 season

The fourth excavation at An Sơn was undertaken in 2007, in a joint collaboration between the Long An provincial museum and the University of Social Science and Humanities in Hồ Chí Minh City. One trench was excavated, Trench 1 (07ASH1), which was 1.5m northwest of the 2004 Trench 3 (Figure 2.8 and Figure 2.9) (Đặng et al. 2008).

2009 season

The fifth excavation at An Sơn was undertaken in 2009, in a joint collaboration between the Long An provincial museum, the Centre for Archaeology, Southern Institute of Social Sciences, Hồ Chí Minh City, the Institute of Archaeology in Hà Nội and The Australian National University. Three trenches were excavated. Trench 1 (09ASH1) was 3x12m, Trench 2 (09ASH2) was 5x5m, and Trench 3 (09ASH3) was 2x10m. Trenches were labelled in consecutive alphabetical order east to west and numeric order north to south. A 2x1m test pit (09ASTS1), was excavated at the western edge of the mound in an effort to locate and identify the natural alluvial basal layers that exist under the recent terracing (Figure 2.8 and Figure 2.9) (Bellwood et al. 2011).

Construction of the site

The 1978 Trench 2 (78ASH2) and 1997 Trench 1 (97ASH1) located on the mound, report a stratigraphic profile 4.5m and 4m deep respectively with three main horizontal layers, comprised of many small harder lenses interspersed with dark lenses rich in ash and charcoal, animal bones and teeth, shell, pottery sherds and artefacts (Lê 1978c; Nishimura and Nguyễn 2002). Nishimura and Nguyễn (2002) suggest that the harder lenses of quarried alluvial soil represented a continuous succession of floors of rammed earth in the middle layers of the site. Post holes c.50cm deep were discovered within these and have been suggested as possible ground level housing, although no plans could be reconstructed from their pattern. The basal cultural layer of the site was derived from an alluvial palaeosol (Bellwood et al. 2011).

In comparison to the horizontal layers in the main mound, the layers on the undulating contours of the lower slopes of the mound are different. Trench 1 (09ASH1) captures sloping layers of occupational material dumped off the main mound, represented by
Figure 2.9. Excavation trenches from 1978 (not including 78ASH2), 1997, 2004, 2007 and 2009 with burials
superimposed layers containing a large amount of broken pottery, extending outward and downward on a 30° slope forming concentric contours around the mound. The stratigraphic profile clearly illustrates a foundation palaeosol (layer 8), with the oldest southeast cultural delimitation of the mound (layer 7), the layers of cultural waste (6-4), and then a layer of clay and very small pottery sherds, the clay being transported in suspension by rainwater flowing off the top of the mound (3) topped by the top soil (layers 2-1) (Figure 2.10). Trenches 04ASH2 and 07ASH1 showed similar stratigraphic profiles (Bellwood et al. 2011).

Trench 2 (09ASH2) captured sloping layers radiating concentrically from a subsidiary mound, which was positioned east of the main mound and not visually obvious, as the top had been removed by recent earthmoving to create rice fields. However, as a separate entity from the main mound it had an independent stratigraphy. The stratigraphic profile clearly shows the oldest layers in the northeast corner of the square, superimposed by layers of rakeout emanating from the subsidiary mound and radiating concentrically toward the southwest (Figure 2.11). Two of the 2004 trenches (04ASH1 and 04ASH3) also captured the stratigraphy of the subsidiary mound (Bellwood et al. 2011).

Trench 3 (09ASH3) captured a relatively unstratified area, further away from the mound. It contained very little cultural material, just layers of clay runoff with many very small pottery sherds from the mound, the clay being transported in suspension with rainwater. A cluster of broken whole pots at the base of Trench 3 on the palaeosol (layer 8) provided a date of 2471-2209BCE. Layer 4 was potentially the only original mound layer to extend into the trench, subsumed by the layers of clay runoff (3-2) and topped by the top soil (layer 1) (Figure 2.12) (Bellwood et al. 2011).

**Dating**

Thirty one well provenanced dates are available from An Sơn (Table 2.4). The dating was undertaken at three separate radiocarbon dating labs, the Radiocarbon Dating Centre at The Australian National University, Australia (ANU); Rafter Laboratories, National Isotope Centre, Institute of Geological and Nuclear Sciences Ltd (GNS Science) in Lower Hutt, New Zealand (NZA) and the $^{14}$C Dating Laboratory at The University of Tokyo (Tka). The samples, acquisitioned from a range of materials including charcoal, pot sherd residue, estuarine shells and human tooth enamel, present a clear sequence providing evidence of continuous occupation at the site for around a thousand years c. 2100-1050BCE. The burials fall within a range between c. 1600-1050BCE.

The charcoal samples taken throughout the stratigraphic profile were consistent in their order, progressing from the basal palaeosol layers providing the oldest dates upward. The enamel dates from the human teeth are late in the occupation sequence, which is
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Figure 2.10. Trench 1 (09ASH1) east and west sections from Bellwood et al. 2011
as expected. The burials are younger than the context within which they are situated as they were dug from higher levels, which had been removed prior to the excavation. The correlation between the dates and the stratigraphy provides a cohesive and convincing chronology for the site.

Although the reliability of $^{14}$C dates obtained from tooth enamel has been questioned (Hedges et al. 1995), it is a routinely utilised material in stable isotopic palaeodietary reconstruction. Enamel has a stable composition, constructed of densely arranged prisms of large crystal size, it has low organic content and porosity and it is resistant to diagenetic processes and microbial influences (Lee-Thorp and Sealy 2008; Tütken and Vennemann 2011; Zazzo and Saliège 2011). Zazzo and Saliège (2011) suggest it is surprising that there is such resistance to its use for radiocarbon dating, given that the majority of the stable isotope community are reluctant to interpret stable isotope values measured from bone due to the current consensus that bone is more prone to diagenetic alteration than enamel. Because of the controversial nature of using human tooth enamel for radiocarbon dating, the following section briefly discusses the issue.
Figure 2.12. Trench 3 (09ASH3) west section from Bellwood et al. 2011
Items historically used to provide $^{14}$C dates for archaeological contexts, such as charcoal and wood, can provide misleading dates because they can often have inbuilt ages (McFadgen 1982). Directly radiocarbon dating human skeletal remains provide the best method for establishing accurate chronologies for archaeological sites. Human skeletal remains provide an unequivocal source of dating if found within the archaeological context that the individuals themselves created. While this is perceived as best practice it is often challenging in tropical and arid regions where the protein in bone collagen used for dating is commonly too degraded to date. Using enamel carbonate to conduct radiocarbon dating is an attractive alternative. Carbonate remains in enamel for a lot longer than collagen in bone and dentine, enamel has larger crystallites, and stable isotopes sourced from enamel are routinely used in palaeodietary analysis, however, its use is controversial.

Historically, studies on dates derived from enamel have been scarce and provide contradictory results, most finding that the dates were too young in comparison to the controls (Grün et al. 1997; Hedges et al. 1995), while some have had success in attaining matching dates from multiple source tissues from the same individual (Cherkinsky 2009; Sereno et al. 2008; Woodman and Beavan Athfield 2009). The limitations of these earlier studies are numerous; all the samples included in the study by Grün et al. (1997) and those from Stanton Harcourt studied by Hedges et al. (1995) had expected age ranges at or exceeding that attainable from radiocarbon dating. This was in one sense a control as the samples were expected to have no traces of $^{14}$C, although they were poorly provenanced or had no reliable comparative date.

Hedges et al. (1995) suggested that all the enamel carbonate dates were too young. The only site that had comparative control dates was Kent’s Cavern (Hedges et al. 1995: 288 Table 1). These dates were sourced from dentine collagen in four cases, and were suggested to be in agreement with archaeological expectation, with the exception of one (OxA4831) which they suggested was also perhaps too young. Interestingly, this one was the only date published in a subsequent study (although wrongly reported as a bone sample) alongside three additional samples of dentine or bone collagen (Stevens and Hedges 2004). This published date was in fact the oldest in the subsequent publication, and the other three were all in a similar age bracket to the enamel carbonate dates in Hedges et al. (1995). This could perhaps be argued as not being relevant, as the focus of the paper was stable isotope analysis, which is less sensitive to diagenesis. However, the point is that subsequent dating of Kent’s Cavern has produced dates consistent with the original enamel dates. It is possible that the original dentine collagen control dates were diagenetically altered, while the enamel dates were actually more accurate.

Microbiological decomposition does not usually occur in enamel carbonate. However, diagenesis can occur; environmental carbonates can be absorbed through isotopic exchange (Cherkinsky et al. 2013). The relatively young dates attained from carbonate
have been attributed to diagenesis. The difficulty with trying to date enamel carbonate is that the potential contaminant and the tissue have the same chemical formula, and it is very difficult to identify or tease out primary and secondary carbonate (Zazzo and Saliègue 2011). Pretreatments have been developed to remove these contaminants, but due to the scarcity of studies conducted on carbonate for dating no consensus has been reached for the most reliable protocols and there is no quality assurance on the data.

Zazzo and Saliègue (2011) undertook a metaanalysis of radiocarbon dates published in the journal Radiocarbon from 1980-2009 and unpublished data from the authors themselves in an attempt to investigate the use of carbonate for radiocarbon dating. They compared samples from the literature where bone and tooth carbonate, either from dentine or enamel, had been dated, and compared this to a reference date for each respective site. Reference dates for the sites included those on bone collagen and on items that were found in association with the individuals to be dated, such as charcoal, eggshell and organic inclusions from pottery. Where more than one date was available from reference materials they calculated an average.

One hundred and sixty four of the dates in the metaanalysis were derived from bone carbonate, only 14 dates in their metaanalysis were from enamel carbonate and “only five enamel-collagen and enamel-charcoal comparisons were found” (Zazzo and Saliègue 2011: 57). They did not comment on the other nine enamel carbonate dates, suggesting that the reference age was perhaps not of high enough quality to do so. Zazzo and Saliègue (2011: 57) argue that “collagen is considered a material of choice for radiocarbon dating” and “evidence suggests collagen and calcined bones are the best reference materials, and that they are all likely to be more resistant than bone apatite to isotopic exchange and/or contamination.” (Zazzo and Saliègue 2011: 57-58). However, it was not always possible to use dates derived from collagen or calcined bone as a reference $^{14}$C date and hence their comparisons between dates obtained from different organic and inorganic fractions are not always compared to the same consistent $^{14}$C standard reference, or in the same manner across their figures. They concluded that these data suggest that carbonate can provide accurate $^{14}$C ages for the Holocene, but it appears it is not reliable for older dates. They further suggested that carbonate dates obtained from bone or tooth enamel were best preserved in arid or semiarid environments, while those obtained from temperate environments were more variable.

Because the majority of the $^{14}$C dates that were obtained from bone apatite were sourced from the literature or were published before the advent of AMS dating, it was not possible to evaluate the differential preservation between bone and enamel carbonate. Zazzo (2014) used AMS $^{14}$C dating in an attempt to quantify the isotope exchange of carbon during early diagenesis in bone, dentine and enamel. Burials representing a broad range of geographic, climatic and temporal contexts were included, some from previously published data as
well as new unpublished data. Enamel, dentine and bone were analysed from the same individual where circumstances permitted.

Zazzo (2014) compared new AMS $^{14}$C dates derived from different tissues from the same individual to reference ages, of which he established three categories. QR1 which are referred to as high quality references ages, included comparative ages that were obtained by directly dating the collagen from the same individual. QR2, considered medium quality references, included a comparable date obtained from the same level as the burial, either through charcoal, shell or collagen from another specimen. QR3 were considered poor quality references estimated from material that was either above or below the individual. Samples which completely lacked quality references were referred to as QR4. Where more than one date was available from reference material the average was calculated. Some 25% (37/151) of samples have QR1 high quality reference ages, 21% (32/151) have QR2 medium reference ages, 15% (23/151) have QR3 poor quality reference ages and 39% (59/151) have no quality reference ages.

Figure 1b (Zazzo 2014: 7) presents the deviation of enamel carbonate, dentine carbonate or bone carbonate from the reference age. The reference ages presented in Zazzo (2014) are sourced from different things (as discussed QR1, QR2 and QR3), which is understandable given the limitations in this sort of study. However, as soon as comparisons are made between dates sourced from an individual to dates from other sources, whether it be a different specimen or charcoal, potential problems arise. Further, if one ‘averages’ the comparative radiocarbon dates and then use these as the reference standard, the original data are lost. This is particularly problematic if one is comparing the enamel carbonate dates to dated material that is ‘associated’, either above or below it.

Focussing on enamel carbonate dating in humans, because it provides a potential alternative to collagen dating, there are no examples of human dates from enamel apatite that have a comparable date from collagen, which has been argued as the material of choice for dating, for comparison among the samples in Zazzo (2014). Any human dates derived from enamel apatite are therefore only compared to reference dates that are either, in turn, derived from a different specimen or from a different item at the same level as the burial (QR2), or above or below the burial (QR3).

Figure 2b (Zazzo 2014: 8) shows the intra-individual differences in the age obtained from either enamel and dentine carbonate or enamel and bone carbonate sourced from the same individual. The figure demonstrates that in some cases there is a large deviation in age between the two fractions dated from the same individual. Using bone or dentine apatite to compare to enamel apatite seems a little strange given the issues with diagenesis. It begs the question, how would this be considered an appropriate control for enamel apatite given Zazzo (2014: 9) suggested that “bone porosity and the environment are two key
factors controlling for the preservation of the chemical composition of bone and enamel apatites”?

What if the variation seen in the dates obtained from different tissues are not a reflection of the actual tissue being analysed? This is difficult to explore as there simply have not been enough systematic tests conducted on this issue. It is argued that enamel carbonate returns dates that are too young, due to the uptake of carbon through diagenesis, the carbon being younger than the specimen and influencing the date. What if the reason why all source tissues in arid environments return similar dates is because the other source tissues are not being affected by diagenesis in those circumstances, whereas in semi tropical and temperate environments they are? Contamination from old carbon could occur either from carbonate enriched groundwater or humic substances.

Zazzo and Saliège (2011) provide a well needed reevaluation of the situation and present more systematic, comprehensive intraindividual analyses, but a robust methodology and suitable presentation of these data are still lacking. Despite all of these issues with the analysis, the results are promising. Zazzo (2014) found that the difference in $^{14}$C between carbonate and the reference age only exceeded 300 years in one case between 0-9000 years ago. It does appear that perhaps enamel carbonate is not appropriate to age older samples, however, Zazzo’s (2014) data include the dates derived from Hedges (1995), the results of which are clearly inappropriate as mentioned above. Including Hedges (1995) data in metaanalyses just keeps perpetuating the poor reputation and stigma associated with dating using enamel carbonate.

These studies (Zazzo 2014; Zazzo and Saliège 2011) have shown that although there were variations in dates attained on all of the tissues in comparison to the reference $^{14}$C age, the bad reputation of enamel carbonate has endured. Because of the small number of systematic analyses and research into this issue, any inconsistencies among the current data are probably inflated and have led to scholars dismissing the technique, possibly without giving it the attention it requires or deserves.

Despite possible arguments against the validity of the $^{14}$C dates, they are consistent with the expectations based on the interpretation of the formation of An Sơn and its stratigraphy. The radiocarbon dates were calibrated by the author using Oxcal 4.1 (Bronk Ramsey 2009), with an IntCal09 calibration curve (Reimer et al. 2009) (Figure 2.13). The remarkable consistency among the enamel dates for An Sơn provides positive support for the accuracy of enamel dating.

Flora and fauna

Ten soil samples from An Sơn were analysed for phytolith content by Professor Tetsuro
Table 2.4. Calibrated radiocarbon sequence for An Sơn

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample context</th>
<th>Sample material</th>
<th>Radiocarbon Age (BP)</th>
<th>Calibrated range (BCE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANU 9709</td>
<td>AS 2009</td>
<td>TS230–240</td>
<td>-22.0 3990 ± 68.2% 80</td>
<td>-2828 -2348 -2682 -2234</td>
</tr>
<tr>
<td>ANU 9711</td>
<td>AS 2009</td>
<td>H3B5 layer 12</td>
<td>-35.7 3880 ± 68.2% 40</td>
<td>-2457 -2300 -2471 -2209</td>
</tr>
<tr>
<td>ANU 10105</td>
<td>AS 2009</td>
<td>H2A1 palaeosol</td>
<td>-19.5 3825 ± 68.2% 40</td>
<td>-2344 -2201 -2459 -2144</td>
</tr>
<tr>
<td>ANU 9712</td>
<td>AS 2009</td>
<td>H2C4 palaeosol</td>
<td>-30.1 3580 ± 68.2% 30</td>
<td>-1964 -1889 -2028 -1786</td>
</tr>
<tr>
<td>ANU 13012</td>
<td>AS 2009</td>
<td>H2D5 palaeosol</td>
<td>-28.5 3450 ± 68.2% 30</td>
<td>-1871 -1694 -1880 -1688</td>
</tr>
<tr>
<td>Tka 11541</td>
<td>AS 1997</td>
<td>Layer 3-5</td>
<td>3990 190 ± 68.2% 190</td>
<td>-2863 -2214 -3011 -1964</td>
</tr>
<tr>
<td>Tka 11526</td>
<td>AS 1997</td>
<td>Layer 3-5</td>
<td>3840 40 ± 68.2% 40</td>
<td>-2428 -2206 -2461 -2155</td>
</tr>
<tr>
<td>Tka 11817</td>
<td>AS 1997</td>
<td>Layer 3-5</td>
<td>3780 120 ± 68.2% 120</td>
<td>-2434 -2035 -2566 -1892</td>
</tr>
<tr>
<td>Tka 11816</td>
<td>AS 1997</td>
<td>Layer 3-5</td>
<td>3690 80 ± 68.2% 80</td>
<td>-2198 -1964 -2341 -1880</td>
</tr>
<tr>
<td>ANU 10880</td>
<td>AS 1997</td>
<td>Layer 3-4</td>
<td>3820 70 ± 68.2% 70</td>
<td>-2435 -2145 -2471 -2041</td>
</tr>
<tr>
<td>Tka 11823</td>
<td>AS 1997</td>
<td>Layer 3-3</td>
<td>3310 110 ± 68.2% 110</td>
<td>-1737 -1458 -1890 -1387</td>
</tr>
<tr>
<td>Tka 11824</td>
<td>AS 1997</td>
<td>Layer 3-2</td>
<td>3310 90 ± 68.2% 90</td>
<td>-1727 -1496 -1874 -1414</td>
</tr>
<tr>
<td>Tka 11822</td>
<td>AS 1997</td>
<td>Layer 3-1</td>
<td>3390 80 ± 68.2% 80</td>
<td>-1866 -1537 -1890 -1501</td>
</tr>
<tr>
<td>Tka 11821</td>
<td>AS 1997</td>
<td>Layer 2-21B</td>
<td>3320 130 ± 68.2% 130</td>
<td>-1748 -1451 -1946 -1316</td>
</tr>
<tr>
<td>ANU 10881</td>
<td>AS 1997</td>
<td>Layer 2-17</td>
<td>3370 80 ± 68.2% 80</td>
<td>-1749 -1532 -1884 -1496</td>
</tr>
<tr>
<td>Tka 11820</td>
<td>AS 1997</td>
<td>Layer 2-17</td>
<td>3310 90 ± 68.2% 90</td>
<td>-1727 -1496 -1874 -1414</td>
</tr>
<tr>
<td>Tka 11818</td>
<td>AS 1997</td>
<td>Layer 2-14</td>
<td>3200 90 ± 68.2% 90</td>
<td>-1608 -1395 -1690 -1265</td>
</tr>
<tr>
<td>Tka 11819</td>
<td>AS 1997</td>
<td>Layer 2-12</td>
<td>3190 110 ± 68.2% 110</td>
<td>-1613 -1320 -1741 -1133</td>
</tr>
<tr>
<td>ANU 9710</td>
<td>AS 2009</td>
<td>H2C4 50-60</td>
<td>-18.2 3370 ± 68.2% 40</td>
<td>-1736 -1616 -1750 -1531</td>
</tr>
<tr>
<td>NZA 34092</td>
<td>AS 2004</td>
<td>H3M1 tooth enamel</td>
<td>-13.2 2967 ± 68.2% 25</td>
<td>-1259 -1130 -1302 -1114</td>
</tr>
<tr>
<td>NZA 34100</td>
<td>AS 2004</td>
<td>H3M3 tooth enamel</td>
<td>-13.7 3168 ± 68.2% 25</td>
<td>-1491 -1416 -1497 -1409</td>
</tr>
<tr>
<td>NZA 34101</td>
<td>AS 2004</td>
<td>H3M8 tooth enamel</td>
<td>-14.1 3199 ± 68.2% 25</td>
<td>-1495 -1443 -1515 -1424</td>
</tr>
<tr>
<td>NZA 34102</td>
<td>AS 2004</td>
<td>H3M10 tooth enamel</td>
<td>-14.2 3231 ± 68.2% 25</td>
<td>-1521 -1456 -1605 -1433</td>
</tr>
<tr>
<td>NZA 34109</td>
<td>AS 2004</td>
<td>H3M13 tooth enamel</td>
<td>-13.6 3187 ± 68.2% 25</td>
<td>-1494 -1433 -1501 -1416</td>
</tr>
<tr>
<td>NZA 34110</td>
<td>AS 2004</td>
<td>H3M14 tooth enamel</td>
<td>-13.8 3209 ± 68.2% 25</td>
<td>-1499 -1448 -1521 -1429</td>
</tr>
<tr>
<td>NZA 34111</td>
<td>AS 2004</td>
<td>H3M17 tooth enamel</td>
<td>-13.4 2956 ± 68.2% 25</td>
<td>-1253 -1129 -1266 -1056</td>
</tr>
<tr>
<td>NZA 34112</td>
<td>AS 2007</td>
<td>H1M3a tooth enamel</td>
<td>-13.2 3009 ± 68.2% 25</td>
<td>-1313 -1213 -1379 -1132</td>
</tr>
<tr>
<td>NZA 34050</td>
<td>AS 2009</td>
<td>H1M1 tooth enamel</td>
<td>-13.4 3149 ± 68.2% 25</td>
<td>-1451 -1406 -1495 -1388</td>
</tr>
<tr>
<td>NZA 34172</td>
<td>AS 2009</td>
<td>H1M2 tooth enamel</td>
<td>-14.2 3060 ± 68.2% 20</td>
<td>-1386 -1310 -1401 -1268</td>
</tr>
<tr>
<td>NZA 34173</td>
<td>AS 2009</td>
<td>H1M3 tooth enamel</td>
<td>-13.5 3109 ± 68.2% 20</td>
<td>-1420 -1325 -1434 -1316</td>
</tr>
<tr>
<td>NZA 34174</td>
<td>AS 2009</td>
<td>H2M3 tooth enamel</td>
<td>-13.8 2953 ± 68.2% 20</td>
<td>-1212 -1129 -1265 -1058</td>
</tr>
</tbody>
</table>
Figure 2.13. Calibrated radiocarbon sequence for An Sơn (95.4% range)
Udatsu from Miyazaki University, Japan. Eight samples were from Trench 2 from the 2009 excavation (09ASH2), representing samples taken every 10cm from 60-130cm below the surface. Two samples were from the 2009 test square (09ASTS1) representing samples taken at 230cm and 295cm respectively. The samples showed evidence for the subfamily Bambusoideae, two tribes Andropogoneae and Paniceae, and the genera *Oryza* and *Phragmites* (highlighted in red in Table 2.5).

<table>
<thead>
<tr>
<th>Family</th>
<th>Subfamily</th>
<th>Tribe</th>
<th>Genus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poaceae</td>
<td>Bambusoideae</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poaceae</td>
<td>Bambusoideae</td>
<td>Oryzeae</td>
<td><em>Oryza</em></td>
</tr>
<tr>
<td>Poaceae</td>
<td>Arundinoideae</td>
<td>Arundineae</td>
<td><em>Phragmites</em></td>
</tr>
<tr>
<td>Poaceae</td>
<td>Panicoideae</td>
<td>Andropogoneae</td>
<td></td>
</tr>
<tr>
<td>Poaceae</td>
<td>Panicoideae</td>
<td>Paniceae</td>
<td></td>
</tr>
</tbody>
</table>

\textit{Oryza sativa japonica} was identified by Katsunori Tanaka from the Faculty of Humanities, Hirosaki University, from the husk of rice incorporated into the temper of a pottery fragment. Sarjeant (2014a) also identified double peaked glumes in SEM backscatter images of the pottery from An Sơn as likely *Oryza*.

The subsistence economy at An Sơn has been described as one centred on the management of domestic pigs and dogs with a strong focus on fishing within local rivers supplemented with the hunting of a range of terrestrial and aquatic mammals and reptiles (Bellwood et al. 2011: 167). There was an extensive assemblage of fauna at An Sơn, the most abundant remains were fish comprising 68% of the sample and including shad, thryssa, carps, catfish, needle fish, eels, barramundi, glassy perchlets, catopra, sleepers, climbing perch, labyrinth fish and snakeheads. Terrestrial mammals and reptiles contributed the other 32% and included mammalian remains of monkey, rat, dog, civet, pig and deer; and reptilian remains including turtles, lizards and crocodiles (Piper et al. 2014).

Both pig and dog were present from the earliest layers in the site and although the dog was domesticated the status of the pig is uncertain. However, the evidence suggests both were managed for consumption as the dog bones featured butchering marks, while the pigs were mostly represented by young individuals 12-18 months old (a preferred culling age in managed populations) (Piper et al. 2014).

\textit{Pottery}

The ceramics recovered from both domestic and mortuary contexts at An Sơn were low fired earthenware vessels representing five broad rim form categories. The first four were vessel forms, the fifth represented cooking stoves or cà ràng (Sarjeant 2014b). Decorative surface treatments or techniques varied considerably across the assemblage and included burnishing, red painting, cordmarking, paddle impression, comb incision, single line
incision, punctate stamping, roulette stamping, appliqué, and white lime infill (Sarjeant 2014b). In terms of stamping, punctate stamping reflected repeated impressions using a toothed implement, while roulette stamping reflected a continuously rolled band motif. Roulette stamping was the most variable form of decoration; some of the patterns were created by knotting twine around a circular item and rolling it onto the surface, while others were created using perishable items to make the impressions. These tools were probably only used a couple of times before being discarded, which contributed to the variability in the decorative styles (Sarjeant 2014b). Notwithstanding, decorated sherds were not generally common among the assemblage from An Sơn. Trench 1 (09ASH1) had the highest density of decorated sherds, which was a reflection of the accumulation of waste from the main mound (Sarjeant 2014b).

Scanning electron microscopy with energy dispersive spectrometry (SEM-EDX) was used to analyse the temper and clay used in the ceramics at An Sơn (Sarjeant 2014b). Five major temper groups were identified, mineral sand, fibre, phosphate, calcareous, or no temper. The two most common temper types were mineral sand and fibre tempers, however, there were no obvious temporal trends in any of the tempers used. Nishimura and Nguyễn (2002) reported that none of the pottery in the basal layers of 97ASH1 had fibre temper, however, these layers were not represented in the stratigraphic profile of the trenches at the base of the mound. Principal components analysis (PCA) and canonical variate analysis (CVA) were employed to investigate the association between clay type and rim form, with results indicating that clay and temper combinations were positively associated with vessel form, suggestive of evidence for a mental template of manufacture (Sarjeant 2014b).

It has been suggested that the mental template for a vessel reflects an inherent ideology of the artisan. This concept may be imagined, copied or learned. Once the vessel has transformed from an abstract concept to a physical form, this knowledge transferred from the mind to the body leaves a memory in the motor skills (Arnold 1985; Deetz 1967). This becomes consolidated and perfected over time through the repetition of production (Sarjeant 2014b). Overall, the ceramic assemblage from An Sơn is conservative and standardised, however, there is variation and some of this can be attributed to temporal trends in technological development (Nishimura and Nguyễn 2002; Sarjeant 2014b). The most obvious morphological and technological changes occur in the vessels of type D, characterised by an undulating rim. The morphology of the rim of these vessels changes throughout the temporal sequence from a wide broad wave, which gets smaller and more concentrated over time, until in its final form it is characterised by small serrations. In terms of technological changes, the bases and wall thicknesses of these vessels changes through the temporal sequence from a curved base, which gets deeper and thinner over time, eventually becoming conical in its ultimate form (Sarjeant 2014b).
The general adherence to the mental template used to make these vessels has several implications, both social and functional. The consistency among the different vessel forms and fabrics reflects their functional success in whatever context they were used, whether domestic or social. Participants in a shared tradition have a shared connection with the specific craft, which may be perpetuated in a continuity of local tradition over many generations, in effect maintaining the memory of their shared past. The variability observed in the design of the motifs probably reflects a form of social identity largely driven by participation in a shared standardised and somewhat conservative tradition (Sarjeant 2014b).

Other artefacts

The artefact assemblages from An Sơn were consistent between the mound and the base of the mound, and are similar to those found in Neolithic contexts in other southern Mainland Southeast Asian sites, for example, Ban Non Wat, Khok Phanom Di and Nong Nor. Stone artefacts included polished and ground imported shouldered and unshouldered quadrangular adzes or axes. Fired clay items included roundels or counters, spherical clay pellets, and baked clay rods or lumps with imprints of leaves, stems and rice husks. The function of these clay items is uncertain, but it has been argued that the spherical clay pellets could have been used in pellet bows to hunt small animals, or like marbles in a game. The larger and rougher baked clay lumps were presumably associated with cooking, perhaps to retain heat in cà rang or as preforms of temper inclusions which were later ground. There were no spindle whorls recovered at An Sơn, but they do occur in other later southern Vietnamese sites, for example, Cù Lao Rùa and Dốc Chùa (Bùi et al. 2010), as well as Suối Chình. Animal bone artefacts included needles, fish hooks, a modified pig tusk and a highly polished fragment of elephant ivory, which was potentially part of an armband, perhaps woven into organic material. Shell artefacts included modified bivalve shells with abraded edges, which were possibly used as harvesting knives, and a variety of different styles of beads, which were found in mortuary contexts and through wet sieving.

Burials

Thirty five skeletons have been recovered from An Sơn, all at the base of the mound, rather than within the mound as observed at other mounded sites in Thailand. They include three from the 1978 excavation, twenty from the 2004 excavation, five from the 2007 excavation and seven from the 2009 excavation. See Appendix 1 for detailed burial descriptions.

The individuals were interred with a range of modest grave goods (Table 2.6 and Appendix 1). The table lists grave goods that were considered associated with the individuals. Often broken pottery was observed under the burials and this is referred to as a sherd sheet. Pottery was the most common artefact associated with burials; included with both males,
Table 2.6. Artefacts associated with the burials from An Sơn

<table>
<thead>
<tr>
<th>ID</th>
<th>Sex</th>
<th>Age</th>
<th>Orientation</th>
<th>Artefacts</th>
<th>Wavy rimmed</th>
</tr>
</thead>
<tbody>
<tr>
<td>04ASH1M1</td>
<td>Subadult</td>
<td>1-4</td>
<td>NE/SW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>04ASH2M1</td>
<td>Subadult</td>
<td>&lt;1</td>
<td>SW/NE</td>
<td>Worked fishbone artefact</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M1</td>
<td>Male</td>
<td>30+</td>
<td>NE/SW</td>
<td>Eight pottery vessels, one shouldered adze and beads around the neck and hands</td>
<td>One serrated</td>
</tr>
<tr>
<td>04ASH3M2</td>
<td>Female</td>
<td>-</td>
<td>-</td>
<td>Two pieces of turtle carapace</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M3</td>
<td>Male</td>
<td>30+</td>
<td>NE/SW</td>
<td>One shouldered adze and a sherd sheet</td>
<td>One serrated</td>
</tr>
<tr>
<td>04ASH3M4</td>
<td>Subadult</td>
<td>10-14</td>
<td>N-S</td>
<td>One pottery vessel</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M5</td>
<td>Female</td>
<td>30+</td>
<td>NE/SW</td>
<td>One pottery vessel and a sherd sheet</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M6</td>
<td>Subadult</td>
<td>5-9</td>
<td>E-W</td>
<td>A sherd sheet</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M7</td>
<td>Female</td>
<td>-</td>
<td>NE/SW</td>
<td>Three pottery vessels</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M8</td>
<td>Male</td>
<td>15-29</td>
<td>NE/SW</td>
<td>One pottery vessel, one bracelet fragment and a sherd sheet</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M10</td>
<td>Indeterminate</td>
<td>15-29</td>
<td>NW/SE</td>
<td>Three pottery vessels</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M13</td>
<td>Male</td>
<td>30+</td>
<td>N-S</td>
<td>Five pottery vessels, a shouldered adze and a sherd sheet</td>
<td>One serrated</td>
</tr>
<tr>
<td>04ASH3M14</td>
<td>Indeterminate</td>
<td>15-29</td>
<td>NE/SW</td>
<td>One pottery vessel</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M16</td>
<td>Subadult</td>
<td>1-4</td>
<td>NE/SW</td>
<td>A sherd sheet</td>
<td>-</td>
</tr>
<tr>
<td>04ASH3M17</td>
<td>Female</td>
<td>15-29</td>
<td>NE/SW</td>
<td>Two pottery vessels</td>
<td>-</td>
</tr>
<tr>
<td>07ASH1M1</td>
<td>Subadult</td>
<td>1-4</td>
<td>N-S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07ASH1M2</td>
<td>Subadult</td>
<td>1-4</td>
<td>N-S</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07ASH1M3</td>
<td>Female</td>
<td>15-29</td>
<td>NE/SW</td>
<td>A sherd sheet, beads around the neck and a clay pellet</td>
<td>-</td>
</tr>
<tr>
<td>07ASH1M3b</td>
<td>Subadult</td>
<td>&lt;1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07ASH1M4</td>
<td>Subadult</td>
<td>1-4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>09ASH1M1</td>
<td>Female</td>
<td>30+</td>
<td>-</td>
<td>A sherd sheet and a dog mandible</td>
<td>One serrated</td>
</tr>
<tr>
<td>09ASH1M2</td>
<td>Female</td>
<td>15-29</td>
<td>NE/SW</td>
<td>Nine pottery vessels, one unshouldered adze, one shouldered adze, a burin and a burnishing stone</td>
<td>One serrated</td>
</tr>
<tr>
<td>09ASH1M3</td>
<td>Male</td>
<td>30+</td>
<td>NE/SW</td>
<td>Two pottery vessels, a sherd sheet and an unshouldered adze</td>
<td>Two serrated</td>
</tr>
<tr>
<td>09ASH1M4</td>
<td>Subadult</td>
<td>1-4</td>
<td>NE/SW</td>
<td>One pottery vessel and a sherd sheet</td>
<td>One serrated</td>
</tr>
<tr>
<td>09ASH2M1</td>
<td>Subadult</td>
<td>&lt;1</td>
<td>SE-NW</td>
<td>-</td>
<td>One serrated</td>
</tr>
<tr>
<td>09ASH2M2</td>
<td>Subadult</td>
<td>&lt;1</td>
<td>NE/SW</td>
<td>One pottery vessel and shell beads around the neck</td>
<td>Two serrated</td>
</tr>
<tr>
<td>09ASH2M3</td>
<td>Subadult</td>
<td>10-14</td>
<td>NE/SW</td>
<td>Three pottery vessels, two pieces of stone, a shell, a shouldered adze and beads around the neck</td>
<td>Two serrated</td>
</tr>
</tbody>
</table>
females and subadults. There were no sex differences in the number of pottery vessels interred with individuals. Of particular interest are the ‘wavy rimmed’ or ‘serrated’ vessels. There were no sex differences in the inclusion of this type of mortuary vessel, however, only males (and one adolescent which could potentially have been male) were interred with two wavy rimmed vessels (Figures 2.14 and Figure 2.15).

The genetic affinities of the people of An Sơn

The craniometrics and dental metrics from the 2004 season from An Sơn have been analysed by Hirofumi Matsumura (see Matsumura et al. 2011a; Matsumura et al. 2015). No material from the 2007 and 2009 seasons has been analysed to date. Moreover, no non-metric dental analysis of material from any season has been carried out to date. As such, the interpretation of the biological relationship of An Sơn to other Southeast Asia populations may be biased due to the small sample size, and as yet incomplete analyses to date, and may possibly change in the future.

The craniometric analyses place the affinity of the An Sơn community as morphologically similar to modern Southeast Asia populations; they are positioned in the modern Southeast Asian cluster (Matsumura et al. 2011a: 73 Figure 4; Matsumura et al. 2015 Figure 3). In the neighbour net split tree analysis (Matsumura et al. 2015 Figure 3) An Sơn presents near the southern Vietnamese sites of Rạch Rừng and Giồng Cá Vồ, those from northern Mán Bạc with modern Southeast Asian morphology and also Ban Chiang from Thailand. The dental metrics from An Sơn place them in a position between the two clusters (Matsumura et al. 2011a Figure 6).

The results of the cranial and dental morphometrics suggest that the inhabitants of An Sơn preserved some genetic traits from the original Southeast Asian indigenous populations (Australo-Melanesians), but also demonstrate genetic input from Northeast Asia (ancient populations originating in what is now southern China). This appears to be quite common among Neolithic through to Iron Age sites in Southeast Asia. The net result of hundreds, if not thousands of years of demic diffusion has resulted in the somewhat heterogeneous grouping of populations we collectively term Southeast Asians today. The differential genetic admixture between northerly derived incoming populations and local indigenous genes helps situate An Sơn, genetically at least, in the past. An Sơn is somewhat similar to Khok Phanom Di in being on the periphery of the demic diffusion zone, but displaying close affinities to populations at the source of the original diffusion of genes into the region. One explanation for this is that, in some cases, there was rapid population movement from the north in a southerly direction, perhaps using coastal routes, from at least 4,000 years ago. All that can be said at the present, a working hypothesis if you will, is that An Sơn is the result of genetic exchange between local indigenous and migrating (from the north) populations that began sometime prior to 4,000 years ago. This combination of
2. Vietnam, its Environment and Archaeology: Contextualising An Sơn and Hòa Diệm

Figure 2.14. Burial 09ASH1M3 with two wavy rimmed vessels (1 and 2) and an unshouldered adze and 09ASH1M4 with a serrated rim vessel (1). Artefact photos by Carmen Sarjeant.
Figure 2.15: Burial 09ASH2M3 with two wavy rimmed vessels (2 and 3) and other associated artefacts. Artefact photos by Carmen Sarjeant.
genes has become what is now commonly known as the Southeast Asian morphology, a morphology with an origin as old as the Neolithic in the region.

Hòa Diêm

This section will introduce the Iron Age site of Hòa Diêm, one of the key sites examined in this thesis. The archaeological history of the site will be presented, followed by an interpretation of the construction of the site from the stratigraphy, the chronology of the site, the flora, fauna and evidence for subsistence, the material culture, the burials and finally the genetic affinities of the individuals from Hòa Diêm.

Hòa Diêm is in Cam Thịnh Đông commune, Cam Ranh City, Khánh Hòa Province on the south central coast of Vietnam. The site is located about 3-5m above present day sea level, on the floodplain of Cam Ranh Bay about 1.3km from the present day coastline (11° 53´ 15˝ N, 109° 06´ 34˝ E) (Figure 1.1). Hòa Diêm is surrounded to the west by the Núi Ta Lua mountain range and to the north by the Trà Dục River tributary running through the Ba Ngòi plains to the ocean. The Cạn River empties into Cam Ranh Bay about 5.5km south of Hòa Diêm.

Hòa Diêm is one of many coastal Sa Huỳnh sites in Vietnam forming part of what has been termed the South China Sea Interaction Sphere (Hung et al. 2013). Chronologically, it belongs to the southern tradition of the late Sa Huỳnh culture (Tradition II – Phase III) (Lâm 2011). Hòa Diêm was originally situated on a dune forming a coastal ridge during the maximum Holocene marine transgression (Kubo 2012), although the area has now changed significantly due to extensive salt and prawn farming.

Archaeological history of the site

1999 season

Hòa Diêm was discovered in 1998 by members of the Vietnamese Institute of Archaeology and the Khánh Hòa provincial museum during a reconnaissance mission. They returned in 1999 to conduct a test excavation. The total excavation area was 50m² and comprised 5 trenches 99HDH1, 99HDH2, 99HDH3, 99HDH4 AND 99HDH5 (Yamagata 2008a).

2002 season

In 2002 another test excavation was undertaken with three trenches measuring 15m² (Yamagata 2008a). Later that year they carried out a larger scale excavation with one trench (02HDH1) of 104m² (Nguyễn 2004a). The trench (10x10) was divided into 1x1m squares, numbered according to their order 1-10 northwest to southeast and A-J northeast to southwest. The trench was extended northwest of A1 to retrieve jars associated with
features 12 and 23, and H1 and I1 to retrieve jars associated with feature 21 (Figure 2.16 and Figure 2.17).

2007 season

In 2007 Hòa Diêm was excavated again in a joint international collaboration between the Centre for Archaeology, Institute of Social Sciences in southern Vietnam, Vietnamese Institute of Archaeology in Hà Nội, the Khánh Hòa provincial Museum, and several universities in Japan, including Waseda, Sophia and Sapporo Universities.

Two test squares were established to identify the limit of the 2002 excavation square (02HDH1) and to examine the distribution of artefacts northeast of this. The first (07HDT1S1) ran along the northeast wall of 02HDH1. The second (07HDT1S2) ran perpendicular to TS1. Trench 1 (07HDH1) was opened 4.5m northeast of 02HDH1, it was 6x8m running northwest to southeast. The trench was divided into 2x2m squares, numbered according to their order 1-4 northwest to southeast and A-C northeast to southwest. Trench 2 (07HDH2) was positioned 20m west of 02HDH1 (Figure 2.16 and Figure 2.17).

2010 season

In 2010 a further excavation season was undertaken in an attempt to establish the extent of Hòa Diêm and a second area, Hòa Diêm 2 (HD2), was opened 200m southeast of Hòa Diêm (HD1) in a small mounded modern cemetery. Four trenches were opened at the original Hòa Diêm site following the same 2x2 grid system of the previous 2007 season. Trench 1 (10HD1H1) was 6x2m, positioned 20m southeast of 07HDH1. It was labelled in 2x2 squares, B-D 15 northeast to southwest. Trench 2 (10HD1H2) was positioned to identify the delimitations of the southern corner of 02HDH1. It was measured 8x2m and labelled in 2x2m squares J 5-8, however, as J5 overlapped 02HDH1 in the southeast corner, only the eastern portion of J 6-8 were excavated. Trench 3 (10HD1H3) was 7x3m, positioned between 02HDH1 and 07HDH1 to link the squares and recover any further jar burials. It was labelled in 2x2m squares as D-E 1-4. D1 and E1 overlapped 07HDT1S2 and E1- E4 overlapped 07HDT1S1. Trench 4 (10HD1H4) was 6x3.5m positioned 2m northeast from 10HD1H2. It was labelled in 2x2m squares F-H 6-7.

In addition to the main trenches, four test squares were opened following the same grid system. Each test square was 2x2m. These were positioned on K11, K15, O11 and O15. In K11 fragmented human skeletal remains were recovered and assumed to be from an extended burial. K15 was extended to encompass parts of K14, L14 and L15 but it remained designated as 10HD1K15. O15 was also extended to encompass part of P15 and was designated 10HD1O15P15 (Figure 2.16 and Figure 2.17).
Figure 2.16. Plan of Hòa Đỉm featuring excavation trenches from 2002, 2007 and 2010 from Yamagata et al. 2012
The second excavation site at Hòa Diệm, Hòa Diệm 2, was opened in an attempt to map the stratigraphy across a larger area. A dense concentration of pottery was identified in the middle of the cemetery mound, however, it was not possible to excavate there, and so two test squares were laid at the edge of the mound. The first test square (10HD2TS1) was 1x2m but was extended to recover an inhumation burial. The second test square (10HD2TS2) was opened 50cm south of TS1. It was also 1x2m and was also extended to recover an inhumation burial.

2011 season

In 2011 an excavation was undertaken by the National History Museum of Vietnam in collaboration with the Khánh Hòa provincial museum. The excavation area was 54.5m (Nguyễn and Matsumura 2014). The results of this excavation have not been synthesised in a publication and as a result are not incorporated into this discussion of Hòa Diệm.

Construction of the site

The stratigraphic profile is very basic and consistent across the whole site, ranging from 60-80cm deep. The deepest layer is the palaeosol (5), overlying this were the burial layers of compact dark sand (4, 3, 2) and the topsoil (1). Kubo (2012) sank three 2m deep cores in three locations during the 2010 excavation at Hòa Diệm 1 to assess the geomorphology of the site and to acquire AMS dates. Coring was conducted in 10HD1H1 in square B15, in test square 10HD1K11 square K11 and in 10HD1H2 square J6-J7. The stratigraphy
among the coring samples is similar, consisting of sand with small gravel inclusions representing coastal sand bar deposits. The basal layer represented in all the cores is organic sand with charcoal and peat indicating wetland or marsh deposits, representing the maximum Holocene transgression. Charcoal was sampled for AMS dating from the basal layer in each core. The preliminary results of the cores and associated radiocarbon dates suggest that Hòa Diêm was located on a beach ridge, positioned slightly higher than the surrounding coastal plain. The ridge which extended along the coast, formed by wave action, would have emerged as a bar of dry coastal land as the sea level retreated following the marine transgression during the early to mid-Holocene (Kubo 2012).

**Dating**

Seventeen well provenanced dates are available from Hòa Diêm (Table 2.7). Five are unpublished and twelve are from reports (Kubo 2012; Yamagata et al. 2012b; 小林紘 et al. 2008). The dating was undertaken at three separate institutions, Rafter Laboratories, National Isotope Centre, Institute of Geological and Nuclear Sciences Ltd (GNS Science) in Lower Hutt, New Zealand (NZA); Paleo Labo, Toda, Saitama, Japan (PLD) and the Institute of Accelerator Analysis, Shirakawa City, Fukushima, Japan (IAAA).

The radiocarbon dates were calibrated by the author using Oxcal 4.1 (Bronk Ramsey 2009), with an IntCal09 calibration curve (Reimer et al. 2009). The marine shell was calibrated using a Marine09 calibration curve (Figure 2.18). These dates were recalibrated for consistency and may differ slightly from the original published dates.

The samples from the basal layer of the site (IAAA 100638, IAAA 100639 and IAAA 100640) date to c. 5250-4700BCE, just prior to the maximum highstand of the mid-Holocene marine transgression of the South China Sea (Proske et al. 2011). The other samples, acquired from a range of different materials including charcoal, marine shell, potsherd temper and human tooth enamel, provide a tight chronological sequence of occupation from c. 850BCE to 250CE. The marine shell (PLD 8335, IAAA 101438, IAAA 111861, IAAA 101439) from the occupation phase range from c. 850-400BCE. The deer bone (IAAA 120343) and pottery temper (IAAA 110213) range from c. 400-150BCE. The burials fall within a range c. 200BCE to 250CE.

The enamel from the teeth of several individuals was dated to try and ascertain whether there was evidence for reuse of the jars and whether there was a temporal difference among jar burials and inhumations between Hòa Diêm 1 and Hòa Diêm 2. The samples of human tooth enamel present a tight and consistent range of dates. The individual buried as an extended inhumation at Hòa Diêm 2 10HD2TS1M1 (IAA 100714) produced the oldest date among the human enamel samples. The individual 10HD1H3M4 (IAAA 101437) presented a date younger than the jar in which it were interred (IAAA 110213).
Table 2.7. Calibrated radiocarbon sequence for Hòa Diêm

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample context</th>
<th>Sample material</th>
<th>δ¹³C</th>
<th>¹⁴C ±</th>
<th>Calibrated range (BCE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NZA 34087</td>
<td>HD 2002</td>
<td>tooth enamel</td>
<td>-12.1</td>
<td>1973</td>
<td>61 ± 40 76</td>
</tr>
<tr>
<td>NZA 34088</td>
<td>HD 2002</td>
<td>tooth enamel</td>
<td>-12.6</td>
<td>1903</td>
<td>126 ± 27 200</td>
</tr>
<tr>
<td>NZA 34089</td>
<td>HD 2002</td>
<td>tooth enamel</td>
<td>-12.5</td>
<td>1876</td>
<td>209 ± 73 218</td>
</tr>
<tr>
<td>NZA 34090</td>
<td>HD 2007</td>
<td>tooth enamel</td>
<td>-13.7</td>
<td>1886</td>
<td>134 ± 75 215</td>
</tr>
<tr>
<td>NZA 34091</td>
<td>HD 2007</td>
<td>tooth enamel</td>
<td>-12.8</td>
<td>1871</td>
<td>210 ± 76 221</td>
</tr>
<tr>
<td>PLD 8336</td>
<td>HD 2007</td>
<td>marine shell</td>
<td>1.2</td>
<td>2970</td>
<td>-812 -768 -951 -747</td>
</tr>
<tr>
<td>PLD 8335</td>
<td>HD 2007</td>
<td>charcoal</td>
<td>-24.3</td>
<td>2445</td>
<td>-732 -416 -751 -408</td>
</tr>
<tr>
<td>IAAA 100638</td>
<td>HD1 2010</td>
<td>soil</td>
<td>5906</td>
<td>30</td>
<td>-4797 -4726 -4842 -4715</td>
</tr>
<tr>
<td>IAAA 100639</td>
<td>HD1 2010</td>
<td>charcoal</td>
<td>6182</td>
<td>31</td>
<td>-5210 -5071 -5221 -5031</td>
</tr>
<tr>
<td>IAAA 100640</td>
<td>HD1 2010</td>
<td>charcoal</td>
<td>6077</td>
<td>33</td>
<td>-5034 -4943 -5201 -4851</td>
</tr>
<tr>
<td>IAAA 101438</td>
<td>HD1 2010</td>
<td>charcoal</td>
<td>2650</td>
<td>30</td>
<td>-828 -798 -895 -788</td>
</tr>
<tr>
<td>IAAA 111861</td>
<td>HD1 2010</td>
<td>charcoal</td>
<td>2460</td>
<td>20</td>
<td>-749 -752 -806 -717</td>
</tr>
<tr>
<td>IAAA 120343</td>
<td>HD1 2010</td>
<td>charcoal</td>
<td>2160</td>
<td>20</td>
<td>-347 -175 -355 -117</td>
</tr>
<tr>
<td>IAAA 110213</td>
<td>HD1 2010</td>
<td>deer bone</td>
<td>2180</td>
<td>30</td>
<td>-355 -192 -366 -166</td>
</tr>
<tr>
<td>IAAA 101437</td>
<td>HD1 2010</td>
<td>tooth enamel</td>
<td>1840</td>
<td>30</td>
<td>133 216 85 242</td>
</tr>
<tr>
<td>IAAA 100714</td>
<td>HD2 2010</td>
<td>tooth enamel</td>
<td>2100</td>
<td>30</td>
<td>-170 -60 -198 -46</td>
</tr>
<tr>
<td>IAAA 101439</td>
<td>HD2 2010</td>
<td>charcoal</td>
<td>2630</td>
<td>30</td>
<td>-819 -792 -840 -772</td>
</tr>
</tbody>
</table>
Two individuals interred in the same jar 02HDH1CHUM4M1 and 02HDH1CHUM4M2 (NZA34087 and NZA34088) produced similar dates, although the 95% confidence interval indicates they could be separated by as much as 100 years. The individual buried in an extended inhumation at the base of Trench 1 in 2002 02HDH1C20M1 (NZA34089) produced a date within the same range as the jar burials. The dating of the jar burial temper, which is earlier than the enamel dated from the individual within the jar, could either support the evidence that enamel dates are consistently too young, or that the jar was reused. The remarkable consistency among the enamel dates for Hòa Diệm, attained from two different groups of researchers and acquired at two different labs, provides positive support for the accuracy of the dates. The charcoal from Hòa Diệm 2 (IAAA 101439) was within a similar range to charcoal dates from Hòa Diệm 1.

Flora and fauna

The subsistence economy at Hòa Diệm was probably focussed on marine resources, fishing for aquatic fish and mammals, and collecting shellfish, supplemented by the management
of domestic cattle/water buffalo and pigs. Sawada conducted the zooarchaeological analysis at Hòa Diệm (Sawada 2012). Vertebrate remains were collected by hand during the excavation. There was no systematic sampling strategy for sieving, so smaller vertebrate remains may not have been recovered. Five taxa were identified including rhinoceros, elephant, cattle/water buffalo, deer, boar and rat. The most dominant taxa identified among the assemblage were cattle/water buffalo, deer and pig.

It has been suggested that the young age profile of the pigs may indicate that they were domesticated and managed, however, the sample size was small. There was some evidence of butchery patterns on the bones, for example, cutting and spiral fracturing suggesting that this was related to human activity (Sawada 2012). The fish remains from the site have not been analysed at this stage. Yamagata (2012a) conducted the malacological study at Hòa Diệm. The most common molluscs at the site were oysters, clams and ark shells. Although these were not counted, the frequency is indicated by weight. No palaeobotanical analyses have been conducted at the site.

**Pottery**

Yamagata et al. (2012b) have suggested that there is an earlier settlement area and a later burial area at Hòa Diệm and have called the pottery associated with these areas settlement pottery and burial pottery. They interpret the features of shell, interspersed with animal bones and artefacts, and clusters of pottery interspersed with shell, as settlement areas at Hòa Diệm. These features were observed in all trenches 07HDH1 and 10HD1H1-H4, however, only 10HD1H1 and 10HD1H4 were exclusively settlement areas with no burials. The other trenches 07HDH1 and 10HD1H3 featured burials and settlement features, some cutting through the latter.

The ceramics recovered from both domestic and mortuary contexts at Hòa Diệm were low fired earthenware vessels. Decorative surface treatments or techniques varied across the assemblage and included burnishing, red and black painting, cordmarking, smoothed cordmarking, comb incision, incision, shell impressions, punctuate stamping and circular stamping. Pedestals sometimes featured triangular or circular cutouts (Yamagata et al. 2012b). Yamagata et al. (2012b) argue a strong resemblance between the pottery of Hòa Diệm and that of Kalanay Cave. Three particularly striking similarities between the two sites are the presence of curvilinear incised lines filled with punctate stamping, rotated pivoting incision and printed seashell decoration without graphite, the latter two of which are not found in other Sa Huỳnh sites (Favereau 2015).

The majority of the jar burials at Hòa Diệm were spherical like those at the southern sites of Giồng Cá Vồ and Giồng Phệt in the coastal suburban district of Cần Giờ, in southeast Hồ Chí Minh City, and not cylindrical or egg shaped like those of the typical Sa Huỳnh
2. Vietnam, its Environment and Archaeology: Contextualising An Sơn and Hòa Diệm

sites further north. Interestingly, another Sa Huỳnh site also in Khánh Hòa Province, Diên Khánh, also has cylindrical burial jars which appear to characterise the most southerly extension of the northern Sa Huỳnh Tradition (Lâm 2011). Six unique burial jars, in a form that has not been encountered at other Vietnamese sites, have also been recovered at Hòa Diём.

Wavelength dispersive X-ray fluorescence spectroscopy was used to analyse the chemical composition of the pottery and petrographic analysis was conducted to examine the tempers. The results suggested that the pottery vessels could have been manufactured locally. Two major temper groups identified were fibre and mineral sand (Kanegae and Tojo 2012).

Other artefacts

Common artefacts associated with the jar burials included iron and bronze artefacts and beads of agate, semiprecious stone, gold and glass (Nguyễn 2004a; Yamagata et al. 2012b). A range of metal artefacts have been recovered including iron knives, points and arrowheads, and bronze ornaments, Wuzhu coins and a bell (Yamagata et al. 2012b). The glass beads were yellow, red, blue, green and black and came in a range of sizes and shapes. The stone beads included carnelian, agate, crystal, jasper and quartz in a range of sizes and shapes (Yamagata et al. 2012b). SEM-EDS analysis of a sample of beads suggested heterogeneity, but was inconclusive, as reliable chemical signatures could not be obtained (Iizuka 2012). Two gold beads were found in B3-C3 of the 2007 Trench 1 (07HDH1). These artefacts are typical of the time period and characterise the interregional trading relationships of the period. The gold beads are likely Mediterranean, the acid-etched beads Indian, and the Bronze Wuzhu coins from the Western and Eastern Chinese Han Dynasties.

Burials

Two burials were recovered from Trench 2 in 1999: 99HDH2M1 was a jar burial and the other was an inhumation 99HDH2M2 (Lương and Nguyễn 1999; Nguyễn and Matsumura 2014). Hòa Diём was excavated twice during 2002, during the first excavation one jar burial and one inhumation burial were recovered (Yamagata 2008a). The second excavation in 2002 exposed 26 features, 22 of which were jar burials and two of which were extended burials (M2 and M20) (Bài et al. 2005; Lương 2001; Nguyễn 2005a; Yamagata et al. 2012b). M19 was recorded as a cremation burial (Lâm 2008).

Fourteen jar burials were recovered during the 2007 season (M1-M14), and two extended burials (M15 and M16) (Yamagata et al. 2012b). All jar burials contained human skeletal remains, except M5 and M14, while M2 and M13 only contained human teeth. Jar burials M6, M7, M8 and M11 contained multiple individuals; M11 had been disturbed.
in prehistory but was assumed to be a jar burial. Ten of the jars had spherical bodies and plain shallow bowl shaped lids (M2-M12). Three jars were unique, as the form of the jars and lids had never been encountered in Vietnam, and were designated as burials (M1, M13 and M14) (Figure 2.19), although one contained no human remains (M14) and one contained only teeth (M13), as noted above. Some fragmented and poorly preserved human skeletal remains, not associated with pottery vessels, were found at the level of the palaeosol and were designated as extended burials (M15 and M16). There were no burials recovered in Trench 2 (07HDH2).

There were nine jar burials recovered during the 2010 season (Yamagata et al. 2012b). Five were recovered in Trench 3 (10HD1H3); these burial jars were all spherical (10HD1H3M1-10HD1H3M5). Three were recovered in test square 10HD1K15; these burial jars were all unique in form to the site and within Vietnam, although the style of the lids had been observed with other jar burials at Hòa Diêm (10HD1K15M1-M3). One spherical burial jar was recovered in test square 10HD1O15P15 (10HD1O15P15M1). Two extended burials were recovered during the 2010 season at Hòa Diêm 2, one in 10HD2TS1 (10HD2M1) and the second in 10HD2TS2 (10HD2M2).

Some of the burials are argued to be primary inhumations (Matsumura et al. 2012a; Yamagata et al. 2012b), however, the jars were clearly reused many times, given the number of individuals represented in jars with variable representation of skeletal elements, many only represented by teeth. This could suggest that rather than being secondary burials they represent primary jar burials which were just reused over time and not completely emptied before reuse. Or it could indicate a combination of primary and secondary burial practices. Multiple individuals within jar burials are uncommon in Vietnam (Yamagata et al. 2012b). However, this could be a reflection of the general preservation of jar burial interments in Vietnam. Whether the jars were buried or remained above ground has yet to be resolved (see Yamagata et al. 2012a for detailed burial descriptions).

The genetic affinities of the people of Hòa Diêm

The cranial and dental morphometric and dental non metric analyses from the 1999, 2002,
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2007 and 2010 seasons from Hòa Diêm have been undertaken by Hirofumi Matsumura (see Matsumura et al. 2012b; Matsumura et al. 2015). Hòa Diêm may represent a similar situation to Mán Bạc (Oxenham and Matsumura 2011), where there are potentially two populations of people represented. In the case of Hòa Diêm they are differentiated by their mortuary practices, extended burials and jar burials. It has been argued that the extended burials are earlier (Yamagata et al. 2012b), so whether these individuals were living in the community at the same time is uncertain. However, their mortuary practices and morphological appearance would suggest that one is represented by an earlier Austroasiatic population who were living there before the Chăm arrived. As a result of this, Matsumura split the Hòa Diêm sample into two groups when conducting the craniometric analyses, with Hòa Diêm 1 representing the individuals from jar burials and Hòa Diêm 2 representing the individuals from extended burials. The craniometrics place the affinity of the Hòa Diêm community as morphologically similar to modern Southeast Asians (Matsumura et al. 2012b: 247 Figure 2; Matsumura et al. 2015 Figure 3). In the most recent neighbour split tree (Matsumura et al. 2015 Figure 3) Hòa Diêm 1 presents near the Indonesian sites of the Moluccas and Sumatra, while Hòa Diêm 2 presents near Laos, Cambodia and Semang Negritos from the Malaysian peninsula.

Due to the poor preservation of teeth in the Hòa Diêm 2 sample their data were combined with the Hòa Diêm 1 sample for the analysis of dental metrics, but they were not included in the analysis for dental nonmetrics. The dental metrics from Hòa Diêm place them among modern Southeast Asian samples (Matsumura et al. 2012b: 248 Figure 4), while the dental nonmetrics place them in a position between the Australo-Melanesian and modern Southeast Asian clusters (Matsumura et al. 2012b: 249 Figure 6; Matsumura and Oxenham 2014: 55 Figure 2).

The results of the craniometrics suggest that there were two populations represented at Hòa Diêm, the older one with an affinity to modern Mainland Southeast Asian populations, while the more recent one has an affinity to Island Southeast Asian populations. The dental metrics suggest an affinity with modern Mainland Southeast Asians, while the dental nonmetrics place them between the two distinct clusters. This is similar to what has been observed with the dental nonmetrics for other populations (see discussion concerning An Sơn, this Chapter), representing the clinal heterogeneous pattern that is seen throughout Southeast Asia which has been attributed to the differential contribution, speed, timing and direction of genetic admixture from northern populations (Matsumura and Oxenham 2014).

Having discussed the environment of Vietnam, the general archaeological trends from the Neolithic through metal period and the specifics of the two key sites analysed in this thesis, the next chapter will provide the bioarchaeological census for An Sơn and Hòa Diêm.
Chapter Three: Bioarchaeological Census of An Sơn and Hôa Diêm

This chapter will present the demographic profile and the tooth census for both An Sơn and Hôa Diêm. An understanding of the age and sex structure of a population is fundamental to bioarchaeological research, providing an essential framework for a more comprehensive understanding of the relative representativeness of the population, aspects of past fertility levels, age progressive diseases or differences in behaviour. The following section will begin by introducing methods of age and sex estimation and reviewing their potential and limitations. Although these techniques for assessing age and sex have a long history, and are well known, they are constantly being improved in response to criticisms regarding the accuracy of the methods themselves as well as the appropriateness of samples used to generate age and sex estimation techniques. The demographic profiles of both An Sơn and Hôa Diêm will then be presented, followed by a discussion of the results. In later chapters, these data will be incorporated into the interpretation and discussion of physiological and oral health.

AGE ESTIMATION

Age estimation entails assessing physiological age, through developmental and/or degenerative changes in the tissues, in order to establish chronological age. Teeth are useful in the assessment of age at death of subadults as they are very resilient and well represented in the archaeological record. The mineralisation and eruption of the dentition is the most accurate means of an estimation of age at death for subadults, as it is less affected by the environment in contrast to skeletal development (Cardoso 2007; Hillson 1996). The dentition begins to develop in utero and mineralisation and eruption continue in a consecutive pattern through childhood and adolescence. Methods for age estimation of subadults using the teeth focus on the mineralisation of the dentition (Fanning 1961; Gustafson and Koch 1974; Moorrees et al. 1963a, 1963b), the eruption and exfoliation of the deciduous dentition and their replacement with the permanent dentition (Schour and Massler 1941; Ubelaker 1989). There are regression equations available for assessing the age of remains using the deciduous dentition (Sema et al. 2009), permanent dentition (Liversidge and Molleson 1999) or both (Liversidge et al. 1993). There are methods which use just one tooth or as many teeth that are available, however, these methods require measurement of the actual tooth or radiographs of the teeth, the availability of which is contingent upon preservation of the tooth, access to the actual tooth or radiographs.

It is important for demographic purposes to be able to determine the age at death of subadults in all age categories to understand the population structure, providing an insight into general health, fertility and possible growth of the population. Although there is a
scarcity of perinatal remains found in archaeological sites, for a range of different reasons, there has been a move toward developing appropriate aging techniques for this age class (Gowland and Chamberlain 2002; Tocheri et al. 2005). In the case of foetal remains or perinates, calcification of the deciduous tooth buds will have begun in utero. However, the fragility of the dental structures means they are often not preserved, making accurate age estimation problematic.

While it is suggested that long bone length is more susceptible to environmental influences, the issues with preservation discussed above in regard to the dentition have stimulated focus on using long bone length for aging perinatal remains. It is suggested that the length of long bones changes dramatically with each gestational week of growth in a neonate and the standards for tooth mineralisation are also likely less accurate than long bone length at perinatal age (Moorrees et al. 1963a). Equations have been developed from individuals of known age for late foetal and perinatal remains by several authors (Scheuer et al. 1980; Scheuer and Black 2000a). Tocheri et al. (2005) used 11 of the most appropriate linear regression equations from Scheuer et al. (1980), Scheuer and Black (2000a) and Sherwood (2000) to provide a single age estimate for the perinates in their sample. Halcrow et al. (2008) then replicated this to assess the age of the perinates from several sites in prehistoric Thailand. Rissech et al. (2008) have developed regression equations using femoral measurements to estimate the age of subadults up to adolescence.

Other methods for assessing the age of foetal skeletons include using the pars basilaris (Scheuer and MacLaughlin-Black 1994) and the morphometry of the vertebral column (Kósa and Castellana 2005). Skeletal growth and epiphyseal fusion are also useful in the estimation of age in subadults. The fusion of epiphyses is the most accurate means of age estimation in children older than 12 years. This period witnesses the gradual union of epiphyses, which can take several years between initial and final closure (Scheuer and Black 2000b).

Although aging of subadults is generally more straightforward than in the case of adults, there are still inherent problems with accuracy and age mimicry, the consequences of which have been highlighted by Gowland and Chamberlain (2002). For instance, they demonstrated with several archaeological populations that when using regression formulae the age distribution of foetal individuals from a population mimic the age distribution of the reference sample used to develop the formulae. However, this bias can be avoided by applying Bayesian estimation methods and using realistic prior probabilities of perinatal mortality (Chamberlain 2000; Gowland and Chamberlain 2002).

The age estimation of adults is particularly problematic as currently available methods rely on rates of degeneration, which differ with age progression and are further influenced by variation in activity and susceptibility to disease, rather than biologically determined
patterns as seen in the development of children. Scholars have recently focused on trying
to refine existing methods, for example, using the pelvis and pubic symphysis (Duric et al. 2005; Hoppa 2000), the auricular surface of the sacroiliac joint (Buckberry and Chamberlain 2002; Igarashi et al. 2005) and the sternal end of the first rib (Kurki 2005; Schmitt and Murail 2004). Also Boldsen et al. (2002) have redefined scores for the pubic symphysis and auricular surface broadening the limits of age estimation. It is general practice to approach age estimation in adults from a systematic multifactorial approach using seriation (Lovejoy et al. 1985) to provide the most accurate estimation.

**Age estimation methods**

A multifactorial approach was undertaken where possible using as many methods as possible, although this was dependent on the preservation for each individual. For subadults, where possible, tooth formation, calcification and eruption were assessed (Ubelaker 1989), diaphyseal length was used to establish an independent age estimate using linear regression equations based on perinates of known gestational age (Rissech et al. 2008; Scheuer et al. 1980; Scheuer and Black 2000a; Sherwood et al. 2000) and epiphyseal fusion was also used in this regard (Scheuer and Black 2000b). Measurements of the diaphyses of subadult long bones were taken using Mitutoyo digital callipers calibrated to the nearest 1/10th mm.

For adults, where possible, late epiphyseal union, pubic symphysis and auricular morphology scores, dental wear, dental pathology and joint degeneration were used to form the most comprehensive estimation of age. Where this was not possible, regression models developed by Oxenham (2001) for northern Vietnamese samples were used to age individuals. Tooth wear was regressed on individuals where aging was relatively accurate and reliable and this was used to estimate the age of those that were less well preserved. These equations were deemed most appropriate given the close geographic and temporal proximity to the sites in this study.

**SEX ESTIMATION**

The estimation of subadult sex is something that has recently become a focus within the discipline. The inability to accurately and reliably provide an estimate of sex for subadults prevents comparative analysis of differences in mortuary context and palaeopathology in relation to sex differences (Knudson and Stojanowski 2008). Recent studies have focussed on differences in the mandible, where Loth and Henneberg (2001) found significant differences in mandibular shape by sex, Franklin et al. (2007) and Scheuer (2002) found little evidence for sexual dimorphism.

The most accurate means of sex estimation from adult skeletal remains are based on morphological variations, assessed either qualitatively or quantitatively, in the pelvis
followed by cranial areas of the skeleton. The morphology of the human pelvis is a reflection of the differences in the reproductive function of females and males and this can be observed in sexually dimorphic features. Females have a characteristically wider and shorter pelvic cavity to facilitate childbirth, which is reflected in a number of areas of the pelvis. As a consequence, the sacrum of a female is wider and shorter than a male, the pubic bone is wider in a mediolateral direction, the subpubic bones are everted anteriorly and the angle of the greater sciatic notch is more open in females compared to males. This last feature has been suggested to be the least reliable of these attributes (Duric et al. 2005).

Phenice (1969) describes several sexually dimorphic features of the pubic bone. A small ventral arc is often visible on the ventral surface of a women’s pubic symphysis while it is absent in males. The ischiopubic rami form a subpubic concavity anteriorly in females compared to males. A sharp ridge is present on the medial aspect of the ischiopubic ramus in females, as opposed to a broader flatter appearance in males. As with age-at-death estimation, it is most beneficial to use a multifactorial approach to allow the comparison of intermediate results with more definitive results when estimating sex (Bruzek 2002). Moreover, it seems clear that at least one methodological variation to the use of the Phenice technique can produce problematic sex estimation results (McFadden and Oxenham 2015).

There are other characteristics that can be used to estimate sex. These are assessed on the premise of universal size differences between males and females. Males are generally larger and more robust than females. There are several features on the cranium and mandible of males which reflect this variation as a result of their more robust musculature. The supraorbital margin, although it is noted that this has been shown to be a less reliable indicator of sex (Duric et al. 2005), the supraorbital ridge/labella, the external occipital protuberance/nuchal crest, the mastoid process, the mental eminence and the gonial angle of the mandible are more prominent and robust in males compared to females (Buikstra and Ubelaker 1994).

Recently, in attempts to find more practical methods for sexing, several new methods have been proposed for situations where preservation is poor or bone is fragmentary. Two examples provide methods where the complete bone is not necessary (Frutos 2003; Safont et al. 2000) and three focus on bones that preserve well (Barrio et al. 2006; Case and Ross 2007; Lynnerup et al. 2006). Barrio et al. (2006) and Case and Ross (2007) focus on metacarpals and the bones of the hands and feet respectively, which although they may be well preserved due to their density, their labile articulations are one of the first areas of the body to decompose (Willis and Tayles 2009) and as a result are susceptible to taphonomic affects and can be displaced or destroyed in primary burials or left behind in the case of a secondary burial.
The postcranial skeletons of adult humans differ not only in shape between males and females but also in size. Variations used to estimate sex include long bone lengths and joint dimensions, often in the context of univariate sectioning points or multivariate functions. This analysis uses various measurements from individuals whose sex has been estimated using more reliable features. These are used to obtain a discriminant function and a section point. The section point is the average of the male and females scores obtained from the discriminant function. The appropriate measurements are then obtained from individuals of unknown sex and the discriminant function equation is applied. The score from this equation is then compared to the section point and if it is less than the sectioning point the individual is estimated to be female and if it is more the individual is more likely to be male (van Vark and Schaafsma 1992). New mathematical approaches are being published to avoid problems associated with the population specificity of published discriminant function models (Albanese 2007; Konigsberg and Frankenberg 2007).

Sex estimation methods

The estimation of sex was only attempted for adults aged 20 years and older. Pelvic and cranial morphology were given priority but where the results were equivocal discriminant function analysis of appropriate metric variables were used. Discriminant function analyses were performed using the equations developed by Oxenham (2001) for northern Vietnamese samples. These equations were deemed most appropriate given the close geographic and temporal proximity to the sites in this study. Discriminant function equations for the mandible, humerus, femur and tibiae were used directly from Oxenham (2001). Oxenham performed discriminant function analysis for the maxilla, mandible, humerus, femur and tibia, after which he developed discriminant equations derived from the variables with the highest discriminatory power (>70%). Sectioning points were established for each equation as the average of the female and male centroids. All measurements (variables) were taken following Buikstra and Ubelaker (1994). The discriminant function analyses were run for all individuals to check their appropriateness for the sample. There was a high degree of agreement between independently sexed individuals using other methods with the discriminant function analyses.

Age and sex estimation results

The skeletal material from the individuals at An Son was relatively well preserved with most elements represented for most individuals. This enabled a multifactorial approach to be employed in the age and sex estimate. There were 27 individuals analysed from An Son. Thirteen were subadults (<1-14) and fourteen were adults (15-50+) (Table 3.1). Close to half the sample was represented by subadults (48.1%), the majority of which were aged less than four years. There was an even representation of young (15-29) and old (30+) adults at An Son (Table 3.3). There were five males and seven females, with a sex ratio of 0.7:1 (Table 3.3).
The skeletal material from the individuals at Hòa Diêm was not very well preserved due to the mode of deposition in jars (discussed in Chapter Two). The reuse of jars and the multiple interment of individuals in jars meant that many individuals were incompletely represented or only represented by dentition. These limitations affected the age and sex estimation of individuals, however, utilising the regression and discriminant function models developed by Oxenham (2001) assisted in the sexing and aging of some individuals where traditional methods were not possible. There were 51 individuals analysed from Hòa Diêm. Twenty six were subadults (<1-14) and twenty five were adults (15-50+) (Table 3.2). Nearly half the sample were subadults (51.0%), there was an absence of perinates, although a large number of subadults were represented by teeth in the 1-4 and 5-9 year age categories. There was a relatively similar representation of young (15-29) and old (30+) adults at Hòa Diêm (Table 3.3). There were nine males and five females, with a sex ratio of 1.8:1 (Table 3.3).

The demographic data for the adults from An Sơn and Hòa Diêm is comparable to that of other Southeast Asia sites. Table 3.3 summarises the demographic profile of the comparative Southeast Asia sites used throughout this thesis. There is a similar proportion
of young (15-29) and old (30+) individuals represented at the sites. Although there is a
slightly higher proportion of older individuals at Mán Bạc, Ban Na Di and Cồn Cổ Ngra
it is only statistically significant at Cồn Cổ Ngra. Most samples have a slightly higher
proportion of males, with the exception of Ban Lum Khao, however, the differences are
not significant. The $^{15}$P$_5$ values are highest for An Sơn (29.4%), Ban Lum Khao (28.8%),
Khok Phanom Di (25.0%) and Mán Bạc (24.4%) (Table 3.4 and Figure 3.1).

**Age and sex estimation discussion**

Demographic data from a skeletal assemblage can assist in understanding whether the
sample structure fits expectations in terms of age and sex distribution and identifying
if there are any anomalies in the data. The demographic profile of a sample will, to a
greater or lesser degree, reflect the aging and sexing methodology used and the accuracy
achieved. A multifactorial method was employed in both the aging of subadults and adults
and the sexing of adults in order to develop as robust an age and sex profile as possible.

There are two particularly important parameters of a demographic profile which can
assist in the assessment of whether the sample meets expectations in terms of its age
and sex distribution. In terms of the age structure of the sample, it has been suggested
that in prehistoric populations between 19-60% (Waldron 1994; Weiss and Wobst 1973)
of the population should be represented by subadults. The sampled populations at both
An Sơn and Hòa Diệm were represented by approximately 50% subadults, which meets
expectations.

The sex structure of the adult sample is expected to be roughly even in prehistoric
populations (Waldron 1994). The sampled populations at both An Sơn and Hòa Diệm
displayed a similar number of adult males and females, which again suggests the samples
are representative of their respective populations.

The comparative Southeast Asian assemblages are also representative samples. The $^{15}$P$_5$
values which provide an indication of fertility levels are highest at the Neolithic sites. They
are also high at Ban Lum Khao, although that is probably a function of the unusually high
number of subadults aged 5-9 years; and Hòa Diệm although that is probably a sample
bias, as the majority of subadults at Hòa Diệm were represented by teeth, as a reflection
of the mortuary practices at the site and the reuse of burial jars.

These demographic data provide a foundation to investigate potential differences in health
among these samples and provides a good grounding for a regional comparison of health
with other Southeast Asian assemblages which will be undertaken and discussed in the
following chapters.
Table 3.3. Demographic profile for adults from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Source</th>
<th>Period</th>
<th>Total</th>
<th>Young</th>
<th>Old</th>
<th>Young-Old</th>
<th>χ²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>1</td>
<td>preNeolithic</td>
<td>89</td>
<td>23</td>
<td>54</td>
<td>0.4:1</td>
<td>12.481</td>
<td>0.000</td>
</tr>
<tr>
<td>An Son</td>
<td>2</td>
<td>Neolithic</td>
<td>14</td>
<td>6</td>
<td>6</td>
<td>1:1</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>3</td>
<td>Neolithic</td>
<td>68</td>
<td>31</td>
<td>37</td>
<td>0.8:1</td>
<td>0.529</td>
<td>0.467</td>
</tr>
<tr>
<td>Man Bac</td>
<td>4</td>
<td>Neolithic</td>
<td>32</td>
<td>11</td>
<td>18</td>
<td>0.6:1</td>
<td>1.690</td>
<td>0.194</td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>5</td>
<td>Bronze Age</td>
<td>59</td>
<td>29</td>
<td>27</td>
<td>1:1</td>
<td>0.071</td>
<td>0.789</td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>6</td>
<td>Bronze Age</td>
<td>50</td>
<td>13</td>
<td>23</td>
<td>0.6:1</td>
<td>2.778</td>
<td>0.096</td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>7</td>
<td>Iron Age</td>
<td>67</td>
<td>28</td>
<td>26</td>
<td>1:1</td>
<td>0.074</td>
<td>0.786</td>
</tr>
<tr>
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<td>2</td>
<td>Iron Age</td>
<td>25</td>
<td>13</td>
<td>10</td>
<td>1.3:1</td>
<td>0.390</td>
<td>0.671</td>
</tr>
</tbody>
</table>

| Age
| Sex

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Source</th>
<th>Period</th>
<th>Young</th>
<th>Old</th>
<th>Young-Old</th>
<th>χ²</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>1</td>
<td>preNeolithic</td>
<td>15</td>
<td>95</td>
<td>0.158</td>
<td></td>
<td></td>
</tr>
<tr>
<td>An Son</td>
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<td>Neolithic</td>
<td>5</td>
<td>17</td>
<td>0.294</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>80</td>
<td>0.250</td>
<td></td>
<td></td>
</tr>
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<td>Man Bac</td>
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<td>Neolithic</td>
<td>10</td>
<td>41</td>
<td>0.244</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>5</td>
<td>Bronze Age</td>
<td>21</td>
<td>73</td>
<td>0.288</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
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<td>Bronze Age</td>
<td>5</td>
<td>55</td>
<td>0.091</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>7</td>
<td>Iron Age</td>
<td>9</td>
<td>74</td>
<td>0.122</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoa Diem</td>
<td>2</td>
<td>Iron Age</td>
<td>10</td>
<td>42</td>
<td>0.238</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Includes sex indeterminate and age-at-death indeterminate adults
2Young 15-29 years; old 30+ years (young-old ratio: young/old)
3Includes only sexed adults (male-female ratio: males/females)
χ² test for equal proportion of young-old and male-female
Source: 1 Oxenham (2006); 2 this study; 3 Tayles (1999); 4 Oxenham and Domett (2011); 5 Domett (2004); 6 Domett (2001); 7 Tayles et al. (2007)
Dental census methods

Recording protocols for the teeth for An Sơn and Hòa Diệm. The status of every observable tooth was recorded as one of the following:

- Erupting
- Present (in situ)
- Present (not in situ)
- Root only (broken)
- Root only (pathological)
- Isolated (no alveoli)
- Antemortem loss
- Postmortem loss
- Unerupted but present
- Unerupted, unknown if present
- Not present and unknown if ever erupted
- Not preserved (tooth or alveoli)

There are instances where teeth, usually third molars, were absent and it was not possible to know whether they were congenitally absent, impacted or lost antemortem with associated resorption of the alveoli, as it was not possible to take radiographs of the alveoli of the individuals for this research. These were recorded, with a consideration of age, as unerupted and unknown if present in younger individuals, or in older individuals not present and unknown if ever erupted.

There were also instances where teeth were recorded as antemortem loss, but it was possible that these loses were due to intentional ablation. It is difficult to differentiate between antemortem loss due to pathology or deliberate ablation if there are no other
associated pathological changes to the alveolar bone or it has completely remodelled. This will be discussed further in the antemortem tooth loss section in Chapter 5.

The number of assessable teeth for each pathology/condition was dependent on the variable of interest and took into account the condition of the tooth and whether the particular pathology could be adequately assessed. The number of occurrences of each pathology were presented as a percentage of the assessable teeth and will be elaborated on in further relevant sections in Chapter 5.

For those pathologies manifesting in the alveoli, they were recorded wherever possible through an observation of the alveolar bone at the position of the tooth. The number of occurrences of each pathology were presented over the number of assessable alveolar positions. These will be further discussed in the relevant sections in Chapter 5.

Subadults were represented by those individuals that were less than 15 years old. The deciduous and permanent dentition was considered separately. The deciduous dentition which was still present in those individuals 6 years and above was included in the deciduous dentition count, therefore such individuals could be represented in both young subadult (1-5) and older subadult (6-14 years) individual counts. Permanent dentition which was ‘unerupted but present’ in individuals less than 5 years was excluded from any subadult analyses.

Ideally subadults age at death can be determined from the eruption of the teeth; however, due to the nature of the context and preservation at Hòa Diệm and subsequent degradation of loose dentition, in a few cases this was not possible. The age of the individuals represented only by a few loose degraded permanent teeth could not be established. While they could be placed in the permanent dentition category, it was not possible to establish if the teeth were unerupted but present (in which case they would be excluded from the sample for assessment) or erupted in which case they would have been in the permanent dentition (6-14) age category.

Adults were represented by those individuals 15 years and older. All adult individuals were included in order to increase the sample size, even though those individuals of indeterminate age or sex could not assist in addressing questions regarding prevalence of oral pathology by sex or age. Adults were analysed in three age groups 15-29, 30+ years and indeterminate and by sex, males, females and indeterminate.

**Dental census results**

The following section presents the status of the teeth of the individuals at An Sơn and Hòa Diệm. Table 3.5 presents the status of the deciduous and permanent dentition of the
subadults from An Sơn. In both the deciduous and permanent groups the highest numbers of teeth were present in situ (58.2% and 57.7% respectively), followed by unerupted but present (19.7% and 15.5% respectively). The status of the teeth at Hòa Diêm (Table 3.6) differed to that at An Sơn with the majority of subadult teeth in the deciduous and permanent groups isolated (no alveoli) (77.6% and 34.1% respectively) and unerupted but present (55.3% for permanent dentition). As discussed earlier, in the case of Hòa Diêm, these were also isolated with no alveoli.

The following tables summarise the status of the adult teeth recorded at An Sơn. The highest number of teeth were present (in situ) with 56% of the overall sample, followed by not preserved (tooth or alveoli) with 19.5% of teeth (Table 3.7).

Males had 70.6% of teeth present (in situ), a higher frequency of which were represented by posterior (68.1%) and mandibular (55.8%) teeth. The next highest category with 10.6% was not preserved (tooth or alveoli), 5.0% were lost postmortem, all of which were anterior (100.0%) and mandibular (100.0%) and 3.8% of teeth were lost antemortem, all of which were posterior (100.0%) with a higher frequency of mandibular loss (66.7%) than maxillary (33.3%) (Table 3.8).

In comparison 33.3% of female teeth were not preserved (tooth or alveoli), 32.3% were present (in situ), a higher frequency of which were posterior (59.7%) with a similar number of maxillary (51.6%) and mandibular (48.4%) teeth present. Antemortem loss was higher in females (12.0%), most frequently the posterior dentition (87.0%) representing a similar number of maxillary (43.5%) and mandibular (56.6%) teeth. There was only 2.6% postmortem loss of dentition among females, the majority of which were posterior (80%) and maxillary (80.0%) teeth (Table 3.9).

Individuals of indeterminate sex had 90.6% of teeth present (in situ), with several unerupted but present (4.7%) (Table 3.10).

The following tables summarise the status of the teeth recorded at Hòa Diêm. The most common status for teeth was isolated (no alveoli) at 40.1%, followed by present (in situ) with 31.3% and postmortem loss 16.8% (Table 3.11).

Males had 40.8% teeth present (in situ), the majority being represented in the posterior (75.5%) and mandibular (73.2%) dentition. The next highest category was isolated (no alveoli) including 25.5% of teeth, there was a higher frequency of isolated posterior (62.9%) and maxillary (77.1%) dentition. Males lost 12.4% of their dentition postmortem, the majority of which were anterior (82.4%) and mandibular (76.5%). Eight percent were lost antemortem, all of which were posterior with a high proportion being mandibular (90.9%) (Table 3.12).
Females had lost 46.0% of their teeth postmortem, a slightly higher number being posterior 55.0% and mandibular 60.0%. The next highest category was present (in situ) including 24.1% of teeth, all of these were posterior (100.0%) with a higher number from the maxilla (66.7%). Twenty three percent of female teeth were isolated (no alveoli), a large number were anterior (65.0%) and maxillary (70.0%) (Table 3.13).

Table 3.14 shows that 63.3% of the teeth of indeterminate individuals were isolated (no alveoli), a higher number of which were posterior (72.6%) representing both maxillary (47.4%) and mandibular (52.6%) dentition to a similar degree.
The status of the teeth at An Sơn and Hòa Diệm largely reflect the level of preservation at the sites. At An Sơn the highest number of teeth in the deciduous and permanent categories for subadults were present in situ or unerupted but present, reflecting the relatively good preservation of the subadults at An Sơn. At Hòa Diệm the highest number of teeth in...
the deciduous and permanent categories for subadults were isolated with no alveoli and unerupted but present (which for Hòa Diêm also included no alveoli), indicating preservation of individuals as a reflection of the mode of deposition and reuse of jar burials at Hòa Diêm, resulting in a large number of individuals being represented by only dentition as discussed in Chapter Two.
At An Sơn the highest number of adult teeth were present in situ followed by not preserved, tooth or alveoli, which reflects the general preservation of adults, with several individuals missing maxillae or mandibles. Examining this by sex, males had a high proportion of teeth present in situ than females. Females had a higher frequency of teeth not preserved, tooth or alveoli, reflecting two individuals that were potentially secondary burials (the crania of 04ASH3M2 and 09ASH1M1). Individuals of indeterminate sex had a very high frequency of teeth present in situ, followed by unerupted but present, unerupted unknown if present and erupting. This reflects the age of the individuals, those of indeterminate sex at An Sơn were aged 15-19 years of age and were well preserved.

At Hòa Diêm the highest number of teeth for adults were isolated with no alveoli and present in situ. Once again this is a reflection of the preservation of individuals and the mode of interment as discussed above. Examining this by sex, the highest number of teeth for males were present in situ followed by isolated with no alveoli. The highest number of teeth for females were lost postmortem followed by present in situ. Individuals of indeterminate sex had a high proportion of teeth isolated with no alveoli. The status of individuals of indeterminate sex is different at Hòa Diêm as well as including individuals 15-19 years of age, it also included those individuals of unknown sex, which as discussed earlier was a reflection of individuals that were only represented by teeth in the jars.

Having discussed the bioarchaeological census of An Sơn and Hòa Diêm, an essential framework in which to provide a more comprehensive understanding of the relative representativeness of the population, aspects of past fertility levels, age progressive diseases or differences in behaviour in the following chapters, the next chapter will examine health as an indicator of childhood stress at An Sơn and Hòa Diêm.
Chapter Four:

Health as an Indicator of Childhood Stress at An Sơn and Hòa Diêm

Osteological markers that manifest as a result of chronic stress can inform on social, nutritional, demographic and other environmental conditions. This chapter investigates three signatures of physiological health; stature (including growth), linear enamel hypoplasia and cribra orbitalia. While each of the three occurs during the developmental period, factors contributing to their manifestation can have an impact on subsequent adult health (Steckel et al. 2002). Structurally, these three facets of physiological health are treated separately: reviews of the relevant literature, followed by a materials and methods section and results. Finally, a discussion section towards the end of the chapter explores the stature, enamel hypoplasia and cribra orbitalia findings in a local and regional context.

Stature and growth

Growth

Before examining the literature on stature, the main focus of this section, a review of the relevant literature on growth is contextually important. Studies of genetically homogenous and heterogeneous populations in a wide variety of environmental contexts suggest that while genes are important predictors of height, environmental factors are largely responsible for mean differences in height across populations (Steckel et al. 2002). Variation among different populations can largely be explained by phenotypic or developmental plasticity occurring in response to social, nutritional, demographic and environmental influences (Kuzawa and Bragg 2012) and “almost any aspect of the physical or sociocultural environment can exert an influence on early childhood mortality, but only if it has some effect on at least one of a small number of more proximate factors intimately related to the risk of death in young children” (Gage et al. 2012: 734-735).

The majority of deaths in developing countries, or preindustrial communities in general, are caused by infectious diseases, although it needs to be recognised that a range of substantive contributing factors lead to disease susceptibility. In children adequate nutrition is important as it provides the individual with a degree of immunocompetence, protecting them from contracting or succumbing to infectious disease, whereas inadequate nutrition leads to an impaired immune system. This synergistic relationship between inadequate nutrition, impaired immune function, infectious disease and growth faltering had a profound effect on childhood morbidity and mortality in prehistoric populations (Stinson 2012). The negative association between growth status and socioeconomic status is globally ubiquitous.
It is important to understand how growth occurs, because although inadequate nutrition and recurrent disease are the largest environmental contributing factors to growth outcomes, these have different effects on individuals depending on where in the life cycle they occur (Stinson 2012). Growth is mediated and regulated in different ways during the developmental period and susceptibility to environmental influences changes depending on these, ultimately affecting attained stature and sexual dimorphism in adulthood (Kuzawa and Bragg 2012).

In terms of growth during different periods of the life cycle, growth is fastest in the prenatal period and infancy, where it is dependent on nutrition (Kuzawa and Bragg 2012). Maternal health works to increase prenatal resistance through antibodies transmitted through the placenta and during early infancy due to the antibodies in breast milk. Growth during these periods is affected by intergenerational maternal health. Growth is most commonly affected by nutrition and disease during infancy, particularly with the cessation of breastfeeding and once the infant starts consuming complementary sustenance and becomes mobile their exposure to pathogens increases and their level of resistance can decrease. Because this transition coincides with a period of growth mediated by nutrition, the effects of nutritional deficits are most severe during this time (Kuzawa and Bragg 2012). The rate of growth decreases during childhood as it gradually becomes mediated by growth hormones rather than nutrition. A loss of height due to growth faltering experienced during this period may be regained through catch-up growth, however, this requires a change of environmental circumstances. Growth during puberty accelerates again, mediated through a combination of growth and sex hormones (Hindmarsh 2002). Environmental influences have less effect on growth in juveniles and adolescents than in earlier periods.

While growth is sensitive to nutrition throughout the entire developmental period, the long term effects of nutrition on final adult stature are most sensitive during infancy and childhood due to their dependence on nutrition during this time, and reduce after this period as growth becomes dependent on growth hormones. Nutritional deficits experienced during childhood and adolescence generally affect the rate of maturation, rather than affecting final stature or size (Kuzawa and Bragg 2012). Stress experienced during childhood will ultimately have the greatest effect on long term development (Allen 1994).

The effect environmental insults exert on the genetic potential for growth is dependent on the timing, severity, duration and frequency of the insult, with the susceptibility to these being dictated by the sex and age of the individual. The term canalization or homeorhesis was coined by Waddington (1957), the metaphor or term refers to an individual’s genetic potential for attained stature in an unconstrained environment being similar to a ball rolling down a canal toward a specified endpoint. The environment has the potential to
impede this genetic course and any deviation from the determined course (and its velocity) is dependent on the severity and duration of the insult. The ability of an individual to return to their predetermined genetic course dictates the possibility of catch-up growth after an insult (Cameron 2002). Catch-up growth is defined by a period of growth which temporarily exceeds that attained under normal circumstances.

**Sex and frailty**

Females generally have a stronger immune response to infectious disease than males and can therefore better endure unfavourable environments (Holland 2013; Ortner 1998; Stini 1985; Stinson 1985). Males suffer relatively higher morbidity and mortality than females during life (Garenne 2015; Klein 2000; Lozano et al. 2012; Roberts et al. 2001) and this appears to be the case even in prenatal environments; studies have found that male foetuses are more affected by prenatal stress than female foetuses (Lampl and Jeanty 2003; Stinson 1985). Males are also generally more vulnerable to environmental insults during development (Stini 1969, 1985; Stinson 1985). Gestational birth weight is thought to be dependent on differential developmental timing between males and females, males who develop slower than females are more dependent on third trimester environmental conditions than females; and due to this premature males are more compromised in health and prone to postnatal mortality (Stinson 1985).

Several studies have also demonstrated that the timing, severity, duration and frequency of environmental insults sustained during childhood are directly related to frailty and increased morbidity and mortality (DeWitte 2010; DeWitte and Wood 2008; Temple 2014). For example, DeWitte (2010), in analysing sex differences in frailty between males and females at East Smithfield cemetery, England, found that among the individuals who all succumbed ultimately to the Black Death, the Black Death was selective with respect to frailty and that mortality was higher for males than females.

**Comparative assemblages**

There is a general trend in bioarchaeology to view a decline in general health as being associated with the introduction and intensification of agriculture all around the world (Cohen and Armelagos 1984; Cohen and Crane-Kramer 2007; Steckel and Rose 2002). However, Southeast Asia has appeared incongruent with global trends (Domett 2001; Douglas and Pietrusewsky 2007; Oxenham 2006). Throughout this chapter physiological health will be contextualised regionally. Table 4.1 provides summary data for the comparative assemblages, the details of which are elaborated on in the relevant methods sections throughout the chapter.
Table 4.1. Summary data for stature, linear enamel hypoplasia and cribra orbitalia from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Source</th>
<th>Period</th>
<th>O/N cm</th>
<th>O/N %</th>
<th>O/N %</th>
<th>O/N cm</th>
<th>O/N %</th>
<th>O/N cm</th>
<th>O/N %</th>
<th>O/N cm</th>
<th>O/N %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>1</td>
<td>preNeolithic</td>
<td>32/74 161.4</td>
<td>93/197</td>
<td>47.2</td>
<td>47/58 81.0</td>
<td>20/43 166.7</td>
<td>12/31 156.2</td>
<td>36/97</td>
<td>37.1</td>
<td>39/75</td>
</tr>
<tr>
<td>An Son</td>
<td>2</td>
<td>Neolithic</td>
<td>5/12 161.3</td>
<td>26/97</td>
<td>26.8</td>
<td>8/10 80.0</td>
<td>2/5 173.8</td>
<td>3/7 148.9</td>
<td>9/37</td>
<td>24.3</td>
<td>13/41</td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>3</td>
<td>Neolithic</td>
<td>66/68 158.3</td>
<td>265/1086</td>
<td>20.7</td>
<td>31/57 54.4</td>
<td>30/32 162.2</td>
<td>36/36 154.3</td>
<td>120/518</td>
<td>23.2</td>
<td>145/568</td>
</tr>
<tr>
<td>Man Bac</td>
<td>4</td>
<td>Neolithic</td>
<td>19/27 156.9</td>
<td>145/200</td>
<td>72.5</td>
<td>19/26 73.1</td>
<td>13/15 161.7</td>
<td>6/12 152.1</td>
<td>79/117</td>
<td>67.5</td>
<td>62/77</td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>5</td>
<td>Bronze Age</td>
<td>43/59 159.7</td>
<td>89/737</td>
<td>12.1</td>
<td>na na</td>
<td>18/27 164.7</td>
<td>25/32 154.7</td>
<td>35/308</td>
<td>11.4</td>
<td>54/429</td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>3</td>
<td>Bronze Age</td>
<td>30/45 162.0</td>
<td>70/473</td>
<td>14.8</td>
<td>na na</td>
<td>17/25 168.0</td>
<td>13/20 155.9</td>
<td>53/338</td>
<td>15.7</td>
<td>17/135</td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>6</td>
<td>Iron Age</td>
<td>13/48 162.0</td>
<td>72/676</td>
<td>10.7</td>
<td>na na</td>
<td>9/27 169.3</td>
<td>4/21 154.6</td>
<td>20/304</td>
<td>6.6</td>
<td>39/238</td>
</tr>
<tr>
<td>Hoa Diem</td>
<td>2</td>
<td>Iron Age</td>
<td>3/14 159.7</td>
<td>26/833</td>
<td>31.3</td>
<td>3/8 37.5</td>
<td>2/9 164.1</td>
<td>1/15 155.3</td>
<td>9/30</td>
<td>30.0</td>
<td>10/15</td>
</tr>
</tbody>
</table>

1Includes all adults 15+ and indeterminate age (LEH linear enamel hypoplasia; CO cribra orbitalia)
2Includes only sexed adults
O observed condition/ N number assessable individuals, teeth or orbits; cm centimeter
Bold signifies statistically significant differences for either sex at p<0.05
Source: 1 Oxenham (2006); 2 this study; 3 Domett (2001); 4 Oxenham and Domett (2011); 5 Domett (2004); 6 Tayles et al. (2007); unless otherwise stated in the methods
% values have been calculated from published data
na data not available
STATURE

Growth, naturally, has a major effect on final or attained adult stature. Every human is born with a genetic potential for adult stature. This potential is dependent on protein production mediated by the endocrine system, which regulates the genetically inherited blueprint for growth. However, this mechanism can be altered by sociocultural factors during growth leading to adverse effects on the expression of protein producing genes and final achieved (as opposed to potential) stature (Cameron 2002).

While all humans experience a similar pattern of growth, its magnitude is dictated by many different factors which ultimately result in the range of statures observed between different individuals and among different populations (Cameron 2002). The heterochronic development of the human skeleton implies that insults borne at different times by an individual will adversely affect the development of different bones depending on the timing of the insult (Bradney et al. 2000).

Individual variation in stature within a population or among different populations can be a reflection of inadequate nutrition and vulnerability to disease; these may be a consequence of socioeconomic status, social inequalities or environmental conditions. Adequate nutrition and health are often a direct reflection of economic and social stability and have been shown to have a demonstrably positive effect on growth in modern populations, while inadequate health and nutrition as a consequence of economic and social instability have a negative effect resulting in compromised stature (Bielicki 1986; Tanner 1987).

Stature is a sexually dimorphic human trait, in general among all populations males are taller on average than females (Eveleth 1975; Wells 2012). A stature difference of about 1% is present from birth (Gustafsson and Lindenfors 2004; Wells 2012) but does not become substantive until puberty, where adult males are on average about 7% taller in stature than adult females (Wells 2012): a direct reflection of growth trajectories between the sexes. Although there may be differences in the extent to which the prenatal and juvenile growth spurts are expressed between males and females, the timing of the events is similar, however, the adolescent growth spurt varies in extent and timing between the sexes. Females enter their growth spurt around two years before males, giving males an extra two years to grow prior to their adolescent growth spurt, which is more intense, resulting in males being taller in stature than females (Cameron 2002).

Sexual dimorphism in body composition is mainly driven by sex steroid hormones during puberty, however, there is some evidence that the ultimate phenotypic expression may be influenced by foetal exposure to them (Wells 2012). Ultimately, differences in reproductive strategy drives sexual dimorphism in humans (Wells 2012).
From a bioarchaeological perspective, although you would expect females to be genetically determined to have a shorter stature than males due to sexual dimorphism, female endurance of stress needs to be considered in a biocultural interpretation of stature. The findings of several studies support the premise that females are more buffered to stressors, with male stature being more effected by adverse changes in their environment (Bielicki and Charzewski 1977; Hall 1978; Hewitt et al. 1955; Kuh et al. 1991; Tobias 1975), although some studies have also reported contradictory results (Brundtland et al. 1980; Greulich 1976). The greater size and physiological composition of males requires higher nutritional sustenance, which has been argued as a reason why males respond more to either positive or adverse nutritional conditions than females (Stinson 1985). However, complications that arise with pregnancy and childbirth can negate the natural female advantage (DeWitte 2010; Gage 1994).

Attained adult stature is dependent on the duration and severity of the environmental stress and any subsequent arrest in growth. Catch-up growth may compensate for any loss if nutrition is adequate following the insult, however, chronic stress can result in a reduction in stature (Stinson 1985). Females, due to their ability to endure stress better than males, would be expected to return to their normal growth curve following a period of stress, however, males would be expected to deviate further from their growth curve, thus increasing the chances of reduced stature. In contrast, males would be expected to benefit more from improved conditions than females. If environmental conditions did not improve adequately for a return to the normal growth curve, a greater variation in male stature than female stature would be expected. Further, if male growth was more retarded than female growth in response to environmental stress this would minimise the expression of sexual dimorphism (Stinson 1985).

Many studies have focussed on interpopulation variation in growth and stature, but few have focussed on intrapopulation variation. Vercellotti and Piperata (2012), when investigating female height and age at first birth, found a significant correlation between the two variables, suggesting that pregnancy during adolescence has a negative impact on the final stature of the mother. Although females are expected to endure stress better than males and be less affected, this study indicates that pregnancy during adolescence can have a considerable effect on maternal growth and lead to reduced achieved stature. The implications of this for bioarchaeological interpretation are important; it would be expected that in prehistoric populations age of first (and subsequent) pregnancy would have been relatively early in life (i.e. during adolescence), possibly not only compromising female attained stature, but also female health in general.

In bioarchaeological analyses stature is often used as a variable to assess differences in health among (and between) populations and over time. In the late nineteenth century the estimation of stature from the human skeleton developed in two separate ways, the first
was numerical, the second anatomical. There is a linear relationship between the length of long bones and stature (McCammon 1970) and it is this relationship which forms the basis for regression equations formulated for estimating stature in skeletal remains. Rollet (1888), using a series of 100 French cadavers, discovered that the proportionality of the skeleton permitted the calculation of stature using long bones not directly contributing to stature (e.g. the humerus). Rollet used those individuals with the same stature to determine the average length of a given long bone (Trotter and Gleser 1952) and produced the first formalised stature tables, listing the actual stature of the individuals and the length of their independent bones following dissection. Manouvrier (1892, 1893), using Rollet’s data, took individuals with the same lengths for a given bone to determine average stature (Trotter and Gleser 1952). Karl Pearson (1899) developed regression equations for the calculation of stature from Rollet’s dataset (Trotter and Gleser 1952). Trotter and Gleser developed new regression equations specifically for forensic use, derived from the Terry and Todd collections of cadavers of known age, sex and ancestry. Throughout the history of stature reconstruction many problems and issues have been identified and addressed such as the population and sex specificity of regression equations (Formicola 1993, 2003; Formicola and Franceschi 1996). The use of regression equations is still central to bioarchaeological assessments of population health, and those of Trotter and Gleser (Trotter 1970; Trotter and Gleser 1952, 1958) are still the most commonly utilised, which is interesting considering this was not the purpose for which they were developed (Feldesman et al. 1990; Meiklejohn and Babb 2011).

While the length of the femur is the most highly correlated bone with stature, the correlation of bone length to stature varies depending on the growth curve and varies among different populations (Eveleth and Tanner 1990). Due to these differences in long bone length among different populations, regression equations are population specific for the sampled populations from which they were derived and should not be applied to other populations. Stature estimates can be determined from skeletal remains of a population using appropriate equations and then compared to standards obtained from genetically similar populations to determine whether the environment, nutrition or disease affected childhood growth. Stature can also be used in concert with other nonspecific indicators of stress to determine if an individual was of compromised health. These should always be interpreted using a biocultural model.

In 1894 there was also another method for stature estimation proposed in order to attain a total skeletal height from reconstructing the skeleton. Dwight (1894) attempted to articulate the skeleton and reconstruct the curvature of the spine. Unfortunately Dwight’s anatomical method was not practical as it was extremely laborious and required a good anatomical knowledge. Fully (1956) developed a method whereby all the bones that contribute to total height are measured independently to estimate stature and then a soft tissue correction is applied to account for intervertebral discs and other soft tissues that
would be present in a fleshed individual. Raxter et al. (2006) republished Fully’s method, correcting some errors in the original methodology and providing more robust regression equations to correct for soft tissue loss and age. This type of application in stature estimation has been found to be more precise than mathematical methods as it is sex and ancestry independent, it takes into account total skeletal height and measures every bone that contributes to living stature, mitigating against the problem of specific population variation. It provides a standard for testing mathematical models in bioarchaeological populations, where stature is not known, as it is personalised to the individual’s proportions (Moore and Ross 2012). The source of any possible error is restricted to variation in soft tissue composition such as intervertebral disks and menisci. The drawback of this method and its use in bioarchaeological analyses is that variable preservation of skeletal elements precludes its successful application in many cases. Because bioarchaeological assessment is a study of skeletal material, assessing live stature is not possible and skeletons are rarely preserved well enough to use the entire skeleton.

Bioarchaeologists are often limited in their options when it comes to stature estimation and are constrained by variables beyond their control, including sample sizes, preservation and lack of appropriate standards. Researchers have focussed on using regression equations. The allure of being able to assess an individuals’ stature and compare it to others, or assess the mean stature of a series of populations in a comparative context, have led bioarchaeologists to adopt what is essentially an individualised forensic reconstruction and apply it incorrectly in inter and intrapopulation comparisons. Stature estimation in bioarchaeology today is based on a number of compounded errors. These include, but are not limited to, applying regression equations which are population specific to prehistoric samples, transforming the data from a single element (or elements) using a regression equation with an inbuilt standard error, using different equations for different elements (with different inbuilt standard errors) for different individuals then adding them together to calculate the mean of the sample, obscuring the original standard errors and instead presenting a standard deviation, and using statistical tests to assess if there are statistically significant differences within or between groups or even if diachronic changes are evident. At the end stage of the analysis one is assessing the significance in differences of completely transformed data. Ideally, you could use the weighted mean of the equations using the standard errors, as at least then the reliability of the observation is being taken into account when the overall mean is calculated.

Because of the often fragmentary state of human skeletal remains, attempts have also been made to develop methods for estimating stature from long bone fragments (Mysorekar et al. 1984; Simmons et al. 1990; Steele and McKern 1969), the calcaneus (Bidmos 2006; Holland 1995), the metacarpals (Meadows and Jantz 1992), the metatarsals (Byers et al. 1989), the skull (Ryan and Bidmos 2007) and portions of the vertebral column (Jason and Taylor 1995). However, these methods are prone to the same issues of transforming data
as discussed above.

Materials and methods

A Paleo-Tech field osteometric board was used to measure the length of adolescent and adult long bones >15 years old with fused epiphyses. In preparation for the examination of stature at An Sơn and Hòa Diêm, first variation in long bone length was investigated for the humerus, radius, ulna, femur and tibia in comparison to the northern Vietnamese assemblages of Neolithic Mán Bạc and preNeolithic Còn Cổ Ngùa using raw unpublished data sourced from Oxenham (pers. comm.). Due to the variable preservation of independent elements the sample varied but are detailed in the results section. Variation in length was examined between the sexes at each site and among the sexes between the sites.

Following the examination of long bone length variation, stature was estimated for An Sơn and Hòa Diêm using equations developed by Sangvichien et al. (n.d; 1985) for the humerus, radius, humerus and radius, ulna, femur, tibia and femur and tibia. Stature estimates were calculated for the sites of Còn Cổ Ngùa and Mán Bạc using raw unpublished data sourced from Oxenham (pers. comm.) and Sangvichien’s equations. Due to the variable preservation of elements the stature estimates varied by site but are detailed in the results section. Variation in stature from elements was examined between the sexes at each site and among the sexes between the sites.

The stature estimates for An Sơn and Hòa Diêm were compared with several other Southeast Asian assemblages to contextualise the stature of the Vietnamese samples at a regional level. The Thai sites of Neolithic Khok Phanom Di (Domett 2001), Bronze Age Ban Lum Khao (Domett 2004) and Ban Na Di (Domett 2001) and Iron Age Noen U-Loke (Tayles et al. 2007) were directly comparable because the stature estimates were derived using the same equations.

Sangvichien et al. (n.d; 1985) developed equations to estimate stature derived from a sample of contemporary cadavers of Thai and Chinese origin. These equations have been applied successfully in other studies of Southeast Asian skeletal remains and they provide what is currently the most appropriate estimation of stature in Southeast Asia. The equations are sex and bone specific, each providing a standard error of estimate to assess the strength of the equation for estimating stature. Recently, two papers have provided new equations derived from Thai cadavers (Mahakanukrauh et al. 2011; Pureepatpong et al. 2012). Mahakanukrauh et al. (2011) tested their equations and Sangvichien’s equations (1985) on a holdout sample and found very accurate and consistent results. Although the order of preference based on the standard error was different between males and females and among the publications, the combination of the maximum length of the femur and tibia consistently provided the most accurate estimation (Mahakanukrauh et
al. 2011; Pureepatpong et al. 2012). Sangvichien et al.’s (1985) equations were used for several reasons; the equations were demonstrated to be accurate and are derived from a sample of individuals unaffected by the recent secular changes in stature documented in Thailand and are perhaps more appropriate for comparison with prehistoric individuals than modern cadavers. Further, the use of these equations provides a level of consistency in comparison with estimated stature determined for individuals from other Southeast Asian assemblages.

For each individual, stature was calculated for each relevant element where a measurement was recorded. Where both sides were present, the mean of the left and right sides was used in the equation. In a manner consistent with previous researchers, the order of preference for stature estimates derived from the equations in the following order, femur and tibia, tibia, femur, humerus and radius, humerus, radius and lastly ulna. For each individual the most appropriate stature estimation was used, rather than averaging the results from all equations. When calculating the average stature for each site the mean was calculated from all individuals.

Traditionally, sexual dimorphism is calculated by taking the male value as a percentage of the female value or vice versa, however, statistically the method is problematic as the measure of dimorphism becomes contingent on which sex is the numerator and which is the denominator (Wells 2012). Using a log-transformed scale, as suggested by Wells (2012), differences relate to fractional differences on the original scale (Cole and Kryakin 2002). Using this approach and multiplying the result by 100, the mean of the two values becomes the denominator for the purposes of percent difference and the differences become equivalent to symmetric percentage differences (sympercents). Sexual dimorphism was calculated as \([(\text{Ln(male value)})–(\text{Ln(female value)})]*100\%\) for stature (Wells 2012).

Independent sample t-tests were used to test intra-sample differences between sexes. Results are presented with equal variance assumed unless homogeneity of variance was violated then the results are presented with equal variance not assumed. One way analysis of variance (ANOVA) was used to test inter-sample differences between sexes. Hochberg post-hoc tests (unless stated otherwise) were used where analysis of variance showed statistical significance. An alpha level of .05 was used for all statistical tests.

**Results**

Table 4.2 presents summary data for each long bone for the four Vietnamese sites. The mean length of each element was longer for males than for females at each site that had comparative data for both sexes. The lack of data and sample sizes at Hòa Diệm prevented any statistical tests being performed. There was a high degree of sexual dimorphism in long bone lengths by sex within each of the other three sites. The length of the humerus
in males was significantly longer than that of females at Cồn Cổ Ngựa ($t(21)=3.538$, $p=0.002$) and An Sơn ($t(2)=7.411$, $p=0.018$). The length of the radius was significantly longer in males at Mán Bạc ($t(16)=3.500$, $p=0.018$) than females. The length of the ulna in males was significantly longer than females at Cồn Cổ Ngựa ($t(4)=3.216$, $p=0.003$) and Mán Bạc ($t(16)=3.550$, $p=0.003$). The length of the femur was significantly longer in males at Cồn Cổ Ngựa than females ($t(7)=2.963$, $p=0.021$). The length of the tibia was significantly longer at Mán Bạc in males ($t(9.301)=3.655$, $p=0.005$) than females.

Analysis of variance shows that there is a significant difference in the length of the ulna among males at the four sites ($F(3,17) = 4.934, p = .012$). Hochberg post-hoc tests reveal that the mean length of the ulna was longer for An Sơn (29.9 cm ± 1.0, $p = .036$) than Mán Bạc (26.5 ± 1.6 cm). The only element with a significant difference in length among

<table>
<thead>
<tr>
<th>Table 4.2. Summary statistics for element length (values in cm)</th>
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<tr>
<td><strong>An Son</strong></td>
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<tr>
<td><strong>Humerus</strong></td>
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<td>standard deviation</td>
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<td><strong>Radius</strong></td>
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<td>n</td>
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<tr>
<td>average</td>
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<tr>
<td>standard deviation</td>
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<tr>
<td>minimum</td>
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<tr>
<td>maximum</td>
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<tr>
<td>range</td>
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<td><strong>Ulna</strong></td>
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<tr>
<td>average</td>
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<tr>
<td>standard deviation</td>
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<td>maximum</td>
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<td>range</td>
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<td>range</td>
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<td><strong>Tibia</strong></td>
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<td>maximum</td>
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<td>range</td>
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</table>
females at the four sites was the humerus \( (F(2,12) = 4.808, p = .029) \). A Hochberg post-hoc test revealed that the mean length of the humerus was longer for Cồn Cổ Ngựa \( (29.6 \pm 1.5 \text{ cm}, p = .032) \) than An Sơn \( (26.4 \pm 0.1) \).

Table 4.3 presents summary data for stature estimates derived from each long bone or combination of long bones for the four Vietnamese sites. The mean stature estimate derived from each element or elements was longer for males than for females at each site that had comparative data from both sexes. The lack of data and small sample size at Hòa Diêm prevented any statistical tests being performed. There was a high degree of sexual dimorphism in stature estimates derived from long bone lengths between the sexes within each of the three remaining sites. Mean stature estimates were consistently significantly larger for males than females derived from the humerus for Mán Bạc \( (t(13)=3.265, p=.006) \) and Cồn Cổ Ngựa \( (t(21)=5.570, p=.000) \); from the radius for Mán Bạc \( (t(16)=5.433, p=.000) \) and Cồn Cổ Ngựa \( (t(7)=4.885, p=.002) \); from the humerus and radius for Mán Bạc \( (t(13)=3.405, p=.005) \) and Cồn Cổ Ngựa \( (t(4)=4.202, p=.014) \); from the ulna for Mán Bạc \( (t(16)=5.672, p=.000) \) and Cồn Cổ Ngựa \( (t(4)=4.229, p=.013) \); from the femur for Mán Bạc \( (t(15)=3.065, p=.008) \) and Cồn Cổ Ngựa \( (t(3.845)=2.927, p=.045) \); from the tibia for Mán Bạc \( (t(9.487)=5.086, p=.001) \) and Cồn Cổ Ngựa \( (t(7)=3.106, p=.017) \); and from the femur and tibia for Mán Bạc \( (t(10.127)=3.644, p=.04) \).

Considering the data from all four sites, analysis of variance demonstrates the only element with a significant difference in stature estimate among males was the ulna \( (F(3, 17) = 4.934, p = 0.12) \). A Hochberg post-hoc test revealed that the stature estimated from the ulna was statistically significantly larger for An Sơn \( (177.4 \pm 3.6 \text{ cm}, p = .036) \) than Mán Bạc \( (165.5 \pm 5.4 \text{ cm}) \). The only element with a significant difference in stature among females at the four sites was the humerus \( (F(2,12) = 4.808, p = .029) \). A Hochberg post-hoc test revealed that the stature estimated from the humerus was statistically significantly larger for Cồn Cổ Ngựa \( (155.4 \pm 4.1 \text{ cm}, p = .032) \) than An Sơn \( (146.6 \pm 2.2 \text{ cm}) \).

Table 4.4 summarises the stature for the individuals from Cồn Cổ Ngựa, An Sơn, Khok Phanom Di, Mán Bạc, Ban Lum Khao, Ban Na Di, Noen U-Loke and Hòa Diêm. Mán Bạc males had the largest stature range of 24.4cm, Khok Phanom Di females had the largest range of 22.1cm. The largest difference between male and female stature was observed at An Sơn, with a difference of 33.1cm, followed by Khok Phanom Di with 29.6cm and Mán Bạc with 29.2cm.

There was a high degree of sexual dimorphism between the sexes in terms of mean stature (Table 4.4 and Figure 4.1). Mean stature estimates were consistently significantly larger for males than females at all sites as demonstrated by t tests for Cồn Cổ Ngựa \( (t(30)=6.030, p=0.0001) \), An Sơn \( (t(3)=4.772, p=0.0175) \), Khok Phanom Di \( (t(64)=6.684, p=0.0001) \), Mán Bạc \( (t(17)=2.845, p=0.0112) \), Ban Lum Khao \( (t(41)=6.550, p=0.0001) \), Ban Na Di
Table 4.3. Summary statistics for element derived stature (values in cm)

<table>
<thead>
<tr>
<th></th>
<th>An Son</th>
<th>Man Bac</th>
<th>Con Co Ngua</th>
<th>Hoa Diem</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>male</td>
<td>female</td>
<td>male</td>
<td>female</td>
</tr>
<tr>
<td>Humerus n</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>average</td>
<td>170.9</td>
<td>146.6</td>
<td>162.6</td>
<td>151.9</td>
</tr>
<tr>
<td>standard deviation</td>
<td>4.1</td>
<td>0.2</td>
<td>6.7</td>
<td>3.6</td>
</tr>
<tr>
<td>minimum</td>
<td>168.0</td>
<td>146.4</td>
<td>155.2</td>
<td>148.1</td>
</tr>
<tr>
<td>maximum</td>
<td>173.8</td>
<td>146.7</td>
<td>176.0</td>
<td>156.0</td>
</tr>
<tr>
<td>range</td>
<td>5.7</td>
<td>0.3</td>
<td>20.8</td>
<td>8.0</td>
</tr>
</tbody>
</table>

| Radius n       | 2      | 2       | 12          | 6        |
| average        | 175.3  | 147.0   | 164.9       | 151.9    |
| standard deviation | 4.9  | 0.9     | 5.4         | 3.0      |
| minimum        | 171.9  | 146.4   | 158.6       | 147.9    |
| maximum        | 178.8  | 147.6   | 175.1       | 156.4    |
| range          | 6.9    | 1.2     | 21.3        | 9.9      |

| Humerus and radius n | 2 | 2 | 10 | 5 | 5 | 1 | 1 |
| average              | 174.5 | 146.1 | 163.9 | 152.0 | 165.4 | 152.0 | 166.7 |
| standard deviation   | 5.3   | 0.6   | 7.2   | 3.8   | 2.9   | 0.0   | 3.6  |
| minimum              | 170.8  | 145.6 | 155.4 | 147.5 | 162.5 | 152.0 | 166.7 |
| maximum              | 178.2  | 146.5 | 176.6 | 157.4 | 170.1 | 152.0 | 166.7 |
| range                | 7.4    | 0.9   | 21.3  | 9.9   | 7.6   | 0.0   | 5.1  |

| Ulna n            | 2      | 2       | 12          | 6        |
| average           | 177.4  | 150.6   | 165.5       | 152.1    |
| standard deviation| 3.6    | 6.3     | 5.4         | 2.6      |
| minimum           | 174.8  | 146.1   | 158.6       | 148.5    |
| maximum           | 179.9  | 155.0   | 177.4       | 155.6    |
| range             | 5.1    | 8.9     | 18.9        | 7.0      |

| Femur n          | 1      | 1       | 11          | 6        |
| average          | 166.6  | 146.0   | 161.4       | 153.3    |
| standard deviation| 0.0   | 0.0     | 5.7         | 4.0      |
| minimum          | 166.6  | 146.0   | 155.6       | 146.6    |
| maximum          | 166.6  | 146.0   | 171.5       | 157.7    |
| range            | 0.0    | 0.0     | 15.9        | 11.1     |

| Tibia n         | 1      | 1       | 9           | 5        |
| average         | 170.2  | 144.2   | 164.1       | 149.2    |
| standard deviation| 0.0   | 0.0     | 8.4         | 2.0      |
| minimum         | 170.2  | 144.2   | 154.5       | 146.7    |
| maximum         | 170.2  | 144.2   | 176.6       | 151.7    |
| range           | 0.0    | 0.0     | 22.1        | 5.1      |

| Femur and tibia n | 1 | 1 | 9 | 5 | 4 | 1 |
| average          | 169.4  | 145.1   | 162.8       | 150.9    |
| standard deviation| 0.0   | 0.0     | 9.1         | 2.6      |
| minimum          | 169.4  | 145.1   | 152.2       | 147.4    |
| maximum          | 169.4  | 145.1   | 176.6       | 153.9    |
| range            | 0.0    | 0.0     | 24.4        | 6.5      |
The Bioarchaeology of An Sơn and Hòa Diêm: Biosocial Insights into Prehistoric Southern Vietnam

\(t(28)=7.240, p=0.0001\) and Noen U-Loke \((t(11)=6.781, p=0.0001\), while Hòa Diêm could not be analysed due to small sample sizes.

Overall, the stature estimates for the comparative Southeast Asian assemblages are very similar. Analysis of variance showed no statistically significant differences among females across all eight sites, however, there was a statistically significant difference in stature among males \((F(7, 103) = 4.437, p = 0.0002\). A Tukey post-hoc test (Table 4.5 and Figure 4.2) revealed that the mean stature was statistically significantly higher in males at Ban Na Di \((168.0 \pm 4.9\text{cm}, p<0.05\) and Noen U-Loke \((169.3 \pm 3.1\text{cm}, p=\)

Table 4.4. Summary statistics for stature for Southeast Asian sites

<table>
<thead>
<tr>
<th>Site</th>
<th>N</th>
<th>Mean</th>
<th>Range</th>
<th>Standard deviation</th>
<th>Sexual dimorphism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>Males</td>
<td>20</td>
<td>166.7</td>
<td>158.2-172.7 (14.5)</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>12</td>
<td>156.2</td>
<td>149.7-163.6 (13.9)</td>
<td>5.2</td>
</tr>
<tr>
<td>An Sơn</td>
<td>Males</td>
<td>2</td>
<td>173.8</td>
<td>169.4-178.2 (8.8)</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>3</td>
<td>148.9</td>
<td>145.1-155.0 (9.9)</td>
<td>5.4</td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>Males</td>
<td>30</td>
<td>162.2</td>
<td>153.8-170.7 (16.9)</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>36</td>
<td>154.3</td>
<td>141.1-163.2 (22.1)</td>
<td>4.5</td>
</tr>
<tr>
<td>Man Bac</td>
<td>Males</td>
<td>13</td>
<td>161.7</td>
<td>152.2-176.6 (24.4)</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>6</td>
<td>152.1</td>
<td>147.4-157.7 (10.3)</td>
<td>3.6</td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>Males</td>
<td>18</td>
<td>164.7</td>
<td>152.4-174.9 (22.5)</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>25</td>
<td>154.7</td>
<td>147.9-162.2 (14.3)</td>
<td>3.8</td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>Males</td>
<td>17</td>
<td>168.0</td>
<td>159.5-176.0 (16.5)</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>13</td>
<td>155.9</td>
<td>150.0-164.4 (14.4)</td>
<td>4.0</td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>Males</td>
<td>9</td>
<td>169.3</td>
<td>165.3-173.3 (8.0)</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>4</td>
<td>154.6</td>
<td>151.5-161.6 (10.1)</td>
<td>4.7</td>
</tr>
<tr>
<td>Hòa Diêm</td>
<td>Males</td>
<td>2</td>
<td>164.1</td>
<td>163.9-164.2 (0.3)</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Females</td>
<td>1</td>
<td>155.3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

See materials and methods section for sources

Figure 4.1. Mean stature for comparative Southeast Asia assemblages
Health as an Indicator of Childhood Stress at An Sơn and Hòa Diệm

Linear enamel hypoplasia is an indicator of a disturbance in growth during the formation of the tooth crown in childhood. Since teeth do not remodel once formed, they provide a permanent and chronological record of developmental disruptions (Cucina and İşcan 1997; Goodman and Rose 1990) and are widely used by bioarchaeologists as an indicator of childhood health.

Enamel hypoplasia is caused by a disturbance during the final stage of tooth formation, the crown stage (Hillson 1996, 2005). During the crown stage the dentine is covered with enamel in a process called amelogenesis, beginning at the dentin surface of the future cusp tip and progressing cervically. The first enamel to be laid down is the cuspal enamel. A matrix is secreted by ameloblasts, the enamel forming cells, in increments (striae of Retzius), which then become mineralised, subsequently another increment of matrix is secreted followed by mineralisation. After the cuspal enamel is completed, enamel continues to be laid down in increments from the dentine outward creating the lateral enamel. An arrest in amelogenic growth interrupts the completion of an increment, so it is shorter, subsequent growth after the stressful episode involves the formation of a new increment.

Table 4.5. *P*-values from Tukey’s post-hoc statistics for male stature from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th></th>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Man Bac</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
<th>Hoa Diem</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean Stature</strong></td>
<td>0.6435</td>
<td>0.0880</td>
<td>0.1714</td>
<td>0.9472</td>
<td>0.9960</td>
<td>0.9315</td>
<td>0.9981</td>
<td></td>
</tr>
<tr>
<td><strong>SD</strong></td>
<td>0.0767</td>
<td>0.0751</td>
<td>1.0000</td>
<td>0.3295</td>
<td>0.8403</td>
<td>0.9630</td>
<td>0.6280</td>
<td></td>
</tr>
<tr>
<td><strong>Tukey’s Q</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0141</td>
<td>0.0180</td>
<td>0.0338</td>
<td></td>
</tr>
<tr>
<td><strong>Significance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0422</td>
<td>0.0140</td>
<td>0.0338</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.2. Differences in mean stature highlighted for comparative Southeast Asian assemblages

<0.05) than Khok Phanom Di (162.3 ± 5.1cm) and Mán Bạc (161.7 ± 7.8cm).

**LINEAR ENAMEL HYPOPLASIA**

Linear enamel hypoplasia is an indicator of a disturbance in growth during the formation of the tooth crown in childhood. Since teeth do not remodel once formed, they provide a permanent and chronological record of developmental disruptions (Cucina and İşcan 1997; Goodman and Rose 1990) and are widely used by bioarchaeologists as an indicator of childhood health.
increment leaving the previous one as incomplete, seen as a deficiency in enamel thickness represented by a hypoplastic groove. At a microscopic level this can be observed in the perikymata which are the endpoints of the developmental increments or the striae of Retzius. Because of the morphology of cuspal enamel, any discrepancies in amelogenesis in this region will not be represented as hypoplastic grooves and are only visible in cross section (Hillson 2005; Reid and Dean 2000; Ritzman et al. 2008).

Historically, in bioarchaeology there has been a tendency to report the prevalence of linear enamel hypoplasia between sexes, within populations and between populations, however, this is only an index of systemic stress, it does not address the chronology, intensity, duration or intervals of the stress events (King et al. 2005; Reid and Dean 2000; Temple et al. 2012). A number of limitations in macroscopic identification of linear enamel hypoplasia include the issue of the smallest defects are harder to identify, there is no standardisation of what is considered a defect among observers so there can be little comparability in the frequency of hypoplasia between studies (Hillson and Bond 1997) and there is often little effort made to correlate different stress episodes on different teeth (Hillson 2005). Due to these limitations there has been an emphasis on assessing the defects microscopically to improve precision.

Bioarchaeological research has increasingly moved from just reporting frequencies of linear enamel hypoplasia to addressing questions of chronology, duration and intervals of linear enamel hypoplasia. Because multiple hypoplastic lines on teeth are indicative of multiple stressful insults to the individual, scholars have tried to correlate the occurrences of these lines to chronological age based on an understanding of the calcification and formation of dentition and the developmental distribution of enamel. If the hypoplastic defects are represented in the same position, on two antimeric teeth, then it is assumed that they represent the same systemic stress episode (Hillson 2005). The chronology of the stress event or events can be better understood by measuring the distance between the cementoenamel junction and the hypoplastic groove (Goodman and Rose 1990) or correlating the stress event within deciles of tooth crown height (Reid and Dean 2000) to provide an approximate age of occurrence of the insult. The duration of the stress event or events can be indicated by the number of perikymata represented within the hypoplastic groove (Guatelli-Steinberg et al. 2004; Temple et al. 2012), while the intervals between the stress event or events can be inferred from the number of perikymata between the hypoplastic grooves (King et al. 2005).

Linear enamel hypoplasia is most easily observable on incisors and canines due to the characteristics of the perikymata. The anterior teeth form as described above, however, the molars are represented by more cuspal enamel than lateral enamel, obscuring potential developmental defects (Hillson 2005; Hillson and Bond 1997; King et al. 2002). Many researchers focus on the incisors and canines, representing a period in dental development...
between 1-6 years of age (Hillson 2005). Although there is a difference in the spacing of perikymata across a tooth’s surface, they are normally more closely spaced toward the cervix, and in any given area of the crown perikymata are normally evenly spaced. Linear enamel hypoplasia are observable as a change in the spacing of perikymata of the teeth, the longer the duration of the insult the more perikymata are involved (Hillson 2005), although there is no necessary correlation between overall defect width, duration and severity of the physiological insult.

The aetiology of linear enamel hypoplasia is multifactorial and as it is generally unattributable the condition is referred to as a nonspecific indicator of stress. The stress event/s had to be severe enough to necessitate the body to divert essential energy away from non-vital processes, for example, the process of amelogenesis, and redirect all resources into processes essential for survival (Aufderheide et al. 1998). These events can include episodes of general malnutrition, specific nutritional deficiencies, childhood illnesses and bacterial and viral infections (Hillson 1996).

Materials and methods

Neither the equipment nor the resources were available to carry out a microscopic study of linear enamel hypoplasia. Traditional methods were employed in the hope that some comparisons could be made by sex and with other suitable Southeast Asian assemblages. Macroscopic analysis was used to identify any linear hypoplastic event presenting as a transverse line, groove or linear arrangement of pits on the surface of the tooth (Hillson 1996). All anterior teeth, where more than 50% of the crown height was preserved, were assessed for linear enamel hypoplasia and results were presented as a percentage of assessable teeth which included those that were present (in situ), present (not in situ) and isolated (no associated alveoli).

Thirteen adults and nine subadults were able to be assessed for linear enamel hypoplasia at An Sơn. Five adults were male, six were female and two were of indeterminate sex. The males had 37 preserved maxillary or mandibular incisors or canines, the females had 41 and the individuals of indeterminate sex had 19. Six subadults were 1-5 years old with 47 preserved deciduous maxillary or mandibular incisors or canines, three were 6-14 years with 20 permanent teeth of those classes. Nineteen adults and fourteen subadults were able to be assessed at Hòa Diệm. Eight adults were male, two were female and nine were of indeterminate sex. The males had 30 preserved maxillary or mandibular incisors or canines, the females had 15 and the individuals of indeterminate sex had 38. Six subadults were 1-5 years old with 11 preserved deciduous maxillary or mandibular incisors or canines, eight were 6-14 years with 29 permanent teeth of those classes, the details of which are presented in the results section.
The frequency of linear enamel hypoplasia for An Sơn and Hòa Diêm was compared with several other Southeast Asian assemblages to contextualise the health of the Vietnamese samples at a regional level. Unfortunately, the recording protocols and methodology varies slightly between the different sites: for Khok Phanom Di, Ban Lum Khao, Ba Na Di and Noen U-Loke all teeth were assessed for linear enamel hypoplasia as present or absent and presented by tooth count (Domett 2001, 2004; Tayles et al. 2007). The data for Ban Lum Khao also differed between publications; the data presented in the most recent publication was used (Tayles et al. 2007). The data for Mán Bạc (Oxenham and Domett 2011) and Cồn Cổ Ngựa (Oxenham unpublished data, pers. comm.) were recorded in a manner consistent with this work, in assessing only incisors and canines.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Subadults are presented in two age classes 1-5 years (deciduous dentition) and 6-14 years (permanent dentition).

Pearson’s uncorrected Chi square tests were used to test intra-sample and inter-sample differences between the sexes and among the sites. An alpha level of .05 was used for all statistical tests.

Results

When examining the prevalence of linear enamel hypoplasia by tooth count (Table 4.6), the frequency was similar in the incisors (27.1%) compared to the canines (26.3%) among the adult population at An Sơn. Males had a higher prevalence of canines affected (26.7%) compared to their incisors (22.7%), while 34.6% of females incisors were affected compared to 26.7% of their canines.

Females had a higher prevalence of linear enamel hypoplasia at 31.7% compared to males at 24.3%. Females had a higher frequency of enamel hypoplasia in the incisors (34.6%) than males with 22.7%, but their canines had the same prevalence (26.7%).

Younger females (15-29 years) had a higher frequency of linear enamel hypoplasia (52.0%) than older females (30+) (0.0%), while older males (30+) had a higher prevalence (25.0%) than younger males (22.2%). This pattern was the same for both sexes for canines and incisors, with the exception of 15-29 year old males who had a higher frequency of linear enamel hypoplasia in the incisors (40.0%) than older males (17.6%).

When examining linear enamel hypoplasia by individual count (Table 4.7) the pattern changes, the frequency was higher in males (60.0%) compared to females (33.3%), higher in the incisors than the canines for males (50.0% to 20.0%) and females (33.3% to 16.7%). Younger individuals were more commonly affected. Having one linear enamel hypoplasia
event on either a canine or an incisor was the most common manifestation with 66.7% of adult individuals in this category. Only one individual had two linear enamel hypoplasia events on at least one tooth, and one had three linear enamel hypoplasia events on at least one tooth. Finally, there were no subadults with linear enamel hypoplasia.

When examining the prevalence of linear enamel hypoplasia by tooth count (Table 4.8) the frequency was higher in the canines (36.8%) compared to the incisors (26.7%) among the adult population at Hòa Diệm. This pattern was repeated between the sexes with 42.9% of male canines affected compared to 18.8% of incisors and 80.0% of female canines affected compared to 60.0% of incisors.

Females had a higher prevalence of linear enamel hypoplasia at 66.7% compared to males at 30.0%. Females had a higher frequency of enamel hypoplasia in both the incisors (60.0%) and canines (80.0%) than males with 18.8% and 42.9% respectively.
Differences between the age classes for enamel hypoplasia in females could not be assessed as there were no older females represented. Older males had a higher prevalence of enamel hypoplasia (41.2%) than younger males (15.4%), while younger individuals of indeterminate sex had a higher frequency (29.2%) than older individuals (0.0%). This pattern was the same for incisors and canines for both males and individuals of indeterminate sex.

When examining linear enamel hypoplasia by individual count (Table 4.9) the pattern changes, and the overall male frequency matches the females (50.0% for both). There were more male individuals with affected canines than incisors (42.9% to 28.6%), while the same number of females and individuals of indeterminate sex had incisors and canines with enamel hypoplasia. Having one linear enamel hypoplasia event on either an incisor or a canine was the most common manifestation with 36.8% of adult individuals in this
There were 27.6% of subadults with permanent dentition and linear enamel hypoplasia (50.0% of individuals), no subadults represented by deciduous dentition had linear enamel hypoplasia.

Females had a statistically significantly higher frequency of linear enamel hypoplasia by tooth count than males at Mán Bạc $X^2(1)=3.951$, $p=0.047$, Noen-U Loke $X^2(1)=10.826$, $p=0.001$ and Hòa Diệm $X^2(1)=5.511$, $p=0.019$. Because of the different recording protocols used between the Vietnamese and Thai assemblages they are not statistically comparable so are treated separately here.

There was a statistically significant difference in the frequency of linear enamel hypoplasia by tooth count among the adults across both the Vietnamese ($X^2(3)=73.6$, $p=0.000$) and Thai ($X^2(3)=76.7$, $p=0.000$) assemblages respectively. There was a statistically significant difference in the frequency of linear enamel hypoplasia by tooth count among the males

### Table 4.8. Linear enamel hypoplasia profile for Hòa Diệm by tooth count

| Permanent Teeth | Incisor | | | | | | Canine | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | N¹ | P² | O³ | %⁴ | T%⁵ | | C⁶ | O⁷ | %⁸ | T%⁹ | Total¹⁰ |
| Male 15-29 | 13 | 1/5 | 3/O | 0.0/0.0 | 0.0 | | 2/5 | 0/2 | 0.0/40.0 | 28.6 | 15.4 |
| 30+ | 17 | 7/3 | 3/O | 42.9/0.0 | 30.0 | | 3/4 | 1/3 | 33.3/75.0 | 57.1 | 41.2 |
| subtotal | 30 | 8/8 | 3/O | 37.5/0.0 | 18.8 | | 5/9 | 1/5 | 20.0/55.6 | 42.9 | 30.0 |
| Female 15-29 | 15 | 7/3 | 3/O | 42.9/100.0 | 60.0 | | 3/2 | 2/2 | 66.7/100.0 | 80.0 | 66.7 |
| subtotal | 15 | 7/3 | 3/O | 42.9/100.0 | 60.0 | | 3/2 | 2/2 | 66.7/100.0 | 80.0 | 66.7 |
| Indeterminate 15-29 | 24 | 3/9 | 1/2 | 33.3/22.2 | 25.0 | | 4/8 | 0/4 | 0.0/50.0 | 33.3 | 29.2 |
| 30+ | 14 | 4/3 | 0/0 | 0.0/0.0 | 0.0 | | 4/3 | 0/0 | 0.0/0.0 | 0.0 | 0.0 |
| subtotal | 38 | 7/12 | 1/2 | 14.3/16.7 | 15.8 | | 8/11 | 0/4 | 0.0/36.4 | 21.1 | 18.4 |
| Subtotal | 83 | 22/23 | 7/5 | 31.8/21.7 | 26.7 | | 16/22 | 3/11 | 18.8 | 36.8 | 31.3 |
| Subadults | 6-14 | 29 | 14/12 | 6/0 | 42.9/0.0 | 23.1 | | 0/3 | 0/2 | 0.0/66.7 | 66.7 | 27.6 |
| Total | 112 | 36/35 | 13/5 | 36.1/14.3 | 25.4 | | 16/25 | 3/13 | 18.8 | 39.0 | 30.4 |
| Deciduous Teeth | | | | | | | | | | | |
| Subadults | 1-5 | 11 | 3/3 | 0/0 | 0.0/0.0 | 0.0 | | 4/1 | 0/0 | 0.0/0.0 | 0.0 | 0.0 |
| TOTAL | 123 | 39/38 | 13/5 | 33.3/13.2 | 23.4 | | 20/26 | 3/13 | 15.0/50.0 | 34.8 | 27.6 |

¹total preserved maxillary and mandibular incisors and canines  
²preserved maxillary/mandibular incisors  
³observed number of maxillary/mandibular incisors with at least one LEH event  
⁴% of maxillary/mandibular incisors with at least one LEH event  
⁵% of maxillary and mandibular incisors combined with at least one LEH event  
⁶preserved maxillary/mandibular canines  
⁷observed number of maxillary/mandibular canines with at least one LEH event  
⁸% of maxillary/mandibular canines with at least one LEH event  
⁹% of maxillary and mandibular canines combined with at least one LEH event  
¹⁰% of maxillary and mandibular incisors and canines combined with at least one LEH event  

across both the Vietnamese ($X^2(3)=34.7, p=0.000$) and Thai ($X^2(3)=45.7, p=0.000$) assemblages respectively. There was a statistically significant difference in the frequency of linear enamel hypoplasia by tooth count among the females across both the Vietnamese ($X^2(3)=29.4, p=0.000$) and Thai ($X^2(3)=33.8, p=0.000$) assemblages respectively. This was investigated further by using Pearson’s uncorrected Chi square tests to examine the relationship between the sites and among the sexes between the sites.

The significant differences among the Vietnamese (Table 4.10) and Thai assemblages (Table 4.11) respectively were a reflection of the different frequencies of linear enamel hypoplasia (Figure 4.3). Mán Bạc (72.5%) had a significantly higher prevalence than all the other Vietnamese sites, followed by Cồn Cổ Ngựa (47.2%), which had a significantly higher prevalence than An Sơn (26.8%) and Hòa Diệm (31.1%). Khok Phanom Di (20.7%) had a significantly higher prevalence of linear enamel hypoplasia in comparison to all the other Thai sites. Ban Na Di (14.8%) had a significantly higher frequency than Noen U-Loke (10.7%), however, there was no significant different between Ban Na Di (14.8%) and Ban Lum Khao (12.1%); or Ban Lum Khao (12.1%) and Noen U-Loke (10.7%).
The significant differences among males from the Vietnamese (Table 4.12) and Thai assemblages (Table 4.13) respectively were a reflection of the different frequencies of linear enamel hypoplasia (Figure 4.4). Males at Mán Bạc had a significantly higher prevalence of linear enamel hypoplasia (67.5%) than males at all of the other Vietnamese assemblages. There were no significant differences in the frequency of linear enamel hypoplasia among the males from the rest of the sites, at Cồn Cổ Ngựa (37.1%), An Sơn (24.3%) or Hòa Diệm (30.0%). Males at Khok Phanom Di had a significantly higher prevalence of linear enamel hypoplasia (23.2%) than all of the other Thai sites. The prevalence for males at Ban Lum Khao (11.4%) and Ban Na Di (15.7%) was not significantly different. However, the frequency for males at Noen U-Loke (6.6%) was significantly lower than all of the other Thai sites.

The significant differences among females from the Vietnamese (Table 4.14) and Thai assemblages (Table 4.15) respectively were a reflection of the different frequencies of linear enamel hypoplasia (Figure 4.4). Females at Mán Bạc (80.5%) had a significantly higher prevalence than the other females at all the sites except Hòa Diệm (37.1%), Cồn Cổ Ngựa (37.1%), An Sơn (24.3%) or Hòa Diệm (30.0%). Males at Khok Phanom Di had a significantly higher prevalence of linear enamel hypoplasia (23.2%) than all of the other Thai sites. The prevalence for males at Ban Lum Khao (11.4%) and Ban Na Di (15.7%) was not significantly different. However, the frequency for males at Noen U-Loke (6.6%) was significantly lower than all of the other Thai sites.
Cổ Ngựa (52.0%) females also had a significantly higher prevalence than all the sites except Hòa Diệm (66.7%). The frequency for females at An Sơn (31.7%) was significantly lower than all of the other Vietnamese sites. Females at Khok Phanom Di (25.5%) had a significantly higher prevalence of linear enamel hypoplasia than females at all the other Thai sites. There were no significant differences between the females at Ban Lum Khao (12.6%), Ban Na Di (12.6%) or Noen U-Loke (15.1%).
CRIBRA ORBITALIA

Cribra orbitalia is a condition that manifests in the roof of the eye orbits typically expressed as perforations to the outer table that are remodelled to a greater or lesser degree in adults. It is caused when blood producing bone marrow expands, which in turn causes an expansion of diploic bone which ultimately begins to break down leading to the characteristic lesions of this condition. The term porotic hyperostosis was first used by Angel in 1966 as a term to collectively encompass both the lesions of the cranial vault and orbital roofs, of which he assumed a common aetiology (Walker et al. 2009). The aetiology of porotic hyperostosis and cribra orbitalia has been extensively discussed in the literature, particularly with regard to whether or not they are caused by the same condition as manifestations can co-occur or occur independently (Blom et al. 2005; Brickley and Ives 2008; Stuart-Macadam 1989; Walker et al. 2009; Wapler et al. 2004). However, as it is likely multifactorial the condition is referred to as a nonspecific indicator of stress. Porotic hyperostosis and cribra orbitalia are both commonly reported in palaeopathological investigations in bioarchaeology as a means of assessing the general health status of individuals (Walker et al. 2009).

Despite the probable multifactorial aetiology of cribra orbitalia, anaemia is perhaps one of the most common underlying stated causes of this particular type of lesion in the literature. Anaemia, literally meaning without blood, in its Greek etymon, is not a disease but rather a condition in which there is either a reduction of red blood cells or a deficiency in their haemoglobin content. Equilibrium among red blood cells is normally maintained in homeostasis where the bone marrow produces red blood cells (erythropoiesis) at the same rate at which they are destroyed (haemolysis). Anaemia generally occurs as a response to one or a combination of three events, blood loss, decreased erythropoiesis or increased haemolysis (Rhoades and Bell 2012).

There are two kinds of anaemia, genetic and acquired. Genetic anaemias, where an individual is predisposed to the condition, include thalassemia and sicklemia. Acquired anaemia, where an individual is predisposed to the condition through environmental factors, includes iron deficiency anaemia. The biological processes underlying the ostensible link between anaemia and cribra orbitalia is relatively well understood.

Red blood cells normally mature in seven days and remain functional for 120 days. The cells contain haemoglobin which carry oxygen from our respiratory systems to the rest of our tissues. Essential nutrients required for maintaining homeostasis of red blood cells include iron and vitamins A, B₁₂, B₆, essential amino acids and folic acid (Martini and Martini 1992). If there is a deficiency, or malabsorption of these essential nutrients, the production of red blood cells is compromised and eventually leads to anaemia. If erythropoiesis is compromised due to anaemia, homeostasis is not maintained and the body goes into a
state of hypoxia, this in turn stimulates the release of a hormone erythropoietin which increases the production and maturation of red blood cells (Halvorsen and Bechensteen 2002; Stockmann and Fandrey 2006). If the hormonal response is not adequate to resume homeostasis, haemopoietic marrow activates increased red blood cell production (Ross and Logan 1969). In the cranial vault hypertrophy of the diplöe containing haemopoietic marrow gradually resorbs the outer table resulting in the porosity associated with porotic hyperostosis and cribra orbitalia. The manifestation of this is dependent on the severity of the condition (Walker et al. 2009).

During development the location of red marrow (the red blood cell forming marrow) changes (Halvorsen and Bechensteen 2002). Erythropoiesis takes place in the yolk sac in utero, then occurs in the liver and spleen and finally the marrow of the bone. Throughout childhood and adolescence the main areas of red blood cell production are the medullary cavities within the appendicular bones and the diplöe of the cranial bones. In adults erythropoiesis takes place in the trabecular bone of the axial skeleton in the vertebral, sternal and costal regions. Active lesions in porotic hyperostosis and cribra orbitalia are almost exclusively only recorded in children and adolescents in archaeological samples (Larsen 2015), and this had been convincingly linked to these developmental changes in the production sites for the red blood cells, suggesting these manifestations are indicators of childhood anaemias (Stuart-Macadam 1985; Stuart-Macadam 1992).

Iron deficiency anaemia has often been suggested in the aetiology of porotic hyperostosis and cribra orbitalia because of the parallels observed in modern clinical and epidemiological data. Porotic hyperostosis is symptomatic of serious types of hereditary haemolytic anaemia, sickleemia and thalassemia major (Hershkovitz et al. 1997) and the co-occurrence of iron deficiency anaemia and marrow hypertrophy is commonly seen in clinical settings (Walker et al. 2009). Walker et al. (2009) suggest that due to the population specificity or rarity of the hereditary conditions, they are unlikely to explain the high prevalence of porotic hyperostosis or cribra orbitalia witnessed in archaeological samples.

Iron deficiency anaemia, associated with poor hygiene or a dietary deficiency in essential nutrients appears to be a more reasonable assumption (Walker 1986). This aetiology has so often been reported in bioarchaeology that iron deficiency anaemia is seemingly synonymous with the occurrence of porotic hyperostosis and cribra orbitalia and the interpretation of the health of individuals in the past. However, Walker et al. (2009) have argued that iron deficiency anaemia should not be considered in the aetiology of porotic hyperostosis or cribra orbitalia because iron stores would be too low to elicit increased erythropoiesis or associated hypertrophy of the bone marrow. Oxenham and Cavill (2010) have demonstrated that Walker et al.’s (2009) dismissal of iron deficiency anaemia in the aetiology of porotic hyperostosis and cribra orbitalia stems from a misunderstanding of the clinical literature, that iron deficiency anaemia does not impede the production of red
blood cells, but actually massively increases the production of ineffective red blood cells.

Walker et al. (2009) suggest that megaloblastic and haemolytic anaemias characterised by the premature death of red blood cells and increased red blood cell production (erythropoiesis) are more appropriate in a differential diagnosis for porotic hyperostosis than iron deficiency anaemia. They suggest that although megaloblastic and haemolytic anaemias may also cause cribra orbitalia, these have a much more complex aetiology, other contributing factors may include megaloblastic anaemia acquired through a diet deficient in vitamin B₁₂, susceptibility to gastrointestinal infections during weaning compounded by poor sanitation, or subperiosteal bleeding as a result of vitamin C and B₁₂ deficiencies (Ortner and Ericksen 1997; Walker et al. 2009).

Materials and methods

Cribra orbitalia was identified using a 10x hand lens, recorded as active or remodelled and presented as a percentage of assessable individuals. An individual was required to have at least one preserved orbital roof with both the anterolateral and medial aspects preserved. Active lesions were defined as perforations with no evidence of remodelling. Remodelled lesions were defined as obliterated lesions presenting evidence of extensively infilled confluent lesions following Oxenham (2006).

Ten adults and six subadults were able to be assessed for cribra orbitalia at An Sơn. Three adults were male, five were female and two were of indeterminate sex. Five subadults were 1-5 years old and one was 6-14. Eight adults and two subadults were assessed for cribra orbitalia at Hòa Diệm. Three adults were male, two were female, and three were of indeterminate sex. One subadult was 1-5 years old and one was 6-14 years, the details of which are presented in the results section.

Adults are presented by sex (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Subadults are presented in two age classes 1-5 years (deciduous dentition) and 6-14 years (permanent dentition).

The frequency of cribra orbitalia for An Sơn and Hòa Diệm was compared with several other Southeast Asian assemblages to contextualise the health of the Vietnamese samples at a regional level. Unfortunately, of the suite of comparative assemblages consistently being used in this thesis there were no comparative data available for Ban Lum Khao, Ba Na Di and Noen U-Loke. The prevalence of cribra orbitalia was very low in these samples potentially due to poor preservation, or concretion on the orbits and was deemed too difficult to accurately investigate and present (Domett 2001: 140). For Khok Phanom Di the original frequency of cribra orbitalia reported in Tayles (1992) was used, although it is noted in a later publication these data were amended as some of the lesions originally
recorded as ‘light’ were excluded on the basis that they represented impressions of blood vessels, rather than cribra orbitalia (Tayles 1999: 161). For the Vietnamese sites Cồn Cô Ngựa and Mán Bạc comparative data (Oxenham 2006; Oxenham and Domett 2011) were recorded in a manner consistent with this work.

Pearson’s uncorrected Chi square tests were used to test intra-sample and inter-sample differences between the sexes and among the sites. An alpha level of .05 was used for all statistical tests.

Results

At An Sơn cribra orbitalia was present in (80.0%) of assessable adults. The frequency was higher in females (80.0%) than males (66.7%) and higher among older aged individuals for both sexes (Table 4.16). One 6-14 year old subadult and 2/5 (40.0%) of 1-5 year olds had cribra orbitalia. At Hòa Diêm cribra orbitalia was present in 37.5% of assessable adults. The frequency was higher in males (66.7%) than females (50.0%) (Table 4.17). One subadult (6-14) had cribra orbitalia, however, there was no evidence for it among 1-5 year olds.

Table 4.16. Cribra orbitalia profile for An Son

<table>
<thead>
<tr>
<th>Adult orbits</th>
<th>N</th>
<th>Absent</th>
<th>Active (%)</th>
<th>Remodelled (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male 15-29</td>
<td>0</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>30+ subtotal</td>
<td>3</td>
<td>1 (33.3)</td>
<td>0 (0.0)</td>
<td>2 (66.7)</td>
<td>2 (66.7)</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>2</td>
<td>1 (50.0)</td>
<td>1 (50.0)</td>
<td>0 (0.0)</td>
<td>1 (50.0)</td>
</tr>
<tr>
<td>30+ subtotal</td>
<td>2</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>2 (100.0)</td>
<td>2 (100.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>1</td>
<td>0 (0.0)</td>
<td>1 (100.0)</td>
<td>0 (0.0)</td>
<td>1 (100.0)</td>
</tr>
<tr>
<td>Subtotal</td>
<td>5</td>
<td>1 (20.0)</td>
<td>2 (40.0)</td>
<td>2 (40.0)</td>
<td>4 (80.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>2</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>2 (100.0)</td>
<td>2 (100.0)</td>
</tr>
<tr>
<td>Subtotal</td>
<td>2</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>2 (100.0)</td>
<td>2 (100.0)</td>
</tr>
<tr>
<td>Subadults 6-14</td>
<td>1</td>
<td>0 (0.0)</td>
<td>1 (100.0)</td>
<td>0 (0.0)</td>
<td>1 (100.0)</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
<td>2 (20.0)</td>
<td>2 (20.0)</td>
<td>6 (60.0)</td>
<td>8 (80.0)</td>
</tr>
<tr>
<td>Subadults 1-5</td>
<td>5</td>
<td>3 (60.0)</td>
<td>2 (40.0)</td>
<td>0 (0.0)</td>
<td>2 (40.0)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>16</td>
<td>5 (31.3)</td>
<td>5 (31.3)</td>
<td>6 (37.5)</td>
<td>11 (68.8)</td>
</tr>
</tbody>
</table>

Most severe lesion form in any given orbit used to score the individual
Absent: no lesions
Active: active lesions
Remodelled: Remodelled lesions
1individuals with at least one assessable orbit
2individuals with active cribra orbitalia (remodelled cases excluded)
3individuals with remodelled cribra orbitalia (active cases excluded)
4all individuals displaying signs of cribra orbitalia (remodelled and active)
N number of assessable individuals
Although there is a scarcity of comparative data for other Southeast Asia assemblages, some attempt at comparisons will be made. There were no significant differences between the sexes at any of the sites. There was a statistically significant difference in the frequency of cribra orbitalia among the adults across all the assemblages $X^2(4)=13.8$, $p=0.008$. This was investigated further by using Pearson’s uncorrected Chi square test to examine the relationship between the sites (Table 4.18). The significant differences were a reflection of the frequency of cribra orbitalia across the sites (Figure 4.5). There was a statistically significantly higher frequency of cribra orbitalia at Cồn Cổ Ngựa (81.0%) than Khok Phanom Di (54.4%) and Hòa Diêm (37.5%). However, there were no significant differences between Cồn Cổ Ngựa (81.0%), An Sơn (80.0%), Mán Bạc (73.1%) Khok Phanom Di (54.4%) or Hòa Diêm (37.5%). There were no significant differences among females or males across the sites (Figure 4.6).

Results summary

The results of the comparison of the raw data and transformed data from the Vietnamese material demonstrated that when comparing (1) element length and (2) derived stature from element length the data transformations caused by using stature estimation...
equations actually increased the likelihood of a significant difference between the sexes. This supports Meiklejohn and Babb’s (2011: 153) observation that “the use of stature as the primary variable, as opposed to individual long bone length, adds unnecessary noise to the analysis”. Despite the potential issues in using equations to estimate stature, Steckel et al.’s (2002) findings “validate the general use of stature as a proxy for health
status” (Meiklejohn and Babb 2011: 170). The average male stature was higher at An Sơn (173.8cm) than Hòa Diêm (164.1cm), while the average female stature was lower at An Sơn (148.9cm) than Hòa Diêm (155.3cm).

When examining the prevalence of linear enamel hypoplasia by tooth count at An Sơn and Hòa Diêm similar patterns were observed among adults. The adult frequency was similar in both assemblages with 26.8% at An Sơn and 31.3% at Hòa Diêm. Females had a higher prevalence of linear enamel hypoplasia in both the canines and the incisors compared to males. Younger females had a higher frequency of linear enamel hypoplasia than older females (although the latter could not be assessed for Hòa Diêm), while the opposite trend was seen in males, older individuals having exhibited higher prevalence than younger males. There were no subadults with permanent dentition with linear enamel hypoplasia at An Sơn, however, 27.6% of subadults with permanent dentition had linear enamel hypoplasia at Hòa Diêm. There were no subadults with deciduous dentition with linear enamel hypoplasia at An Sơn or Hòa Diêm.

When examining the prevalence of cribra orbitalia at An Sơn and Hòa Diêm about 80% of individuals at An Sơn had evidence for cribra orbitalia, however, it was lower at Hòa Diêm with 37.5% of the sample affected. The frequency was higher in females than males at An Sơn and higher among older aged individuals for both sexes. At Hòa Diêm cribra orbitalia was higher in males than females but there were no discernible age differences. Fifty percent of subadults had cribra at both An Sơn and Hòa Diêm.

DISCUSSION

The following discussion draws on the data presented in this chapter as an indicator of childhood health and disease using three commonly reported nonspecific indicators of stress, stature, linear enamel hypoplasia and cribra orbitalia, and their role in adult morbidity and mortality. Firstly the osteological paradox and underlying issues of sex and frailty are discussed. Following this a focus on contemporary disease vectors in the region is carried out in order to examine their potential contribution to the aetiology of these conditions. This, in turn, contextualises the final section of the discussion which deals specifically with the individual stress signatures of stature, linear enamel hypoplasia and cribra orbitalia from a regional perspective.

Sex and frailty

There are sex differences in the prevalence of infectious diseases, with males suffering relatively higher morbidity and mortality than females during life (Garenne 2015; Klein 2000; Lozano et al. 2012; Roberts et al. 2001) with suggestions that females are immune privileged (Giefing-Kröll et al. 2015). Immunocompetence is mediated largely by oestrogen and females have stronger cellular and humoral immune responses to infectious
disease and antigenic stimulus than males (Fish 2008; Markle and Fish 2014). While this increased immunity can aid in the defence against and removal of certain pathogens, predisposition to certain autoimmune diseases and immunopathology as a response to certain infectious diseases has also been recognised (Amur et al. 2012; Fischer et al. 2015; Giefing-Kröll et al. 2015). Although it would be intuitive to assume that these would not have any marked affect until the onset of puberty and associated hormonal changes, differences have been observed during the foetal and childhood periods (Muenchhoff and Goulder 2014) which is likely due to mini puberty (Garenne 2015; Muenchhoff and Goulder 2014) during infancy where there is a surge of sex steroids. This is particularly relevant when interpreting sex differences in adults as a reflection of childhood health.

When assessing the general health of a population it is important to consider the inherent variability in susceptibility to death (hidden heterogeneity) among individuals. While we will never know cause of death with any certainty at the individual level, assessing the mortality and morbidity profile of the population can provide some insights. One way to deal with this is to examine adult health as a direct consequence of childhood stress in consideration of the underlying strength or frailty of the individuals of interest (DeWitte 2010; DeWitte and Wood 2008; Temple 2014). The three variables of stress presented in this chapter, stature, linear enamel hypoplasia and cribra orbitalia manifest in different frequencies among the different populations as a consequence of three potential childhood states, frail children, medium frail children and strong children (Domett 2001; Lukacs 1992a; Wood et al. 1992).

Frail children would be expected to have a low immunity and high susceptibility to extrinsic factors and suffer an acute response to these, if they got sick it would be expected that they would die before manifesting any skeletal signatures of their affliction. They would be represented in the subadult population with low to no evidence for linear enamel hypoplasia and cribra orbitalia.

Medium frail children would be expected to have a medium immunity and susceptibility to extrinsic factors and suffer a chronic response to these, if they got sick it would be expected that they would be strong enough to endure this and potentially several episodes of stress, and die manifesting skeletal signatures of their affliction. The timing, duration, severity and frequency of the stress events would influence their mortality, they could either die as subadults with moderate to high enamel hypoplasia and cribra orbitalia or as adults with moderate to high enamel hypoplasia and cribra orbitalia; and, depending on their ability to compensate for these episodes of stress with catch-up growth, either low adult stature or tall stature.

Strong children would be expected to have a high immunity and low susceptibility to extrinsic factors, if they got sick it would be expected they would suffer inconsequentially
manifesting minimal skeletal signatures of their affliction. They would be represented in the adult population with low to no evidence for linear enamel hypoplasia and cribra orbitalia and tall stature.

A paradoxical outcome of this is that while the state of childhood health is ultimately reflected in adult morbidity and mortality, the mortality profile of subadults gives more of an indication of the fertility level and growth of a population (Larsen 2015) than the overall health of a population as discussed in Chapter Three.

The following section summarises a range of the most plausibly relevant conditions seen in modern day Vietnam and potentially in Vietnamese antiquity in highlighting the chief likely underlying causes of reduced stature (and growth disruption), linear enamel hypoplasia and cribra orbitalia.

Contemporary disease vectors as analogues for bioarchaeological health outcomes

Within prehistoric Southeast Asia, a tropical area, there are a number of different pathogens that would have influenced childhood morbidity and mortality. Although it is not possible to ascertain what these may have been with any certainty during antiquity, due to the vagaries of pathogen evolution, ecology and survival, as well as host and environment interactions, some inferences can be made using modern data (Lim and Vythilingam 2014; Stanfield et al. 1991). It is also not possible to directly extrapolate patterns of aetiology or epidemiology in prehistory from modern clinical data, however, a consideration of common themes will be considered as a potentially useful framework within which to explore these issues.

Respiratory tract infections, diarrhoeal disease and malaria are the leading causes of childhood mortality in tropical countries today (Lozano et al. 2012; Webb 1991). Although the effects of these are asymptomatic in skeletal manifestation, their potential contribution to the aetiology of nonspecific indicators of childhood stress must be considered as must their periodicity, synergistic nature and potential comorbidity from concomitant infections that would contribute to increased frailty and susceptibility.

Pneumonia can be caused by a number of bacteria, viruses and fungi. *Streptococcus pneumoniae* and *Haemophilus influenza* are common causes of bacterial pneumonia in children in Vietnam, particularly in those less than two years old (Anh et al. 2009). It is transmitted through inhalation of the bacteria, which commonly reside in the nose or throat, into the lungs and direct contact with respiratory secretions from infected individuals. It can also be spread through air borne droplets. Symptoms include a cough, difficulty breathing and possibly associated fever. Respiratory infections are more common in male children in contemporary Vietnam (Anh et al. 2007; Anh et al. 2009).
Diarrhoea is a common symptom of a range of bacterial, viral and parasitic infections. Bacteria such as *Campylobacter*, *Shigella*, *Enterohaemorrhagic escherichia coli* and *Salmonella* are common food borne pathogens found in children in Vietnam, particularly in those less than one year of age (Isenbarger *et al.* 2001; Thompson *et al.* 2015). They can be contracted through the consumption of infected food or water and potentially via faecal oral transmission. Infections from these bacteria cause diarrhoea, fever and vomiting. Viruses transmitted via the faecal oral route, such as Rotavirus and norovirus, are commonly found in children in Vietnam (Thompson *et al.* 2015). Symptoms include vomiting and diarrhoea, often associated with fever and abdominal pain. Diarrhoeal disease is more common in male children in contemporary Vietnam (Isenbarger *et al.* 2001; Thiem *et al.* 2012; Thompson *et al.* 2015).

Parasitic zoonotic infections from food borne pathogens in Vietnam includes trematodes (liver flukes) such as *Opisthorchis viverrine* and *Clonorchis sinensis* (Nguyễn *et al.* 2003). There is a very clear geographical distribution of these, *Clonorchis sinensis* is only found in northern Vietnam, while *Opisthorchis viverrine* is only found in southern Vietnam (Nguyễn *et al.* 2003; Nguyễn and Thanh 2011). Freshwater snails are the primary host, they ingest parasitic eggs and release larvae, which are then consumed by a secondary host, fish. The third host is a mammal which can then release eggs back into freshwater by way of their faeces. The trematodes reside in the bile ducts, and symptoms of mild infections include general feelings of illness sometimes associated with abdominal pain. Chronic infections can result in inflammation of the infected organs, fibrosis of tissues and cholangiocarcinoma; a form of bile duct cancer.

Eating raw fish in Vietnam is a very common historical and enduring tradition but one mostly practiced by adult males (Nguyễn 2004b) and not generally by individuals younger than 18-20 years (Phan *et al.* 2010). There is a very clear pattern in the clinical literature with a high prevalence of coinfection (Do *et al.* 2007; Nguyễn and Thanh 2011) and the prevalence of trematodes being higher in males than females, higher in adults than children, and highest in older adults 40+ years (Dang *et al.* 2008; Do *et al.* 2007; Kino *et al.* 1998; Nguyễn 2004b; Nguyễn and Thanh 2011; Nguyễn *et al.* 2015). Although the effects of trematodes likely has a smaller impact on children, cross contamination during shared meals or the consumption of associated sauces or garnishes mean that individuals who did not themselves eat raw fish are also commonly infected (Phan *et al.* 2010).

Intestinal parasitic infections from soil transmitted helminths such as hookworm (*Necator americanus* and *Ancylostoma duodenale*), whipworm (*Trichuris trichiura*) and roundworm (*Ascaris lumbricoides*) are common in Vietnam (Needham *et al.* 1998; van der Hoek *et al.* 2003; Verle *et al.* 2003). It has been argued that the prevalence of whipworm and roundworm is lower in southern Vietnam than northern or central Vietnam, while hookworm is endemic throughout the country (Needham *et al.* 1998; van der Hoek *et
The worms reside in the intestine of the affected host, secreting eggs that are transmitted in human faeces to soil. From the soil they become infective and can then be ingested by humans through poor hygiene and sanitation practices, or in the case of hookworm by larval penetration of the skin, and once in another host they mature into adult worms within the intestine. Infections from these parasites cause diarrhoea, loss of appetite, reduced absorption of micronutrients, abdominal pain and fatigue. Hookworms can cause chronic blood loss within the intestine which can result in anaemia, while roundworm may compete for Vitamin A within its host.

Vietnamese adults generally have a higher prevalence of helminths than infants (Trang et al. 2007; Verle et al. 2003). Roundworm is usually the most prevalent helminth found in subadults less than 5 years old (Trang et al. 2007; Verle et al. 2003), although one study found a very high frequency of whipworm and roundworm in children by 5 years old (Needham et al. 1998), while hookworm showed lower rates in the young but increased with increasing age (Needham et al. 1998; Verle et al. 2003). It has been suggested that, in general, children aged 5-15 years have a higher prevalence than relatively younger or older age groups (van der Hoek et al. 2003). In two studies of school children who were aged between 5-8 years (Lê et al. 2007) and 14-15 years (Uga et al. 2005), both showed a high prevalence of whipworm and roundworm, with each study finding lower levels of hookworm respectively as well as a high prevalence of coinfection (Lê et al. 2007; Nguyễn et al. 2015; Uga et al. 2005). Finally, general helminth infections are higher in females and girls (Nguyễn et al. 2015; Trang et al. 2007; Uga et al. 2005), particularly hookworm (Needham et al. 1998; Trang et al. 2007; Verle et al. 2003).

Malaria is a parasitic infection caused by the protozoa *Plasmodium* spp. transmitted by female *Anopheles* mosquitoes. *P. falciparum* and *P. vivax* are the most common species of *Plasmodium* in Southeast Asia and Vietnam (Erhart et al. 2005; Thang et al. 2008). The parasites reproduce in the liver infecting red blood cells. Symptoms of malaria include headache, fever and vomiting. Males appear to suffer more during blood stage malaria due to hormonal influences (Bernin and Lotter 2014; Cernetich et al. 2006), whereas females appear to have some level of immunity to malaria (Klein et al. 2008), however, this is compromised during pregnancy (Reubin 1992; Vlassoff and Bonilla 1994). Pregnant women who contract malaria are more predisposed to anaemia and hypoglycaemia and are more likely to suffer miscarriage, stillbirth, premature delivery, infants of low birth weight and maternal death (Chongsuphajaisiddhi 1991).

Anaemia, common in contemporary Vietnam, is a condition where the oxygen carrying red blood cells or the amount of red blood cells is inadequate to meet functional needs. Iron deficiency is a common cause of anaemia, however, there are a number of other causes including deficiencies in folate, Vitamin A or B12, chronic inflammation, parasitic infections or inherited conditions. The symptoms include fatigue, weakness and general
cognitive impairments. Traditionally, the Vietnamese diet is low in bioavailable iron and high in absorption inhibitors, significantly increasing the prevalence of iron deficiency (Nguyễn et al 2006b). The Vietnamese environment has a high presence of parasitic intestinal pathogens that may increase anaemia risk. Anaemia is highest in women and children, particularly in pregnant women and children <2 years of age (Nguyễn et al 2006b). A study of school children in Vietnam suggested that anaemia was high, although not necessarily associated with iron deficiency, suggesting that other proximate causes, particularly coinfection with intestinal parasites, were contributing to anaemia (Lê et al 2007) and perhaps competing for essential vitamins. The youngest group of children at 5 years had the highest prevalence of anaemia and boys had a higher prevalence of anaemia, and lower haemoglobin concentrations, than girls (Lê et al 2007).

Although one could argue that these modern clinical data reflect underlying environmental or cultural behaviours, the theme of underlying susceptibility in males conforms to the general observations of males suffering higher levels of morbidity than females.

**Stature**

Unfortunately, the sample sizes reflecting stature at An Sơn and Hòa Diêm are both very small and therefore meaningful comparisons are limited. The stature estimates for An Sơn and Hòa Diêm and the other Southeast Asia assemblages demonstrate that mean stature was significantly lower in females than males at all sites, which is to be expected due to sexual dimorphism (Wells 2007).

As discussed above there are a range of tropical illnesses which would have contributed to stress during childhood and likely had an effect on attained stature in some individuals. There were no statistically significant differences among female stature across all the assemblages over time, however, there were statistically significant differences among male stature over time. This perhaps reflects sex differences in the prevalence of infectious disease with males suffering higher morbidity (Garenne 2015; Klein 2000; Lozano et al. 2012; Roberts et al. 2001) and the ability of females to endure stress better than males (Bielicki and Charzewski 1977; Hall 1978; Hewitt et al. 1955; Tobias 1975) and return to their normal growth curve following a period of stress (Stinson 1985).

In terms of temporal differences, Neolithic An Sơn, Khok Phanom Di and Mán Bạc had the shortest mean female stature. Mán Bạc and Khok Phanom Di also had statistically significantly shorter male stature, and as a result had the smallest degree of stature sexual dimorphism. This was not seen at An Sơn and as mentioned this may be due to the small sample size. The small degree of sexual dimorphism in stature witnessed at the Neolithic sites may indicate that these populations were experiencing nutritional stress, and reflect the differential ability of males and females to deal with stress (Ortner 1998;
4. Health as an Indicator of Childhood Stress at An Sơn and Hòa Diệm

Stini 1985; Stinson 1985). It has been suggested that as a consequence of nutritional stress males would deviate further from their growth curve and would not attain their genetic potential. This would minimise the amount of sexual dimorphism and result in a larger degree of variation in stature among males (Stinson 1985). There was a large degree of variation among the males at Mán Bạc, however, the same range of variation was not observed at An Sơn or Khok Phanom Di. Although, the largest difference between male and female stature was observed at An Sơn, with a difference of 33.1cm from the shortest female to the largest male, followed by Khok Phanom Di with 29.6cm and Mán Bạc with 29.2cm. This is interesting because these three sites are representative of the Neolithic Demographic Transition. The range of variation among the male stature at Mán Bạc may be a function of the genetically heterogeneous composition of the population (Matsumura and Oxenham 2014; Oxenham and Matsumura 2011) rather than a direct result of stress. It has been suggested that males would benefit more from improved conditions than females (Stinson 1985) and this may explain why in the Bronze and Iron Age assemblages stature is significantly higher in males at Ban Na Di and Noen U-Loke than at Neolithic Khok Phanom Di and Mán Bạc. Again this was not seen at Hòa Diệm, however, the sample size is small.

**Linear enamel hypoplasia**

There was no attempt at microscopic analyses undertaken in the assessment of linear enamel hypoplasia among these samples, all were recorded macroscopically, and therefore no definitive conclusion could be drawn on the chronology, duration or interval of the stress. It is discussed here as a general nonspecific indicator of stress.

As discussed above, there are a range of tropical illnesses which would have contributed to stress during childhood and likely contributed in the aetiology of linear enamel hypoplasia in some individuals. Despite the fact that it is argued that males suffer more from infectious disease (Garenne 2015; Klein 2000; Lozano et al. 2012; Roberts et al. 2001) and females are more buffered to environmental stressors than males (Ortner 1998; Stini 1985; Stinson 1985), females consistently had a higher frequency of linear enamel hypoplasia than males, across all the sites with the exception of Ban Na Di. Although this difference was only significant at Mán Bạc, Noen U-Loke and Hòa Diệm. This pattern may suggest that females sustained or had more adverse reactions to environmental insults than males did during childhood. Alternatively, it could suggest that the males (being more prone to infectious diseases and less adept at buffering environmental stressors) suffered more acutely, with more of those who were frail dying as subadults or more of those who were of medium frailty succumbing to the stress and not surviving into adulthood than their respective female counterparts.

The Vietnamese and Thai frequencies of linear enamel hypoplasia were not statistically
comparable due to different recording protocols. Only the canines and incisors were
examined for the Vietnamese samples, while all the dentition was examined for the Thai
samples, resulting in a larger denominator in observations/number of assessable teeth and
therefore deflating the overall prevalence. However, some broad temporal observations
can be made. The preNeolithic and Neolithic sites all have the highest frequency of
linear enamel hypoplasia. The high frequency at Cồn Cổ Ngựa may be a reflection of
the temporal period of the site. The fact that Mán Bạc has a similarly high frequency,
and the population is argued to be genetically heterogeneous with a significant number
of individuals potentially genetically related to the individuals from Cồn Cổ Ngựa, is
interesting (Matsumura and Oxenham 2014; Oxenham and Matsumura 2011). An Sơn
and Khok Phanom Di, both sites influenced by the Neolithic Demographic Transition,
also show significantly higher rates of linear enamel hypoplasia than the later sites. Hòa
Diêm also displays high levels, but this is probably explained by the context of the site;
as discussed in earlier chapters it is a jar burial site where the majority of individuals are
represented by teeth and the sample may thus be skewed. The other Bronze and Iron Age
sites have lower and similar levels of linear enamel hypoplasia.

Cribra orbitalia

There was no attempt at microscopic or thin sectioning analyses undertaken in the
assessment of cribra orbitalia among these samples, all were recorded macroscopically
and therefore no definitive conclusions could be drawn on the aetiology. However, a
differential diagnosis of cribra orbitalia must take into consideration the possible
underlying aetiology of the disease.

As discussed above there are a range of tropical illnesses which would have contributed
to stress during childhood and likely contributed in the aetiology of cribra orbitalia,
particularly perhaps malaria and intestinal parasitic infections leading to vitamin
deficiency and anaemia. Malaria is one of the leading causes of childhood mortality
(Chongsuphajaisiddhi 1991; Lozano et al. 2012: 2111 Figure 2), and cribra orbitalia has
recently been found to be highly correlated with malaria (Smith-Guzmán 2015) which
has also recently been shown to be a ‘souvenir’ pathogen acquired after the introduction
of agriculture (Harper and Armelagos 2013).

The prevalence of cribra orbitalia was higher than linear enamel hypoplasia, once again
suggesting the differing aetiologies and differing levels of severity of these conditions
(Smith-Guzmán 2015). Males had higher rates of cribra orbitalia at all of the sites, except
An Sơn, but the only statistically significant sex difference was at Mán Bạc where males
had a higher frequency than females. This higher frequency may be a reflection of male
physiology as research has suggested males suffer more during blood stage malaria than
females (Bernin and Lotter 2014; Cernetich et al. 2006) and although it has not been
investigated ‘mini puberty’ during infancy, where there is a surge of sex steroids (Garenne 2015; Muenchhoff and Goulder 2014), may have an effect on childhood susceptibility to malaria. There were no significant differences among males or females between the assemblages, although there was a significant temporal difference among adults over time where the frequency of cribra orbitalia was higher at Cồn Cổ Ngựa than Khok Phanom Di and Hòa Diêm. Although there are limitations with the lack of comparative data, it has been suggested that cribra orbitalia was absent or occurring at very low frequencies in the Bronze and Iron Age sites and this is why it was not reported (Domett 2001). This would suggest, very broadly, a decline in cribra orbitalia over time.

Conclusions

Interpreting health from prehistoric samples is prone to a number of inherent issues outlined in the osteological paradox, which emphasises the fundamental limitation of using the dead to extrapolate inferences regarding the health of the population (selective mortality), the inherent variability in susceptibility to death (hidden heterogeneity in frailty) and the invisible demographic parameters such as population growth or decline (demographic nonstationarity). This discussion has attempted to deal with these issues as much as possible, but interpreting the health of individuals is particularly complex and multifaceted and obscured by intrinsic and extrinsic factors that not only differ between the sexes but are also age dependent. This chapter has only focussed on childhood health as reflected in adults, but a range of contributing factors would have played into their frailty in adulthood, and these can be mediated by sex, hormones and age, which are fluid and variable over the course of an individual’s lifecycle.

This discussion has largely focussed on main temporal observations that may be of relevance among the comparative sites, due to the limitations in the lack of standardisation in the recording and reporting protocols for the physiological health of comparative assemblages. With a larger sample of assemblages dating to the Neolithic in Southeast Asia, it would appear that there is a temporal trend in health where it was worse during the Neolithic Demographic Transition and improved into the Bronze and Iron Ages, which would appear to largely match the global patterns of poorer health with the introduction of agriculture.

Having discussed stature, linear enamel hypoplasia and cribra orbitalia as indicators of childhood stress at An Sơn and Hòa Diêm the next chapter examines oral health and extramasticatory modifications at An Sơn and Hòa Diêm.
Chapter Five:

Oral Health and Extramasticatory Modifications

This chapter will examine the oral health of the individuals from An Sơn and Hòa Diêm. The implications for oral health will initially be presented on a global scale after which the focus will be on Southeast Asia in general. This will set the scene to examine the oral profiles of the individuals from these two sites. The first section will explore pathological conditions of the oral environment including caries, pulp chamber exposure, alveolar lesions and antemortem tooth loss. The second section will examine extramasticatory modifications including interproximal grooves, chipping and staining. Each pathology and/or condition will be introduced, the methods of assessment described and the results presented. At the end of the chapter the discussion will focus on the possible contributing factors to the oral profiles of the individuals, including diet, behaviour and sex-mediated physiology in an attempt to understand the aetiology and epidemiology of the pathologies and the life histories of these individuals. An important thematic context of the discussion will be the Neolithic Demographic Transition; the implications being discussed regionally and within the wider context of Southeast Asia.

Teeth are an extremely useful resource and often well preserved in the archaeological record. The enamel can provide carbon apatite to date the individual, the stable isotopes can reflect diet, tooth morphology can reflect familial relations, and pathologies affecting them can be indicative of the nutritional and oral status of the individual during their childhood development. Teeth undergo minimal remodelling and are very resilient, so are often used as a comparative proxy of health between different populations. Information may be lost through antemortem tooth loss or excessive tooth wear, but again this can provide us with information such as the abrasiveness of the diet or the age of the individual.

Everything occurring in the oral environment has the potential to be correlated. Teeth erupt and once they do they are subjected to microorganisms that can be potentially harmful. The effects of ingesting food are multifaceted: plaque can cause periodontal disease; the bacteria present to facilitate the conversion of carbohydrates into simple sugars secrete an acid which can cause demineralisation of the enamel of the teeth that can lead to carious lesions; gross lesions can expose the pulp chamber; also coarse food causes attrition which wears teeth and can eventually expose the pulp chamber, the exposed pulp is susceptible to infection, causing alveolar lesions; attrition in combination with continued eruption and periodontal disease can cause antemortem tooth loss (Hillson 2000). The body also has very strong mechanisms in place to counteract pathological assault, caries can stabilise, enamel can remineralise, secondary dentine can be secreted, chronic pulpitis can heal, infected pulp can contain an infection and rejuvenate, or infected alveolar bone can
contain an infection and the alveolus can remodel. Such reparative processes complicate the synergistic relationship between pathologies (Hillson 2001).

A range of oral environmental factors, whether they be dietary, for example, what a person is eating; physiological, for example, changes in salivary rates or hormone levels in pregnant women; extramasticatory, for example, non-dietary oral activities; or cultural modifications, for example, tooth ablation or filing, can result in or exacerbate a pathological condition and may have an adverse effect on health. Therefore, all oral conditions investigated are dealt with in this chapter, excluding linear enamel hypoplasia, which is an indicator of childhood stress and was dealt with in Chapter Four.

The agricultural transition, where modern humans began growing domesticated crops of grain and cereals on which they relied on as their staple, marked an important change in prehistory. The timing and intensity of this transition and the plethora of associated affects have been thoroughly researched. Work over the last few decades focussing on the consequences of the adoption of agriculture on oral health have found a general decline in many regions of the world during this period (Larsen 1983, 1995, 1998; Larsen et al. 1991; Lukacs 1992b, 1996; Turner II 1979). A general consensus has formed that higher caries prevalence is associated with the intensification of agriculture, based on the cariogenicity of carbohydrates as the staple (Larsen 1995; Lubell et al. 1994; Turner II 1979). As a consequence increased caries rates have being argued as evidence of a dietary change in the transition to agriculture (Roosevelt 1984; Rose et al. 1984; Temple and Larsen 2007).

The exception to this trend has been Southeast Asia, which has showed little evidence for an increase in oral pathologies with the intensification of agriculture (Domett 2001, 2004; Domett and Oxenham 2011; Domett and Tayles 2006; Douglas 2006; Halcrow 2006; Halcrow et al. 2013; Kirkland 2010; Oxenham 2001; Oxenham and Domett 2011; Oxenham et al. 2002a; Oxenham et al. 2006; Oxenham et al. 2002b; Oxenham and Tayles 2006; Pietrusewsky and Douglas 2002a; Pietrusewsky and Ikehara-Quebral 2007; Tayles 1999; Tayles et al. 2009; Tayles et al. 2000; Tayles et al. 2007).

Bioarchaeological research, including investigations of oral health, have been undertaken at several sites in Thailand spanning from the Neolithic to the Iron Age (Domett 1999, 2004; Douglas 1996, 2006; Nelson 1999; Pietrusewsky and Douglas 2002a; Tayles 1992; Tayles et al. 2007) and in Vietnam from the preNeolithic to the Bronze Age (Oxenham 2001, 2006; Oxenham et al. 2006; Oxenham et al. 2002b). The improvement seen in oral health, especially in caries, is discordant with what is observed in other areas of the world with the transition to, and intensification of, agriculture.

Bioarchaeologists have typically relied on behavioural and dietary explanations for
disparities in oral health between the sexes (Lukacs and Largaespada 2006). Interpretations of differences in caries rates between males and females have focussed on differences in diet and food consumption associated with sexual division of labour (Larsen 1983). These interpretations have also been the favoured interpretations in research in Southeast Asia.

It seems that despite the huge variety of factors, both intrinsic and extrinsic, that affect the aetiology and prevalence of caries and other oral pathologies, researchers are still focussing on the relationship between the consumption of carbohydrates and caries, still explaining differences between the sexes using behaviour rather than physiology, in attempting to find a consensus regarding the relationship between caries and agriculture (Tayles et al. 2009; Temple and Larsen 2007), rather than exploring alternative interpretations in the aetiology of oral disease.

Recent publications have pushed the boundaries of the traditional consensus of behavioural interpretations for differential rates of oral health between the sexes (Lukacs and Largaespada 2006), focussing attention on the impact multiple pregnancies would have on women’s oral health as fertility increased during changes associated with the adoption and intensification of agriculture (Lukacs 2008).

In the following sections the frequency and patterning of caries, antemortem tooth loss and alveolar lesions for An Sơn, Hòa Diêm and several other Southeast Asian assemblages are compared. Table 5.1 provides summary data for the comparative assemblages, the details of which are elaborated on in the relevant methods sections throughout the chapter. It should be noted that the oral health data presented for Ban Lum Khao and Noen U-Loke in earlier publications (Domett 2001; Tayles et al. 2000) changes slightly in later publications due to a reassessment of the material. This original data is still being published for comparative purposes by some researchers (Lukacs and Thompson 2008; Pietrusewsky and Ikehara-Quebral 2007) and may cause confusion. The data used in this research is sourced from the most recent and accurate publications. The data for Ban Lum Khao is sourced from Domett (2004) and Noen U-Loke is sourced from Tayles et al. (2007).

SECTION I: ORAL PATHOLOGY

Caries

Introduction

Caries is a complex multibacterial, multifactorial disease which is caused by a synergistic relationship between many factors (Hillson 1996; Larsen 1997). Caries develops when
### Table 5.1. Summary data for caries, antemortem tooth loss and alveolar lesions from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Source</th>
<th>Period</th>
<th>O/N</th>
<th>%</th>
<th>O/N</th>
<th>%</th>
<th>O/N</th>
<th>%</th>
<th>O/N</th>
<th>%</th>
<th>O/N</th>
<th>%</th>
<th>O/N</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>1</td>
<td>preNeolithic</td>
<td>14/951</td>
<td>1.5</td>
<td>69/1430</td>
<td>4.8</td>
<td>22/1430</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>An Son</td>
<td>2</td>
<td>Neolithic</td>
<td>30/257</td>
<td>11.7</td>
<td>26/287</td>
<td>9.1</td>
<td>13/287</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>3</td>
<td>Neolithic</td>
<td>139/1282</td>
<td>10.8</td>
<td>183/2047</td>
<td>8.9</td>
<td>122/2047</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Man Bac</td>
<td>4</td>
<td>Neolithic</td>
<td>64/581</td>
<td>11.0</td>
<td>19/727</td>
<td>2.6</td>
<td>13/727</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>5</td>
<td>Bronze Age</td>
<td>39/874</td>
<td>4.5</td>
<td>59/1138</td>
<td>5.2</td>
<td>15/1138</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>6</td>
<td>Bronze Age</td>
<td>24/515</td>
<td>4.7</td>
<td>38/707</td>
<td>5.4</td>
<td>15/707</td>
<td>2.1</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>7</td>
<td>Iron Age</td>
<td>46/956</td>
<td>4.8</td>
<td>69/1334</td>
<td>5.2</td>
<td>34/571</td>
<td>6.0</td>
<td></td>
<td></td>
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<tr>
<td>Hoa Diem</td>
<td>2</td>
<td>Iron Age</td>
<td>6/292</td>
<td>2.1</td>
<td>11/222</td>
<td>5.0</td>
<td>5/222</td>
<td>2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Total (%)**

<table>
<thead>
<tr>
<th>Caries</th>
<th>AMTL</th>
<th>AL</th>
</tr>
</thead>
<tbody>
<tr>
<td>O/N</td>
<td>%</td>
<td>O/N</td>
</tr>
<tr>
<td>7/445</td>
<td>1.6</td>
<td>7/333</td>
</tr>
<tr>
<td>10/124</td>
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<td>6.9</td>
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<td>27/354</td>
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<td>7/397</td>
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<td>32/447</td>
</tr>
<tr>
<td>12/368</td>
<td>3.3</td>
<td>12/147</td>
</tr>
<tr>
<td>19/422</td>
<td>4.5</td>
<td>22/382</td>
</tr>
<tr>
<td>1/105</td>
<td>1.0</td>
<td>1/104</td>
</tr>
<tr>
<td>5/102</td>
<td>4.9</td>
<td>0/65</td>
</tr>
</tbody>
</table>

**By Sex (%)**

<table>
<thead>
<tr>
<th>Caries</th>
<th>Antemortem tooth loss</th>
<th>Alveolar lesions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>Females</td>
<td>Males</td>
</tr>
<tr>
<td>33/688</td>
<td>4.8</td>
<td>35/540</td>
</tr>
<tr>
<td>6/134</td>
<td>4.5</td>
<td>20/91</td>
</tr>
<tr>
<td>41/944</td>
<td>4.3</td>
<td>142/1103</td>
</tr>
<tr>
<td>6/429</td>
<td>1.4</td>
<td>13/270</td>
</tr>
<tr>
<td>28/531</td>
<td>5.3</td>
<td>31/607</td>
</tr>
<tr>
<td>7/466</td>
<td>1.5</td>
<td>31/241</td>
</tr>
<tr>
<td>13/466</td>
<td>2.8</td>
<td>2/241</td>
</tr>
<tr>
<td>16/252</td>
<td>6.1</td>
<td>15/260</td>
</tr>
</tbody>
</table>

1. Includes all adults 15+ and indeterminate age (AMTL antemortem tooth loss; AL alveolar lesions)
2. Includes only sexed adults

O observed condition in teeth/ N number assessable teeth (or alveoli)

Bold signifies statistically significant differences for either sex at p<0.05

Source: 1 Oxenham (2006); 2 this study; 3 Tayles (1999); 4 Oxenham and Domett (2011); 5 Domett (2004); 6 Domett (2001); 7 Tayles et al. (2007); unless otherwise stated in the method

% values have been calculated from published data

Note: the denominator for AMTL was the same for all sites excluding Noen U-Loke where the preservation of bone impeded the assessment of lesions
there is an imbalance in the microflora and increase in pathogens around the dentition. Plaque produces bacteria to facilitate the conversion of carbohydrates into simple sugars, during which they secrete an acid (Sheiham 2001).

*Streptococcus mutans* and *S. sobrinus* are common in the microbiology of caries. These bacteria metabolise the dietary sugars, stimulating a drop in oral pH. If the pH drops to a critical level (below 5.4) calcium and phosphate ions are lost from enamel, leaving it vulnerable to demineralisation. The rate at which the pH equalises depends on the amount and duration of exposure to sugar and host resistance. The effects of the bacteria are dependent on host susceptibility and mitigated by host resistance which include saliva secretion and its antibodies and buffering capability (Sheiham 2001).

Many studies have been conducted to try and establish the cariogenicity of different foods we ingest. The Foods, Nutrition and Dental Health programme were established by the American Dental Health Foundation in 1970 in response to the need for standardised methodologies in regard to these studies. Meeting annually, the consensus of these conferences (Hefferen 1986) was that it is not possible to accurately assess the cariogenicity of food as there are too many confounding factors that affect caries potential (Stookey 2008). Modern methods now focus on assessing the potential cariogenic nature of foods using animal models and plaque pH (Curzon and Hefferen 2001), incubation studies, enamel slab studies, human epidemiology studies and clinical trials (Sheiham 2001). The information from research of this nature can provide information on potential cariogenicity but caution in interpreting the implications of the results is important (Sheiham 2001). Researchers have continued to assess foods based on their cariogenicity, however, they have acknowledged the putative nature of cariogenicity (Palmer *et al.* 2010).

It has been suggested that the potential cariogenicity of food is not correlated with the carbohydrate content of the food in question (Kandelman 1997) and that the concentration of sugar and its ability to induce caries is unclear (Bowen 1994); it is argued the frequency of consumption of potentially cariogenic foods has more affect than the actual potential cariogenicity of food (Krasse 2001; Marshall *et al.* 2005).

Microscopic lesions are continuously forming on teeth but are usually cleared away by the actions of attrition, abrasion and erosion; enamel cavities are a late manifestation of the disease. The initial stages of the disease involve demineralisation under the intact surface of the tooth which is only visible in microscopic sections (Jones and Boyd 1987; Tveit *et al.* 1994). It then progresses through a range of stages, beginning as a small opacity, increasing in size and eventually penetrating the dentine and then the pulp chamber itself. It may take years for visible signs of caries to develop, in the majority of cases; this is a slow progressive disease with erratic irregularity, with active and static phases.
There are three types of caries, chronic, arrested and rampant caries. Carious lesions generally follow patterns in their predilection of tooth type. Because the enamel surface is permanent and does not remodel, biofilm accumulates and subsequent caries more commonly develop in areas where the actions of attrition, abrasion or erosion cannot reach them. Lesions are more frequently found in the posterior teeth as their morphology, deep fissures and occlusal pits can trap food and harbour bacteria leaving them more vulnerable than other teeth with simpler cusp morphology (Hillson 2001).

It has been suggested in the analysis of prehistoric populations that occlusal attrition could have assisted in preventing caries, with low levels beneficial in the clearance of food particles and higher levels changing the complex occlusal fissure morphology. Nonetheless, in some groups, for example, Australians and !Kung San, caries increased with increased attrition (Moody 1960; van Reenen 1966). It is argued that increasing attrition increased the prevalence of chipping, creating areas of exposed dentine and dental plaque accumulation. Dentine demineralises at a higher pH than enamel and is therefore more susceptible to caries (Sheiham 2001; Ten Gate et al. 1995).

While root caries can occur as a result of periodontal disease which effectively reduces the surrounding alveolar margin thus facilitating exposure of the roots, attrition has also been linked to root caries. Teeth continue to erupt as a result of changing tooth morphology and height (Whittaker et al. 1990). It is suggested that if attrition is severe in a population, this could increase tooth eruption and predispose the roots to the microorganisms present in the mouth. Finally, the position of interproximal grooves on the cementoenamel junction can predispose to cervical caries (Hillson 2001).

As well as being age progressive, caries are involved in a complex synergistic relationship with other pathologies: “All of these features and consequences of caries show a gradual progression with age, and the mouths of people who are susceptible to caries accumulate more carious lesions, more lesions which penetrate into the dentine, more exposed pulp chambers, more teeth affected by periapical inflammation, and more teeth lost by extraction” (Hillson 2001: 259)

Although caries is one of the most commonly recorded pathologies in archaeological samples, the techniques used for identification, recording and analysis have lacked consistency (Hillson 2001). It is recommended by Hillson (2001), in addition to recording caries by sex and age, the position and prevalence of lesions is also important, as the maxillary and mandibular dentition have a differential susceptibility to caries (Thylstrup and Fejerskov 1994). It is important to take into consideration patterns of tooth wear, chipping and fractures on teeth. Given the seeming fluidity in the status of carious lesions, most caries are recorded when manifesting as macroscopically observable cavitated lesions. It is common for caries to be recorded as present or absent per tooth, however,
Caries may manifest in several different locations on one tooth, each of these with a potentially different underlying aetiology, so it is important to record multiple incidences (Hillson 2001).

Lukacs (1995) highlighted the issue that observed caries prevalence is not a realistic representation of caries rates in a population as caries may have been lost with antemortem tooth loss. He suggested a caries correction factor to compensate for the loss of antemortem teeth (Lukacs 1995). This concept has further been modified and expanded on (Duyar and Erdal 2003; Erdal and Duyar 1999). When assessing the corrected caries prevalence following Lukacs (1995) Tayles et al. (2000) and Domett (2001) made two modifications; they used gross caries as a proxy for pulp exposure from caries and they used dental attrition grades 6-8 following Molnar’s tooth wear scheme (1971) as a proxy for pulp chamber exposure (not caused by caries). A concern with this approach is it may not adequately reflect the level of pulp exposure, as it would likely overestimate it and not reflect the necessary correction factor. This modification has been cited and applied by other researchers (Douglas 2006; Douglas and Pietrusewsky 2004), although corrected caries rates are no longer being presented in Southeast Asian data (Domett 2004; Domett and Tayles 2006; Tayles et al. 2007).

Although the observed caries rates may not be an accurate representation of the life history of caries in an individual, at least the data are based on real observations as opposed to transformed data and are more easily comparable among sites. If a comprehensive recording scheme is followed, such as proposed by Hillson (2001) the interaction between these oral pathologies should be highlighted, elucidating probable causal interactions within the oral environment.

Materials and methods

Caries was recorded following the methodology and recommendations of Hillson (2001) and Oxenham (2001). Every tooth was assessed for the presence of carious lesions. Caries was identified macroscopically as a necrotic cavity and the position, size and type of caries was recorded. The types were:

A - lesion initiated on interproximal attrition facet
BL - buccal or lingual lesions of crown (not CEJ, occlusal or interproximal)
C - lesion associated with antemortem chipping of enamel rim
GG - massive crown/root destruction (initiation point unclear)
OF - occlusal fissure system initiation
OWFD - occlusal wear facet initiation (dentine exposed)
OG - occlusal gross (fissure/occlusal facet initiation unclear)
P - buccal molar or upper lingual incisor pit initiation
R - lesion (groove) following cementoenamel junction or just on root
RG - gross root lesion but also includes other sites (initiation site unclear)

It is acknowledged that recording the carious lesions this way is absolutely underestimating the prevalence of the disease, but given the difficulties in diagnosing caries in other ways (Espelid et al. 1994); the limitations of resources for radiography, avoiding invasive thin sectioning procedures and, most importantly, in keeping consistency with other researchers these methods were chosen.

The carious teeth were presented as a percentage of assessable teeth which included those that were present (in situ), present (not in situ), isolated (no associated alveoli) and root only (pathological). There was one individual from An Sơn, a young adult female (07ASH1M3a) with an extremely high prevalence of carious lesions (Willis and Oxenham 2013a), who stood out as an obvious outlier. Throughout this chapter the data tables for An Sơn are presented excluding this individual in the first instance and then including her for comparative purposes.

Thirteen adults and ten subadults were able to be assessed for caries at An Sơn. Five adults were male, six were female (including 07ASH1M3a) and two were of indeterminate sex. The males had 124 assessable teeth, the females had 94 and the individuals of indeterminate sex had 58. Seven subadults were 1-5 years old with 89 assessable teeth, three subadults were 6-14 years with 47 assessable teeth. Twenty four adults and twenty seven subadults were able to be assessed at Hòa Diểm. Nine adults were male, four were female and 11 were of indeterminate sex. The males had 105 assessable teeth, the females had 43 and the individuals of indeterminate sex had 144. Fourteen subadults were 1-5 years old with 76 assessable teeth, six subadults were 6-14 years with 42 and seven subadults were of indeterminate age with 22 assessable teeth, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Subadults are presented in two age classes 1-5 years (deciduous dentition) and 6-14 years (permanent dentition).

Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges; and inter-sample differences between the sexes and among the sites. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

**Results**

Table 5.2 summarises the prevalence and patterning of carious lesions for An Sơn excluding 07ASH1M3a. Every adult had at least one carious lesion, which resulted in
### Table 5.2: Caries profile: An Sơn seasons 2004, 2007 and 2009 (excluding 07ASH1M3a)

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N¹</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>29</td>
<td>9/20</td>
<td>0/1</td>
</tr>
<tr>
<td>30+</td>
<td>95</td>
<td>31/64</td>
<td>3/6</td>
</tr>
<tr>
<td>subtotal %</td>
<td>124</td>
<td>40/84</td>
<td>3/7</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>45</td>
<td>17/28</td>
<td>1/5</td>
</tr>
<tr>
<td>30+</td>
<td>26</td>
<td>14/12</td>
<td>4/6</td>
</tr>
<tr>
<td>indeterminate</td>
<td>4</td>
<td>3/1</td>
<td>2/1</td>
</tr>
<tr>
<td>subtotal %</td>
<td>75</td>
<td>34/41</td>
<td>7/12</td>
</tr>
<tr>
<td>Male 30+</td>
<td>47</td>
<td>20/27</td>
<td>0/5</td>
</tr>
<tr>
<td>Female 30+</td>
<td>26</td>
<td>14/12</td>
<td>4/6</td>
</tr>
<tr>
<td>indeterminate</td>
<td>4</td>
<td>3/1</td>
<td>2/1</td>
</tr>
<tr>
<td>subtotal %</td>
<td>75</td>
<td>34/41</td>
<td>7/12</td>
</tr>
<tr>
<td>Subtotal %</td>
<td>257</td>
<td>93/164</td>
<td>10/22</td>
</tr>
<tr>
<td>Subadults 6-14</td>
<td>47</td>
<td>20/27</td>
<td>0/5</td>
</tr>
<tr>
<td>Total Subtotal</td>
<td>304</td>
<td>113/191</td>
<td>10/27</td>
</tr>
<tr>
<td>Deciduous Teeth</td>
<td>1-5</td>
<td>89</td>
<td>47/42</td>
</tr>
<tr>
<td>TOTAL Subtotal</td>
<td>393</td>
<td>160/233</td>
<td>12/27</td>
</tr>
</tbody>
</table>

1 total/preserved teeth  
2 preserved anterior teeth (incisors/canines)/ preserved posterior teeth (premolars/molars)  
3 preserved maxillary teeth/preserved mandibular teeth  
4 total caries  
5 total individuals (O/N)  
O observed condition in teeth or individuals/ N number of assessable teeth or individuals
an overall frequency of 12.5%. Females had statically significantly higher rates of caries by tooth count (25.3%) than males (8.1%) \( (X^2(1)=11.195, p=0.001) \). With regard to individual counts, 100% of both males and females had at least one lesion.

In adults the highest prevalence of lesions was found in the posterior dentition (13.4% compared to 10.8% in the anterior). The maxillary dentition (14.7%) had more lesions than the mandibular (10.2%). Adults in the older age class had a higher prevalence of caries than younger individuals among males, 9.5% compared to 3.4% and among females 38.5% compared to 13.3%. However, the difference was only statistically significant among females \( X^2(1)=5.961, p=0.015 \). An examination of the point of initiation of the lesions among adults shows that overall the three most common types were massive crown/root destruction with initiation point unclear at 34.4%, the interproximal attrition facet (28.1%) and lesion following the cementoenamel junction or just on the root (15.6%).

When examining the lesion positions by sex, those initiated on the interproximal attrition facet were the most common site for females (47.4%), however, there were no males with lesions at this location. The most common type of carious lesion for males was massive crown/root destruction with initiation point unclear (50%) which, incidentally, was the second highest for females (26.3%). Of the subadults with permanent dentition, 10.6% had lesions, with 66.7% of individuals affected. Of the subadults with deciduous dentition, 2.2% had lesions, with 14.3% of individuals affected. Table 5.3 presents the data for caries including the individual 07ASH1M3a, the caries prevalence for female tooth count increases to 41.5% in comparison to males 8.1% \( (X^2(1)=34.282, p=0.000) \), while the rate for the adult sample increases to 18.8%.

Table 5.4 summarises the prevalence and patterning of carious lesions for Hòa Diêm. There was an overall frequency of 2.1% of caries among the adults with 25% of individuals affected. Females had the highest rate of caries with 2.3% of teeth affected (25% of individuals), while males only had 1% (11.1% of individuals). The small number of individuals with caries meant it was not possible to make comparisons between the age classes. All of the caries were in the posterior dentition (2.9%) for all adults, the lesions occurred in the maxillary (1.5%) and mandibular (2.6%) dentition, however, the latter was more common.

An examination of the point of initiation in adults shows that the most common type of caries was on the occlusal fissure system (33.3%), while other lesion types included the interproximal attrition facet (16.7%), massive crown root destruction (16.7%), occlusal wear facet initiation (dentine exposed) (16.7%) and lesion (groove) following cementoenamel junction or just on the root (16.7%). It was not possible to make comparisons between the sexes based on caries type as there were too few to make any meaningful observations. There were no subadults with permanent dentition with carious
<table>
<thead>
<tr>
<th></th>
<th>Permanent Teeth</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
<th></th>
<th>%</th>
<th>I (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anterior/Posterior</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>N</td>
<td>O</td>
<td>%</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>29</td>
<td>9/20</td>
<td>0/1</td>
<td>0.0/5.0</td>
<td>15/14</td>
<td>1/0</td>
</tr>
<tr>
<td>30+</td>
<td>95</td>
<td>31/64</td>
<td>3/6</td>
<td>9.7/9.4</td>
<td>45/50</td>
<td>7/2</td>
</tr>
<tr>
<td>subtotal</td>
<td>124</td>
<td>40/84</td>
<td>3/7</td>
<td>7.5/8.3</td>
<td>60/64</td>
<td>8/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>64</td>
<td>26/38</td>
<td>12/14</td>
<td>46.2/36.8</td>
<td>26/38</td>
<td>11/15</td>
</tr>
<tr>
<td>30+</td>
<td>26</td>
<td>14/12</td>
<td>4/6</td>
<td>28.6/50.0</td>
<td>18/8</td>
<td>5/5</td>
</tr>
<tr>
<td>indeterminate</td>
<td>4</td>
<td>3/1</td>
<td>2/1</td>
<td>66.7/100.0</td>
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<td>18/21</td>
<td>41.9/41.2</td>
<td>48/46</td>
<td>19/20</td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>15-29</td>
<td>58</td>
<td>19/39</td>
<td>0/3</td>
<td>0.0/7.7</td>
<td>28/30</td>
<td>1/2</td>
</tr>
<tr>
<td>subtotal</td>
<td>58</td>
<td>19/39</td>
<td>0/3</td>
<td>0.0/7.7</td>
<td>28/30</td>
<td>1/2</td>
</tr>
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<tr>
<td>Subtotal</td>
<td>276</td>
<td>102/174</td>
<td>21/31</td>
<td>20.6/17.8</td>
<td>136/140</td>
<td>28/24</td>
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<td></td>
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<td>1.9</td>
</tr>
<tr>
<td>Subadults</td>
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<td>20/27</td>
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<td>0.0/18.5</td>
<td>21/26</td>
</tr>
<tr>
<td></td>
<td></td>
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<tr>
<td>Total</td>
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<td>122/201</td>
<td>21/36</td>
<td>17.2/17.9</td>
<td>157/166</td>
<td>28/29</td>
</tr>
<tr>
<td></td>
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<td>38.6</td>
<td>3.5</td>
<td>1.8</td>
<td>29.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Deciduous Teeth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subadults</td>
<td>1-5</td>
<td>89</td>
<td>47/42</td>
<td>2/0</td>
<td>4.3/0.0</td>
<td>43/46</td>
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<tr>
<td>TOTAL</td>
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<td>23/36</td>
<td>13.6/14.8</td>
<td>200/212</td>
<td>30/29</td>
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<td>37.3</td>
<td>3.4</td>
<td>1.7</td>
<td>28.8</td>
<td>6.8</td>
</tr>
</tbody>
</table>

1 total preserved teeth
2 preserved anterior teeth (incisors/canines) / preserved posterior teeth (premolars/molars)
3 preserved maxillary teeth/preserved mandibular teeth
4 total caries
5 total individuals (O/N)
O observed condition in teeth or individuals/ N number of assessable teeth or individuals
### Table 5.4. Caries profile: Hòa Diệm 2002 and 2007

#### Permanent Teeth

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N'</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>53</td>
<td>13/40</td>
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</tr>
<tr>
<td>30+</td>
<td>52</td>
<td>17/35</td>
<td>0</td>
</tr>
<tr>
<td>subtotal</td>
<td>105</td>
<td>30/75</td>
<td>0</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female 15-29</td>
<td>42</td>
<td>15/27</td>
<td>0</td>
</tr>
<tr>
<td>30+</td>
<td>1</td>
<td>0/1</td>
<td>0</td>
</tr>
<tr>
<td>subtotal</td>
<td>43</td>
<td>15/28</td>
<td>0</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>15-29</td>
<td>99</td>
<td>24/75</td>
</tr>
<tr>
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<td>41</td>
<td>14/27</td>
<td>0</td>
</tr>
<tr>
<td>Indeterminate</td>
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<tr>
<td>subtotal</td>
<td>144</td>
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<tr>
<td>%</td>
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<tr>
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</tr>
<tr>
<td>%</td>
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<tr>
<td>Subadults 6-14</td>
<td>42</td>
<td>23/19</td>
<td>0</td>
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<tr>
<td>%</td>
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<td></td>
</tr>
<tr>
<td>Deciduous Teeth</td>
<td>Subadults 1-5</td>
<td>76</td>
<td>10/66</td>
</tr>
<tr>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Subadults indeterminate</td>
<td>22</td>
<td>7/15</td>
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</table>

#### Deciduous Teeth

<table>
<thead>
<tr>
<th></th>
<th>Subadults 1-5</th>
<th>%</th>
<th>Subadults indeterminate</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
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#### TOTAL

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<thead>
<tr>
<th></th>
<th>432</th>
<th>1/6</th>
<th>0.8/1.9</th>
<th>202/230</th>
<th>3/4</th>
<th>1.5/1.7</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>2</th>
<th>1</th>
<th>1</th>
<th>7</th>
<th>1.6</th>
<th>7/51 (13.7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
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</tr>
</tbody>
</table>

1. Total preserved teeth
2. Preserved anterior teeth (incisors/canines)/ preserving posterior teeth (premolars/molars)
3. Preserved maxillary teeth/preserved mandibular teeth
4. Total caries
5. Total individuals (O/N)
lesions. There was one subadult with deciduous dentition with one lesion.

The previous section presented the caries data as multiple lesions per tooth, with site information, following the recommendation of Hillson (2001). The following two tables present the adjusted frequency of caries when it is recorded as present or absent (this method does not take into consideration multiple lesions on a tooth). This is to allow for comparison with other researchers who have recorded caries prevalence in this way. There were no males, indeterminate adults or subadults with multiple lesions of caries per tooth, therefore the only data which has changed is females. When the female data is reevaluated (excluding 07ASH1M3a) the overall frequency of caries is 22.7% (Table 5.5). The rate of caries is still statistically significantly higher in females (22.7%) than males (8.1%) X²(1)=8.497, p=0.004. These data were used for comparative purposes with other sites (see earlier Table 5.1, later Figures 5.1 and 5.2 and Willis and Oxenham 2013b). When 07ASH1M3a is included (Table 5.6) the overall female caries is 35.1% and statistically higher than males (X²(1)=24.693, p=0.000). There were no teeth with

| Table 5.5. Caries profile: An Sơn seasons 2004, 2007 and 2009 (excluding 07ASH1M3a) |
|-------------------------------|-----------------|--------------|-----------------|
| **Permanant Teeth**           | **Anterior/Posterior** | **Maxillary/Mandibular** | **Total** |
|                               | N   | N       | O   | %   | N   | O   | %   | O¹ | %   | P² (%) |
| **Male**                      |     |         |     |     |     |     |     |     |     |       |
| 15-29                         | 29  | 9/20    | 0/1 | 0.0/5.0 | 15/14 | 1/0 | 6.7/0.0 | 1  | 3.4 | 1/1 (100.0) |
| 30+                           | 95  | 31/64   | 3/6 | 9.7/9.4 | 45/50 | 7/2 | 15.6/4.0 | 9  | 9.5 | 4/4 (100.0) |
| Subtotal                      | 124 | 40/84   | 3/7 | 7.5/8.3 | 60/64 | 8/2 | 13.3/3.1 | 10 | 8.1 | 5/5 (100.0) |
| **Female**                    |     |         |     |     |     |     |     |     |     |       |
| 15-29                         | 45  | 17/28   | 1/4 | 5.9/14.3 | 19/26 | 2/3 | 10.5/11.5 | 5  | 11.1 | 2/2 (100.0) |
| 30+                           | 26  | 14/12   | 4/5 | 28.6/41.7 | 18/8  | 4/5 | 22.2/62.5 | 9  | 34.6 | 2/2 (100.0) |
| Indeterminate                 | 4   | 3/1     | 2/1 | 66.7/100.0 | 4/0   | 3/0 | 75.0/0.0  | 3  | 75.0 | 1/1 (100.0) |
| Subtotal                      | 75  | 34/41   | 7/10 | 20.6/24.4 | 41/34 | 9/8 | 22.0/23.5 | 17 | 22.7 | 5/5 (100.0) |
| **Indeterminate**             | 58  | 19/39   | 0/3  | 0.0/7.7  | 28/30 | 1/2 | 3.6/6.7   | 3  | 5.2  | 2/2 (100.0) |
| Subtotal                      | 58  | 19/39   | 0/3  | 0.0/7.7  | 28/30 | 1/2 | 3.6/6.7   | 3  | 5.2  | 2/2 (100.0) |
| **Subtotal**                  | 257 | 93/164  | 10/20 | 10.8/12.2 | 129/128 | 18/12 | 14.0/9.4 | 30 | 11.7 | 12/12 (100.0) |
| %                             |     |         |     |     |     |     |     |     |     |       |
| **Subadults**                 | 67  | 20/27   | 0/4  | 0.0/14.8 | 21/26 | 0/4 | 0.0/15.4 | 4  | 8.5  | 2/3 (66.7) |
| **Total**                     | 304 | 113/191 | 10/24 | 8.8/12.6 | 150/154 | 18/16 | 12.0/10.4 | 34 | 11.2 | 14/15 (93.3) |
| %                             |     |         |     |     |     |     |     |     |     |       |
| **Deciduous Teeth**           |     |         |     |     |     |     |     |     |     |       |
| Subadults                     | 89  | 47/42   | 2/0  | 4.3/0.0  | 43/46 | 2/0 | 4.7/0.0   | 2  | 2.2  | 1/7 (14.3) |
| **TOTAL**                     | 393 | 160/233 | 12/24 | 7.5/10.3 | 193/200 | 20/16 | 10.4/8.0 | 36 | 9.2  | 15/22 (68.2) |
| %                             |     |         |     |     |     |     |     |     |     |       |

¹Total preserved teeth
²Preserved anterior teeth (incisors/canines)/ preserved posterior teeth (premolars/molars)
³Preserved maxillary teeth/preserved mandibular teeth
⁴Total caries
⁵Total individuals (O/N)
O observed condition in teeth or individuals/ N number of assessable teeth or individuals
5. Oral Health and Extramasticatory Modifications

The prevalence of caries by tooth count was higher in females than males across all the sites, significantly so in the females at Neolithic An Sơn (X²(1)=8.497, p=0.004), Khok Phanom Di (X²(1)=19.808, p=0.000) and Mán Bạc (X²(1)=8.513, p=0.004); and Bronze Age Ban Lum Khao (X²(1)=12.430, p=0.000) and Ban Na Di (X²(1)=5.682, p=0.017). There was a statistically significant difference in the frequency of caries by tooth count among the adults across all the assemblages (X²(7)=136, p=0.000), among the males across all the assemblages (X²(7)= 40.7, p=0.000) and among the females across all the assemblages (X²(7)= 78.7, p=0.000). This was investigated further by using Pearson’s uncorrected Chi square tests to examine the relationship between the sites and among the sexes between the sites.

The significant differences among adults (Table 5.7) were a reflection of the frequency

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Permanent Teeth</td>
</tr>
<tr>
<td>N¹</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Male</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>%</td>
</tr>
<tr>
<td>Female</td>
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<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>%</td>
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<tr>
<td>Indeterminate</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Subtotal</td>
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<td>%</td>
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<tr>
<td>Subadults</td>
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</tr>
<tr>
<td>Subadults</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>%</td>
</tr>
</tbody>
</table>

¹total preserved teeth
²preserved anterior teeth (incisors/canines)/ preserved posterior teeth (premolars/molars)
³preserved maxillary teeth/preserved mandibular teeth
⁴total caries
⁵total individuals (O/N)
O observed condition in teeth or individuals/ N number of assessable teeth or individuals
of caries across the assemblages, the prevalence increases from the preNeolithic to the Neolithic, where it is significantly higher and then decreases in the Bronze and Iron ages (Figure 5.1). There was a statistically significantly lower frequency of caries in adults at preNeolithic Cồn Cổ Ngựa (1.5%) than all the other sites except Hòa Diём (2.1%). There were no significant differences between adults at Neolithic An Sơn (11.7%), Khok Phanom Di (10.8%) and Mấn Bạc (11.0%), however, the adults in these assemblages had significantly higher frequencies than all the other sites. There were no significant difference in the frequency of caries in adults between Bronze Age Ban Lum Khao (4.5%) and Ban Na Di (4.7%); and Iron Age Noen U-Loke (4.8%) and Hòa Diём (2.1%) (except Hòa Diём and Noen U-Loke).

The significant differences among males (Table 5.8) across the assemblages were a reflection of the differential frequency of caries which sees a similar and higher prevalence in the Neolithic decreasing in the Bronze and Iron Ages (Figure 5.2). There was a statistically significantly lower frequency of caries in males at preNeolithic Cồn Cổ Ngựa (1.6%) than Neolithic An Sơn (8.1%), Khok Phanom Di (6.9%) and Mấn Bạc (7.6%); and Iron Age Noen U-Loke (4.5%), but there were no significant differences among those sites. There were no significant differences in the prevalence of caries in males at Bronze Age Ban Lum Khao (1.8%) and Ban Na Di (3.3%) and Iron Age Noen U-Loke and Hòa Diём (1.0%) (except between Noen U-Loke and Ban Lum Khao).

Table 5.7. P values from Chi square statistics for adult caries from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th></th>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Man Bac</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>0.000</td>
<td>0.697</td>
<td>0.781</td>
<td>0.912</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>An Son</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.864</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Man Bac</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.896</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.723</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.064</td>
<td></td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.039</td>
<td>0.060</td>
<td>0.039</td>
</tr>
<tr>
<td>Hòa Diём</td>
<td>0.489</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.064</td>
<td>0.060</td>
<td>0.039</td>
</tr>
</tbody>
</table>

Figure 5.1. Caries prevalence for comparative Southeast Asian assemblages
The significant differences among females (Table 5.9) across the assemblages were a reflection of the differential frequency of caries which sees an abrupt increase in the Neolithic decreasing in the Bronze and Iron Ages (Figure 5.2). There was a statistically significantly lower frequency of caries in females at preNeolithic Cồn Cổ Ngựa (2.1%) than all the other sites except Hòa Diệm (2.3%). There were no significant differences in the prevalence of caries in females between Neolithic An Sơn (22.7%), Khok Phanom Di (14.6%) and Mán Bạc (15.5%), however, these sites had significantly higher frequencies than all the other sites. There were no significant difference in the frequency of caries in females between Bronze Age Ban Lum Khao (6.7%) and Ban Na Di (8.2%); and Iron Age Noen U-Loke (5.2%) and Hòa Diệm (2.3%).
Introduction

Aggressive carious lesions, chipping and attrition can penetrate the pulp chamber of teeth, if this occurs it is exposed to the microorganisms of the oral environment and is susceptible to infection and pulpiteis. The pulp can contain the infection and recover, however, more commonly it dies as a consequence. The subsequent infection or inflammation transfer to the tooth root providing access for microorganisms to the apical foramen where inflammation is initiated in the surrounding tissue, in this scenario the infection can also be contained, however, chronic inflammation will often persevere (Hillson 2001). The infection can manifest in a number of ways within the alveolar bone and these will be discussed further in the section dealing with alveolar lesions.

Materials and methods

Pulp chamber exposure was identified visually where the enamel was missing and the pulp chamber was visible; and were presented as a percentage of assessable teeth which included those that were present (in situ), present (not in situ), isolated (no associated alveoli) and root only (pathological). The sample of assessable teeth is the same as that presented for caries.

Thirteen adults were able to be assessed for pulp chamber exposure at An Sơn. Five adults were male, six were female (including 07ASHIM3a) and two were of indeterminate sex. The males had 124 assessable teeth, the females had 94 and the individuals of indeterminate sex had 58. Twenty four adults were able to be assessed at Hòa Diệm. Nine adults were male, four were female and 11 were of indeterminate sex. The males had 105 assessable teeth, the females had 43 and the individuals of indeterminate sex had 144, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

Results

Table 5.10 summarises the position and prevalence of pulp chamber exposure at An Sơn. Pulp chamber exposure was purely a result of caries. There was no attrition severe enough to expose the pulp chamber. The overall frequency was 5.4% in adult teeth with 50% of individuals affected.

Females had the highest prevalence of pulp chamber exposure with 6.7% of teeth affected,
compared to males with 5.6%. Examining individual counts 60% of males compared to 40% of females were affected. The older age class of males had a higher frequency with 7.4% while no younger individuals were affected, the same pattern was seen in females with 11.5% of older individuals and only 4.4% of younger individuals affected. There was a very similar proportion of pulp chamber exposure on the anterior (7.5%) and posterior (7.8%) dentition of the males, while in females the posterior teeth showed a higher percentage affected with 7.3% compared to 5.9% in the anterior dentition. Interestingly, all pulp chamber exposure in males occurred in the maxillary dentition with 11.7% teeth affected, while in females all cases of exposure occurred in the mandibular dentition at 14.7%. None of the subadults with permanent or deciduous dentition had pulp chamber exposure.

Table 5.11 summarises the data including 07ASH1M3a. When she is included the prevalence of affected teeth increases to 11.7% for females overall and the individual female count increases to 50%. The overall prevalence for affected teeth in adults increases to 7.2% and 53.8% of individuals.

No substantial inferences can be made from pulp chamber exposure at Hòa Diêm, as only one 30+ male had pulp chamber exposure on a posterior, mandibular tooth. This resulted in an overall frequency of 0.3% among adults (4.2% of individuals) Table 5.12.

**Alveolar lesions**

*Introduction*

The typical manifestation of chronic inflammation caused by pulp chamber exposure is
a periapical granuloma within the alveolar bone. These small granulomas, situated at the root apices, are an accumulation of granulation tissue and are characterised by smooth walled compact bone where the surrounding bone has resorbed.

Unless they penetrate the surface of the bone they can be difficult to detect in archaeological material without the assistance of radiography. Sometimes they are discernible visually as a small fenestration or where damage has occurred in the thinned buccal plate of the alveolar bone. If the granulation tissue is replaced by fluid, they are then termed periodontal cysts, which are synonymous with granulomas, except for an increase in size, which consequently means they may breech the alveolar bone making more of a visual

Table 5.12. Pulp chamber exposure profile: Hòa Diêm 2002 and 2007

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N¹ N O %</td>
<td>N O % O¹ %</td>
<td></td>
</tr>
<tr>
<td>Male 15-29</td>
<td>29 9/20 0/0 0.0/0.0</td>
<td>15/14 0/0 0.0/0.0</td>
<td>0 0/0 0/1 (0.0)</td>
</tr>
<tr>
<td>30+</td>
<td>95 31/64 3/4 9.7/6.3</td>
<td>45/50 7/0 15.6/0.0</td>
<td>7 7.4 3/4 (75.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>124 40/84 3/4 7.5/7.8</td>
<td>60/64 7/0 11.7/0.0</td>
<td>7 5.6 3/5 (60.0)</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>64 26/38 1/7 3.8/18.4</td>
<td>26/38 0/8 0.0/21.1</td>
<td>8 12.5 2/3 (66.7)</td>
</tr>
<tr>
<td>30+</td>
<td>26 14/12 1/2 7.1/16.7</td>
<td>18/8 0/3 0.0/37.5</td>
<td>3 11.5 1/2 (50.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>4 3/1 0/0 0.0/0.0</td>
<td>4/0 0/0 0.0/0.0</td>
<td>0 0/0 0/1 (0.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>94 43/51 2/9 4.7/17.6</td>
<td>48/46 0/11 0.0/23.9</td>
<td>11 11.7 3/6 (60.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>58 19/39 0/2 0.0/5.1</td>
<td>28/30 1/1 3.6/3.3</td>
<td>2 3.4 1/2 (50.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>58 19/39 0/2 0.0/5.1</td>
<td>28/30 1/1 3.6/3.3</td>
<td>2 3.4 1/2 (50.0)</td>
</tr>
<tr>
<td>Total</td>
<td>276 102/174 5/15 4.9/8.6</td>
<td>136/140 7/12 5.1/8.6</td>
<td>20 7.2 7/13 (53.8)</td>
</tr>
</tbody>
</table>

Table 5.11. Pulp chamber exposure profile: Hòa Diêm seasons 2004, 2007 and 2009

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N¹ N O %</td>
<td>N O % O¹ %</td>
<td></td>
</tr>
<tr>
<td>Male 15-29</td>
<td>53 13/40 0/0 0.0/0.0</td>
<td>17/36 0/0 0.0/0.0</td>
<td>0 0/0 0/3 (0.0)</td>
</tr>
<tr>
<td>30+</td>
<td>52 17/35 0/1 0.0/2.9</td>
<td>29/23 0/1 0.0/4.3</td>
<td>1 1.9 1/6 (16.7)</td>
</tr>
<tr>
<td>subtotal</td>
<td>105 30/75 0/1 0.0/1.3</td>
<td>46/59 0/1 0.0/1.7</td>
<td>1 1.0 1/9 (11.1)</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>42 15/27 0/0 0.0/0.0</td>
<td>27/15 0/0 0.0/0.0</td>
<td>0 0/0 0/3 (0.0)</td>
</tr>
<tr>
<td>30+</td>
<td>1 0/1 0/0 0.0/0.0</td>
<td>1/0 0/0 0.0/0.0</td>
<td>0 0/0 0/1 (0.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>43 15/28 0/0 0.0/0.0</td>
<td>28/15 0/0 0.0/0.0</td>
<td>0 0/0 0/4 (0.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>42 24/75 0/0 0.0/0.0</td>
<td>41/58 0/0 0.0/0.0</td>
<td>0 0/0 0/7 (0.0)</td>
</tr>
<tr>
<td>30+</td>
<td>41 14/27 0/0 0.0/0.0</td>
<td>20/21 0/0 0.0/0.0</td>
<td>0 0/0 0/2 (0.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>4 0/4 0/0 0.0/0.0</td>
<td>2/2 0/0 0.0/0.0</td>
<td>0 0/0 0/2 (0.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>144 38/106 0/0 0.0/0.0</td>
<td>63/81 0/0 0.0/0.0</td>
<td>0 0/0 0/11 (0.0)</td>
</tr>
<tr>
<td>Total</td>
<td>292 83/209 0/1 0.0/0.5</td>
<td>137/155 0/1 0.0/0.6</td>
<td>1 0.3 1/24 (4.2)</td>
</tr>
</tbody>
</table>

Table 5.12. Pulp chamber exposure profile: Hòa Diêm 2002 and 2007

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N¹ N O %</td>
<td>N O % O¹ %</td>
<td></td>
</tr>
<tr>
<td>Male 15-29</td>
<td>26 9/31 0/0 0.0/0.0</td>
<td>17/35 0/0 0.0/0.0</td>
<td>0 0/0 0/3 (0.0)</td>
</tr>
<tr>
<td>30+</td>
<td>26 14/12 1/2 7.1/16.7</td>
<td>18/8 0/3 0.0/37.5</td>
<td>3 11.5 1/2 (50.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>4 3/1 0/0 0.0/0.0</td>
<td>4/0 0/0 0.0/0.0</td>
<td>0 0/0 0/1 (0.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>94 43/51 2/9 4.7/17.6</td>
<td>48/46 0/11 0.0/23.9</td>
<td>11 11.7 3/6 (60.0)</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>58 19/39 0/2 0.0/5.1</td>
<td>28/30 1/1 3.6/3.3</td>
<td>2 3.4 1/2 (50.0)</td>
</tr>
<tr>
<td>subtotal</td>
<td>58 19/39 0/2 0.0/5.1</td>
<td>28/30 1/1 3.6/3.3</td>
<td>2 3.4 1/2 (50.0)</td>
</tr>
<tr>
<td>Total</td>
<td>276 102/174 5/15 4.9/8.6</td>
<td>136/140 7/12 5.1/8.6</td>
<td>20 7.2 7/13 (53.8)</td>
</tr>
</tbody>
</table>
impact during assessment of archaeological material. Both granulomas and cysts are relatively symptomless and cause little discomfort in life.

Periapical inflammation may manifest differently if there is an accumulation of pus. These can be acute or chronic; an acute infection builds up pressure in a swelling that eventually ruptures and is usually painful and accompanied by fever. The chronic infection manifests as a rough walled periapical abscess, it releases through a sinus or channel, but does not cause pain. Chronic abscesses are rare in archaeological material (Dias and Tayles 1997). The distinction between these lesions in dry bone is not straight forward; however, the specific aetiology is not as important as the amount of bone lost, as it has possible implications in the aetiology of antemortem tooth loss.

**Materials and methods**

No attempt to differentiate between periapical granulomas, periodontal cysts or periapical abscesses was made due to the problematic nature of distinguishing between them in dry bone. All lesions in the alveolar bone were recorded as alveolar lesions. The alveolar lesions prevalence was recorded, wherever possible, through macroscopic observation of the alveolar bone at the positions of teeth that were present (in situ), present (not in situ), antemortem loss, postmortem loss, erupting, root only (broken), root only (pathological), and unerupted but present. The prevalence of alveolar lesions were presented over the number of assessable alveoli positions.

Twelve adults were able to be assessed for alveolar lesions at An Sơn. Five adults were male, five were female (including 07ASHIM3a) and two were of indeterminate sex. The males had 134 assessable alveoli positions, the females had 112 and the individuals of indeterminate sex had 62. Seventeen adults were able to be assessed at Hòa Diêm. Nine adults were male, three were female and five were of indeterminate sex. The males had 102 assessable alveoli positions, the females had 65 and the individuals of indeterminate sex had 55, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges; and inter-sample differences between the sexes and among the sites. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

**Results**

Table 5.13 summarises the prevalence and position of alveolar lesions among the individuals from An Sơn excluding 07ASH1M3a. The overall frequency of alveolar lesions among adults was 4.5% (45.5% of individuals).
Table 5.13. Alveolar lesions profile: An Sơn 2004, 2007 and 2009 seasons (excluding 07ASH1M3a)

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>O</td>
<td>%</td>
</tr>
<tr>
<td>Male</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>29</td>
<td>10/19</td>
<td>0/0</td>
</tr>
<tr>
<td>30+</td>
<td>105</td>
<td>39/66</td>
<td>3/2</td>
</tr>
<tr>
<td>subtotal</td>
<td>134</td>
<td>49/85</td>
<td>3/2</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>47</td>
<td>15/32</td>
<td>1/4</td>
</tr>
<tr>
<td>30+</td>
<td>44</td>
<td>18/26</td>
<td>0/2</td>
</tr>
<tr>
<td>subtotal</td>
<td>91</td>
<td>33/58</td>
<td>1/6</td>
</tr>
<tr>
<td>Indeterminate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>62</td>
<td>22/40</td>
<td>0/1</td>
</tr>
<tr>
<td>subtotal</td>
<td>62</td>
<td>22/40</td>
<td>0/1</td>
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<tr>
<td>Total</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>287</td>
<td>104/183</td>
<td>4/9</td>
</tr>
</tbody>
</table>

1 total preserved alveoli  
2 preserved anterior alveoli (incisors/canines)/ preserved posterior alveoli (premolars/molars)  
3 preserved maxillary alveoli/ preserved mandibular alveoli  
4 total alveolar lesions  
5 total individuals (O/N)  
O observed condition in alveoli or individuals/ N number of assessable alveoli or individuals
Females had a higher prevalence of alveoli affected with 7.7% (50% of individuals) compared to males with 3.7% (40.0% of individuals). These data were used for comparative purposes with other sites (see earlier Table 5.1, later Figures 5.3 and 5.4 and Willis and Oxenham 2013b). Alveolar lesions were more common in the older age classes for males, with 4.8% (50.0% of individuals), with no younger males having alveolar lesions. The opposite pattern is seen with females with 10.6% of alveoli affected in the younger age classes (50% of individuals) and 4.5% of the older age class (50% of individuals).

The prevalence of alveolar lesions was higher in the anterior alveoli among males (6.1%) compared to the posterior (2.4%), while the reverse pattern was seen in females with 10.3% of the posterior alveoli affected compared to the anterior at 3.0%. Both sexes saw a higher frequency in the maxillary teeth, in the males 5.3% compared to 2.6% mandibular, and for females 11.1% compared to 4.3% mandibular. There were no alveolar lesions observed in subadults with permanent or deciduous dentition.

Table 5.14 summarises the alveolar lesion data including 07ASH1M3a; the female prevalence of alveolar lesions increases very slightly to 8.0% (60% of individuals) and the overall frequency among adults increases to 4.9% (50% of individuals).

Table 5.15 summarises the alveolar lesion data for Hòa Diêm. Only male individuals had alveolar lesions, 4.9% of male alveoli (55.6% of individuals) were affected. The older age class were more affected with 6.0% compared to 3.8% of the younger age class. Alveolar lesions were more prevalent in the posterior alveoli (5.7%) compared to the anterior (3.1%) and the mandibular alveoli (5.3%) compared to the maxillary (3.8%). The overall frequency of alveolar lesions was 2.3% (29.4% of individuals). There were no alveolar lesions in subadults with permanent dentition or deciduous dentition.

There were no significant differences in the prevalence of alveolar lesions between the sexes, except at Khok Phanom Di, where females had a significantly higher frequency ($X^2(1)=5.274, p=0.022$). There was a statistically significant difference in the frequency of alveolar lesions by alveoli position among the adults across all the assemblages ($X^2(7)=94.8, p=0.000$), among the males across the assemblages ($X^2(7)=27.6, p=0.000$) and among females across the assemblages ($X^2(7)=70.9, p=0.000$). This was investigated further by using Pearson’s uncorrected Chi square tests to examine the relationship between the sites and among the sexes between the sites.

The significant differences among adults (Table 5.16) were a reflection of the frequency of alveolar lesions across the sites which were generally higher in the Neolithic and generally lower in the Bronze and Iron Ages (Figure 5.3). There was a statistically significantly higher prevalence of alveolar lesions in adults at Neolithic An Son (4.5%) and Khok Phanom Di (6.0%); and Iron Age Noen U-Loke (6.0%) than all the other assemblages. There were no

<table>
<thead>
<tr>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>O</td>
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<tr>
<td>Male 15-29</td>
<td>29</td>
<td>10/19</td>
</tr>
<tr>
<td>30+</td>
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<td>39/66</td>
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<td>subtotal</td>
<td>134</td>
<td>49/85</td>
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<tr>
<td>Female 15-29</td>
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<td>62</td>
<td>22/40</td>
</tr>
<tr>
<td>Total</td>
<td>308</td>
<td>112/196</td>
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</table>

1Total preserved alveoli  
2preserved anterior alveoli (incisors/canines)/ preserved posterior alveoli (premolars/molars)  
3preserved maxillary alveoli/ preserved mandibular alveoli  
4total alveolar lesions  
5total individuals (O/N)  
O observed condition in alveoli or individuals/ N number of assessable alveoli or individuals
Table 5.15. Alveolar lesions profile: Hòa Diêm 2002 and 2007

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
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<th>Total</th>
</tr>
</thead>
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<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Male</td>
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<tr>
<td>15-29</td>
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<td>15/57</td>
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</tr>
<tr>
<td>30+</td>
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<td>32/70</td>
<td>1/4</td>
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<tr>
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<td>0/0</td>
</tr>
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<td>10/15</td>
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<td>17/36</td>
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<td>0/2</td>
<td>0/0</td>
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<tr>
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<td>17/38</td>
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</tr>
<tr>
<td>Total</td>
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<td>69/153</td>
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</tr>
</tbody>
</table>

1 Total preserved alveoli
2 preserved anterior alveoli (incisors/canines)/ preserved posterior alveoli (premolars/molars)
3 preserved maxillary alveoli/ preserved mandibular alveoli
4 total alveolar lesions
5 total individuals (O/N)
O observed condition in alveoli or individuals/ N number of assessable alveoli or individuals
significant differences between those sites with a lower frequency preNeolithic Cồn Cô Ngựa (1.5%), Neolithic Mán Bạc (1.8%), Bronze Age Ban Lum Khao (1.3%) and Ban Na Di (2.1%); and Iron Age Hòa Diệm (2.3%).

The significant differences among males (Table 5.17) across the assemblages were a reflection of the differential frequency of alveolar lesions but there was no discernible temporal pattern (Figure 5.4). There was a statistically significantly higher frequency of alveolar lesions in males at Neolithic Khok Phanom Di (4.7%) and Iron Age Noen U-Loke (6.1%) than preNeolithic Cồn Cô Ngựa (1.6%), Neolithic Mán Bạc (1.9%) and Bronze Age Ban Lum Khao (1.7%).

The significant differences among females (Table 5.18) across the assemblages were a reflection of the differential frequency of alveolar lesions but there was no discernible temporal pattern (Figure 5.4). There was a statistically significantly higher frequency of alveolar lesions in females at Neolithic An Sơn (7.7%) and Khok Phanom Di (7.1%); and Iron Age Noen U-Loke (5.8%) than preNeolithic Cồn Cô Ngựa (1.7%), Neolithic Mán Bạc (1.5%) and Bronze Age Ban Lum Khao (1.0%).
5. Oral Health and Extramasticatory Modifications

Table 5.17. *P* values from Chi square statistics for male alveolar lesions from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th></th>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Man Bac</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
<th>Hoa Diem</th>
</tr>
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<tr>
<td>Con Co Ngua</td>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>An Son</td>
<td>0.196</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Khok Phanom Di</td>
<td>0.001</td>
<td>0.793</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Man Bac</td>
<td>0.738</td>
<td>0.354</td>
<td>0.012</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Ban Lum Khao</td>
<td>0.896</td>
<td>0.258</td>
<td>0.003</td>
<td>0.843</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>0.164</td>
<td>0.783</td>
<td>0.093</td>
<td>0.361</td>
<td>0.240</td>
<td></td>
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</tr>
<tr>
<td>Noen U-Loke</td>
<td>0.000</td>
<td>0.447</td>
<td>0.341</td>
<td>0.003</td>
<td>0.001</td>
<td>0.028</td>
<td></td>
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</tr>
<tr>
<td>Hoa Diem</td>
<td>0.067</td>
<td>0.908</td>
<td>1.000</td>
<td>0.153</td>
<td>0.099</td>
<td>0.429</td>
<td>0.847</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.18. *P* values from Chi square statistics for female alveolar lesions from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th></th>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Man Bac</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
<th>Hoa Diem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>An Son</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>0.000</td>
<td>0.825</td>
<td></td>
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</tr>
<tr>
<td>Man Bac</td>
<td>1.000</td>
<td>0.009</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>0.313</td>
<td>0.000</td>
<td>0.000</td>
<td>0.772</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Ban Na Di</td>
<td>0.557</td>
<td>0.002</td>
<td>0.000</td>
<td>0.786</td>
<td>1.000</td>
<td></td>
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</tr>
<tr>
<td>Noen U-Loke</td>
<td>0.001</td>
<td>0.515</td>
<td>0.454</td>
<td>0.015</td>
<td>0.000</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoa Diem</td>
<td>0.613</td>
<td>0.058</td>
<td>0.050</td>
<td>0.725</td>
<td>0.911</td>
<td>1.000</td>
<td>0.098</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.4. Alveolar lesions between the sexes for comparative Southeast Asian assemblages

**Antemortem tooth loss**

*Introduction*

Permanent teeth will only be lost prematurely through trauma, chronic pathology or intentional removal (ablation). As discussed earlier, the final culmination of a range of oral pathologies is tooth loss. This may be induced by gross caries, pulp chamber exposure and periapical infection, severe attrition with continuous eruption or periodontal disease.

Periodontal disease is initiated by the presence of microorganisms in a plaque biofilm which accumulates on the surface of teeth and their roots and is characterised by an inflammatory response in the periodontal ligaments of the teeth (Hillson 2000). It gradually
agitates the periodontal connective tissue, which secures the root in the socket of the
alveolar bone, manifesting as porosity which develops into a recess around the roots as the
bone is resorbed. The disease usually affects sequential dentition and the amount of bone
loss increases with age, gradually exposing the roots of the teeth and reducing support of
the dentition until teeth are lost. Periodontal disease is cited as the most common cause of
tooth loss in contemporary populations worldwide (Darveau 2010).

Tooth extraction in response to pain has an extensive history (Hillson 2000), however, of
the pathologies discussed the only one likely to require tooth removal due to pain is acute
periapical inflammation which does not result in significant bone loss or the development
of a sinus. Periapical bone loss is an unlikely cause of antemortem tooth loss, however, it
could be a contributing factor in conjunction with remodelling associated with periodontal
disease or continuous eruption (Hillson 2001).

In extremely worn teeth, which have continued to erupt, the socket may be very shallow
due to remodelling, with the root only held in place by the gingiva. In archaeological
material this would be represented by a shallow, remodelled crypt and tooth roots.

Intentional removal of teeth is termed tooth ablation. This has been documented in
different cultures across the world (Pietrusewsky and Douglas 1993). It is not always
possible to distinguish between teeth lost pathologically or those that were intentionally
removed. An examination of the pattern of antemortem tooth loss in individuals is
required to investigate possible ablation as intentional removal will often be symmetrical
or patterned.

Materials and methods

Antemortem tooth loss was recorded as progressive destructive resorption of the alveolar
bone (Lukacs 1989) wherever possible through macroscopic observation at the positions
of teeth that were present (in situ), present (not in situ), antemortem loss, postmortem
loss, erupting, root only (broken), root only (pathological) and unerupted but present. The
prevalence of antemortem tooth loss was presented over the number of assessable alveoli
positions. The sample of assessable alveoli is the same as that presented for alveolar
lesions.

Twelve adults were able to be assessed for antemortem tooth loss at An Sơn. Five adults
were male, five were female (including 07ASHIM3a) and two were of indeterminate
sex. The males had 134 assessable alveoli, the females had 112 and the individuals of
indeterminate sex had 62. Seventeen adults were able to be assessed at Hòa Diêm. Nine
adults were male, three were female and five were of indeterminate sex. The males had
102 assessable alveoli, the females had 65 and the individuals of indeterminate sex had

150
5. Oral Health and Extramasticatory Modifications

55, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

Results

Table 5.19 summarises the prevalence of antemortem tooth loss at An Sơn, excluding 07ASH1M3a. The overall frequency of antemortem tooth loss was 9.1% for all adult teeth (27.3% of individuals). Females had a significantly higher frequency of antemortem tooth loss at 22.0% (50% of individuals) than males with 4.5% (20.0% of individuals) $X^2(1)=16.240, p=0.000$. These data were used for comparative purposes with other sites (see earlier Table 5.5, later Figures 5.6 and 5.2 and Willis and Oxenham 2013b). Adults in the older age class were more affected for both sexes, 5.7% of older males had antemortem tooth loss, while there were no cases among young males; and a significantly higher number of older females had antemortem tooth loss (31.8%) compared to only 12.8% of young females $X^2(1)=4.811, p=0.028$.

Among the adults, the highest prevalence of antemortem tooth loss was found in the posterior dentition with 12.6% compared to 2.9% of the anterior dentition. All antemortem tooth loss in males was among the posterior dentition (7.1%) and in females a significant proportion (29.3%) occurred in the posterior teeth in comparison to the anterior (9.1%) $X^2(1)=3.905, p=0.048$. A similar frequency was observed in the mandibular (9.8%) and the maxillary (8.2%) dentition among adults. There was a higher prevalence among the mandibular dentition in males (5.2%) and females (23.9%) than the maxillary dentition in both at 3.5% and 20.0% respectively. There was no antemortem tooth loss observed in subadults with permanent or deciduous dentition.

Table 5.20 presents the antemortem tooth loss data including 07ASH1M3a; the overall prevalence of antemortem tooth loss in females increases to 20.5% of teeth affected (60% of individuals) compared to males 4.5% ($X^2(1)=15.128, p=0.000$). This increases the prevalence very slightly to 9.4% of adult teeth (33.3% of individuals).

Table 5.21 summarises the presence of antemortem tooth loss for Hòa Diêm. The overall frequency among adults was 5.0% (23.5% of individuals). Only males had antemortem tooth loss with 10.8% affecting 44.4% of individuals. Males from the older age range suffered a significantly higher prevalence with 20.0% loss compared to only 1.9% in the younger age class $X^2(1)=6.881, p=0.009$. All antemortem tooth loss occurred in posterior alveoli (15.7%) and was more common in the mandibular alveoli (13.2%) than maxillary
Table 5.19. Antemortem Tooth Loss (AMTL) profile: An Sơn 2004, 2007 and 2009 seasons (excluding 07ASH1M3a)

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N 1</td>
<td>N 2</td>
<td>O 3</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>29</td>
<td>10/19</td>
<td>0/0</td>
</tr>
<tr>
<td>30+</td>
<td>105</td>
<td>39/66</td>
<td>0/6</td>
</tr>
<tr>
<td>subtotal</td>
<td>134</td>
<td>49/85</td>
<td>0/6</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>47</td>
<td>15/32</td>
<td>0/6</td>
</tr>
<tr>
<td>30+</td>
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<td>subtotal</td>
<td>91</td>
<td>33/58</td>
<td>3/17</td>
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<tr>
<td>Indeterminate</td>
<td>15-29</td>
<td>62</td>
<td>22/40</td>
</tr>
<tr>
<td>subtotal</td>
<td>62</td>
<td>22/40</td>
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</tr>
<tr>
<td>Total</td>
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<td>104/183</td>
<td>3/23</td>
</tr>
</tbody>
</table>

1 total preserved alveoli
2 preserved anterior alveoli (incisors/canines)/ preserved posterior alveoli (premolars/molars)
3 preserved maxillary alveoli/preserved mandibular alveoli
4 total antemortem tooth loss, note excludes cases of deliberate tooth ablation
5 total individuals (O/N)
6 observed condition in alveoli or individuals/ N number of assessable alveoli or individuals
Table 5.20. Antemortem Tooth Loss (AMTL) profile: An Sơn 2004, 2007 and 2009 seasons

<table>
<thead>
<tr>
<th></th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N¹</td>
<td>O</td>
<td>%</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>15</td>
<td>10</td>
<td>0.0</td>
</tr>
<tr>
<td>Male 30+</td>
<td>105</td>
<td>39</td>
<td>0.6</td>
</tr>
<tr>
<td>subtotal Male</td>
<td>134</td>
<td>49</td>
<td>0.6</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>68</td>
<td>23</td>
<td>0.9</td>
</tr>
<tr>
<td>Female 30+</td>
<td>44</td>
<td>18</td>
<td>0.6</td>
</tr>
<tr>
<td>subtotal Female</td>
<td>112</td>
<td>41</td>
<td>0.6</td>
</tr>
<tr>
<td>Indeterminate 15-29</td>
<td>62</td>
<td>22</td>
<td>0.0</td>
</tr>
<tr>
<td>subtotal Indeterminate</td>
<td>62</td>
<td>22</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>308</td>
<td>112</td>
<td>3/26</td>
</tr>
</tbody>
</table>

¹total preserved alveoli
²preserved anterior alveoli (incisors/canines)/ preserved posterior alveoli (premolars/molars)
³preserved maxillary alveoli/ preserved mandibular alveoli
⁴total antemortem tooth loss, note excludes cases of deliberate tooth ablation
⁵total individuals (O/N)
O observed condition in alveoli or individuals/ N number of assessable alveoli or individuals
Table 5.21. Antemortem Tooth Loss (AMTL) profile: Hòa Diêm 2002 and 2007

<table>
<thead>
<tr>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>52</td>
<td>15/37</td>
</tr>
<tr>
<td>30+</td>
<td>50</td>
<td>17/33</td>
</tr>
<tr>
<td>subtotal</td>
<td>102</td>
<td>32/70</td>
</tr>
<tr>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>40</td>
<td>10/30</td>
</tr>
<tr>
<td>30+</td>
<td>25</td>
<td>10/15</td>
</tr>
<tr>
<td>subtotal</td>
<td>65</td>
<td>20/45</td>
</tr>
<tr>
<td>Indeterminate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15-29</td>
<td>53</td>
<td>17/36</td>
</tr>
<tr>
<td>30+</td>
<td>2</td>
<td>0/2</td>
</tr>
<tr>
<td>subtotal</td>
<td>55</td>
<td>17/38</td>
</tr>
<tr>
<td>Total</td>
<td>222</td>
<td>69/153</td>
</tr>
</tbody>
</table>

^1 Total preserved alveoli
^2 Preserved anterior alveoli (incisors/canines)/preserved posterior alveoli (premolars/molars)
^3 Preserved maxillary alveoli/preserved mandibular alveoli
^4 Total antemortem tooth loss, note excludes cases of deliberate tooth ablation
^5 Total individuals (O/N)
O observed condition in alveoli or individuals/ N number of assessable alveoli or individuals
(3.8%). There were no subadults with permanent or deciduous antemortem tooth loss.

The prevalence of antemortem tooth loss by alveoli position was higher in females than males across all the sites, except Ban Lum Khao and Hòa Diệm, significantly so in the females at Neolithic An Sơn (X²(1)=16.240, p=0.000), Khok Phanom Di (X²(1)=45.472, p=0.000) and Mán Bạc (X²(1)=7.314, p=0.007); Bronze Age Ban Na Di (X²(1)=40.313, p=0.000); and Iron Age Noen U-Loke (X²(1)=16.048, p=0.000). There was a statistically significant difference in the frequency of antemortem tooth loss by tooth count among the adults across all the assemblages (X²(7)=58.2, p=0.000), among the males across all the assemblages (X²(7)=34.3, p=0.000) and among the females across all the assemblages (X²(7)=70.1, p=0.000). This was investigated further by using Pearson’s uncorrected Chi square tests to examine the relationship between the sites and among the sexes between the sites.

The significant differences among adults (Table 5.22) were a reflection of the frequency of antemortem tooth loss across the sites, it increases significantly in the Neolithic (except at Mán Bạc) and is lower and stable in the Bronze and Iron Ages (Figure 5.5). There was a statistically significantly higher prevalence of antemortem tooth loss in adults at Neolithic An Sơn (9.1%) and Khok Phanom Di (8.9%) than all the other assemblages. There were

Table 5.22. P values from Chi square statistics for adult antemortem tooth loss from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Man Bac</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>0.004</td>
<td>0.000</td>
<td>0.014</td>
<td>0.678</td>
<td>0.584</td>
<td>0.675</td>
</tr>
<tr>
<td>An Son</td>
<td></td>
<td>0.947</td>
<td>0.000</td>
<td>0.013</td>
<td>0.032</td>
<td>0.011</td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td></td>
<td></td>
<td>0.000</td>
<td>0.000</td>
<td>0.003</td>
<td>0.006</td>
</tr>
<tr>
<td>Man Bac</td>
<td></td>
<td></td>
<td></td>
<td>0.007</td>
<td>0.859</td>
<td>0.845</td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hoa Diem</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.5. Antemortem tooth loss for comparative Southeast Asian assemblages
no significant differences between those sites with a lower frequency preNeolithic Cồn Cổ Ngựa (4.8%), Bronze Age Ban Lum Khao (5.2%) and Ban Na Di (5.4%); and Iron Age Noen U-Loke (5.2%) and Hòa Diêm (5.0%). Neolithic Mán Bạc (2.6%) had a significantly lower frequency than all the other assemblages.

The significant differences among males (Table 5.23) were a reflection of the frequency of antemortem tooth loss across the sites but there was no discernible pattern (Figure 5.6). There was a statistically significantly lower prevalence of antemortem tooth loss in males at Neolithic Mán Bạc (1.4%) and Bronze Age Ban Na Di (1.5%) than all the other assemblages except Iron Age Noen U-Loke (2.8%). There was a statistically significantly higher prevalence of antemortem tooth loss in males at Iron Age Hòa Diêm (10.8%) than

Table 5.23. *P* values from Chi square statistics for male antemortem tooth loss from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th></th>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Mán Bạc</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
<th>Hòa Diêm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>0.874</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>An Son</td>
<td>0.664</td>
<td>0.943</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khok Phanom Di</td>
<td>0.003</td>
<td>0.031</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mán Bạc</td>
<td>0.705</td>
<td>0.709</td>
<td>0.417</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>0.003</td>
<td>0.037</td>
<td>0.006</td>
<td>0.897</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>0.070</td>
<td>0.319</td>
<td>0.130</td>
<td>0.132</td>
<td>0.037</td>
<td>0.155</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>0.014</td>
<td>0.063</td>
<td>0.004</td>
<td>0.000</td>
<td>0.034</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>Hòa Diêm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.24. *P* values from Chi square statistics for female antemortem tooth loss from comparative Southeast Asian assemblages

<table>
<thead>
<tr>
<th></th>
<th>Con Co Ngua</th>
<th>An Son</th>
<th>Khok Phanom Di</th>
<th>Mán Bạc</th>
<th>Ban Lum Khao</th>
<th>Ban Na Di</th>
<th>Noen U-Loke</th>
<th>Hòa Diêm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con Co Ngua</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mán Bạc</td>
<td>0.344</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Lum Khao</td>
<td>0.318</td>
<td>0.000</td>
<td>0.000</td>
<td>0.855</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ban Na Di</td>
<td>0.003</td>
<td>0.040</td>
<td>0.996</td>
<td>0.001</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noen U-Loke</td>
<td>0.260</td>
<td>0.000</td>
<td>0.005</td>
<td>0.071</td>
<td>0.031</td>
<td>0.043</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hòa Diêm</td>
<td>0.067</td>
<td>0.000</td>
<td>0.004</td>
<td>0.148</td>
<td>0.120</td>
<td>0.005</td>
<td>0.031</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.6. Antemortem tooth loss between the sexes for comparative Southeast Asian assemblages
any of the other assemblages (except An Sơn (4.5%)). There were no statistical differences among preNeolithic Cồn Cổ Ngựa (4.8%), Neolithic An Sơn (4.5%) and Khok Phanom Di (4.3%), Bronze Age Ban Lum Khao (5.3%).

The significant differences among females (Table 5.24) were a reflection of the frequency of antemortem tooth loss across the sites (Figure 5.6). There was a statistically significantly higher frequency of antemortem tooth loss in females from Neolithic An Sơn (22.0%) than all the other assemblages and at Neolithic Khok Phanom Di (12.9%) and Bronze Age Ban Na Di (12.9%) than all the other assemblages. There were no significant differences between preNeolithic Cồn Cổ Ngựa (6.5%), Neolithic Mán Bạc (4.8%) and Bronze Age Ban Lum Khao (5.1%).

SECTION II: EXTRAMASTICATORY MODIFICATIONS OF TEETH

Interproximal grooves

Introduction

Interproximal grooves have been documented in the dentition of individuals from many different cultures in Africa, Europe, Asia, Oceania and the Americas spanning over a million years (Bermudez De Castro et al. 1997; Berryman et al. 1979; Blakely and Beck 1984; Bonfiglioli et al. 2004; Brown and Molnar 1990; Frayer 1991; Frayer and Russell 1987; Hillson 1996; Lukacs and Pastor 1988; Milner and Larsen 1991; Molnar 2008; Schulz 1977; Ubelaker et al. 1969; Ungar et al. 2001; Wallace 1974). They are grooves that manifest on the interproximal surfaces of dentition in a parallel line, on or near the cementoenamel junction. They are semicircular in cross section with a defined superior and inferior edge with a smooth surface. They are commonly found on adjacent teeth, however, they do occur in isolation. They are more frequent on the posterior dentition, although they have been documented on the anterior dentition also.

There is no consensus on the aetiology of interproximal grooves. Two basic hypotheses have been put forward to explain interproximal grooves, the tooth picking hypothesis and the stripping hypothesis, although within these two hypotheses there are many alternative interpretations for materials used and the motivation behind the behaviour. It is possible that these aetiologies are not mutually exclusive.

The tooth picking hypothesis was first suggested by Siffre (1911) (cited in Formicola 1988) who suggested abrasion by a toothpick could have caused the grooves, Ubelaker et al. (1969) suggested the use of probes to remove impacted food, to provide therapeutic or palliative relief from caries and other gingival irritation, while Berryman et al. (1979)
suggested a combination of grit and the use of an inflexible probe to alleviate irritation associated with dental pathologies. Bone and wood have both been suggested as materials that these probes may have been made from.

The stripping hypothesis suggests stripping animal sinews, or other plant fibres through the teeth (Blakely and Beck 1984; Brown and Molnar 1990; Lukacs and Pastor 1988; Schulz 1977). The morphology, direction and size of the grooves are important in the interpretation of the material being orally manipulated as demonstrated by Erdal (2008).

Alternative interpretations have included sucking liquid containing abrasive particles through the teeth (Wallace 1974), the effects of non-bacterial acids or chemical erosion (Brothwell 1963; Pindborg 1970) or rootlets chemically dissolving the dental tissue post mortem (Wells 1967). Some doubt has been cast over several of these interpretations, however, the tooth picking and stripping hypotheses endure as the most common explanations for interproximal grooves.

**Materials and methods**

Every observable tooth was examined for interproximal grooves. Interproximal grooves were identified as a continuous smooth semicircular groove on the enamel surface with defined superior and inferior edges. They were differentiated from other potentially similar conditions, for example, carious lesions of the cementoenamel junction by their lack of necrotic tissue and their artificial symmetry and morphology.

Interproximal grooves were presented as a percentage of assessable teeth which included those that were present (in situ), present (not in situ) or isolated (no associated alveoli). Thirteen adults were able to be assessed for interproximal grooves at An Sơn. Five adults were male, six were female (including 07ASHIM3a) and two were of indeterminate sex. The males had 119 assessable teeth, the females had 85 and the individuals of indeterminate sex had 58, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

**Results**

Table 5.25 summarises the prevalence and position of interproximal grooves for An Sơn. Only one young female showed evidence for interproximal grooves, representing 2.4% of female teeth (16.7% of individuals). There were no individuals with interproximal grooves at Hòa Điểm.
5. Oral Health and Extramasticatory Modifications

Table 5.25. Interproximal grooves profile: An Sơn 2004, 2007 and 2009 seasons

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N(^1)</td>
<td>N</td>
<td>O</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>29</td>
<td>9/20</td>
<td>0/0</td>
</tr>
<tr>
<td>30+</td>
<td>90</td>
<td>28/62</td>
<td>0/0</td>
</tr>
<tr>
<td>subtotal</td>
<td>119</td>
<td>37/82</td>
<td>0/0</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>58</td>
<td>25/33</td>
<td>1/1</td>
</tr>
<tr>
<td>30+</td>
<td>23</td>
<td>13/10</td>
<td>0/0</td>
</tr>
<tr>
<td>indeterminate</td>
<td>4</td>
<td>3/1</td>
<td>0/0</td>
</tr>
<tr>
<td>subtotal</td>
<td>85</td>
<td>41/44</td>
<td>1/1</td>
</tr>
<tr>
<td>Indeterminate</td>
<td>15-29</td>
<td>58</td>
<td>19/39</td>
</tr>
<tr>
<td>subtotal</td>
<td>58</td>
<td>19/39</td>
<td>0/0</td>
</tr>
<tr>
<td>Total</td>
<td>262</td>
<td>97/165</td>
<td>1/1</td>
</tr>
</tbody>
</table>

\(^1\)total preserved teeth  
\(^2\)preserved anterior teeth (incisors/canines)/ preserved posterior teeth (premolars/molars)  
\(^3\)preserved maxillary teeth/preserved mandibular teeth  
\(^4\)total interproximal grooves  
\(^5\)total individuals (O/N)  
O observed condition in teeth or individuals/ N number of assessable teeth or individuals

Chipping

Introduction

Chipping is an irregular antemortem crack with associated loss of enamel, or enamel and dentine on the mesial, distal, buccal or lingual edge of the tooth (Bonfiglioli et al. 2004). Chipping can result from masticatory activities including food processing or consumption of abrasive foods, for example, snail shells, small stones, fruit stones and bone; or extramasticatory activities including leather softening, tool making and stabilising items while working on them. Differences between the sexes may indicate different dietary or behavioural extramasticatory activities (Bonfiglioli et al. 2004; Larsen 1997). Hillson (2001) recommends recording tooth chipping and fracturing as a separate category as potential sites of caries initiation.

Materials and methods

Chipping was recorded for every observable tooth following Milner and Larsen (1991). It was identified macroscopically as a discontinuity in enamel, or enamel and dentine with irregular edges. Differentiation between potential antemortem and postmortem chipping was evaluated based on a visual assessment of colour and appearance. Chipping was presented as a percentage of assessable teeth which included those that were present (in situ), present (not in situ) or isolated (no associated alveoli). The prevalence of assessable teeth is the same as for interproximal grooves.

Thirteen adults were able to be assessed for chipping at An Sơn. Five adults were male, six were female (including 07ASHIM3a) and two were of indeterminate sex. The males had 119 assessable teeth, the females had 85 and the individuals of indeterminate sex had
Twenty four adults were able to be assessed at Hòa Diêm. Nine adults were male, four were female and 11 were of indeterminate sex. The males had 103 assessable teeth, the females had 43 and the individuals of indeterminate sex had 144, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

Results

Table 5.26 summarises the prevalence and position of chipping at An Sơn. The total prevalence of chipped teeth was 3.1% among adults (23.1% of individuals). Males and females had a very similar frequency of chipped teeth, males with 2.5% (20.0% of individuals) and females with 2.4% (16.7% of individuals). There was no pattern to the position of the chipping. In males chipping only occurred on the posterior teeth (3.7%), while in females it was common among the anterior (2.4%) and posterior (2.3%) dentition. Males had a higher number of chipped teeth in the maxillary (3.6%) compared to mandibular (1.6%) dentition, while females only had chipped mandibular dentition (5.4%). All individuals with chipped teeth were in the young age class.

Table 5.27 summarises the prevalence and position of tooth chipping for Hòa Diêm. Tooth chipping was present at Hòa Diêm but only in individuals of indeterminate sex. Tooth chipping occurred in 4.9% of their teeth (27.3% of individuals). The frequency was higher in younger individuals (28.6%) than older individuals (0.0%). It occurred
Staining

Introduction

Staining has been observed on the teeth of individuals from archaeological sites in Southeast Asia (Fox 1970; Oxenham et al. 2002a; Pietrusewsky and Ikehara-Quebral 2007). In contemporary Southeast Asia and the Pacific betel nut chewing is a ubiquitous pastime probably for its mild stimulant effect (Oxenham et al. 2002a). Betel nut (Areca catechu) can be chewed by itself, or rolled with pepper leaf (Piper betel) and a lime paste (calcium hydroxide Ca(OH)_2) into a wad (Oxenham et al. 2002a; Rooney 1993). When masticated this colours the saliva brownish red, which can discolour teeth. As well as habitual chewing, betel nut leaves and nuts have been used for medicinal purposes in Southeast Asia including treating diarrhoeal and urinary infections, parasites such as tape worm, inflammation associated with the throat and bronchial tubes, oedema, muscle and joint pain in the lower back, vitamin deficiencies and sunstroke (Perry 1980).

It has also been shown to inhibit the growth of Streptococcus mutans (de Miranda et al. 1996; Iwamoto et al. 1991). Several studies have found that betel nut can have a cariostatic affect in the oral environment (Chatrchaiwiwatana 2006; Möller et al. 1977; Nigam and Srivastava 1990; Schamschula et al. 1977), however, contrary results have also been published (Reichart and Gehring 1984; Williams et al. 1996). It is possible that in addition to any antimicrobial characteristics of the betel nut, the act of chewing alone would stimulate excessive saliva, which has been demonstrated to be beneficial in the

<table>
<thead>
<tr>
<th>Table 5.27. Chipping profile: Hòa Diêm 2002 and 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Teeth</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Anterior/Posterior</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Male</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Female</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Indeterminate</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

1 total preserved teeth
2 preserved anterior teeth (incisors/canines)/ preserved posterior teeth (premolars/molars)
3 preserved maxillary teeth/preserved mandibular teeth
4 total chipping
5 total individuals (O/N)
6 O observed condition in teeth or individuals/ N number of assessable teeth or individuals

exclusively in the posterior dentition (6.6%) and was more common in the maxillary (9.5%) than mandibular (1.2%) dentition. No subadults had chipped teeth at either site.
remineralisation of enamel and its cariostatic affect (Stookey 2008) also if chewed as a rolled wad it could assist in clearance of food particles and if lime paste was added that could assist in neutralising acidogenic bacteria (Hanson and Butler 1997). Betel nut has also been reported to have some negative effects. It has been implicated in the aetiology of periodontal disease (Chang et al. 1998; Chatrchaiwiwatana 2006; Jeng et al. 1996), submucous fibrosis (Maher et al. 1994; Murti et al. 1995), diabetes (Boucher et al. 1994) and cancer (Secretan et al. 2009).

It is not known how long betel nut has been used in Southeast Asia, however, the earliest evidence from an archaeological context comes from Spirit Cave, Thailand dated to c. 9000-5500BCE (Gorman 1969; Higham 2002), but whether the remains of betel nut were incidental or due to human activity is unknown. Individuals with stained teeth from the Duyong Cave on Palawan Island, Philippines dated c. 2660BCE are noted by Fox (1970), although the source of the staining and the cultural implications of this are not discussed. There were Andara shells found in association with the skeletons, one which contained lime, implying that the staining could have been from betel nut and thus potentially the oldest evidence for the practice (Zumbroich 2007).

The earliest established evidence for human use of betel nut in Southeast Asia is c. 330CE at Núi Nắp in northern Vietnam (Oxenham et al. 2002a). Oxenham et al. (2002a) suggested that the individuals from Núi Nắp, an Iron Age site in northern Vietnam were using betel nut to deliberately stain their teeth. They tested a sample using gas chromatography mass spectrometry (GC/MS) analysis and identified tannins specific to betel nut in the sample. The staining was concentrated on the labial aspect of the anterior teeth, with diminishing colour on the premolars and none on the molars or occlusal surfaces of the teeth.

Zumbroich (2009) suggests that many of the early ethnographies wrongly associated teeth blackening with the effects of chewing betel nut. An academic debate about the tradition of tooth blackening impeded further research into the cultural reasoning and methods of this practice while it was still widely practiced (Zumbroich 2009). Recent ethnographic studies have shown that staining teeth was common across Southeast Asia, in many different cultures (Zumbroich 2007, 2009, 2011), a custom that is still practiced in some areas of Vietnam and Cambodia (Tayanin and Bratthall 2006). It would appear that this practice developed independently in many areas of Southeast Asia, the indigenous communities using locally available, native species of plants (Zumbroich 2009). There have been a vast number of different plants and methods used for staining (Zumbroich 2009), that are prepared and applied in different ways at different frequencies. The ephemeral nature of the ingredients used for staining meant that reapplication was necessary to achieve the desired aesthetic look. Some of the plants have antimicrobial affects (Tayanin and Bratthall 2006; Zumbroich 2011). There are also many different reasons among different communities for staining their teeth. It is believed to enhance
aesthetics, increase the strength of teeth and protect the individual from disease and pain. It has also been described as part of different socially mediated life stages (Tayanin and Bratthall 2006; Zumbroich 2011).

Materials and methods

Every side of every tooth was observed for the presence of staining. Staining was recorded as a noticeable deviation from the natural colour of the tooth. The colour and location were noted and the intensity (as either solid colour, or diffuse and patchy colour) and the distribution (as either >90% or <90% of the tooth surface) were recorded. Differentiation between potential antemortem and postmortem (taphonomic) staining was evaluated based on a visual assessment of the discolouration, appearance and coverage on the teeth and patterning among teeth. Staining on teeth was presented as a percentage of assessable teeth which included those that were present (in situ), present (not in situ) or isolated (no associated alveoli). The prevalence of assessable tooth positions is the same as for interproximal grooves and chipping.

Thirteen adults and ten subadults were able to be assessed for staining at An Sơn. Five adults were male, six were female (including 07ASHIM3a) and two were of indeterminate sex. The males had 119 assessable teeth, the females had 85 and the individuals of indeterminate sex had 58. Seven subadults were 1-5 years old with 89 assessable teeth, three subadults were 6-14 years with 47 assessable teeth. Twenty four adults and twenty seven subadults were able to be assessed at Hòa Diệm. Nine adults were male, four were female and 11 were of indeterminate sex. The males had 103 assessable teeth, the females had 43 and the individuals of indeterminate sex had 144. Fourteen subadults were 1-5 years old with 76 assessable teeth, six were 6-14 with 42 and seven subadults were of indeterminate age with 22 assessable teeth, the details of which are presented in the results section.

Adults are presented by sex, (males, females and indeterminate), in three age classes (15-29, 30+ years and indeterminate). Subadults are presented in two age classes 1-5 years (deciduous dentition) and 6-14 years (permanent dentition). Pearson’s uncorrected Chi square tests were used to test intra-sample differences between the sexes and age ranges; and inter-sample differences between the sexes and among the sites. Yates continuity correction was used where appropriate. An alpha level of .05 was used for all statistical tests.

Results

Table 5.28 summarises the prevalence and position of staining at An Sơn. Staining was observed on the labial surfaces of the anterior dentition and the buccal and occlusal surfaces of the posterior dentition. There were no cases of dark staining of solid colour
Table 5.28. Staining profile: An Sơn seasons 2004, 2007 and 2009

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior</th>
<th>Maxillary/Mandibular</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>O</td>
<td>%</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>29</td>
<td>9/20</td>
<td>31/10</td>
</tr>
<tr>
<td>30+</td>
<td>90</td>
<td>28/62</td>
<td>9/23</td>
</tr>
<tr>
<td>subtotal</td>
<td>119</td>
<td>37/82</td>
<td>12/33</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>58</td>
<td>25/33</td>
<td>10/21</td>
</tr>
<tr>
<td>30+</td>
<td>23</td>
<td>13/10</td>
<td>0/0</td>
</tr>
<tr>
<td>indeterminate</td>
<td>4</td>
<td>3/1</td>
<td>0/0</td>
</tr>
<tr>
<td>subtotal</td>
<td>85</td>
<td>41/44</td>
<td>10/21</td>
</tr>
<tr>
<td>Indeterminate 15-29</td>
<td>58</td>
<td>19/39</td>
<td>7/25</td>
</tr>
<tr>
<td>subtotal</td>
<td>58</td>
<td>19/39</td>
<td>7/25</td>
</tr>
<tr>
<td>Subtotal</td>
<td>262</td>
<td>97/165</td>
<td>29/79</td>
</tr>
<tr>
<td>Subadults 6-14</td>
<td>47</td>
<td>20/27</td>
<td>1/23</td>
</tr>
<tr>
<td>Total</td>
<td>309</td>
<td>117/192</td>
<td>30/102 25.6/53.1</td>
</tr>
</tbody>
</table>

Subadults

| Deciduous teeth Subadults | 1-5 | 89 | 47/42 | 39/40 | 83.0/95.2 | 43/46 | 37/42 | 86.0/91.3 | 83 | 93.3 | 7/7 (100.0) |

TOTAL | 398 | 164/234 | 69/142 | 42.1/60.7 | 195/203 | 94/117 | 48.2/57.6 | 215 | 54.0 | 17/23 (73.9) |

1. Total preserved teeth
2. Preserved anterior teeth (incisors/canines)/ preserved posterior teeth (premolars/molars)
3. Preserved maxillary/mandibular teeth
4. Total staining
5. Total individuals (O/N)

- O observed condition in teeth or individuals
- N number of assessable teeth or individuals
>90% of the tooth surface. The coverage was generally diffuse and patchy on <90% of the tooth surface. The overall frequency of staining among adults was 41.2% of teeth (61.5% of individuals). This increased to 54.0% (73.9% of individuals) across the whole population. There was a very similar prevalence of stained teeth among males (37.8%) and females (36.5%), however, 80.0% of male individuals and only 33.3% of female individuals had stained teeth.

There was a higher prevalence of younger individuals with staining on their teeth, males in the younger age class had 44.8% of their teeth stained (100% of individuals), compared to 35.6% of older age class (75% of individuals). Females in the younger age class 53.4% (66.7% of individuals) had a significantly higher frequency of staining than older individuals (0.0%) X²(1)=17.717, p=0.000. The posterior dentition had significantly more staining (47.9%) than the anterior dentition (29.9%) among the adult population X²(1)=8.152, p=0.004, this pattern was seen in males, females and individuals of indeterminate sex but was only significant in females X²(1)=4.989, p=0.026. The mandibular dentition were more frequently stained (45.8%) compared to the maxillary dentition (36.6%) among the adult population and this trend was also seen in males, females and indeterminate individuals. The same patterns were observed in subadults with permanent dentition and subadults with deciduous dentition as in the adults.

Table 5.29 summarises the prevalence and position of tooth staining among individuals from Hòa Diêm. Staining was observed on the labial surfaces of the anterior dentition and the buccal and occlusal surfaces of the posterior dentition. There were cases of dark staining of solid colour on >90% of the tooth surface and where this occurred there was a very clear distinction between the stained region and the gingival region of the tooth surface.

The overall frequency of staining was 57.6% of teeth among adults (75.0% of individuals). There was also a high incidence of dark staining of solid colour >90% of tooth face among adults on 37.2% of teeth (66.7% of individuals). The overall frequency of tooth staining was significantly higher in females than males for staining with 72.1% of female teeth compared to 53.4% of male teeth X²(1)=4.380, p=0.036 and was also higher for dark staining with 48.8% of female teeth compared to 39.8% of male teeth. However, the individual count was slightly higher for males with 77.8% of individuals affected compared to females with a slightly lower 75.0% of individuals.

Staining was significantly higher in the anterior teeth (88.0%) than the posterior teeth (45.4%) among adults X²(1)=43.898, p=0.000. This trend was true for males at 96.7% (35.6% posterior) X²(1)=29.440, p=0.000, females at 100.0% (57.1% posterior) X²(1)=6.914, p=0.009 and individuals of indeterminate sex at 76.3% (49.1% posterior) X²(1)=8.446, p=0.004. Dark staining was also significantly higher in the anterior dentition
Table 5.29. Staining profile: Hòa Diêm 2002 and 2007

<table>
<thead>
<tr>
<th>Permanent Teeth</th>
<th>Anterior/Posterior^2</th>
<th>Maxillary/Mandibular^2</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Staining O %</td>
<td>Dark staining O %</td>
<td>N</td>
</tr>
<tr>
<td>Male 15-29</td>
<td>13/14</td>
<td>92.3/17.7</td>
<td>17/36</td>
</tr>
<tr>
<td>30+</td>
<td>16/12</td>
<td>88.2/21.8</td>
<td>28/22</td>
</tr>
<tr>
<td>subtotal</td>
<td>29/26</td>
<td>90.0/19.2</td>
<td>45/58</td>
</tr>
<tr>
<td>Female 15-29</td>
<td>15/16</td>
<td>83.3/16.7</td>
<td>27/15</td>
</tr>
<tr>
<td>30+</td>
<td>0/0</td>
<td>0.0/100.0</td>
<td>0/0</td>
</tr>
<tr>
<td>subtotal</td>
<td>15/16</td>
<td>93.3/6.7</td>
<td>28/15</td>
</tr>
<tr>
<td>Indeterminate 15-29</td>
<td>14/23</td>
<td>95.0/5.0</td>
<td>20/21</td>
</tr>
<tr>
<td>30+</td>
<td>0/0</td>
<td>0.0/100.0</td>
<td>0/0</td>
</tr>
<tr>
<td>subtotal</td>
<td>14/23</td>
<td>100.0/0.0</td>
<td>20/21</td>
</tr>
<tr>
<td>Subtotal</td>
<td>290</td>
<td>83/307</td>
<td>73/94</td>
</tr>
</tbody>
</table>

1 total preserved teeth
2 preserved anterior teeth (incisors/canines)/preserved posterior teeth (premolars/molars)
3 preserved maxillary/mandibular teeth
4 total staining
5 total staining individuals O/N
6 total dark staining is solid colour 90%+ of tooth face
7 total dark staining individuals O/N
across all adults with 79.5% of anterior dentition stained compared to posterior (20.3%) \( \chi^2(1)=88.922, p=0.000 \), this trend was the same for males at 90% (19.2% posterior) \( \chi^2(1)=41.602, p=0.000 \), females at 93.3% (25.0% posterior) \( \chi^2(1)=15.621, p=0.000 \) and individuals of indeterminate sex at 65.8% (19.8% posterior) \( \chi^2(1)=27.200, p=0.000 \). Staining was slightly higher in the maxillary teeth (59.6%) than mandibular (55.8%) among adults, a similar pattern was observed with dark staining with 42.6% of maxillary teeth stained compared to 32.5% of mandibular teeth.

The distribution of staining was similar between the younger and older aged males, 50.9% and 56.0% respectively, this pattern was similar for dark staining, 35.8% and 44.0% respectively. Differences between the age ranges for females could not be examined due to the small sample of assessable teeth for older aged females.

Subadults with permanent dentition had neither dark staining nor staining, subadults with deciduous dentition did not have dark staining but a high proportion had staining with 22.4% of all teeth (57.1% of individuals). In contrast to adults, the subadult staining was higher on the posterior dentition with 24.2% compared to the anterior at 10.0% and on the mandibular dentition with 26.8% compared to 17.1% on the maxillary teeth. Over the entire population 42.8% of teeth showed evidence for staining (51.0% of individuals) and 25.1% of teeth showed evidence for dark staining (31.4% of individuals).

**Discussion**

Given the age progressive nature, in addition to the potentially confounding issue of sex, evidence for extramasticatory activity and oral health will be considered with reference to the demographic profile of the relevant sites. Comparing populations with different age structures without due consideration can result in erroneous interpretations. Unfortunately, due to small sample sizes only provisional inferences can be made regarding differences in prevalence by age or sex. The cultural behaviours and oral histories of the individuals from An Sơn and Hòa Diệm will be presented prior to a discussion of the oral pathology findings for these sites. The discussion is structured as a regional comparison, the inferences of which will be discussed using a model framed around the relevant themes of the Neolithic Demographic Transition and fertility.

*Cultural behaviours*

Differences observed between the sexes in extramasticatory activity can provide potential insight into a range of different behaviours, which may in turn predispose or exacerbate a number of pathological conditions. Looking at interproximal grooves, although only one young female showed evidence for these, the sample size of female adults was relatively small. It was not possible to observe the interproximal grooves under a scanning electron microscope, however, the presence of such grooves could potentially indicate that the
inhabitants at An Sơn were using their mouths for non-dietary related repetitive tasks.

In consideration of the aetiology of interproximal grooves, the stripping hypothesis (Blakely and Beck 1984; Brown and Molnar 1990; Erdal 2008; Lukacs and Pastor 1988; Schulz 1977) is suggested as a more favourable explanation over the tooth picking hypothesis (Berryman et al. 1979; Ubelaker et al. 1969) for An Sơn. Personal observations from clinical data by Formicola (1991) suggest that grooves have been caused by repetitive use of dental floss, but never from tooth picks (although the case might be different if the toothpicks were made from bone). The interproximal grooving observed is usually at the cementoenamel junction, an area covered by gingiva in living individuals, and it would likely be uncomfortable to repetitively probe the area with a toothpick (or bone pick), while fibre held at either end easily reaches that area.

The size of the grooves and the matching pattern on adjacent mesial and distal surfaces of the teeth, suggests the repetitive habitual action of slipping flexible material through the teeth as the most likely cause. The cause of these grooves may or may not have been related to a sex-specific activity. The repetitive action causing these grooves over time compromised the integrity of the tooth structure, stripping the enamel and exposing the dentine, thus likely predisposing affected individuals to cervical caries (Hillson 2001). The two highest caries types with an identifiable initiation point in females were A - lesion initiated on interproximal attrition facet and R - lesion (groove) following cementoenamel junction or just on the root. As discussed, the synergistic relationship among the oral pathologies would likely have contributed to the aetiology of antemortem tooth loss in the older individuals and possibly the loss of other teeth with grooves.

The prevalence of tooth chipping was low at An Sơn and Hòa Diêm with males and females showing a similar frequency. At An Sơn males most commonly had chipping on the maxillary dentition with chips only occurring on the posterior teeth, while females had chipping on both the anterior and posterior dentition but only the mandibular teeth were affected. Three individuals had chipped teeth at Hòa Diêm, however, they were all of indeterminate sex. Chipping can result from masticatory activities including food processing, consumption of abrasive foods or extramasticatory activities (Bonfiglioli et al. 2004), any of which could have caused the chipping seen in these samples. The chipped teeth from both sites were all observed in the younger age class. Food would be more likely to get caught in chipped teeth, thus potentially exacerbating bacterial loads; chipping can also exposure the pulp chamber, and depending on the severity such factors can play a role in the development of caries and other diseases, eventually leading to antemortem tooth loss (Hillson 2000). It is possible that more individuals had chipped teeth, but due to the synergistic and age progressive nature of oral pathology older individuals with chipped teeth may have lost them, which is a possible reason why chipping is only seen in the younger age classes.
There were no cases of dark staining of solid colour covering >90% of the tooth surface at An Sơn. The overall frequency of staining covering <90% of the tooth surface was relatively high and male and female teeth showed a similar proportion of staining, however, there was a higher percentage of male individuals with staining. There were a higher proportion of individuals in the younger age classes with stained teeth for males. There were no older aged female individuals showing evidence for stained teeth, while older males did show staining. Staining was observed on subadults both 1-5 and 6-14 years of age.

The posterior mandibular dentition showed a higher prevalence of staining than the anterior maxillary dentition in males, females and those of indeterminate sex at An Sơn. The diffuse and patchy distribution on the labial and buccal surfaces of the dentition and the higher prevalence of staining on the occlusal posterior mandibular teeth suggests that there was no effort to stain the visible teeth for aesthetic purposes. This pattern would suggest an unintentional staining rather than purposeful staining, by something chewed rather than applied.

There was a higher frequency of staining of teeth at Hòa Diêm than An Sơn, with a high prevalence of dark staining of solid colour >90% of the tooth surface. There was a higher frequency of staining and dark staining in female teeth by tooth count, but a similar proportion of individual males and females displayed tooth staining. Staining and dark staining was more prevalent in the anterior maxillary dentition in males, females and indeterminate adults at Hòa Diêm. This pattern is the opposite to that seen at An Sơn, and the patterning of the staining on the Hòa Diêm teeth is similar to that previously described and documented at Núi Nấp by Oxenham et al. (2002a). The concentration on the labial aspect of the anterior teeth, the diminishing intensity on the premolars and the absence on the molars and occlusal surfaces of the teeth suggests that the staining was intentional, and that these individuals were deliberately staining the visible aspect of their teeth. This was practiced by both young and old males and young females at Hòa Diêm.

Subadults with permanent dentition had neither staining nor dark staining. However, over 50% of subadults with deciduous dentition had staining (no dark staining). In contrast to the adults, the subadult staining was more common on the posterior and mandibular dentition. This is synonymous with the patterns seen at An Sơn. It is possible that the mothers were feeding young infants betel nut as they were teething or to help alleviate other ails (Oxenham et al. 2008a). Ethnographic literature shows a general consensus in the notion that there are some medicinal qualities in chewing betel nut (Zumbroich 2007) and staining teeth (Tayanin and Bratthall 2006). While the temporal origins of these beliefs are not known, research at other sites in Vietnam and Southeast Asia has shown that this has long been practiced (Fox 1970; Oxenham et al. 2002a; Pietrusewsky and Ikehara-Quebral 2007).
It is beyond the scope of this study to determine the exact methods or to understand the motives behind the tooth staining, but ethnographic information has provided some tentative hypotheses. In an attempt to understand the cause of staining, betel nut chewing has been proposed as the most likely causative agent. As for the reasoning, it would appear that the staining was more incidental at An Sơn and more focussed and intentional at Hòa Diêm. At both sites only young females have staining, while all males of all ages do. This could be a result of different gendered habitual activities or practices or mixed uses for betel nut. It is possible that in the Neolithic period betel nut was chewed for its stimulant and medicinal properties and possibly used for staining with respect some age-based customs associated with younger adult individuals. This is consistent with the ephemeral nature of the materials used for staining and the literature that suggests that intentional staining may have been associated with the life ways of younger individuals (Tayanin and Bratthall 2006; Zumbroich 2011).

As betel stained teeth gained impetus in the cultural customs of these communities, more effective methods for blackening teeth evolved over time. The incidence of dark staining at Hòa Diêm appears more intentional than at An Sơn and suggests that the intentional staining of teeth had become more refined and commonly practiced and more focussed on the anterior dentition, which is suggestive of an aesthetic purpose. This is not to say it was not also chewed for its stimulant or medicinal purposes.

**Oral pathology**

The pattern of caries distribution is similar between An Sơn and Hòa Diêm. The predilection of caries followed the expected patterns, females had a much higher prevalence than males and older aged individuals had a higher incidence than younger individuals. Caries were more common on the posterior dentition and massive crown/root destruction was the most common type of caries recorded among the adults at An Sơn. All of the adult individuals from An Sơn had at least one carious lesion, while a quarter of individuals from Hòa Diêm had lesions.

Pulp chamber exposure at An Sơn affected both the anterior and posterior dentition in males and females, however, in males it was the maxillary teeth that were affected while in females it was the mandibular dentition. At An Sơn, pulp chamber exposure was more prevalent in females than males. The pattern was similar to caries because they were directly associated; caries was the cause of all pulp chamber exposure. The sample size for Hòa Diêm mitigated against useful inferences.

Older aged males and females had a higher prevalence of alveolar lesions at An Sơn and Hòa Diêm (except when 07ASH1M3a was included). There were no females at Hòa Diêm with alveolar lesions, but this again is probably due to preservation and the small
female sample. There were fewer assessable alveoli for individuals at Hòa Diêm due to the variable preservation and secondary use of the jar burials related to the mortuary tradition.

The patterns of antemortem tooth loss are the same for An Sơn and Hòa Diêm, in all regards, except sex distribution, however, the latter is likely a sampling bias. Antemortem tooth loss affected older individuals, was more common on the posterior teeth and more prevalent in the mandibular dentition. Antemortem tooth loss was higher in females than males at An Sơn, however, there were no females affected at Hòa Diêm. It is very likely that this is a sampling bias because of the poor preservation of alveoli and the small female sample.

Females had a higher prevalence of caries, a higher frequency of pulp chamber exposure, alveolar lesions and antemortem tooth loss than males at An Sơn. Females had a higher prevalence of caries, pulp chamber exposure and alveolar lesions in the younger age class than their males counterparts, the concomitant effects of these oral pathologies likely led to the higher antemortem tooth loss in all age classes in females compared to males. The possible reasons for this will be further discussed later in the chapter.

Oral health is age progressive and as expected there was a higher frequency of alveolar lesions, antemortem tooth loss and caries in older individuals among the comparative assemblages (Willis and Oxenham 2013b), however, the demographic profiles of the sites suggest that the ratio of younger individuals to older individuals was only uneven at Cồn Cổ Ngựa with a significantly higher number of older individuals (see Table 3.3 in Chapter Three). For the remaining comparative assemblages age should not bias the observations of oral health.

Across the Southeast Asian assemblages caries was statistically significantly higher for females compared to males at An Sơn, Khok Phanom Di, Mán Bạc, Ban Lum Khao and Ban Na Di; and antemortem tooth loss was statistically significantly higher for females compared to males at An Sơn, Khok Phanom Di, Mán Bạc, Ban Na Di and Noen U-Loke.

There is a very clear temporal trend of poor oral health evidenced in the Southeast Asian Neolithic, particularly in the prevalence of caries and antemortem tooth loss with a general decline in oral pathology over time, indicating improved dental health leading into the Bronze and Iron Ages. Neolithic An Sơn is similar to the profiles of Neolithic Khok Phanom Di and Mán Bạc; while Iron Age Hòa Diêm is more similar to the later Metal Age sites in the region (Figure 5.7).

Historically, it has been argued that Southeast Asia does not fit the ‘worldwide’ trend of increased caries prevalence with the intensification of agriculture. Khok Phanom had been
the only anomalous site in Southeast Asia with a high frequency of caries. The question as to why there was an improvement through time with the intensification of agriculture, in stark contrast to the general pattern seen in other areas of the world is a question that has been examined by other researchers in Southeast Asia. Are these changes that are seen in caries rates with the transition to agriculture a reflection of changes in diet? Changes in social structure? Are the differences between the sexes in caries rates a result of differences in diet or differences in behaviour? Many suggestions have been put forward to try and address these questions. Most have focussed on diet, particularly the cariogenicity of rice and the higher nutritional value of rice (Halcrow et al. 2013; Oxenham 2001; Tayles et al. 2009; Tayles et al. 2000); and the later development of social complexity in the area and subsequent emergence of large scale agriculture (Oxenham et al. 2006). Sex differences have been explained focussing on traditional dietary behavioural models, sexual division of labour, differential access to food, or differential oral behaviours (Domett 2001, 2004; Douglas 2006; Oxenham 2006; Oxenham et al. 2008b; Pietrusewsky and Douglas 2002a; Pietrusewsky and Ikehara-Quebral 2007; Tayles 1999; Tayles et al. 2000; Tayles et al. 2007). Ultimately, perhaps a “complex set of as yet undefined social and environmental factors” (Domett and Tayles 2006: 238) are to blame.

Two clear patterns have emerged from the synthesis of the Southeast Asian data in this chapter. Oral health is poor in the Neolithic but improves in the subsequent Bronze and Iron Ages; and female oral health is almost always worse than that of males, with the exception of alveolar lesions. The frequency of alveolar lesions did not conform to the same pattern as caries and antemortem tooth loss with age or sex among the assemblages. This may have been a result of difficulties in observing alveolar lesions in dry bone. On the other hand, antemortem tooth loss and caries vary in a similar manner as anticipated in that antemortem tooth loss is often the subsequent result of aggressive caries. Mán Bạc did not show the same elevated levels of antemortem tooth loss as the other Neolithic
sites, however, this may be a result of the common cultural practice of tooth ablation observed in individuals obscuring antemortem tooth loss (Oxenham and Domett 2011).

The following discussion will focus on caries as a proxy for oral health. It is acknowledged that this is simplistic; however, the synergistic relationship between the oral pathologies has been demonstrated earlier in the chapter, showing caries as aetiologically relevant in pulp chamber exposure, alveolar lesions and antemortem tooth loss.

_Cariogenicity of rice_

Tayles _et al._ (2000) first questioned the relationship between caries and rice agriculture in Southeast Asia, and then nine years later, after again reviewing the literature they found “no simple or universally applicable explanation for patterns of changing caries frequencies during human prehistory” (Tayles _et al._ 2009: 162). In their literature review they neglected to include some key papers, addressing developments in the interpretation of caries (Lukacs 2008; Lukacs and Largaespada 2006). These will be addressed here, later in the discussion.

As discussed in earlier chapters, the implications of the archaeological botanical evidence indicate the individuals at An Sơn were cultivating and consuming rice and although no palaeobotanical analyses have been conducted at Hòa Diêm, it is assumed that they would also have been cultivating rice given that the site is temporally located in the Iron Age. The rice consumed would have been unpolished, it is probable that it was threshed and winnowed, discarding the indigestible outer husk. This would have meant that the germ layer with potential anticariogenic properties (Madsen and Edmonds 1962) would have provided some attrition, which can be beneficial in the clearance of food particles, and the perpetual low degree of attrition can change the morphology of the tooth, removing the fissures and spaces where plaque often gets caught (see discussions in Tayles _et al._ 2009; Tayles _et al._ 2000).

The cariogenicity of rice has often been discussed in the aetiology of Southeast Asia caries, some arguing rice is not cariogenic and therefore a potential explanation as to why Southeast Asian shows different oral health patterns to other areas of the world during the adoption and intensification of agriculture (Tayles _et al._ 2009; Tayles _et al._ 2000; although see arguments to the contrary in Temple and Larsen 2007). The cariogenicity of food itself is near impossible to scientifically demonstrate. However, the World Health Organisation (1990) have suggested an extensive review of evidence showed rice to be of low potential cariogenicity. While the cariogenicity of starchy foods potentially increases when cooked with sugar (Rugg-Gunn and Nunn 1999), there is no evidence that the inhabitants of Southeast Asia were including sugar with their rice, although it cannot be discounted.
Recently there has been an increase in the number of Neolithic Southeast Asian assemblages excavated in Vietnam (Bellwood et al. 2011; Oxenham and Domett 2011). This chapter has integrated new data from An Sơn and Mán Bạc which have shown very high levels of caries and poor oral health similar to Khok Phanom Di. These three sites are from different environments, with different subsistence patterns; however, there are a few things they have in common. They are Neolithic sites, representing early rice consuming communities and the females all have a high prevalence of caries. These new data require a fundamental shift in the way we view both oral health and human behaviour in this region. It seems that in Southeast Asia, the changes seen in other areas of the world with the adoption of agriculture did occur during the initial stages of the Neolithic. But if rice is not cariogenic what other potential factors could play into the aetiology of caries? If the changes seen globally during the adoption of agriculture are only seen in the Neolithic in Southeast Asia why is this the case? Is the higher carious prevalence in females important? These questions need to be evaluated in regard to fertility and the Neolithic Demographic Transition.

Sex and Fertility

Bioarchaeologists investigating the repercussions of the adoption and intensification of agriculture have found a significant increase in caries prevalence over time (Cohen and Armelagos 1984; Larsen 1983; Lukacs 1992b). Sex differences have been recorded in prehistoric populations, across many different cultures engaging in different subsistence economies (Larsen 1983, 1998; Lukacs 1996; Walker and Erlandson 1986) and Lukacs and Thomson’s (2008) meta-analysis of these prehistoric sites shows a consistent pattern of sex differences in caries prevalence. A recent metaanalysis from contemporary South Asian populations (Lukacs 2011) demonstrated the same patterns of poor oral health in females are still present.

Bioarchaeologists have typically relied on behavioural explanations for disparities in caries rates between males and females focussing on differences in diet and food consumption associated with apparent sexual divisions of labour (Lukacs and Largaespada 2006). The effect of pregnancy on the prevalence of caries in females is something that has previously been suggested as a casual factor, however, the reasons are not specified or discussed, or alternatively dismissed as unsupported. “There is a conventional belief that pregnancy compromises dental health provoking dental caries and tooth loss. However, such a relationship is not borne out by scientific evidence” (Larsen 1998: 175). This is despite the fact that the disparities in caries prevalence between males and females, the effects of sex specific hormones (Delman 1955; Laine et al. 1988; Legler and Menaker 1980; Liu and Lin 1973; Muhler and Shafer 1955), the size of salivary glands (Percival et al. 1994), the flow and chemical composition of saliva (Worthman 1995) and the confounding effect of pregnancy in females (Salvolini et al. 1998) have been researched and discussed
in the clinical literature for decades. Only recently have these been discussed in the bioarchaeological literature (Ferraro and Vieira 2010; Fields et al. 2009; Lukacs 2008; Lukacs and Largaespada 2006; Watson et al. 2010).

Genetics can increase susceptibility in certain individuals to oral pathologies. New techniques for analysing genetics are contributing to an appreciation of the sex differentiation in oral health. Genome-wide association studies have become prolific. A study has found caries suggestive loci, loci influencing caries susceptibility, and genes affecting saliva flow, taste and smell and diet preference (Vieira et al. 2008). A caries protective locus was discovered on the X chromosome, which has been linked to the differences in prevalence of caries between the sexes (Vieira et al. 2008). Studies on genes influencing enamel formation suggest a difference in gene loci regulating the development of enamel, ameloblastin, amelogenin and tuftelin, which contribute to caries susceptibility (Deeley et al. 2008; Patir et al. 2008). Structural defects in their micro composition make them more vulnerable to bacteria in the oral environment (Patir et al. 2008). These recent developments in genomics have increased our understanding of cariogenesis (Russell et al. 2008) and the implications for sexual differentiation in susceptibility and expression of oral health.

The disparities between the sexes in the prevalence of caries is almost universal (Haugejorden 1996) and is more accepted by epidemiologists and clinicians of oral health than by bioarchaeologists. In fact the disparity in caries has facilitated further investigation in the health sciences and is the central focus of several research projects (Lukacs and Largaespada 2006). The results of such research are important in the understanding of caries susceptibility between males and females and the implications of this for interpreting oral health in past populations.

Oestrogen has been found to be positively correlated with caries prevalence (Delman 1955; Laine et al. 1988; Legler and Menaker 1980; Liu and Lin 1973; Muhler and Shafer 1955), levels of which are higher in females throughout their lives and particularly so during puberty, menstruation and pregnancy (Worthman 1995). Studies have also found females have smaller salivary glands (Percival et al. 1994) and saliva flow rates are significantly lower than males (Dodds et al. 2005; Dowd 1999) partially due to oestrogen (Muhler and Shafer 1955). Saliva has several primary functions, protection, buffering, antimicrobial action, food clearance, digestion and taste, tissue repair and tooth integrity (Lukacs and Largaespada 2006). A reduction in the flow of saliva in females would reduce the functionality of those features of saliva already mentioned, leaving females at a disadvantage and more vulnerable than males, which has important implications for interpreting differential caries prevalence between the sexes (Lukacs and Largaespada 2006).
This clinical research clearly illustrates that women are more susceptible to caries than males. The confounding effects of pregnancy modifies the biochemical composition of saliva (Salvolini et al. 1998), reduces the salivary buffering capability, facilitating increases in the level of streptococcus mutans (Villagrán 1999 cited in Lukacs and Largaespada 2006) and lowers the immune system (Cheyney 2007). The prevalence of caries (Orosz et al. 1975) and poor gingival health (Muramatsu and Takaesu 1994) have both been shown to be correlated with pregnancy. Finally, the food cravings and aversions and morning sickness in pregnant woman; suggested evolutionary adaptations to ensure foetal viability and health, may also influence the cariogenic food choices of pregnant women (Flaxman and Sherman 2000; Vallianatos 2007). These studies would suggest that females are predisposed to higher levels of caries and that pregnancy is a further compounding factor. This needs to be taken into consideration when assessing the oral health of individuals in prehistory. While the complex aetiology of caries includes many synergistic factors, males and females will always both be affected, however, pregnancy cannot be overlooked as a major contributing factor to the higher prevalence among females.

Antemortem tooth loss has also been shown to be higher in females than in males in prehistoric samples and clinical studies. Skeletal samples with differential tooth loss between the sexes have been reported from Oman, Japan and Mexico (Cucina and Tiesler 2003; Nelson et al. 1999; Oyamada et al. 2007; Watson et al. 2010). Clinical studies from Chile, India, Brazil and Saudi Arabia have also demonstrated a female bias in tooth loss (Al Shammery et al. 1998; Corraini et al. 2009; López and Baelum 2006; Shigli et al. 2009). It has been shown that antemortem tooth loss is commonly attributed to caries rather than periodontal disease (Meisel et al. 2008) and tooth loss is also associated with parity (Meisel et al. 2008; Russell et al. 2008).

In contemporary populations it is well know that caries, gingivitis, periodontal disease, erosion and tooth mobility are associated with pregnancy and modern clinical literature attests to poor oral health in females (Boggess 2008; Gajendra and Kumar 2004; Russell and Mayberry 2008; Silk et al. 2008). Global studies in prehistory (Lukacs and Thompson 2008) and modern clinical research (Haugejorden 1996) have found consistent sex differences in oral health (Lukacs 2008, 2011).

Is this also the case in Vietnam? The National Oral Health Survey of Vietnam (Do et al. 2011) suggests that more than 80% of the contemporary adult population of Vietnam have decayed, filled or missing teeth with an average of five affected teeth per person. They found a statistically significant difference between the prevalence of caries in females compared to males, with females having a higher number of carious teeth than males. A cross-sectional epidemiological study of adults in urban and rural areas of southern Vietnam (Nguyễn et al. 2010) found missing teeth were frequent in all age ranges. The
number of teeth missing averaging one at the age of 20 years to eight at the age of 80 years. Females also had significantly higher levels of decayed and filled teeth than males. The low number of filled teeth and high number of decayed and missing teeth overall indicates that the main treatment for decay is extraction.

So what are the implications of this for assessing oral health in prehistory? “In societies with preindustrial intensive agricultural subsistence economies and high birth rates, the negative impact on women’s oral health and dental caries rates will be greater than among hunter and foragers or horticulturalists with low birth rates and less cariogenic diets” (Lukacs and Largaespada 2006: 550). The point made by Lukacs and Largaespada should be considered when assessing the general prevalence of caries in Southeast Asia during the adoption of agriculture; it is perhaps important to assess the fertility rates of the sites, as female caries could be more reflective of fertility rates than diet or behaviour.

Neolithic Demographic Transition

The Neolithic Demographic Transition suggests that significant increases in fertility occurred in Neolithic communities as a result of sedentism, a reliable constant food source and decreased birthing intervals (Bocquet-Appel and Naji 2006). The effects of the Neolithic Demographic Transition has been demonstrated in many areas of the world (Bocquet-Appel and Naji 2006) with cemetery data showing an increase in birth rates. The literature suggests a stable or declining birth rate in preagricultural groups, followed by a marked increase in fertility, following the transition to agriculture, which remained stable for 500-700 years, followed by a levelling off or decline in birth rates (Bocquet-Appel and Naji 2006). This has been shown in Neolithic Europe and North Africa (Bocquet-Appel 2002), in the Southwest and Eastern Woodlands of the US (Bocquet-Appel and Naji 2006) and in Mexico, Oaxaca and the Titicaca Basin (Bandy 2005).

Evidence suggests that increases in fertility are slower in agricultural homelands than spread zones and therefore higher rates of population growth are anticipated in populations peripheral to the origin regions of agriculture (Bocquet-Appel and Naji 2006). It has been suggested that sedentism may have been more important in reducing the birth interval than dietary change (Bocquet-Appel and Naji 2006), however, Bellwood and Oxenham suggest a consideration of both as a “mutually reinforcing combination, as of equal significance” (2008: 22).

The effect of the Neolithic Demographic Transition on fertility has been investigated using the demographic data from several cemetery sites in Southeast Asia (Bellwood and Oxenham 2008) and was also recalculated using $\delta^{13}P$ values in Table 3.4 in Chapter Three. Fertility was shown to be higher at Neolithic An Sơn, Khok Phanom Di and Mán Bạc and Bronze Age Ban Lum Khao. The high level at Ban Lum Khao is probably reflective
of an unusually high number of 5-9 year olds at the site. The data from Bronze Age Ban Na Di, Non Nok Tha and Iron Age Noen U-Loke suggest low levels of fertility, possibly stagnation or decline (Bellwood and Oxenham 2008: 26; and Chapter Three). This is exactly what you would expect, high levels of fertility in the Neolithic, sustained for a period, then decreasing and stabilising.

The spread of agriculture into Southeast Asia from what is now politically southern China likely occurred around 2500-2000BCE (Oxenham and Matsumura 2011), just earlier than the settlement of Mán Bạc and Khok Phanom Di. The fertility data (Bellwood and Oxenham 2008; Domett and Oxenham 2011; and Chapter Three) conform to the Neolithic Demographic Transition model, with high rates of population growth anticipated in Southeast Asia in populations peripheral to the origins of wet rice agriculture in China (Bellwood and Oxenham 2008). If the clinical evidence for an association of pregnancy with caries rates is correct, and there was an explosion in fertility during the Neolithic Demographic Transition with higher number of pregnancies in women during this period, then you would expect to see an increase in caries prevalence in women during the transition to agriculture.

In evaluating fertility and caries prevalence in light of the Neolithic Demographic Transition Lukacs (2008) suggests that the expression of a sex differentiation in caries frequency between males and females will follow the same expression as rises in fertility. He suggests that in geographical origin regions of agriculture, caries will show a small and insignificant increase, as a reflection of the gradual impact of changes in fertility, diet and division of labour. While in the peripheral spread zones, where the transition to agriculture is more abrupt and dramatic, caries would increase at a distinct but discontinuous rate, the effect of increasing fertility resulting in a rapid decline in women’s oral health. This hypothesis is supported by the results of this research. Strong peaks in caries rates are seen in the females in the Neolithic in the comparative Southeast Asian sites. Females consistently have higher caries rates than males and these have been shown to be statistically significant at the Neolithic sites of An Sơn, Mán Bạc and Khok Phanom Di, and Bronze Age sites Ban Lum Khao (Domett 2004; Oxenham and Domett 2011; Willis and Oxenham 2013b). Females also have higher levels of antemortem tooth loss than males across all sites with the exception of Ban Lum Khao (which is probably explained by the demographics of the site, with a small sample of older aged females (Domett 2004)).

Further support is seen in light of the data from the preNeolithic site Cồn Cổ Ngựa. In comparison with the other Neolithic sites, Cồn Cổ Ngureka does not fit the same oral health profile as An Sơn, Mán Bạc and Khok Phanom Di. Cồn Cổ Ngureka has been described morphologically as Australo-Melanesian rather than modern Southeast Asian, indicating a population of indigenous hunter gatherers (Matsumura et al. 2001). This differs from
the Mán Bạc and An Sơn skeletal assemblages which are largely modern Southeast Asian in morphology (Matsumura and Oxenham 2014; Matsumura et al. 2015) although there is evidence at Mán Bạc for genetic heterogeneity (Matsumura and Oxenham 2014; Oxenham and Matsumura 2011). Cồn Cỏ Ngựa would be expected to have stable or declining fertility and low levels of caries with no significant differentiation between the sexes. The $P_{5}$ values (Chapter Three) and caries prevalence support this. As there are insufficient assemblages dating prior to the Neolithic Demographic Transition and the introduction of agriculture in Southeast Asia to test this it is difficult to corroborate.

After a spike in birth rates during the Neolithic Demographic Transition, it levels off in most parts of the world after about 1000 years (Bocquet-Appel 2011). After the initial boom in fertility in these new environments, the factors which initially contributed to the boom likely contributed to its demise. The pressures of sedentary lifestyles, growth of local populations, increased transmissible infectious disease loads and zoonoses from domesticates led to increased morbidity and mortality, factors well recognised in a general decline in health following the introduction of agriculture (Larsen 1997, 2015). Moreover, such factors may have been accentuated by over intensification within fragile environments (Bellwood and Oxenham 2008). This would explain the decrease in caries and the decrease in differentiation between the prevalence seen in males and females from the Bronze Age into the Iron Age in Southeast Asia.

The complex aetiology of caries, the synergistic relationship between oral pathologies, the limitations of sample sizes, the cumulative effect of aging and inconsistent methods of recording and presenting data make differences in oral health among different populations over time very difficult to interpret. There is no doubt that all the possible contributing aetiologies discussed above played some role in the oral health of these individuals at An Sơn and Hòa Diệm, however, out of the many possible contributions to poor oral health, the key point made here is that females almost always have higher levels of oral pathologies and the male prevalence remains fairly stable over time. The reasons for this have been discussed, but it seems plausible that the higher levels of oral pathologies in the earlier sites are directly related to increases in female fertility during the Neolithic Demographic Transition, which eventually decreased and then stabilised over time. The results of a generalised linear model of oral health of Southeast Asian assemblages found females had more oral lesions than males. Males and females had a similar level of oral lesions in the preNeolithic and Iron Age assemblages, while females had higher rates in the Neolithic. Finally, older individuals in each assemblage had more oral lesions than younger individuals. These findings suggest that as anticipated caries was age progressive, females were more predisposed to poor oral health and that this was a temporal phenomenon, worst during the Neolithic Demographic Transition (Willis and Oxenham 2013b). It should be stressed again, however, that although females may be predisposed to poorer oral health due to their biology, oral pathologies are complex, synergistic and
multifactorial. The general biological costs associated with the Neolithic Demographic Transition would impact both males and females (Enwonwu 2010; Enwonwu et al. 2002; Moynihan and Petersen 2004; Petersen 2003; World Health Organisation 2003). However, the most parsimonious explanation for the elevated rates of oral pathologies in communities influenced by the Neolithic Demographic Transition with major changes in subsistence and demography is the relationship between increased fertility, female biology and nonspecific compromised health. The results of which suggest that “the current consensus that oral health did not decline with the adoption/intensification of agriculture in Southeast Asia, is no longer viable” (Willis and Oxenham 2013b: 9).

Having discussed oral health and extramasticatory modifications at An Sơn and Hòa Diêm the following chapter examines palaeodiet at An Sơn and Hòa Diêm.
Chapter Six:

Palaeodietary Analysis of An Sơn and Hòa Diêm

Introduction

This chapter begins with a detailed discussion of stable isotopes in order to provide a context in which to assess diet at An Sơn and Hòa Diêm. Following this overview the methods and materials, results and discussion relating to the stable dietary isotopic analysis of the An Sơn and Hòa Diêm samples is presented.

This first section begins by introducing stable isotopes and the development of their application in palaeodietary studies. The introduction goes on to discuss the most common tissues used for isotope analysis, potential sources of diagenesis and how the quality of collagen and apatite are assessed. Following this the methodology of stable isotopes and mass spectrometry is introduced. How stable isotopes are applied in subsistence studies, the variation observed in plants and animals in different environments and the assumptions that are used in palaeodietary reconstruction from animal models are then explored. Following this the differences in what apatite and enamel actually reflect in diet and whether or not apatite sourced from different tissues are comparable is reviewed. Dietary reconstruction models and their utility in palaeodietary reconstruction are then investigated, with the final section reviewing Southeast Asian research and dietary isotopic baselines before the analysis of the An Sơn and Hòa Diêm samples.

All living organisms are composed of elements which have been absorbed or consumed from the surrounding environment and metabolised to become part of the cellular makeup of that organism. There are 118 chemical elements in the periodic table and each element has one or more isotopes. Each isotope of an element has the same number of protons for that element but a different number of neutrons, giving each isotope a different atomic mass. Many elements have both radioactive isotopes (unstable spontaneous neutron decay states which transform the isotope) and stable isotopes (isotopes which do not spontaneously decay). For example, the element oxygen contains the stable isotopes $^{16}$O, $^{17}$O and $^{18}$O. The differences in mass reflect slightly different chemical and physical properties. Stable isotopes do not decay, the carbon in $^{12}$C and $^{13}$C will remain unchanged in a dead organism, however, unstable isotopes do decay, the radioactive isotope of carbon $^{14}$C will change to $^{14}$N over time (Katzenberg 2008).

**Isotope effects** during chemical reactions occur as a result of differences in the mass of isotopes. In a **reaction** isotopic ratios change during chemical processes such as photosynthesis and metabolism. The **reaction rate** is controlled by the speed at which the chemical bonds between the isotopes of an element break; the lighter the mass of the
isotope, the faster the reaction rate (\(^{12}\text{C}\) reacts faster than \(^{13}\text{C}\)). This results in fractionation, a differential expression of the isotopes between the **substrate** (food) and the **product** (consumer’s tissues). The process of fractionation and the ensuing stable isotope variation provides a foundation to develop and test palaeodietary research questions (Schoeninger 1995).

**The development of stable isotope application in dietary studies**

The concept of a ‘stable isotope’ was first described in relation to unstable (radioactive) isotopes in the early 20\(^{th}\) century, in the Nobel prize winning research of Frederick Soddy (1921) and J.J. Thomson (1906) (Choppin et al. 2002). Subsequent research undertaken by chemists and pharmacists had, by the mid 1930s, identified most of those isotopes known today. The 1950s and 1960s saw advances in stable isotope analysis within the disciplines of chemistry, biology and geochemistry (Katzenberg 2008).

The potential for the utilisation of carbon stable isotopes in dietary studies came about in two separate but associated areas of research (van der Merwe 1982). Researchers using the \(^{14}\text{C}/^{12}\text{C}\) ratio to calibrate prehistoric organic remains to a modern standard as a reference realised they needed a correction factor based on the \(^{13}\text{C}/^{12}\text{C}\) ratio of the sample. As a result of these corrections for fractionation they noticed anomalies in \(^{14}\text{C}\) dates obtained from human remains; they also found that maize and charcoal analysed from archaeological sites gave similarly inconsistent results (Bender 1968; Hall 1967b, 1993). At the same time this work was being carried out, biochemical research was being undertaken on the photosynthetic pathways of plants (Smith and Epstein 1971). Scientists radiocarbon dating organic remains expected maize to produce equivalent stable carbon isotopes as wood charcoal (Katzenberg 2008), however, it provided anomalous results. Maize has higher \(^{13}\text{C}\) to \(^{12}\text{C}\) in comparison to plants from temperate regions as it fixes carbon using a different pathway. This revelation of how the fractionation of \(^{13}\text{C}\) affected apparent radiocarbon ages incited further interest among archaeologists in the utility of stable carbon for dietary studies (Katzenberg 2008). Hall (1967a) presented a prophetic statement at a conference in 1967, about the possibility of using this knowledge to understand the reliance of consumers on foods that could be differentiated using stable isotopes.

The first human tissue used for palaeodietary studies was bone collagen. Again the experience of scientists with \(^{14}\text{C}\) dating was beneficial because techniques for isolating collagen in bone had already been refined. This application of stable isotopes for palaeodietary analysis was first realised in 1978 in a study of the \(\delta^{13}\text{C}\) of the humans of the Woodland site in eastern North America (van der Merwe and Vogel 1978). The second element used in palaeodietary studies was nitrogen. The controlled feeding experiments of DeNiro and Epstein (1978, 1981) using numerous animal species revealed the association
between the ratios of nitrogen and carbon expressed in diet and animal tissues. Subsequent research using nitrogen isotopes revealed the different trophic, climatic and regional expressions in isotope ratios (Ambrose and DeNiro 1987; Schoeninger and DeNiro 1984). The next section will discuss the most common isotopes and source tissues analysed for palaeodietary reconstruction.

While the stable isotopes of carbon and nitrogen are the isotopes most frequently used in bioarchaeological investigations of human and animal skeletal remains, the isotopes of oxygen, strontium, lead and sulphur have also been studied in tooth enamel and bone although sulphur has limitations in archaeological remains, due to the small atomic weight of sulphur (Katzenberg 2008), which until recently made it hard to analyse with isotope ratio mass spectrometry (IRMS).

Bioarchaeological and palaeodietary studies of human remains are usually confined to using bone and teeth for analysis, as soft tissues are rarely preserved. Dry bone is about 70% inorganic and 30% organic by weight, and 85-90% of the organic portion is collagen (Katzenberg 2008). Collagen is a structural protein made up of polypeptide chains in a triple helix (Fratzl 2008), and is laid down during the creation or repair of bone in an organic matrix interspersed with calcium phosphate in the form of hydroxyapatite. This close structural relationship prolongs the survivorship of collagen in bone (Tuross et al. 1980), unfortunately though collagen can decay over time with the speed of the degradation influenced by the temperature and moisture level of the burial environment.

In palaeodietary studies, collagen is the preferred material for analysis, containing 11-16% nitrogen and 35% carbon (van Klinken 1999). A second biological source of carbon that is thought to reflect lifetime isotopic intake from diet is in the carbonate CO$_3^-$ sourced from apatite in tooth enamel or the mineral portion of bone. Sullivan and Krueger (1981) suggested using carbon sourced from bone mineral as an alternative for stable isotope analyses if collagen was highly degraded. This was challenged by Schoeninger and DeNiro (1982) and further debated for some years (reviewed by Lee-Thorp and van der Merwe 1991). Two main points were made for the utility of apatite, 1) carbon isotopes from carbonate in biological apatite can be used where collagen has degraded and 2) it records dietary information from a different dietary component relative to collagen.

Arguments against the reliability of isotopic signals from apatite were that bone carbonate can be altered postmortem by a leaching of environmental carbonates from the soil into the native bone carbonate and therefore alter both the isotopic signature of the bone and the ratios of carbon isotopes. These concerns were addressed through the development of techniques to remove the secondary carbonates (Lee-Thorp 1989).

Using isotopes derived from dentine and enamel needs to be examined in the context
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of tooth biology, structure and development. Humans develop two sets of dentition throughout their lifetime. The first set, the deciduous dentition, is characterised by 20 non-permanent teeth. These begin forming about 6 weeks in utero, mineralising around the time of birth and erupting sequentially from around 6 months to 3 years of age, where deciduous tooth eruption and root formation is complete (Scheuer and Black 2000b). The second set, the permanent dentition, is characterised by 32 permanent teeth. The first permanent molar begins mineralising around birth, the rest of the permanent dentition forms and mineralises in the alveolar throughout childhood, erupting in a sequential pattern from 6 years to 12 years (Scheuer and Black 2000b). The third molars are the last to develop, between 6-12 years of age, and may erupt during adolescence, early adulthood, or not at all (Scheuer and Black 2000b).

Teeth are comprised of two main parts, the crown and the root, which are composed of three types of tissue, enamel, dentine and cementum. The core of the tooth, the pulp chamber, is protected and surrounded by dentine, the portion which creates the crown is protected by the hard enamel and the portion which creates the roots is protected by cementum. Enamel, dentine and cementum tissues are all comprised of organic and inorganic components but in differing proportions. The inorganic portion of enamel, dentine and cementum is almost entirely composed of calcium phosphates, most of which are hydroxyapatite (Hillson 1996).

Enamel is almost entirely inorganic and acellular, by dry weight it is composed of 96% inorganic minerals (hydroxyapatite), <1% organic protein (amelogenin), and water (Williams and Elliott 1989). Ninety percent of the organic portion of enamel is amelogenin (Hillson 1996). In mature enamel, the crystallites are at least 1600nm long and packed together in a dense, finely crystalline mass (Hillson 2005). Enamel is one of the most robust hard tissues in the human body and its solid and stable crystalline nature makes it resistant to erosion. If underlying dentine becomes brittle, the lack of underlying integrity can cause enamel to fracture and erode (Hillson 2005). By dry weight cementum is 70% inorganic, 21% collagen and 1% other organic substances (Williams and Elliott 1989).

Dentine differs to enamel in that it is a living cellular structure. Dentine by dry weight is 72% inorganic minerals (apatite), 18% organic protein (collagen) and 2% other organic substances (Williams and Elliott 1989). The mineral crystallites are shorter than enamel (~20-100nm) and seeded within the fine fibred mats of collagen. Dentine does not remodel like bone, primary dentine is laid down in successive layers during tooth formation and once it is formed it is permanent. Secondary dentine is formed on the walls and roof of the pulp chamber (Hillson 2005) usually in response to excessive tooth wear or pathology. Archaeological dentine can be soft or brittle, which may result in fracturing (Hillson 2005). Enamel and cementum protect the dentine but damage to an archaeological tooth can leave dentine exposed to moisture in the burial environment. The following section
will discuss diagenesis, possible methods for identifying it and how the quality of collagen and apatite are assessed.

**Bone diagenesis and collagen quality assessment**

Chemical indicators of calcified tissues are used as a source of inference in dietary reconstruction, climate, genetics and dating (Lee-Thorp and Sealy 2008). An understanding of calcified tissue diagenesis, most commonly termed ‘bone diagenesis’ for simplicity (Lee-Thorp and Sealy 2008) is fundamental and has been thoroughly investigated over the past two decades. The first bone diagenesis meeting took place in 1988 (Tütken and Vennemann 2011) and is a quadrennial event.

Diagenesis is defined as the rearrangement or recombination of elements of a mineral or chemical resulting in an altered state. ‘Bone diagenesis’ is the term used for the degradation and recombination of elements from the burial environment, of both organic and inorganic parts, within calcified tissue. Diagenesis of bones and teeth is influenced by many external influences including the environmental temperature, humidity and hydrology; the soil pH and reduction-oxidation conditions of the burial matrix and skeletal tissues; and microbial degradation (Tütken and Vennemann 2011). Diagenesis has been shown to be highly geographically, site and matrix specific. “Understanding, characterising and quantifying diagenetic processes in fossil skeletal remains are important when deciphering to what extent the original chemical information stored in the bioapatite and the biomolecules has been altered or retained” (Tütken and Vennemann 2011: 2).

Collagen can be altered in two ways, degradation of the original protein and contamination by exogenous substances from the burial environment. Collagen degradation is more common in tropical areas, while exogenous contamination is more common in temperate areas (van Klinken 1999). In collagen degradation, heat, humidity, or rising/falling water levels in the burial environment cause the breakdown of collagen α-chains the peptide bonds joining amino acids and the loss of peptides from the triple-helical structure of the collagen. While collagen degradation can result in changes to the weight % carbon to nitrogen (C:N) ratios (due to the loss of protein and therefore nitrogen), such degradation does not necessarily compromise the integrity of the delta (δ) values of the collagen stable isotope signature. Exogenous contaminants, the most common of which are humic acids and melanoidins (van Klinken 1999), leach from burial soil and interact with the collagen. They can affect both the carbon to nitrogen weight % ratio as well as the delta (δ) values of the collagen stable isotope signature.

The degree of diagenetic alteration occurring in bone can be assessed by collagen content, histological integrity, porosity, the content of elements incorporated diagenetically and apatite crystallinity. However, these indicators often do not correlate well with each other.
(Hedges 2002), and not all of them are applicable to apatite (Tütken and Vennemann 2011). Analyses that can quantify diagenetic influences on the chemical and structural integrity of bone and teeth include chemical analyses such as isotope ratio mass spectrometry (IRMS) and inductively coupled plasma mass spectrometry (ICPMS), mineralogical analyses including X-ray diffraction (XRD) and X-ray fluorescence (XRF), microscopic analyses like light microscopy (LM), cathodoluminescence (CL), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) and spectroscopic analyses including Raman, and infrared (IR) techniques (King et al. 2011; Trueman et al. 2008; Tütken and Vennemann 2011).

A standard set of quality control measures, including the atomic C:N ratio, %C and %N and collagen yield, are commonly utilised by the stable isotope community. These are automatically reported on analyses conducted with conventional modern mass spectrometers (Lee-Thorp and Sealy 2008) and are the most common and reliable tests.

The atomic weight C:N ratio is based on the percentage of carbon and nitrogen in a sample, this value is measured during combustion in a continuous-flow mass spectrometer. The equation used to calculate the atomic C:N ratio is:

\[
C:N = \left(\frac{\%C_{\text{sample}}}{\%N_{\text{sample}}}\right) \times 1.1666
\]

The C:N ratio was originally suggested by DeNiro (1985) who found archaeological mammalian bone that fell within the C:N range 2.9-3.6 had δ¹³C and δ¹⁵N values consistent with their ecology and modern equivalents from earlier studies. A C:N ratio between 2.9–3.6, because of its remarkable consistency (Lee-Thorp and Sealy 2008), is still the most commonly cited range in assessing collagen preservation and often the only criteria used. Samples that are not within this range are considered diagenetically altered and unsuitable either due to contamination or poor preservation, extreme values are more commonly associated with samples with low collagen yield than contamination (Ambrose 1990; Schoeninger et al. 1989). Several variations of this range have been used. A range of 2.6-3.4, cited as the conventionally acceptable range normally found in fresh bone, was used by Schoeninger et al. (1989). van Klinken suggested that the range of 2.9-3.6 advocated by DeNiro was too broad to identify contamination in samples. A range of 3.1-3.5 for C:N ratios was adopted at the Oxford radiocarbon dating laboratory (van Klinken 1999). Recent experimental work by Harbeck and Grupe (2009) found that C:N ratios higher than 3.6 retained reliable stable isotopic signatures and they suggested the C:N ratio range could be extended, if the samples passed the other quality control criteria.

The %C and %N values represent the amount, by weight, of the two elements in the prepared collagen. Percent carbon and nitrogen are measured with an elemental analyser
coupled to a continuous flow isotope ratio mass spectrometer, and these values are used in calculating C:N ratios. Using a sample comprised of modern mammalian bones and teeth, prehistoric herbivore teeth and historic and prehistoric human bone, Ambrose (1990) suggested the utility of %C and %N and collagen yield in addition to the C:N ratio.

Higher values of %C indicate samples have been altered by organic carbon, while lower values indicate addition of inorganic substances (van Klinken 1999). Ambrose (1990) argued that %C and %N are the most reliable indicators of collagen preservation. Ambrose found that very low levels of %C and %N in collagen are unequivocal indicators of poor preservation or diagenetic alteration and suggested, like Schoeninger et al. (1989), that collagen yield and C:N ratios are less reliable indicators of the quality of the preserved collagen (Ambrose 1990). A value of ≥3% for %C carbon and ≥1% for %N nitrogen are acceptable (Ambrose 1993). Brock et al. (2010; 2012) use %N as an indicator for the presence of collagen, citing 0.76 %N as the cut-off based on regression analyses for identifying viable samples. It has been found that %C and %N can provide inconsistent results that contradict C:N ratios. Iacumin et al. (1998) reported samples that had %C and %N values within the acceptable range, however, they had collagen yields lower than 1% or a C:N ratio above 3.6.

Collagen yield is an assessment of the percentage of collagen in the sample following chemical extraction of the protein. van Klinken (1999) suggested collagen yield is the most reliable indicator of degradation. Yield can indicate whether there is sufficient protein remaining to provide viable stable isotopic values, as protein loss or degradation will result in a low collagen yield. A collagen yield of >1% is acceptable (Dobberstein et al. 2009; van Klinken 1999). When collagen yield was lower than 1% in bone or dentine, the C:N ratio was found to be an inadequate indicator of preservation (Ambrose 1990; Schoeninger et al. 1989). Ambrose (1990) found that samples with low collagen yield have variable C:N ratios, low carbon and nitrogen concentrations, and δ¹³C and δ¹⁵N values unlike modern collagen. Samples with yields as low as 1% can provide acceptable stable isotope results, because collagen molecules are surprisingly robust, with the structural amino acids, C:N ratio and the integrity of δ¹³C and δ¹⁵N remaining intact until a critical point in fibril denaturation, where the hydrogen bonds are broken (Collins et al. 2002; Koon 2006; Lee-Thorp 2008) and more than 99% of the original collagen is gone (Dobberstein et al. 2009). At the Oxford radiocarbon dating laboratory, a cut-off point of 1% collagen is used and cases where yield is 0.5-1% are considered marginal for further analysis (van Klinken 1999). For apatite, there are no robust quality control measures.

Testing the quality of samples ensures representative isotopic signatures for dietary reconstruction. As reviewed above there has been significant debate over which are the best quality control criteria. The key papers often cited for these quality controls (Ambrose 1990; Ambrose 1993; DeNiro 1985), were predominantly developed using bone, except
for Ambrose (1990) who included herbivore teeth in his sample. Schoeninger et al. (1989: 290) concluded “neither the superficial appearance, the percentage of residue extracted, nor the C to N ratios can be used to predict how well collagen is preserved”. van Klinken (1999: 687) examined the question of whether the quality criteria discussed above can reliably distinguish contaminated or degraded samples from good ones and concluded that there is “no unequivocal way to detect natural levels of contamination with the discussed parameters”.

One problem with constructing these criteria for acceptable or non-acceptable samples is that they are based on viable samples, ones that passed gelatinisation in the first place, those samples which did not make it past that point are not included in the reference sample, they do not offer comparable measures (for instance C:N ratios), and “data sets are biased towards those that have produced acceptable end results” (van Klinken 1999: 688). van Klinken (1999: 692) found that while almost all of the quality control protocols have the potential to indicate questionable samples, “none of the indicators on its own is sufficiently powerful to indicate contamination or degradation with sufficient sensitivity” and that “no fail-safe ranges can be given for acceptance” of viable samples. Several studies have used artificial degradation to test the utility of these protocols on bone (Dobberstein et al. 2009; Harbeck and Grupe 2009). Harbeck and Grupe (2009: 55) concluded “no quality criterion taken alone is sufficient for the acceptance of stable isotopic data obtained from archaeological collagen as being valid”. In assessing these criteria, some samples which fall outside the recommended range may be included upon justification (Britton et al. 2012; Eerkens et al. 2011; Waters-Rist et al. 2011; Wright and Schwarcz 1999).

Although these studies have found that none of these criteria alone stand to provide a definitive measure of quality, used in concert they can provide some indication of diagenetic alteration and considering the importance of the implications drawn from the study of these they serve a purpose. But are these protocols appropriate for dental tissues? Studies of diagenesis have predominantly focussed on bone “although bone has been frequently investigated, little attempt has been made to combine textural, mineralogical, and chemical information for modern and fossil teeth” (Kohn et al. 1999: 2737). “Diagenetic pathways in bone, dentine and enamel and their organic and inorganic components vary markedly because of their chemical and structural differences” (Tütken and Vennemann 2011: 2). Dobberstein et al. (2008: 182) state “So far, there are no systematic data on collagen degradation in teeth. Although tooth and bone are mineralized tissues, their morphology and biochemistry are completely different. Thus, the data on collagen degradation in bone cannot be transferred uncritically to dental tissues.”

Ambrose (1990) found different results between the bone samples and the tooth samples, the latter which were a mix of enamel and dentine. Ambrose (1990) found that whole
teeth have significantly lower collagen yield, lower carbon and nitrogen concentrations in collagen and similar C:N ratios to bone. The lower carbon and nitrogen concentrations are thought to be a product of the lower collagen yield. Despite this, studies using dentine from historic teeth (Beaumont et al. 2012; Schroeder et al. 2009) or from temperate areas (Chenery et al. 2010; Fuller et al. 2003), have found that samples fall within an acceptable range for C:N. The following section will discuss the methods for measuring isotopes using mass spectrometry.

**Methodology of isotopic analysis**

Isotopes are measured as ratios, the heavier isotope to the lighter isotope, for example, $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$. These are measured with reference to international standards PDB (belemnite from the Pee Dee Formation in South Carolina) for carbon and AIR for nitrogen. The following equation defines the isotope ratio, expressed in permil (%) to distinguish the difference between the ratio of the sample stable isotopes and standard stable isotopes, with $R$ representing $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$.

\[
\delta = \left( \frac{[R_{\text{sample}}]}{[R_{\text{standard}}]} - 1 \right) \times 1000 \%
\]

For example,

\[
\delta = \left( \frac{[^{13}\text{C}/^{12}\text{C}]_{\text{sample}}}{[^{13}\text{C}/^{12}\text{C}]_{\text{PDB}}} - 1 \right) \times 1000\%
\]

Stable isotope analysis includes an appropriate ‘standard’ which is chosen to cover the probable isotopic range of the unknown material being analysed. A standard is a material with a known and replicable isotopic range. There are two types of standard used in an analytical measurement run of samples of unknown values. The primary standard is a laboratory reference material which is used to determine isotopic and elemental values. Commonly used laboratory reference standards are produced by the National Institute of Standards and Technology (NIST), the International Atomic Energy Agency (IAEA) and the United States Geological Survey (USGS). The second type of standard is a ‘control’ material which is used to determine precision and accuracy. Control materials have well-known and highly reproducible isotope values; for bone protein a commonly used control is EDTA, but laboratories will also create their own control materials or ‘internal standards’. Control materials provide an internal check of how accurate a given analytical run is, and a means by which to check the reproducibility of the results for the unknown material. All data reported by a laboratory should also include the type of external and internal standards used, and should quote the standard’s accepted value as well as the average value in the analytical run including the standard deviation of the analyses, as the standard deviation of the control material analysed provides the ‘plus/minus’ values to be quoted for the isotopic results of the unknown samples.
Mass spectrometry

Isotope ratio mass spectrometers (IRMS) measure the abundance ratios of stable isotopes. Isotope ratio mass spectrometers have four parts, the inlet, the ioniser, the analyser and the detector. The solid sample is converted to a gas that enters the mass spectrometer. For the elements hydrogen (H), oxygen (O), nitrogen (N), and carbon (C), the gases H₂, CO₂, N₂ and CO₂ are used respectively. Original work with stable isotopes required the sample of collagen or carbonate to be combusted before analysis, the resultant gases separated before entry into the inlet. Newer spectrometers now integrate the combustion process to convert the sample into the requisite gas, allowing a continuity of analysis. Collagen samples are precisely weighed (which allows for subsequent %weight of each element to be calculated) and placed in tin capsules that are loaded into a revolving automated sample tray, which drops them into the furnace where gases are produced. These gases are transported by helium and divided before entering the inlet of the mass spectrometer. The gas then continues to the ion source, where some of its molecules are ionised through electron bombardment, manipulating and directing them into a beam. This beam is then focussed through a flight tube to the analyser zone. The mass analyser passes the beam through the poles of a magnet, dividing the beam into smaller beams. This division of the ion beams into multiple beams, based on mass of each isotope, produces the mass spectrum. The concentration of the different beams is measured in the detector and reported as isotope ratios for example, \( ^{13}\text{CO}_2 : ^{12}\text{CO}_2 \). The aliquots are alternately analysed with samples of a known standard, providing a known ratio with which to compare the values of the unknown sample.

Alternative methods of analysis have been developed for samples which cannot easily be converted into a gas. Thermal ionisation mass spectrometry was developed to analyse strontium isotopes. Laser ablation inductively coupled plasma mass spectrometry was developed for pinpoint analysis of heavier elements like strontium (Latkoczy et al. 2001; Prohaska et al. 2002). Gas chromatography combustion isotope ratio mass spectrometry was developed to isolate and analyse specific compounds (Stott et al. 1999; Tripp and Hedges 2004). The next section will discuss the application of stable isotopes to subsistence studies.

Applying stable isotopes to subsistence studies

Information pertaining to the diet of past human populations traditionally relied on evidence preserved in the archaeological record, as a reflection of foods the individuals consumed, bones, shells, seeds and pollen (Miracle and Milner 1998; Ungar and Teaford 2002). The disadvantage of this approach is the interpretation of dietary practices is solely reliant on observations of preserved, recovered and visible material. Recovery and preservation of floral and faunal material very rarely reflect the proportions in which they were consumed (Ambrose 1993). Stable isotopes cannot be used to directly identify
specific foods, but can be used to identify the isotopic composition of potential foods featured in the diet and the isotopic composition of the tissues of the consumer. Using that data and appropriate enrichment factors a profile of the diet is developed and compared to the isotopic composition of the consumer’s tissues to interpret the diet of the individuals of interest. To accurately assess the diet of an individual, the local values for likely foods must be known. Local values are important because these vary by region or climate. The following section will discuss the isotopic variation in plants.

Dietary studies focus on stable isotope values in humans and other animals, but this must take into consideration the values in plants, as they contribute to the diet of both. The isotopic values of plants are dependent on relative humidity, temperature and soil nutrients; while in animals isotopic values are dictated almost entirely by their diet. Almost all plants (excluding fungi) acquire their energy through photosynthesis. Photosynthesis is a chemical process where plants use energy from sunlight to convert atmospheric carbon dioxide (CO₂) into organic compounds, particularly glucose. Depending on the photosynthetic pathway of the plant, the way that they fix carbon from the atmosphere (C₃, C₄ or CAM), the ratio of ¹²C to ¹³C isotopes is reflected differently in the tissues relative to the atmosphere due to fractionation.

Contemporary atmospheric CO₂ levels are slightly higher than they were in the past due to the burning of fossil fuels, this is referred to as the Suess effect (Keeling 1979). Modern atmospheric CO₂ has a δ¹³C of -8‰, originally, in preindustrial times the value was around -7‰. If we use modern plant δ¹³C values as proxies for ancient diet sources, we must adjust their carbon value by ~1.5‰ to correctly assess how terrestrial plant diets would affect consumer carbon values.

There are three types of terrestrial plants, which differ in their expression of ¹³C, based on their photosynthetic pathway; C₃ plants, C₄ plants and CAM plants. These different pathways produce different isotopic signatures because heavier isotopes with a higher mass (¹³C) usually react slower than lighter isotopes with a smaller mass (¹²C) (Katzenberg 2008). Only slight variations occur within each photosynthetic type (O’Leary 1981) but the differences allow us to differentiate between those plants that featured in an individual’s diet. C₃ plants usually dominate in temperate climates and include all trees, most forbs, wheat, rice, nuts and most other vegetables and fruit, which use the Calvin pathway for photosynthesis. C₄ plants are tropical grasses and some shrubs that include maize, sorghum, millet and sugar cane that use the Hatch – Slack pathway for photosynthesis. Adapted to heat and aridity they minimise water loss by reducing the amount of time that their stomata, the pores in their leaves, are open. CAM plants are succulents such as cacti, euphorbias, agaves and pineapple and use crassulacean acid metabolism (Ambrose 1993). They show large variation in isotopic fractionation with temperature, which other plants do not (O’Leary 1981).
As a result of their different way of fixing atmospheric carbon for photosynthesis, $C_3$ plants express $^{13}C$ values between -20 to -35‰ and $C_4$ plants express values between -9 to -14‰ (Deines 1980). Slight variations in these ranges are cited throughout the literature (Bender 1971; Bentley et al. 2005; Bentley et al. 2007; Heaton 1999; Katzenberg 2008; King 2008; Krigbaum 2005; O’Leary 1995; Smith and Epstein 1971). However, the pertinent point is that the ranges are non-overlapping. These distinctly separate ranges of $C_3$ and $C_4$ plants provide the opportunity for investigating carbon to determine diet in prehistoric human tissues.

In palaeodietary reconstruction $\delta^{13}C$ values are most commonly used to differentiate between the consumption of $C_3$ and $C_4$ plants, which cluster in distinctive non-overlapping groups, and marine and terrestrial plants, which differ by at least 7‰. Terrestrial plants only have one carbon source for photosynthesis, atmospheric $CO_2$ with a modern $\delta^{13}C$ of -8‰. The carbon source for photosynthesis in marine plants is dissolved bicarbonate $HCO_3^-$, with a $\delta^{13}C$ of 0‰ (Ambrose 1993; Katzenberg 2008; Smith and Epstein 1971; Tauber 1981). Therefore, plants from marine environments will have higher $\delta^{13}C$ values compared to terrestrial plants. Freshwater plants have several carbon sources, in addition to $CO_2$ from the atmosphere and the water, the rocks and soils in the environment provide carbonate and bicarbonate and the other plants and animals provide organic carbon from decomposition and waste. Due to these multiple sources of carbon freshwater plants have variable $\delta^{13}C$ values. This difference in the $\delta^{13}C$ value of the plants is then reflected in mammals, including humans who consume from these three ecosystems.

The $\delta^{13}C$ of terrestrial plants is variable depending on their access to $CO_2$, in forests this is called the ‘canopy effect’. There is a vertical gradient of decreasing $\delta^{13}C$ values in the leaves of plants from the top of the canopy to floor of the forest (Ambrose 1993; Heaton 1999; Krigbaum 2001; Medina and Minchin 1980; van der Merwe and Medina 1989, 1991; Vogel 1978a). There are similar variations in plants growing in closed and open areas, as they have differential access to irradiance and $CO_2$. Vegetation grown in open areas with access to sun and abundant $CO_2$ have reported $\delta^{13}C$ values around -27‰, which is also the average value of $C_3$ vegetation. Understory $C_3$ vegetation, which have less access to sun and depend on recycled $CO_2$, have reported $\delta^{13}C$ values ≤-30‰. These possible environmental effects must be taken into consideration when assessing the diet of individuals. Another environmental effect is demonstrated in plants growing at high altitudes (above 1000m) which have been shown to have higher $\delta^{13}C$ values compared to plants at lower altitudes, due their adaptation to the lower partial pressure of $CO_2$ (Körner et al. 1991).

Most plants obtain nitrogen from the decomposition of other organic matter in the soil, which produces nitrate ($NO_3^-$) or ammonia ($NH_3$). Legumes are the exception and obtain nitrogen through a symbiotic relationship with the bacterium Rhizobium. These bacteria
exist among the roots of legumes and can fix nitrogen, combining it with other elements to make it available to the plant (Brill 1977). Most legumes, therefore, have nitrogen values closer to atmospheric nitrogen (0‰) (Delwiche and Steyn 1970; Katzenberg 2008), lower than other plants, however, not all legumes utilise this form of symbiosis (Codron et al. 2005; Muzuka 1999) and some are similar to other plants which have higher δ¹⁵N values.

Environmental variation in δ¹⁵N has been identified in plants from coastal and inland environments; and arid and wetter regions (Heaton 1987; Shearer et al. 1983; Virginia and Delwiche 1982). Marine plants also have a δ¹⁵N value about 4‰ higher than terrestrial plants (Ambrose 1993; Schoeninger and DeNiro 1984). In addition to this δ¹⁵N of collagen is different between organisms due to their nitrogen balance (Fuller et al. 2005) and can vary among different domestic animals; it may also be affected by consumption of plants with nitrogen fixing bacterium, for example, legumes (DeNiro and Hastorf 1985), or plants which have been manured (Bogaard et al. 2007).

Both carbon and nitrogen demonstrate trophic level effects. δ¹³C values increase by about 1‰ per trophic level (DeNiro and Epstein 1978) while nitrogen is successively enriched with trophic level (Minagawa and Wada 1984; Schoeninger and DeNiro 1984). Nitrogen isotope ratios (¹⁵N/¹⁴N) increase from plants to herbivores and to secondary carnivores. Herbivorous animals who consume only plants have δ¹⁵N values which are about 3‰ higher than their diet. It has been suggested that enrichment might be slightly larger in humans (O’Connell et al. 2012). Carnivorous freshwater fish present a particularly strong trophic level effect, resulting in higher ¹⁵N values. The status of the animal, whether carnivorous, herbivorous or omnivorous and where in the trophic food chain they sit has an effect on their expression of stable isotopes.

If tissues other than bone collagen are used for analysis, we should be aware that the metabolic process for each tissue can alter δ¹⁵N and can produce different δ¹⁵N values within the same individual (Vanderklift and Ponsard 2003). It has also been demonstrated that δ¹⁵N is sensitive to environmental or physiological stress among animals of the same species; arid and wetter regions produce variations in δ¹⁵N between water stressed animals and equivalent non stressed animals, with higher δ¹⁵N for the same species in arid regions (Ambrose 1991; Heaton et al. 1986).

Schoeninger and DeNiro (1984) were the first to discover that herbivores of the same species under water stressed conditions had higher δ¹⁵N. Ambrose and DeNiro (1986) proposed a model to explain this. During the normal physiological processes nitrogen is lost with urea expelled in urine. Urea is depleted in ¹⁵N in comparison to the diet. If an individual is deprived of water, adaptations to physiological processes result in a dramatic increase in the loss of urea, because urea is depleted in ¹⁵N, more ¹⁴N is lost during fractionation, resulting higher δ¹⁵N values. The enriched ¹⁵N retained in the individual is
incorporated into its amino acids and into the tissues (Ambrose and DeNiro 1986). The end result is a higher $\delta^{15}N$ value in comparison to other animals that are water dependent and do not have the same mechanisms for dealing with water stress.

An abnormally low intake of protein for a species also causes elevated $\delta^{15}N$ values. This can be caused by environmental stress, heat and water stress resulting in a reduction in food intake. Any circumstances where the body is in starvation mode or obtains inadequate sources of protein cause the body to catabolise its own cells. This produces higher $\delta^{15}N$ values in new cells, relative to that in the original cells, for example, in a water stressed individual these are already enriched in $^{15}N$. This has been demonstrated in birds (Hobson et al. 1993; Hobson and Clark 1992) and human skeletal remains (Katzenberg and Lovell 1999; White and Armelagos 1997).

Sulphur $\delta^{34}S$ can provide additional information to palaeodietary analysis. Sulphur has not been commonly used in archaeological studies due to extended laboratory preparation and the large sample required for analysis. $\delta^{34}S$ is now able to be measured in conjunction with $\delta^{13}C$ and $\delta^{15}N$ using CF-IRMS requiring about ~10mg of collagen per sample. Sulphur is measured as a ratio $^{32}S$ to $^{34}S$ relative to the meteorite standard Canyon Diablo Troilite (now the Vienna CDT) (Coplen and Krouse 1998).

There are two primary sulphur reservoirs, the metallic core of the earth which has a $\delta^{34}S$ value close to 0‰ and oceanic sulphate with a $\delta^{34}S$ value of close to 20‰. The largest source near the earth’s surface are sedimentary rocks, however, their $\delta^{34}S$ values are variable, dependent on their age and composition (Faure 1977). Plants acquire sulphur in a range of ways with most absorbing sulphate through their roots from the weathering of geological formations, however, they can also attain sulphur through dry or wet processes. Wet processes involve the uptake of sulphur from sea spray or acid rain ($H_2SO_4$). Dry processes involve incorporation of $SO_2$ gas. Plant $\delta^{34}S$ varies depending on local geology, with values ranging from -22 to 22‰ (Peterson and Fry 1987). There are differences in the expression of $\delta^{34}S$ between plants and animals in freshwater and marine environments. Marine organisms have $\delta^{34}S$ values close to 20‰ while freshwater organisms can have $\delta^{34}S$ values from -22 to 22‰ (Peterson and Fry 1987) as a result of the anaerobic bacteria that reside in freshwater sources which have the ability to reduce sulphate ions to hydrogen sulphide (Faure 1977). Few studies have focussed on controlled feeding experiments to determine fractionation between diet and $\delta^{34}S$ in the consumer tissues of mammals, however, one found that fractionation in $\delta^{34}S$ between a $C_3$ diet and consumer hair was negligible at -1‰, while fractionation between a $C_4$ diet and consumer hair was +4‰ (Richards et al. 2003). Sources of $\delta^{34}S$ in the foodweb include underlying local bedrock, the atmosphere and microbial action in the soil. Sampling local human and faunal $\delta^{34}S$ can provide a local signature of the foodweb for a specific area. Once this is established, immigration and residence can be examined using $\delta^{34}S$ providing there is a
distinction in the geology or environment of the locals and immigrants. $\delta^{34}$S values also have potential in palaeodietary reconstruction when used as an accessory to $\delta^{13}$C and $\delta^{15}$N (Richards et al. 2003).

**Summary of isotope effects**

$\delta^{13}$C can be used to differentiate between C$_3$ and C$_4$ plants and animals that consume them and between the consumption of marine and terrestrial foods. If the $\delta^{13}$C of an individual’s tissues are high, which could be due to the consumption of C$_4$ or marine foods, you can examine $\delta^{15}$N to differentiate between them. The consumption of a diet of marine foods would result in high $\delta^{15}$N values due to the high trophic levels in marine foodwebs. If the high $\delta^{13}$C values were due to the consumption of C$_4$ plants, the $\delta^{15}$N values would be lower. It is important to be aware of the possible causes of an enrichment or depletion of isotope ratios in $^{13}$C and $^{15}$N in human samples as there are many subtle differences in their expressions due to the environment of the animals the humans are consuming (Table 6.1). It is imperative to use a food web from the region under investigation and use a biogeographical model to interpret the results due to environmental differences in expression of $\delta^{13}$C and $\delta^{15}$N values.

Table 6.1. Common causes for enrichment or depletion of carbon and nitrogen

<table>
<thead>
<tr>
<th>CARBON</th>
<th>Enriches $^{13}$C (less -)</th>
<th>Depletes $^{13}$C (more -)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trophic level - consuming other animals 1‰</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consuming marine animals (indirect plant)</td>
<td>Consuming terrestrial animals (indirect plant)</td>
<td></td>
</tr>
<tr>
<td>Consuming grazing animals (indirect plant)</td>
<td>Consuming browsing animals (indirect plant)</td>
<td></td>
</tr>
<tr>
<td>Consuming C4 plants</td>
<td>Consuming C3 plants</td>
<td></td>
</tr>
<tr>
<td>Eating plants from high altitudes</td>
<td>Eating plants from low altitudes</td>
<td></td>
</tr>
<tr>
<td>Consuming plants in cleared areas</td>
<td>Consuming plants in covered areas</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NITROGEN</th>
<th>Enriches $^{15}$N</th>
<th>Depletes $^{15}$N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trophic level - consuming other animals 3‰</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consuming drought adapted animals</td>
<td>Consuming legumes</td>
<td></td>
</tr>
<tr>
<td>Consuming plants that have been manured</td>
<td>Consuming animals that eat legumes (indirect plant)</td>
<td></td>
</tr>
</tbody>
</table>

**Assumptions about isotopes for diet reconstruction**

The reconstruction of diet using carbon and nitrogen isotopes is grounded in the assumption “you are what you eat (plus a few ‰)” (DeNiro and Epstein 1976). This adage epitomises what we know about isotopic signatures in food in a given diet and the trophic effect of enrichment at each step of the food chain. But how and in what proportion carbon and nitrogen are sourced from the diet is also important for modelling what an individual’s collagen isotopic signature indicates about past diet.

There is no nitrogen in carbohydrates and fats (Ambrose et al. 1997; Lassar-Cohn 1908;
Sanders and Emery 2003), therefore the nitrogen isotope ratio of consumer tissues are mainly a reflection of dietary protein, plus the enrichment from the trophic level effect. For the $\delta^{15}N_{\text{collagen}}$ of a consumer’s tissues, you are what you eat plus 3-4‰ (Minagawa and Wada 1984; Schoeninger and DeNiro 1984).

In order to elucidate dietary information from carbon isotopes in tissues, it is important to understand how carbon is utilised by the body and what the carbon analysed from tissue is actually reflecting in terms of the diet. This was debated early in palaeodietary analyses and two models were proposed to explain how dietary carbon is reflected in collagen.

The first model was the linear mixing model. This model suggested that carbon in collagen is representative of the whole diet (protein, carbohydrates and fats), these are scrambled together and are all represented equally in the carbon from bone collagen (Schoeninger 1989; Schwarz 1991; van der Merwe 1982). This model was used to try and calculate the specific contributions of particular foods to the diet, for example, maize or marine foods. Vogel and van der Merwe (1977) used this model to interpret maize consumption in New York State. They assumed the carbon content of collagen varied linearly and attempted to calculate maize consumption over time. This assumption was also used in other studies to estimate the amount of marine and terrestrial resources consumed (Chisholm et al. 1982; Chisholm et al. 1983; Schoeninger et al. 1983; Schoeninger 1989; Schwarz et al. 1985; Spielmann et al. 1990; Tauber 1981; van der Merwe 1982; Walker and DeNiro 1986; White and Schwarz 1989).

Kennedy (1988), who performed experiments on rats, demonstrated that the collagen from rats consuming a low animal protein diet presented a larger input of carbon from carbohydrates, suggesting that some of the carbon represented in the collagen was reflecting non-protein sources, the amount dependent on how much of the diet was derived from protein sources. The linear mixing model is appropriate for determining dietary differences between similar types of animals, for example, grazers and browsers (Tieszen 1991; Vogel 1978b), while the utility of the model becomes problematic when applied to omnivores consuming protein, carbohydrates and fats with differential carbon isotopes values (Klepinger and Mintel 1986).

The second model was the routing model or direct transmission model. This model suggested that the carbon ratio reflected in all tissues in the consumer directly reflect the isotopic ratio of foods consumed, that the carbon from protein is preferentially routed and synthesised in protein and bone collagen (Chisholm et al. 1982; Chisolm 1989; Krueger and Sullivan 1984; Sullivan and Krueger 1983).

Krueger and Sullivan (1984) were the first to propose that carbon from the carbonate of bones and teeth reflect different dietary components than carbon in collagen, they
suggested that the carbon from collagen in bone is a reflection of the growth substrate (protein), while the carbon from bone mineral is a reflection of the energy substrate (proteins, carbohydrates and fats not used for synthesising protein tissue). They suggested the dietary protein consumed is primarily routed for synthesising protein in tissues, including collagen. While fats, carbohydrates and surplus protein not used for synthesising tissues are metabolised to CO$_2$ and reflected in the blood as bicarbonate.

Based on this assumption, bone apatite and bone collagen carbon values could be investigated experimentally in comparison to the proportion of carbohydrates, fats and protein consumed. The differences between $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ ($\Delta^{13}C_{\text{apatite-collagen}}$) were expected to be around $+3\%$ for carnivores and $+7\%$ for herbivores (Krueger and Sullivan 1984). Because of their omnivorous diet humans were anticipated to have intermediate values. This prediction was later substantiated (Lee-Thorp 1989). It was also suggested that carbon reflected in bone apatite represents trophic level effects because the spacing ($\Delta^{13}C_{\text{apatite-collagen}}$) was larger in herbivores ($+7\%$) than carnivores ($+3$ to $+4\%$) (Krueger and Sullivan 1984; Lee-Thorp 1989).

Independent, controlled feeding experiments (Ambrose and Norr 1993; Tieszen and Fagre 1993) demonstrated that Krueger and Sullivan were correct in their assertion that carbon from collagen is primarily reflective of the consumption of protein from the diet, while carbon from apatite reflects the whole diet. The reason for this lies in the constituents of essential and nonessential amino acids in collagen. The essential amino acids are sourced from protein, while the nonessential amino acids may be from protein or synthesised from other dietary sources and the dissolution of biological products in the body (Katzenberg 2008). The carbonate in the bone forms from dissolved bicarbonate in the blood originally sourced from dietary carbohydrates, fats and protein. Therefore, carbon in apatite reflects the whole diet and collagen is more indicative of protein consumption.

Controlled feeding experiments have been essential in our understanding of the causes of isotopic enrichment or depletion in biological tissues. Ambrose and Norr (1993), and Tieszen and Fagre (1993) independently tested the routing model to understand the relationship with diet and how it is reflected in bone collagen and bone apatite. Both conducted controlled feeding studies using rats and mice respectively. Ambrose and Norr (1993) selected proteins from opposite photosynthetic pathways ($C_3$ or $C_4$), cellulose, starch and oils; and Tieszen and Fagre (1993) used protein, cellulose, starch and lipids. Controlling the source of food and analysing the tissues they were able to assess the contribution of different macronutrients in the tissues of the consumers. Both studies supported the findings of Krueger and Sullivan (1984).

These controlled feeding studies of animals by Ambrose and Norr (1993) and Tieszen and Fagre (1993), and further case studies by Ambrose et al. (1997) and Norr (1995),
all suggest that collagen does utilise the routing model, with amino acids from ingested protein preferentially used in the production of collagen. Two of the diets in particular demonstrate how dietary protein is preferentially reflected in the tissues. The carbon of one diet constituted 95% C$_3$ (carbohydrates and fats) and 5% C$_4$ protein by weight, the second constituted 95% C$_4$ non-protein and 5% C$_3$ protein by weight (Ambrose and Norr 1993: 17 Table 4). These diets differed by 12‰ in their whole diet carbon value, however, the bone collagen values of the rats differed by only 1‰. An analysis of the collagen tissue value would suggest that both rat diets consisted of high C$_4$, however, that was not the case. The low protein diet demonstrates that about half the δ$^{13}$C represented in the consumer’s tissues came from protein in their diet. This has implications in palaeodietary reconstruction, when the constituents of a diet are unknown but potentially non-monoisotopic, where protein and non-protein food sources have different carbon isotope ratios, δ$^{13}$C$_{\text{collagen}}$ may not accurately predict diet (Ambrose et al. 1997; Froehle et al. 2010).

In order to elucidate dietary information from carbon isotopes in tissues, an understanding of the multiple isotopic fractionations that occur from dietary consumption to consumer tissues is vital. In the rats of Ambrose and Norr’s (1993) study that were fed a primarily C$_3$ diet, the collagen diet spacing (Δ$^{13}$C$_{\text{collagen-diet}}$) was +9.6‰ while for the rats on the C$_4$ diet it was -1.5‰. The mean Δ$^{13}$C$_{\text{collagen-diet}}$ values ranged from -2.3‰ to +10.0‰. These rats were not what they ate +5‰, however, the Δ$^{13}$C$_{\text{collagen-diet}}$ reflected a simple linear function reflecting the difference between the δ$^{13}$C value of the whole diet and the dietary protein (Ambrose et al. 1997). These experiments showed that while the Δ$^{13}$C$_{\text{collagen-diet}}$ is variable, it is a reflection of the difference between the δ$^{13}$C of protein and the whole diet. The rats were what they ate +5‰ only when the protein and non protein constituents of the diet had identical δ$^{13}$C values. Therefore, where the Δ$^{13}$C$_{\text{protein-diet}}$ = 0‰ the rats were what they ate +5‰ regardless of the proportion of protein in the diet; low, normal or high. This enrichment was not affected by the amount of protein consumed. This suggests that if the carbon isotopes of protein and non protein sources are different, the isotopic composition of the whole diet may not be accurately reflected by analysing collagen in dietary studies (Ambrose et al. 1997).

These studies, however, found that bone apatite accurately reflects the whole diet, utilising the linear mixing model (Schwarcz 1991). Apatite does not under or overestimate the contribution of carbon from proteins, carbohydrates or fats (Ambrose and Norr 1993; Tieszen and Fagre 1993). The Δ$^{13}$C$_{\text{apatite-diet}}$ was consistent between both experimental feeding studies, you are always what you eat plus about 9.4‰. Ambrose and Norr found that they could only force the Δ$^{13}$C$_{\text{apatite-diet}}$ to vary between 8.8‰ and 10.9‰ regardless of the portion of protein to non-protein or differences in the carbon isotopic composition of food (Ambrose et al. 1997). Bone apatite can then be used with collagen to further elucidate possible ambiguities in the interpretation of collagen.
The protein portion of the diet has important implications for understanding dietary composition because of its correlation with collagen. The findings of these studies suggest that for δ\textsuperscript{13}C<sub>apatite</sub> you are always what you eat +9.4‰ and for δ\textsuperscript{13}C<sub>collagen</sub> you are what you eat +5‰ if you are consuming a monoisotopic diet, therefore Δ\textsuperscript{13}C<sub>apatite-collagen</sub> will be 4.4‰ if the diet is monoisotopic, if the diet is not monoisotopic the Δ\textsuperscript{13}C<sub>apatite-collagen</sub> value will either be higher or lower than 4.4‰. Ambrose et al. (1997) suggested if the Δ\textsuperscript{13}C<sub>apatite-collagen</sub> results in a value greater than 4.4‰, the dietary protein is more depleted than the whole diet, for example, consuming C\textsubscript{3} protein and C\textsubscript{4} carbohydrates. If the Δ\textsuperscript{13}C<sub>apatite-collagen</sub> is smaller than 4.4‰, the dietary protein is more enriched than the whole diet, for example, C\textsubscript{4} marine protein and C\textsubscript{3} carbohydrates.

While these experimental feeding studies supported Krueger and Sullivan’s (1984) findings, the values for diet-tissues differed between the rats in Ambrose and Norr’s (1993) study and the free ranging animals in Krueger and Sullivan’s. Apatite was originally suggested to be indicative of trophic level effects, as the Δ\textsuperscript{13}C<sub>apatite-diet</sub> values for herbivores were 11-14‰ and carnivores were 8-9‰ (Krueger and Sullivan 1984; Lee-Thorp 1989). The interpretation of the differences in the Δ\textsuperscript{13}C<sub>apatite-diet</sub> were modelled on the assumption apatite is a derivative of the metabolism of energy (Ambrose et al. 1997). If carnivores were deriving a large amount of energy from fats, with lower δ\textsuperscript{13}C values than other dietary sources, this would explain the difference in spacing, however, Tieszen and Fagre’s study (1993) questioned this assertion. The alternative explanation is that ruminant herbivores generate a large amount of methane which is depleted in δ\textsuperscript{13}C in comparison to diet, this is balanced by respired CO\textsubscript{2} with a high δ\textsuperscript{13}C value. It has been suggested that the enriched CO\textsubscript{2} explains the high herbivore Δ\textsuperscript{13}C<sub>apatite-diet</sub> values (Hedges and van Klinken 2000). As rats, carnivores and humans produce little methane and consume relatively low protein, low fat diets they probably do not have the same high Δ\textsuperscript{13}C<sub>apatite-diet</sub> values. It has therefore been suggested that a Δ\textsuperscript{13}C<sub>apatite-diet</sub> value of ~9.4‰ is probably more appropriate for humans (Ambrose et al. 1997). Ruminant herbivores are probably not a good analogue for human diet reconstruction.

These previous studies focussed on rodents to study the presentation of isotopic ratios in tissues and how these relate to diet. The results of these feeding studies have had important implications for dietary reconstruction as most researchers have used this as a basis to interpret their results (Tykot et al. 2009). However, it has been suggested that as rodents differ to humans in their size, feeding habits, digestive physiology and metabolic rate (Baker 2008) they may also not be good analogues for humans. As a result, some researchers have used swine as an alternative animal model (Warinner and Tuross 2009). Swine are more similar to humans than rodents in their size, omnivorous diet, amino acid requirements (van der Merwe et al. 2003) and digestive physiology, including a monogastric gastrointestinal tract (Warinner and Tuross 2009). With this justification several feeding studies have been conducted on swine (Hare et al. 1991; Howland et
These researchers found discrepancies between bone and enamel apatite and diet, however, each study had several confounding factors which made any inferences regarding the offsets problematic (Warinner and Tuross 2009). Howland et al. (2003), who raised swine on six different controlled diets and analysed the bone collagen and apatite, found that $\Delta^{13}C_{\text{apatite-diet}}$ values for bone ranged from 8.7 to 12.1‰, while Passey et al. (2005) who also conducted a controlled feeding study on swine, but analysed enamel apatite rather than bone, found a 13.3‰ difference in $\Delta^{13}C_{\text{apatite-diet}}$. This difference was attributed by Passey et al. (2005) to the differential digestion of dietary components in the mixed diets.

Table 6.2. Alternative values for tissue enrichment and spacing based on swine studies $\varepsilon$

<table>
<thead>
<tr>
<th>Carbon $\varepsilon$</th>
<th>$\delta^{13}C$ Tissue</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>$\delta^{13}C$ bone collagen-diet ($C_3$)</td>
<td>(Howland et al. 2003: 50 Table 3)</td>
</tr>
<tr>
<td>4</td>
<td>$\delta^{13}C$ bone collagen-diet ($C_4$)</td>
<td>(Howland et al. 2003: 50 Table 3)</td>
</tr>
<tr>
<td>1.4</td>
<td>$\delta^{13}C$ bone collagen-diet ($C_3$)</td>
<td>(Hare et al. 1991: 282 Table 2)</td>
</tr>
<tr>
<td>3.2</td>
<td>$\delta^{13}C$ bone collagen-diet ($C_4$)</td>
<td>(Hare et al. 1991: 282 Table 2)</td>
</tr>
<tr>
<td>4.2</td>
<td>$\delta^{13}C$ bone collagen-diet ($Diet_{raw}$)</td>
<td>(Warinner and Tuross 2009: 1693 Table 4)</td>
</tr>
<tr>
<td>3.3</td>
<td>$\delta^{13}C$ bone collagen-diet ($Diet_{raw}$)</td>
<td>(Warinner and Tuross 2009: 1693 Table 4)</td>
</tr>
<tr>
<td>3.7</td>
<td>$\delta^{13}C$ bone collagen-diet</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Carbon $\varepsilon$</th>
<th>$\delta^{13}C$ Tissue</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.1</td>
<td>$\delta^{13}C$ bone apatite-diet ($C_3$)</td>
<td>(Howland et al. 2003: 50 Table 3)</td>
</tr>
<tr>
<td>11.2</td>
<td>$\delta^{13}C$ bone apatite-diet ($C_4$)</td>
<td>(Howland et al. 2003: 50 Table 3)</td>
</tr>
<tr>
<td>12.2</td>
<td>$\delta^{13}C$ bone apatite-diet ($Diet_{raw}$)</td>
<td>(Warinner and Tuross 2009: 1693 Table 4)</td>
</tr>
<tr>
<td>12</td>
<td>$\delta^{13}C$ bone apatite-diet ($Diet_{raw}$)</td>
<td>(Warinner and Tuross 2009: 1693 Table 4)</td>
</tr>
<tr>
<td>11.9</td>
<td>$\delta^{13}C$ bone apatite-diet</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta^{13}C_{\text{apatite-collagen}}$</th>
<th>$\delta$ Tissue</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1</td>
<td>$\delta^{13}C$ enamel apatite-bone collagen ($Diet_{raw}$)</td>
<td>(Warinner and Tuross 2009: 1693 Table 4)</td>
</tr>
<tr>
<td>10.8</td>
<td>$\delta^{13}C$ enamel apatite-bone collagen ($Diet_{raw}$)</td>
<td>(Warinner and Tuross 2009: 1693 Table 4)</td>
</tr>
<tr>
<td>10.5</td>
<td>$\delta^{13}C$ enamel apatite-bone collagen</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nitrogen $\varepsilon$</th>
<th>$\delta^{15}N$ Tissue</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>$\delta^{15}N$ bone collagen-diet ($C_3$)</td>
<td>(Hare et al. 1991: 282 Table 2)</td>
</tr>
<tr>
<td>2.2</td>
<td>$\delta^{15}N$ bone collagen-diet ($C_4$)</td>
<td>(Hare et al. 1991: 282 Table 2)</td>
</tr>
<tr>
<td>2.3</td>
<td>$\delta^{15}N$ bone collagen-diet</td>
<td></td>
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</tbody>
</table>

$\varepsilon =$ enrichment factor  
$\bar{x} =$ average
Most scholars dealing with isotopic enrichment between diet and animal tissues use a simple equation of $\Delta_{A-B} = \delta^{13}C_A - \delta^{13}C_B$. Passey et al. (2005) suggest using an algebraic equation to estimate dietary values, because $\Delta_{A-B} = \delta^{13}C_A - \delta^{13}C_B$ is accurate when the isotopic differences are less than 10‰ but if the difference is more than 10‰ the equations become specific to the region of the isotopic scale in which it was calculated (PDB or AIR).

As it is not possible to study human diet, modern animal studies provide possible analogues. It is important to try and select appropriate enrichment factors ($\varepsilon$) when reconstructing diet. Due to the variations in the literature between different species in animal feeding studies, for example, swine and rats, both possibilities are presented below.

To estimate the protein and bulk dietary value from $\delta^{13}C_{\text{collagen}}$ from tooth gelatin when using $\varepsilon$ based on modern animal studies:

$$=(((1+(\delta^{13}C_{\text{collagen}}/1000))/(1+(\varepsilon \delta^{13}C_{\text{collagen-diet}}/1000))-1)*1000)$$

To estimate the bulk dietary value from $\delta^{13}C_{\text{apatite}}$ from tooth enamel when using $\varepsilon$ based on modern animal studies:

$$=(((1+(\delta^{13}C_{\text{apatite}}/1000))/(1+(\varepsilon \delta^{13}C_{\text{apatite-diet}}/1000))-1)*1000)$$

To estimate the protein dietary value from $\delta^{15}N_{\text{collagen}}$ from tooth gelatine when using $\varepsilon$ based on modern animal studies:

$$=(((1+(\delta^{15}N_{\text{collagen}}/1000))/(1+(\varepsilon \delta^{15}N_{\text{collagen-diet}}/1000))-1)*1000)$$

Using swine as an analogue:

$\varepsilon \delta^{13}C_{\text{collagen-diet}} = 3.7$ (Hare et al. 1991; Howland et al. 2003; Warinner and Tuross 2009)

$\varepsilon \delta^{13}C_{\text{apatite-diet}} = 13.9$ (Passey et al. 2005; Warinner and Tuross 2009)

$\varepsilon \delta^{15}N_{\text{collagen-diet}} = 2.3$ (Hare et al. 1991)

Using rats as an analogue:

$\varepsilon \delta^{13}C_{\text{collagen-diet}} = 5.0$ (Ambrose et al. 1997)

$\varepsilon \delta^{13}C_{\text{apatite-diet}} = 9.4$ (Ambrose et al. 1997)

**Bone apatite and enamel apatite**

In considering the issues of discrepancies between different tissues found in swine studies, Warinner and Tuross (2009) performed a controlled monoisotopic feeding study on 11 swine. They sampled bone collagen from two sites, and bone apatite and enamel
apatite from each animal to understand how the dietary components were reflected in the tissues. They found that the positions sampled for bone collagen were equivalent in their expression of $\delta^{13}C_{\text{collagen}}$. However, they found that bone apatite and enamel apatite were not equivalent in their expression of $\delta^{13}C_{\text{apatite}}$: enamel apatite was enriched over bone apatite (Warinner and Tuross 2009). Their finding that enamel apatite was consistently enriched over bone apatite by an average of $2.3\%$ in $\delta^{13}C$ may have important implications for dietary reconstruction when using enamel apatite.

Warinner and Tuross (2009) also focused on the relationship between $\delta^{13}C_{\text{diet}}$ and $\delta^{13}C_{\text{collagen}}$ using their data and data from previously published experiments on rodents and swine. They argued that swine are physically more analogous to humans than rodents. They also suggested $\delta^{13}C_{\text{apatite}}$ correlates more closely with $\delta^{13}C_{\text{diet}}$ than $\delta^{13}C_{\text{collagen}}$ does. Froehle et al. (2010) reevaluated Warinner and Tuross’ sample, however, they only used the $\delta^{13}C$ bone collagen and bone apatite data. They omitted experimental data from enamel apatite. They demonstrated that the disparities between rodents and swine cited by Warinner and Tuross (2009) were actually a reflection of differences in the protein composition of the experimental diets rather than metabolic differences between the animals. They argue that rodents and swine provide equally good (or poor) analogues for human diet reconstruction (Froehle et al. 2010).

Although the disparities noted by Warinner and Tuross were dismissed by Froehle et al. (2010), the enrichment of tooth enamel apatite over bone apatite is important as it may have implications for human dietary analysis from teeth. Current models for dietary reconstruction based on regression equations developed from metaanalyses (for example, Froehle et al. 2010, 2012; Kellner and Schoeninger 2007) use bone apatite to ascertain empirical associations between the isotopic ratios of apatite and diet. It is unclear if these can be imposed on isotopic ratios found in tooth enamel in archaeological applications due to the disparities in enrichment between bone and enamel apatite (Warinner and Tuross 2009).

The correlation between carbon isotope ratios in bone collagen and bone apatite in comparison to tooth dentine collagen and enamel apatite are not well understood in humans. One study investigated the differences in bone apatite and enamel apatite from marine mammals (Clementz et al. 2007). Paired samples of bone and teeth were collected from each animal and analysed; the $\Delta^{13}C_{\text{enamel apatite-bone apatite}}$ ranged from $-3.2\%$ to $2.8\%$. Manatees, dugongs, harbour porpoises and sea otters had positive offsets, while elephant seals, harbour seals, northern fur seals and sea lions had negative offsets. These discrepancies were attributed to the timing of enamel formation and seasonal variation in the diet in different species (Clementz et al. 2007).

Bone apatite and enamel apatite are both formed from carbonates and bicarbonates.
dissolved in the blood, so most researchers have not questioned whether the tissues in humans are equivalent. Teeth are a more viable source for isotopic analysis in many situations as they are less prone to diagenesis, so this is something that needs to be resolved. Loftus and Sealy (2012) recently investigated this issue using three archaeological human collections from the coastal western and southern Cape regions in South Africa. They sampled apatite from the enamel and compared it to published data for bone collagen and apatite from the same individuals to investigate the relationship between them and assess whether there was any evidence for an offset in enamel apatite over bone apatite ($\Delta^{13}C_{\text{enamel apatite-bone apatite}}$). The found a slight enrichment of 0.6‰ in tooth enamel apatite over bone apatite, however, the difference was much smaller than the 2.3‰ reported by Warinner and Tuross (2009) and there was no evidence for a systematic or fixed offset between the two tissues. They suggest that carbon isotope ratios in both enamel and bone can act as reliable proxies for dietary interpretation. One limitation of this study is that the authors suggest some possible diagenetic alteration to some or all of the original bone apatite samples. Because the surrounding matrices of the burials was shell, they suggest that any diagenetic affect would result in the $^{13}C$ enrichment of the bone apatite (Loftus and Sealy 2012). If this were the case it would result in a smaller $\Delta^{13}C_{\text{enamel apatite-bone apatite}}$, obscuring the possible offset between enamel apatite and bone apatite. The possible alteration of the apatite samples reduces the validity of this study. So the questions of whether bone $\delta^{13}C_{\text{apatite}}$ and enamel $\delta^{13}C_{\text{apatite}}$ are analogous remain uncertain. This will be discussed further in the methodology section.

Very few studies of human dietary analysis have used enamel apatite and dentine collagen as proxies for bone apatite and bone collagen, van der Merwe et al. (2003) being an exception. They analysed bone collagen, dentin collagen and enamel apatite and found that bone collagen was 1.0‰ more depleted on average than dentine collagen. They did not provide any information on the difference between bone apatite and enamel apatite.

Metaanalysis and dietary reconstruction models

There has been an evolution in dietary reconstruction models in recent years, developed using metaanalyses of animal data from controlled feeding experiments. Kellner and Schoeninger (2007: 113) suggested that the dietary information based on the offset between $\delta^{13}C_{\text{apatite}}$ and $\delta^{13}C_{\text{collagen}}$ ($\Delta^{13}C_{\text{apatite-collagen}}$) is minimal in its predictive power for dietary reconstruction because it is not specific to a particular combination of protein or whole diet. They developed a bivariate model of $\delta^{13}C_{\text{collagen}}$ against $\delta^{13}C_{\text{apatite}}$ using data from four experimental feeding studies of rodents and swine with documented experimental dietary protein sources (Ambrose and Norr 1993; Howland et al. 2003; Jim et al. 2006; Tieszen and Fagre 1993). Using this model, $\delta^{13}C_{\text{collagen}}$ against $\delta^{13}C_{\text{apatite}}$ data is plotted and is assessed on where it lies in relation to the regression lines, for C$_3$ protein, marine protein and C$_4$ protein. They tested the model using free ranging animals with
diets based on specific macronutrients (C₃ protein, C₄ protein or marine protein) (Lee-Thorp 1989; Nelson et al. 1986; Schoeninger and DeNiro 1982; Sullivan and Krueger 1981) and archaeological human remains from assemblages where diet was independently well documented (Ambrose and Krigbaum 2003; Hedman et al. 2002; Lee-Thorp 1989; Yesner et al. 2003). Plotting the carbon isotope ratios of δ¹³Ccollagen and δ¹³Capatite, the data present in discrete groups based on their protein consumption.

Froehle et al. (2010) developed a regression model closely based on that of Kellner and Schoeninger (2007), with some minor adjustments. They used the animal data from Warinner and Tuross’ study (2009) which included swine and rodent data (Ambrose and Norr 1993; Hare et al. 1991; Howland et al. 2003; Jim et al. 2006; Tieszen and Fagre 1993; Warinner and Tuross 2009). In contrast to Kellner and Schoeninger (2007), they combined the C₄ and marine animals into one group and plotted the δ¹³Capatite and δ¹³Ccollagen on different axes. Using this model, the δ¹³Capatite axis represents the ratio of C₃ to C₄ foods in the diet and the δ¹³Ccollagen axis represents the protein-specific regression lines, which distinguish between the consumption of C₃ and C₄ foods. Froehle et al. (2010) also demonstrated that plotting ∆¹³Cprotein-diet against ∆¹³Ccollagen-diet can elucidate whether protein was depleted or enriched in comparison to diet. Bioarchaeological researchers wishing to determine δ¹³Cdiet fromapatite or collagen, or δ¹³Cprotein or δ¹³Cenergy where the diet or constituents are unknown, can use the equations in Kellner and Schoeninger (2007) to then estimate these and plot them accordingly.

Froehle et al. (2012) further refined their earlier bivariate carbon dietary reconstruction model by including nitrogen collagen (δ¹⁵N). Using data from eight different archaeological populations with individual measurements of δ¹³Ccollagen, δ¹³Capatite and δ¹⁵N with independent evidence of diet, Froehle et al. (2012) conducted multivariate cluster analysis and discriminant function analysis on the raw isotopic data to study the three isotopic variables and their relationship to diet simultaneously. The inclusion of δ¹⁵N allows for discrimination between the consumption of C₄ and marine protein, an element that was lacking in the bivariate carbon models. The analysis formed five discrete clusters based on diet (Froehle et al. 2012: 4). Two linear functions (F1 and F2) were developed to allow other researchers to utilise their model (Froehle et al. 2012: 6). The carbon variables dominate F1, while the nitrogen dominates F2. To independently test and corroborate their findings they included a small sample of experimental rats, which presented as anticipated given their diets.

These multivariate dietary reconstruction models based on metaanalyses have huge potential for aiding in dietary analysis and reconstruction. The only limitation is that these models are all developed using bone from animals fed controlled diets. It does not test the validity of enamel or dentine from teeth. If enamel δ¹³Capatite is enriched over bone δ¹³Capatite, then these models would overestimate C₄ or marine consumption in the diet.
Research using stable isotopes has been used to infer diet from skeletal remains from archaeological sites in almost every country, from our ancient ancestors through to historic populations. Research into subsistence practices has been used to identify the introduction of specific identifiable agriculture crops into the diet, such as maize in northeastern North America (Katzenberg et al. 1995; van der Merwe and Vogel 1978) and millet in China (Pechenkina et al. 2005; Pechenkina et al. 2002), and it has also been used to estimate differential reliance on marine and terrestrial resources (Keegan and DeNiro 1988; Walker and DeNiro 1986). The scope of stable isotope analysis is increasing and now being used for purposes other than specific dietary analysis, such as tracing migration and inferring matri-locality (Bentley et al. 2009; Bentley et al. 2005; Bentley et al. 2007) and for identifying weaning practices (Beaumont et al. 2012; Dupras et al. 2001; Eerkens et al. 2011; Fuller et al. 2006; Katzenberg and Pfeiffer 1995; Kinaston et al. 2009; Schurr and Powell 2005; Wright and Schwarz 1998). Relatively few studies have been conducted on diet in Southeast Asia.

**Southeast Asian research on source diet isotope baselines**

Research into subsistence practices in Southeast Asia have traditionally used faunal remains from archaeological assemblages (Higham and Kijingam 1979; Higham 1975), human dentition (Domett 2001; Pietrusewsky and Douglas 2002a; Pietrusewsky and Douglas 2002b; Tayles 1992; Tayles et al. 2000) and ethnographic analogy (White 1984, 1989, 1995) for palaeodietary inference. These do provide evidence of subsistence; however, they are limited by preservation, sampling, food preparation methods and the excavation and sieving protocols themselves. Ethnographic analogy can go some way to identifying procurement and preparation strategies, however, the environment, food availability and technology may have changed significantly over time and not be reflective of the time period of study (King 2008).

For An Sơn and Hòa Diệm previous researchers have established some assumptions that can be employed in a palaeodietary investigation. The ecological conditions of Southeast Asia, with a humid climate and lowland rainforests is ideal for C₃ plants, relatively few C₄ plants inhabit the area because of the monsoonal wet seasons (Krigbaum 2005). Due to these conditions it has been suggested that it is unlikely that the few C₄ cultigens were an integral or staple crop in Southeast Asia (Krigbaum 2003). Researchers investigating diet in regions which are predominantly C₃ have less opportunity for investigating differentiation or temporal changes in diet and because of this are often discouraged, which is one reason why stable isotope analyses have not been a large focus in Southeast Asia. Nonetheless, there are opportunities for identifying subtle nuances in C₃ biomes, such as differences in plants grown in open areas or under the canopy of other plants for
instance (Krigbaum 2005).

Krigbaum (Krigbaum 2003; Krigbaum 2005; Krigbaum 2001) studied subsistence and palaeodiet using the stable isotopes $\delta^{18}$O and $\delta^{13}$C from tooth enamel from the inhabitants of several assemblages from Borneo in Island Southeast Asia. These studies focussed on $\delta^{13}$C to interpret diet, using $\delta^{18}$O to assist in examining the variability (Krigbaum 2005). A comparison of these sites identified a temporal shift in carbon interpreted as a diachronic change in the area plants consumed were grown and collected in.

King (2008) investigated palaeodiet in northeast Thailand using four assemblages, two from the Sakon Nakhon Basin, Ban Chiang and Ban Na Di and two from Upper Mun River Valley in the Khorat Basin, Ban Lum Khao and Noen U-Loke. He measured the $\delta^{15}$N and $\delta^{13}$C of modern plants to provide a broad range of the most probable types of plants that would have been consumed in prehistory, he also measured the $\delta^{15}$N, $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ from modern faunal tissue, modern bone and prehistoric bone. He sampled $\delta^{15}$N, $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ in bone from individuals from the four assemblages and developed an interpretation of palaeodiet using the floral and faunal data as a baseline foodweb. King (2008) found a statistically significant enrichment in $\delta^{15}$N, $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ over time, which he attributed to a greater consumption of fish and/or carnivorous animals, domesticated animals and open field carbohydrate foods respectively. King and Norr (2006) used Ban Chiang as a specific case study of synchronic and diachronic dietary patterns in northeast Thailand focussing on the $\delta^{15}$N, $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ from the bone of 30 individuals sourced from King (2006, 2008).

Bentley et al. (2005) sampled $^{87}$Sr/$^{86}$Sr, $\delta^{18}$O and $\delta^{13}$C$_{\text{apatite}}$ from tooth enamel of individuals from Ban Chiang, in the Upper Mun River Valley, northeast Thailand to infer geographic location and diet, using animal remains as a geographic control. They suggest a cultural transition to matrilocality at the site, where men raised elsewhere married into the community. Bentley et al. (2007) examined $^{87}$Sr/$^{86}$Sr, $\delta^{18}$O and $\delta^{13}$C$_{\text{apatite}}$ from tooth enamel of individuals from the Neolithic site of Khok Phanom Di in the Bang Pakong Valley, Thailand to investigate human mobility and marital residence during a transitional period from hunting and gathering to agriculture. A similar scenario to what was witnessed at Ban Chiang was also seen at Khok Phanom Di, and a regional transition was proposed. Bentley et al. (2009) analysed $^{87}$Sr/$^{86}$Sr, $\delta^{18}$O and $\delta^{13}$C$_{\text{apatite}}$ from tooth enamel of individuals from the Bronze Age site of Ban Lum Khao in the Upper Mun River Valley, northeast Thailand to assess mobility. The isotopic evidence suggests that women immigrants from different communities were buried with certain types of pottery as a form of social identity. This pattern was not seen among males, suggesting a possible patrilocal marriage system.

Cox (2009) examined human migration in three prehistoric assemblages in northeast Thailand from the Upper Mun River Valley, Ban Lum Khao, Noen U-Loke and Ban Non
Palaeodietary Analysis of An Sơn and Hòa Diêm Wat, using dental morphological traits, to identify genetic relations and isotopic analysis of $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}_{\text{apatite}}$ from tooth enamel, to infer diet and residence. There were no significant differences in $\delta^{13}\text{C}$ over time. The results showed that long-range migration was more common during the early occupation of the Upper Mun River Valley but there was relatively low migration in the region overall; with little evidence for long term distance migration in the later periods (Cox et al. 2011).

Bower et al. (2006) examined the $\delta^{15}\text{N}_{\text{collagen}}$ and $\delta^{13}\text{C}_{\text{collagen}}$ from tooth dentine, the $\delta^{13}\text{C}_{\text{apatite}}$ from tooth enamel and the Ba:Sr ratio from two assemblages from Vietnam, Cồn Cổ Ngũa, a preNeolithic site and Núi Náp, an Iron Age site in northern Vietnam. Unfortunately the attempt to retrieve $\delta^{15}\text{N}_{\text{collagen}}$ or $\delta^{13}\text{C}_{\text{collagen}}$ from tooth dentine was unsuccessful at Cồn Cổ Ngũa. The $\delta^{15}\text{N}_{\text{collagen}}$ and $\delta^{13}\text{C}_{\text{collagen}}$ values from Núi Náp suggest that the diet was predominantly based on C$_3$ plants and terrestrial protein with the addition of some marine foods. Núi Náp had significantly lower $\delta^{13}\text{C}_{\text{apatite}}$ compared to Cồn Cổ Ngũa. The Ba:Sr suggests that the consumption of marine resources at Cồn Cổ Ngũa was higher than at Núi Náp.

These studies have not focussed on using $\delta^{13}\text{C}_{\text{apatite}}$ to exclusively investigate diet, but as a tool to assist in understanding residence, migration and marital custom. However, these studies provide comparative data. In using $\delta^{13}\text{C}$ to estimate diet, these researchers used rat modelling and subtracted 9.4‰ from diet values where appropriate to infer the $\delta^{13}\text{C}_{\text{apatite}}$ values of the individuals in their samples. The following section will discuss the methods and materials employed in the investigation of diet among the An Sơn and Hòa Diệm samples.

Materials and methods

Dental samples from An Sơn and Hòa Diệm were used for analyses of $\delta^{15}\text{N}_{\text{collagen}}$ and $\delta^{13}\text{C}_{\text{collagen}}$ from dentine and $\delta^{13}\text{C}_{\text{apatite}}$ from enamel. Third molars were selected wherever possible for this analysis as they are the last to form thus reflecting the best approximation of an adult diet; second molars were selected if the third was not available.

The stable isotope analysis was conducted by the Rafter Laboratories, National Isotope Centre, Institute of Geological and Nuclear Sciences Ltd (GNS Science) in Lower Hutt, New Zealand. Individual molars were physically examined for root inclusions and soil from the burial context. The crown enamel was physically separated from the dentine.

Tooth dentine samples were pulverised in a retch mill to $<450\mu$m and demineralised in 0.5M HCl while stirred at room temperature for 1 hour. Insoluble collagen was filtered from the solution, rinsed and dried in a vacuum oven at 30°C. The insoluble collagen was gelatinised with 0.01 M HCl in a nitrogen atmosphere at 90°C for 16 hours. The soluble
gelatin was then double filtered through Whatman GF/C and 0.45µm Acrodisc filters and lyophilised to weigh yields.

Tooth enamel samples were first pretreated with a 0.5M HCl acid wash, then rinsed with deionised water, dried and pulverised to 0.75µm. Acid hydrolysis was performed on the pretreated enamel (CO₂ evolution) by mixing 0.64% orthophosphoric acid with the powdered enamel in an evacuated side-arm flask, reacting to produce CO₂. The CO₂ was cryogenically distilled and transferred to Pyrex tubes with CuO and silver wire, combusted at 900°C, cryogenically distilled and graphitised for AMS analysis.

Carbon and nitrogen were analysed on an ANCA elemental analyser coupled with a Europa Geo 20-20 mass spectrometer. Samples were combusted with oxygen at 1020°C in tin capsules. All samples were reported with respect to the VPDB and AIR, normalised to internal standards of the laboratory. Leucine (-22.7‰ for δ¹³C, 2.2‰ for δ¹⁵N), Montana Soil (-17.1‰ for δ¹³C, 7.6‰ for δ¹⁵N), Caffeine (-38.0‰ for δ¹³C, -7.4‰ for δ¹⁵N), GNS Moa Bone (-21.0‰ for δ¹³C, 9.8‰ for δ¹⁵N) and Sercon Flour (-27.3‰ for δ¹³C, 2.8‰ for δ¹⁵N). The analytical precision for these measurements was 0.3‰ for δ¹⁵N and 0.2‰ for δ¹³C.

For sulphur the samples were weighed out in duplicate in tin capsules and run against standard V₂O₅ on a EuroVector Elemental Analyser connected to a GVI IsoPrime mass spectrometer. All results were reported with respect to VCDT, normalised to the internal standards of the laboratory R18742, R2268, and R2298 with reported values of -3.2‰, +3.3‰ and +8.6‰ respectively for δ³⁴S. The analytical precision for these measurements was 0.6‰ for δ³⁴S on the SEA.

**Quality control**

Three criteria were used in the assessment of the integrity and preservation of the collagen samples, collagen yield by weight, atomic C:N ratio and %C and %N.

Samples were considered viable if:
- The collagen yield was ≥1% (Dobberstein et al. 2009; van Klinken 1999)
- The %C was ≥3%, %N was ≥1% (Ambrose 1993) and %S was ≥0.15% (Nehlich et al. 2011)
- The C:N ratio was within the range 2.9-3.6 (DeNiro 1985)

A provision was made to include samples which met the first two criteria but had a C:N of 3.6-4.5 (Harbeck and Grupe 2009).

These criteria were chosen to assess collagen quality for a number of reasons. Collagen content is lower in tissues from tropical regions (van Klinken 1999) and teeth produce
lower collagen yield and %C and %N values than bone (Ambrose 1990). However, because the samples all had adequate collagen yield, the %C and %N and C:N ratios should be reliable (Ambrose 1990; Schoeninger et al. 1989). There were several samples that were outside the normal range for C:N 2.9-3.6 advocated by DeNiro (1985), however, due to the issues outlined above and in the introduction to this chapter regarding quality controls, these were included.

**Tissue offsets and indication of isotopic values of diet sources**

Following the assumption that $\delta^{13}C_{\text{apatite}}$ represents the whole diet, enriched by 9.4‰, and $\delta^{13}C_{\text{collagen}}$ represents the protein portion of the diet, enriched by 5.0‰ (for a monoisotopic diet); the offset between $\delta^{13}C_{\text{apatite}}$ and $\delta^{13}C_{\text{collagen}}$ ($\Delta^{13}C_{\text{apatite-collagen}}$) can be used to infer the difference between the protein portion of the diet represented by $\delta^{13}C_{\text{collagen}}$ and the whole diet represented by $\delta^{13}C_{\text{apatite}}$. Because of these differences in the offsets, the $\Delta^{13}C_{\text{apatite-collagen}}$ for a diet would equal 4.4‰ where the protein and whole diet were the same. If the $\Delta^{13}C_{\text{apatite-collagen}}$ is <4.4‰ the protein portion of the diet ($\delta^{13}C_{\text{collagen}}$) is enriched compared to the whole diet ($\delta^{13}C_{\text{apatite}}$), if the $\Delta^{13}C_{\text{apatite-collagen}}$ is >4.4 the protein portion of the diet ($\delta^{13}C_{\text{collagen}}$) is depleted compared to the whole diet ($\delta^{13}C_{\text{apatite}}$).

Using this assumption data can be tested to identify whether a diet is monoisotopic by subtracting 9.4 from the $\delta^{13}C_{\text{apatite}}$ and 5.0 from the $\delta^{13}C_{\text{collagen}}$. If the $\Delta^{13}C_{\text{apatite-collagen}} = 0$, this suggests the $\delta^{13}C_{\text{apatite}}$ and $\delta^{13}C_{\text{collagen}}$ are equivalent and diet is monoisotopic. If the end values are not the same, this suggests that the diet was not monoisotopic. For example, if one had a diet which was similarly enriched in $\delta^{13}C$ for protein and whole diet:

\[
\begin{align*}
\delta^{13}C_{\text{apatite}} - \varepsilon \cdot \delta^{13}C_{\text{apatite-diet}} &= a \\
\delta^{13}C_{\text{collagen}} - \varepsilon \cdot \delta^{13}C_{\text{collagen-diet}} &= b \\
a - b &= 0 \\
-10 - 9.4 &= -19.4 \\
-14.4 - 5 &= -19.4 \\
-19.4 - -19.4 &= 0 \\
\end{align*}
\]

The $\Delta^{13}C_{\text{apatite-collagen}}$ would confirm if the protein and whole diet were equivalent (monoisotopic). To illustrate offsets in the respective tissues, the $\delta^{13}C$ values were adjusted $\delta^{13}C_{\text{apatite}} - 9.4$ and $\delta^{13}C_{\text{collagen}} - 5$. These were then plotted by $\Delta^{13}C_{\text{apatite-collagen}}$, with placement at 4.4‰ for $\Delta^{13}C_{\text{apatite-collagen}}$ indicative of a monoisotopic diet, where adjusted $\Delta^{13}C_{\text{apatite-collagen}} = 0$.

**Multivariate dietary reconstruction models**

As discussed in the introduction, several dietary reconstruction models have been published recently. These were used to test the data from An Sơn and Hòa Diệm. The first
was Froehle et al.’s (2010) bivariate regression model, closely based on that of Kellner and Schoeninger (2007). The model plots raw $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ values and provides two comparative regression lines. Placement on the $\delta^{13}C_{\text{apatite}}$ axis is the ratio of $C_3$ to $C_4$ foods in the diet and position relative to the regression lines discriminates between protein sources, either $C_3$ or $C_4$/marine.

To further elucidate diet Froehle et al.’s (2012) multivariate model was used. Two linear functions (F1 and F2) were calculated for each individual following Froehle et al. (2012: 6) as:

\[
F_1 = (0.322 \times \delta^{13}C_{\text{apatite}}) + (0.727 \times \delta^{13}C_{\text{collagen}}) + (0.219 \times \delta^{15}N) + 9.354
\]

\[
F_2 = (0.393 \times \delta^{13}C_{\text{apatite}}) + (0.133 \times \delta^{13}C_{\text{collagen}}) + (0.622 \times \delta^{15}N) - 8.703
\]

The position of individuals relative to the clusters are indicative of their diet. Cluster 1 represents a diet 100:0 ($C_3$:$C_4$); $C_3$ protein. Cluster 2 represents a diet 30:70 ($C_3$:$C_4$); >50% $C_4$ protein. Cluster 3 represents 50:50 ($C_3$:$C_4$); marine protein. Cluster 4 represents a diet 70:30 ($C_3$:$C_4$); ≥65% $C_3$ protein. Cluster 5 represents 30:70 ($C_3$:$C_4$); ≥65% $C_3$ protein (Froehle et al. 2012: 4 Table 1).

**Palaeodietary reconstruction**

To provide the most accurate assessment of human stable isotope data and reconstruction of palaeodiet, it is important to compare the data to local floral and faunal data from the same location, or at least the same region, as the human remains (Cheung et al. 2012; Katzenberg 2008; Norr 1995). Due to financial constraints funds were not available to sample floral or faunal isotopic data from An Sơn.

Christopher King’s (2008) floral and faunal data, sourced from modern and archaeological samples from northeast Thailand, were used as a biogeographical foundation for the palaeodietary reconstruction. This interpretation was strengthened using information from the archaeological record on local fauna and flora from An Sơn; using faunal data analysed and published by Piper and colleagues (2014) and preliminary phytolith data independently analysed and provided by Tetsuro Udatsu (pers. comm.) to assist in the dietary reconstruction and interpretation at An Sơn. Piper et al. (2014) analysed the vertebrate taxa recovered from the 2009 excavation at An Sơn. The number of identified specimens are presented in Piper et al. (2014 Table 1). Only Sawada’s (2012) report for the mammalian remains from Hòa Diêm was available, no comprehensive reports have been published yet on the faunal or floral remains, however, in consideration of the location of the site in a coastal area it was assumed that the sources of food would have been similar to An Sơn with the addition of marine resources. The only limitation using King’s (2008) baseline was it was developed to interpret the diet of inland sites and no marine animals were included in developing the foodweb.
The preservation of plant remains from archaeological contexts in Southeast Asia is rare, and botanical remains recovered tend to underestimate the variety of plants (wild and domestic) that would have been available for consumption during prehistoric times. King (2008) analysed the carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) values of a range of modern $C_3$ and $C_4$ plants, providing a comparative database of plant foods likely to have been consumed in prehistoric Thailand and arguably at An Sơn and Hòa Diêm in Vietnam. The $C_3$ plants cover a variety of cereals, fruits, legumes, tubers and vegetables; the $C_4$ types represent cereals. The $\delta^{13}C$ values of the modern plants were adjusted $+1.5\%$ to compensate for modern atmospheric changes in carbon composition (Marino and McElroy 1991; Tieszen and Fagre 1993). The raw stable isotopic data for the plant remains are presented in King (2008 Appendix A). King (2008) cautions that the $\delta^{15}N$ values of some of the plants may have been inadvertently affected by the use of fertilisers, altering their $\delta^{15}N$ value.

Animal remains recovered from archaeological sites in Southeast Asia are limited to those that are preserved, other potential food sources such as insects are usually not preserved in the archaeological record. King (2008) collected modern faunal samples, modern bone samples and prehistoric bone samples. The $\delta^{13}C$ values for modern faunal tissue samples were adjusted $+1.5\%$, to compensate for modern atmospheric changes in carbon composition. The $\delta^{15}N$ values of modern and archaeological faunal bone samples were adjusted $+0.6\%$, to represent the isotopic composition of flesh. The raw stable isotopic data for the animal remains are presented in King (2008 Table 6.3, Appendix B1 and B2). Figure 6.1 presents the isotopic ranges for $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ from modern plants, modern tissue, modern bone and archaeological bone analysed by King (2008), creating a biogeographical baseline.

To estimate $\delta^{13}C$ dietary values rats were used as an analogue. Rats were chosen for several reasons, experimental feeding studies using rats have produced the most consistent results for the amount of fractionation between tissues (Ambrose and Norr 1993; Tieszen and Fagre 1993), the difference in fractionation between tissues in these studies is less than $10\%$, which mitigates the need for algebraic equations to estimate dietary values (Passey et al. 2005), and finally it provides consistency with other important comparative assemblages, which allows for regional comparisons to contextualise the results.

The following assumptions were used:

\[ \varepsilon \delta^{13}C_{\text{collagen-diet}} = 5.0\% \] (Ambrose et al. 1997)
\[ \varepsilon \delta^{13}C_{\text{apatite-diet}} = 9.4\% \] (Ambrose et al. 1997)
\[ \Delta^{13}C_{\text{apatite-collagen}} = 4.4\% \] (Ambrose et al. 1997)
\[ \varepsilon \delta^{15}N_{\text{collagen-diet}} = 3.0\% \] (Minagawa and Wada 1984; Schoeninger and DeNiro 1984)
Figure 6.1. Biogeographic baseline based on data provided by King 2008
Contextualising palaeodiet within Southeast Asia

An Sơn and Hòa Diệm were compared and contrasted with several other Southeast Asian and Chinese assemblages. The sites used for comparative purposes in this section include several from the suite of assemblages used throughout this thesis to contextualise results regionally that had available isotope data, with the addition of several further sites to assist in the interpretation. The Vietnamese assemblages include Iron Age Núi Nấp c. 330CE from Thanh Hóa province and preNeolithic Cồn Cổ Ngựa; the Thai assemblages include Neolithic Khok Phanom Di and Bronze Age Ban Lum Khao and Ban Na Di; and finally Ban Chiang located in Sakon Nakhon Basin, which spans the Neolithic through to the Iron Age c. 2100BCE-200CE. The Chinese sites include Neolithic Jiangzhai c. 4950-4050BCE and Shijia c. 4350-4050BCE both from Shannxi province. The stable isotopes analysed from different assemblages vary depending on the research objectives of the projects. Stable isotopes pertinent to this investigation for comparative purposes include $\delta^{15}N_{\text{collagen}}$, $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$. Different source tissues have also been analysed including bone and dentine for $\delta^{15}N_{\text{collagen}}$, $\delta^{13}C_{\text{collagen}}$ and bone and enamel for $\delta^{13}C_{\text{apatite}}$.

Recent discussions have focussed on apatite and collagen and whether these tissues are synonymous in their reflection of diet (Loftus and Sealy 2012; Warinner and Tuross 2009). This was investigated because of the possible implications and impact of this on the palaeodietary reconstruction and comparisons between different assemblages presenting their isotopic data using different tissues. Ban Chiang offered a good opportunity to examine this as it spans a long temporal sequence and represents a large sample of individuals.

Ban Chiang was also used to investigate dietary spacing as an indicator of the isotopic contribution from different constituents of the diet, using $\varepsilon \delta^{13}C_{\text{collagen-diet}} = 5.0\%$ and $\varepsilon \delta^{13}C_{\text{apatite-diet}} = 9.4\%$ (Ambrose et al. 1997). $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ were then plotted by increasing $\Delta^{13}C_{\text{apatite-collagen}}$, which forced the values to cross at 4.4‰ on the $\Delta^{13}C_{\text{apatite-collagen}}$ axis, representing a diet in which both protein and whole diet had similar $\delta^{13}C$ values. The protein portion of the diet of those individuals whose $\Delta^{13}C_{\text{apatite-collagen}}$ was below 4.4‰ was enriched compared to their whole diet, while the protein portion of the diet of those whose $\Delta^{13}C_{\text{apatite-collagen}}$ was above 4.4‰ was depleted compared to the whole diet.

Pearson correlation was used to test whether there was any covariance between stable isotopes. Independent sample t-tests were used to test inter-sample differences between the sites and intra-sample differences between sexes. Results are presented with equal variance assumed unless homogeneity of variance was violated then the results are presented with equal variance not assumed. An alpha level of .05 was used for all statistical tests.
Results

Quality control

Tables 6.3 and 6.4 provide information pertaining to the quality control measures derived from the teeth. Two out of 12 teeth from An Sơn and seven out of 20 from Hòa Diêm failed at processing for collagen. Ten samples from An Sơn were viable with collagen yields of 1.0% – 15.3%. Thirteen samples from Hòa Diêm were successful with collagen yields of 2.9% - 22.7%. Eight samples from An Sơn were viable with %C of 4.6-32.6 and %N of 1.2-10.9. Two samples from An Sơn were not viable with %C of 2.6-3.0 and %N of 0.8-0.9. Eight samples from Hòa Diêm were viable with %C of 8.3-19.0 and %N of 1.2-5.2. Five samples from Hòa Diêm were not viable with %C of 2.1-4.4 and %N of 0.3-0.6.

Three samples from An Sơn were within the desired range of 2.9-3.6 for viable, well preserved protein. Four samples from An Sơn had C:N ratios higher than desirable between 3.7-3.8, however, the %C and %N values for these samples suggest sufficient protein to provide confidence in the δ13C and δ15N values. Three samples from An Sơn were not viable with C:N ratios of 4.0-4.6 and very low %C and %N values suggesting native protein was significantly deteriorated.

Seven individuals from Hòa Diêm had C:N ratios higher than desirable between 3.8-4.5, however, the %C and %N values for these individuals suggest sufficient protein to provide confidence in the δ13C and δ15N values. Six samples from Hòa Diêm were not viable with C:N ratios of 7.4-9.8 and very low %C and %N values suggesting native protein was significantly deteriorated.

The pattern was very consistent between %C (Figure 6.2) and %N (Figure 6.3) when plotted against C:N at An Sơn and Hòa Diêm. The three samples from An Sơn with a C:N ratio within the desired range had %C values between 24.8-32.6 (Figure 6.2) and %N values between 8.0-10.9 (Figure 6.3). The six samples from Hòa Diêm which were not viable, indicated in red, had the highest C:N values (7.4-9.8) and had extremely low %C and %N values (2.1-4.4 and 0.3-1.2 respectively) (Figure 6.2) and (Figure 6.3).

Two of the three samples from An Sơn which were not viable had considerably lower δ15N_{collagen} and δ13C_{collagen} values than the viable samples (Figure 6.4). There was no obvious pattern in the samples which passed or failed for collagen quality at An Sơn.

Three of the samples from Hòa Diêm which were not viable had considerably lower δ15N_{collagen} values than the other samples and three samples had considerably lower δ13C_{collagen} values compared to the other viable samples (Figure 6.5). When assessing the viability of the samples from Hòa Diêm, none of the teeth from the 2007 excavation were
<table>
<thead>
<tr>
<th>ID</th>
<th>Calibrated C(^1)</th>
<th>Sex</th>
<th>Age</th>
<th>Collagen yield</th>
<th>%C</th>
<th>%N</th>
<th>C:N (^1) (^{13})C(_{\text{collagen}})</th>
<th>(\delta^{15})N(_{\text{collagen}})</th>
<th>(\delta^{34})S</th>
<th>(\delta^{13})C(_{\text{apatite}})</th>
<th>Quality control</th>
</tr>
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<td>04ASH3M1</td>
<td>1302 BCE to 1114 BCE</td>
<td>Male</td>
<td>30-39</td>
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<td>11.1</td>
<td>8.2</td>
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<td>1501 BCE to 1416 BCE</td>
<td>Male</td>
<td>40-49</td>
<td>1.1</td>
<td>24.8</td>
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<td>-</td>
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<td>Adolescent</td>
<td>15-19</td>
<td>1.0</td>
<td>8.1</td>
<td>2.5</td>
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<td>1266 BCE to 1056 BCE</td>
<td>Female</td>
<td>20-29</td>
<td>15.3</td>
<td>9.9</td>
<td>3.1</td>
<td>3.7</td>
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<td>11.0</td>
<td>-</td>
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<td>-21.0</td>
<td>7.5</td>
<td>-</td>
<td>-13.9</td>
</tr>
<tr>
<td>09ASH1M2</td>
<td>1401 BCE to 1268 BCE</td>
<td>Female</td>
<td>20-29</td>
<td>10.1</td>
<td>-</td>
<td>-</td>
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<tr>
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<td>1605 BCE to 1433 BCE</td>
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<td>15-19</td>
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<td>-</td>
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\(^1\)The C:N was calculated from the original output for %C and %N which have been rounded to 1 decimal place here.
Table 6.4. Quality control summary for Hòa Diêm

<table>
<thead>
<tr>
<th>ID</th>
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<th>Sex</th>
<th>Age</th>
<th>Collagen yield</th>
<th>%C</th>
<th>%N</th>
<th>C:N</th>
<th>$\delta^{13}$C$_{collagen}$</th>
<th>$\delta^{15}$N$_{collagen}$</th>
<th>$\delta^{34}$S</th>
<th>$\delta^{13}$C$_{apatite}$</th>
<th>Quality control</th>
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<tbody>
<tr>
<td>02HDC20M1</td>
<td>73 CE to 218 CE</td>
<td>Male</td>
<td>30-39</td>
<td>7.4</td>
<td>8.4</td>
<td>2.3</td>
<td>4.4</td>
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<td>-17.52</td>
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<tr>
<td>02HDC4M2</td>
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<td>Male</td>
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<tr>
<td>07HDM4a</td>
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<td>Failed</td>
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</tbody>
</table>

$^{1}$The C:N was calculated from the original output for %C and %N which have been rounded to 1 decimal place here
Figure 6.2. %C and C:N values for An Sơn and Hòa Diêm (red indicates nonviable samples)

Figure 6.3. %N and C:N values for An Sơn and Hòa Diêm (red indicates nonviable samples)

Figure 6.4. Protein quality for $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ for An Sơn (red indicates nonviable samples)
Sulphur analysis requires at least 10mg of purified collagen, and while many dentine samples produced good C:N ratios and collagen yields, the starting amount of material from any one tooth would necessarily provide a limited amount of collagen for isotope analysis. Consequently, only four samples had sufficient collagen for sulphur analysis in addition to the carbon and nitrogen. One sample produced $\delta^{34}S$ values from An Sơn (8.2‰). Three samples produced $\delta^{34}S$ values from Hòa Diêm (8.5, 9.6 and 10.3‰ respectively). Due to the low success of $\delta^{34}S$, this was not investigated any further.

### Stable isotopes

Table 6.5 summarises the isotope values derived for each individual from An Sơn. Table 6.6 provides descriptive statistics for the $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ from the tooth dentine, the $\delta^{13}C_{\text{apatite}}$ from the tooth enamel and the spacing between the enamel apatite and dentine collagen ($\Delta^{13}C_{\text{apatite-collagen}}$) for the individuals from An Sơn.

The range for $\delta^{13}C_{\text{collagen}}$ is -19.9‰ to -18.9‰ (1.0‰) and the range for $\delta^{15}N_{\text{collagen}}$ is 9.5‰ to 11.7‰ (2.2‰) (Table 6.6). There is a strong positive correlation between $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ $r(5)=0.667$ $p=0.102$ (Figure 6.6). There is a slightly wider range of $\delta^{13}C$ values for $\delta^{13}C_{\text{collagen}}$ (Figure 6.6) than for $\delta^{13}C_{\text{apatite}}$ (Figure 6.7) when plotted against $\delta^{15}N_{\text{collagen}}$.

The $\delta^{13}C_{\text{apatite}}$ values range from -13.8‰ to -13.2‰ (0.6‰) (Table 6.6). $\delta^{13}C_{\text{apatite}}$ is weakly positively correlated with $\delta^{15}N_{\text{collagen}}$ $r(5)=0.305$, $p=0.505$ (Figure 6.7) and $\delta^{13}C_{\text{collagen}}$ $r(6)=0.294$, $p=0.522$ (Figure 6.8).

The mean $\Delta^{13}C_{\text{apatite-collagen}}$ is 6.2‰ (Table 6.6). This indicates the protein portion of the diet and the whole diet had different $\delta^{13}C$ ratios. There is an inverse correlation between
### Table 6.5. Isotope data for An Sơn

<table>
<thead>
<tr>
<th>ID</th>
<th>Calibrated C(^{14})</th>
<th>Sex</th>
<th>Age</th>
<th>(\delta^{13})C(_{\text{collagen}})</th>
<th>(\delta^{15})N(_{\text{collagen}})</th>
<th>(\delta^{13})C(_{\text{apatite}})</th>
<th>(\Delta^{13})C(_{\text{apatite-collagen}})</th>
<th>(\delta^{13})C(<em>{\text{collagen}}) - (\epsilon) (\delta^{13})C(</em>{\text{diet}})</th>
<th>(\delta^{13})C(<em>{\text{apatite}}) - (\epsilon) (\delta^{13})C(</em>{\text{diet}})</th>
<th>(\delta^{15})N(<em>{\text{collagen}}) - (\epsilon) (\delta^{15})N(</em>{\text{diet}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>04ASH3M1</td>
<td>1302 BCE to 1114 BCE</td>
<td>Male</td>
<td>30-39</td>
<td>-19.57</td>
<td>11.11</td>
<td>-13.20</td>
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<td>Male</td>
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<td>-19.95</td>
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<td>-13.61</td>
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<td>-24.9</td>
<td>-23.0</td>
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<td>Adolescent</td>
<td>15-19</td>
<td>-19.84</td>
<td>10.78</td>
<td>-13.80</td>
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<td>7.8</td>
</tr>
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<td>Female</td>
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<td>-22.8</td>
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<tr>
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<td>Female</td>
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<td>-24.9</td>
<td>-22.6</td>
<td>7.7</td>
</tr>
<tr>
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<td>1495 BCE to 1388 BCE</td>
<td>Female</td>
<td>40-49</td>
<td>-19.29</td>
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### Table 6.6. Stable isotope statistics for An Sơn

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<tr>
<th>N</th>
<th>(\delta^{13})C(_{\text{collagen}}) Mean</th>
<th>(\delta^{13})C(_{\text{collagen}}) Maximum</th>
<th>(\delta^{13})C(_{\text{collagen}}) Minimum</th>
<th>(\delta^{13})C(_{\text{collagen}}) Range</th>
<th>(\delta^{13})C(_{\text{collagen}}) Standard deviation</th>
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<td>7</td>
<td>-19.61</td>
<td>-19.95</td>
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<td>0.4</td>
</tr>
<tr>
<td>N</td>
<td>(\delta^{15})N(_{\text{collagen}}) Mean</td>
<td>(\delta^{15})N(_{\text{collagen}}) Maximum</td>
<td>(\delta^{15})N(_{\text{collagen}}) Minimum</td>
<td>(\delta^{15})N(_{\text{collagen}}) Range</td>
<td>(\delta^{15})N(_{\text{collagen}}) Standard deviation</td>
</tr>
<tr>
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<td>11.70</td>
<td>9.48</td>
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<tr>
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<td>(\delta^{13})C(_{\text{apatite}}) Maximum</td>
<td>(\delta^{13})C(_{\text{apatite}}) Minimum</td>
<td>(\delta^{13})C(_{\text{apatite}}) Range</td>
<td>(\delta^{13})C(_{\text{apatite}}) Standard deviation</td>
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<tr>
<td>7</td>
<td>6.4</td>
<td>6.6</td>
<td>5.5</td>
<td>1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>(\delta^{13})C(_{\text{apatite-collagen}}) Mean</td>
<td>(\delta^{13})C(_{\text{apatite-collagen}}) Maximum</td>
<td>(\delta^{13})C(_{\text{apatite-collagen}}) Minimum</td>
<td>(\delta^{13})C(_{\text{apatite-collagen}}) Range</td>
<td>(\delta^{13})C(_{\text{apatite-collagen}}) Standard deviation</td>
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<td>5.5</td>
<td>1.1</td>
<td>0.4</td>
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<tr>
<td>(\delta^{15})N(_{\text{apatite-collagen}}) Mean</td>
<td>(\delta^{15})N(_{\text{apatite-collagen}}) Maximum</td>
<td>(\delta^{15})N(_{\text{apatite-collagen}}) Minimum</td>
<td>(\delta^{15})N(_{\text{apatite-collagen}}) Range</td>
<td>(\delta^{15})N(_{\text{apatite-collagen}}) Standard deviation</td>
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<td>6.2</td>
<td>6.6</td>
<td>5.5</td>
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</table>
Figure 6.6. $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ values for An Sơn.

Figure 6.7 $\delta^{13}\text{C}_{\text{apatite}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ values for An Sơn.

Figure 6.8. $\delta^{13}\text{C}_{\text{apatite}}$ and $\delta^{13}\text{C}_{\text{collagen}}$ values for An Sơn.
6. Palaeodietary Analysis of An Sơn and Hòa Diệm

$\Delta^{13}C_{\text{apatite-collagen}}$ and $\delta^{15}N_{\text{collagen}}$ values for An Sơn (Figure 6.9).

In the case of An Sơn, the $\delta^{13}C_{\text{collagen}}$ values are consistently lower than the $\delta^{13}C_{\text{apatite}}$ values when the adjusted $\delta^{13}C_{\text{collagen}} = \varepsilon \delta^{13}C_{\text{collagen-diet}}$ and $\delta^{13}C_{\text{apatite}} = \varepsilon \delta^{13}C_{\text{apatite-diet}}$ values (Table 6.5) are plotted by $\Delta^{13}C_{\text{apatite-collagen}}$ (Figure 6.10).

Table 6.7 summarises the isotope values derived for each individual from Hòa Diệm. Table 6.8 provides descriptive statistics for the $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ from the tooth dentine, the $\delta^{13}C_{\text{apatite}}$ from the tooth enamel and the spacing between the enamel apatite and dentine collagen $\Delta^{13}C_{\text{apatite-collagen}}$ for the individuals from Hòa Diệm.

The range for $\delta^{13}C_{\text{collagen}}$ is -17.4‰ to -14.9‰ (2.6‰) and the range for $\delta^{15}N_{\text{collagen}}$ is 11.2‰ to 13.8‰ (2.6‰) (Table 6.8). There is a strong positive correlation between $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ $r(5)=0.762$, $p=0.047$ (Figure 6.11).

It was only possible to obtain $\delta^{13}C_{\text{apatite}}$ values from three individuals from Hòa Diệm and only one of those individuals had sufficiently preserved collagen for reliable $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$. The $\delta^{13}C_{\text{apatite}}$ value for this individual was -12.5‰ and the $\Delta^{13}C_{\text{apatite-collagen}}$ value was 4.6‰ (Table 6.8).

Changes over time were assessed for $\delta^{15}N_{\text{collagen}}$, $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$. There is no association between the y axes of the graphs, other than to demonstrate changes in the stable isotope (represented on the right y axis) over time (represented on the left y axis). There is no consistent pattern in $\delta^{15}N_{\text{collagen}}$ (Figure 6.12) or $\delta^{13}C_{\text{collagen}}$ (Figure 6.13) for the individuals from An Sơn over time, while the $\delta^{13}C_{\text{apatite}}$ becomes slightly higher over time (Figure 6.14). It was not possible to examine changes over time at Hòa Diệm due to the
Figure 6.10. $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ plotted by $\Delta^{13}$C$_{\text{apatite-collagen}}$ for An Sơn.
### Table 6.7. Isotope data for Hòa Diêm

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<th>δ¹³C apatite</th>
<th>δ¹⁵N collagen</th>
<th>δ¹³C apatite - ε δ¹³C collagen</th>
<th>δ¹³C collagen - ε δ¹³C diet</th>
<th>δ¹³C apatite - ε δ¹³C diet</th>
<th>δ¹⁵N collagen - ε δ¹⁵N diet</th>
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<td>Adolescent</td>
<td>Male</td>
<td>30-39</td>
<td>-14.85</td>
<td>13.84</td>
<td>-22.5</td>
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<tr>
<td>02HDC5M1a</td>
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<td>Male</td>
<td>30-39</td>
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### Table 6.8. Stable isotope statistics for Hòa Diêm

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<th>Parameter</th>
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<th>Mean</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Standard Deviation</th>
</tr>
</thead>
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<td>-14.85</td>
<td>-17.44</td>
<td>2.6</td>
<td>1.0</td>
</tr>
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<td>δ¹⁵N collagen</td>
<td>7</td>
<td>12.95</td>
<td>13.84</td>
<td>11.25</td>
<td>2.6</td>
<td>0.9</td>
</tr>
<tr>
<td>δ¹³C apatite</td>
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<td>-12.47</td>
<td>-12.47</td>
<td>-12.47</td>
<td>0.0</td>
<td></td>
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<tr>
<td>Δ¹³C apatite-collagen</td>
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<td>4.60</td>
<td>4.60</td>
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<td>0.0</td>
<td></td>
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</tbody>
</table>
Figure 6.11. $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ values for Hòa Diêm

Figure 6.12. $\delta^{15}N_{\text{collagen}}$ over time at An Sơn

Figure 6.13. $\delta^{13}C_{\text{collagen}}$ over time at An Sơn
limited available results.

Overall, the variation within $\delta^{15}N_{\text{collagen}}$, $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ values for all individuals at An Sơn has already been demonstrated, but when comparing differences by sex, Table 6.9 shows males have lower mean $\delta^{13}C_{\text{collagen}}$ (-19.8‰) and $\delta^{15}N_{\text{collagen}}$ (10.2‰) levels compared to females (-19.4‰ and 11.1‰ respectively) (Figure 6.15).

Males have a wider range in $\delta^{15}N_{\text{collagen}}$ (1.6‰) than females (1.0‰) (Table 6.9 and Figure 6.16) while females have a slightly wider range in $\delta^{13}C_{\text{collagen}}$ (0.9‰) than males (0.4‰) (Table 6.9 and Figure 6.17). Males have the same range in $\delta^{13}C_{\text{apatite}}$ (0.4‰) as $\delta^{13}C_{\text{collagen}}$ (0.4‰), females have a wider range in $\delta^{13}C_{\text{collagen}}$ (0.9‰) than $\delta^{13}C_{\text{apatite}}$ (0.2‰) (Table 6.9 and Figure 6.17).

Males have very consistent $\Delta^{13}C_{\text{apatite-collagen}}$ with a range of 0.1‰, while females have a wider range of 1.1‰. Males have larger mean $\Delta^{13}C_{\text{apatite-collagen}}$ (6.4‰) than females (6‰) (Table 6.9 and Figure 6.18). These differences between the sexes were not statistically significant for $\delta^{15}N_{\text{collagen}}$ $t(4)=1.627$, $p=0.197$, $\delta^{13}C_{\text{collagen}}$ $t(4)=1.524$, $p=0.202$, $\delta^{13}C_{\text{apatite}}$...
Figure 6.15. $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ values for An Sơn by sex

Figure 6.16. $\delta^{13}C_{\text{apatite}}$ and $\delta^{15}N_{\text{collagen}}$ values for An Sơn by sex

Figure 6.17. $\delta^{13}C_{\text{apatite}}$ and $\delta^{13}C_{\text{collagen}}$ values for An Sơn by sex
6. Palaeodietary Analysis of An Sơn and Hòa Diệm

\[ t(4) = 0.728, p = 0.507 \text{ or } \Delta^{13}C_{\text{apatite-collagen}} t(4) = 1.135, p = 0.320. \]

Table 6.10 provides the descriptive statistics for the individuals from Hòa Diệm by sex. It was not possible to make any comment about sex differences in diet at Hòa Diệm, since there were no females represented. Further, because there was only one individual with a \( \delta^{13}C_{\text{apatite}} \) value, changes in the \( \Delta^{13}C_{\text{apatite-collagen}} \) by \( \delta^{15}N_{\text{collagen}} \) could not be presented.

The isotope values of individuals from An Sơn and Hòa Diệm cluster as distinct groups (Figure 6.19). An Sơn has a significantly lower and tighter range of \( \delta^{15}N_{\text{collagen}} \) values \[ t(12) = 5.176, p = 0.000 \], and a significantly lower and narrower range of \( \delta^{13}C_{\text{collagen}} \) values \[ t(12) = 8.188, p = 0.000 \] compared to Hòa Diệm.

An Sơn had a tight range of \( \delta^{13}C_{\text{apatite}} \) values. There was only one individual from Hòa Diệm who had a \( \delta^{13}C_{\text{apatite}} \) value, so it is difficult to know whether it is representative of the site as a whole. The apatite value was significantly higher for the individual from Hòa Diệm \( t(6) = 4.295, p = 0.005 \) than any of the individuals from An Sơn (Figure 6.20).

Table 6.10. Stable isotope statistics for Hòa Diệm by sex

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean (( \delta^{13}C_{\text{collagen}} ))</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Range</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
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<td>( \delta^{13}C_{\text{collagen}} )</td>
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<td>-15.92</td>
<td>-17.08</td>
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<tr>
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<td></td>
<td>( \delta^{15}N_{\text{collagen}} )</td>
<td>4</td>
<td>13.22</td>
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<td>1.1</td>
</tr>
<tr>
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<td>( \delta^{13}C_{\text{apatite}} )</td>
<td>1</td>
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<td>-12.47</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \Delta^{13}C_{\text{apatite-collagen}} )</td>
<td>1</td>
<td>4.6</td>
<td>4.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Indeterminate (15-19)</td>
<td></td>
<td>( \delta^{13}C_{\text{collagen}} )</td>
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<td>-16.73</td>
<td>-17.02</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
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<td>( \delta^{15}N_{\text{collagen}} )</td>
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<td>13.24</td>
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</tr>
<tr>
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<td>( \delta^{13}C_{\text{collagen}} )</td>
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<td>-17.44</td>
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</tr>
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<td>11.25</td>
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<tr>
<td></td>
<td></td>
<td>( \delta^{13}C_{\text{apatite}} )</td>
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<tr>
<td></td>
<td></td>
<td>( \Delta^{13}C_{\text{apatite-collagen}} )</td>
<td></td>
<td></td>
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</table>
Figure 6.19. $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ values for An Sơn and Hòa Điểm

Figure 6.20. $\delta^{13}\text{C}_{\text{apatite}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ values for An Sơn and Hòa Điểm

Figure 6.21. $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ values for An Sơn and Hòa Điểm by sex
Investigating differences between the sexes is problematic as the sample is so small, but it is interesting that the females represented seem to be more concentrated in their $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ values (Figure 6.21), while the males have a more diverse range for both. Females also have higher $\delta^{15}N_{\text{collagen}}$ values than the majority of males at An Sơn. There were no significant differences reflected, so whether this is real or a product of the small sample is unclear.

**Multivariate dietary reconstruction models**

The results using Froehle et al.'s (2010) bivariate regression model are presented in Figure 6.22. The majority of individuals from An Sơn fall just above the C$_3$ protein line, the individual from Hòa Diệm falls between the C$_3$ and C$_4$/marine protein lines. None of the individuals are positioned at the extreme 100% C$_3$ diet end of the lines.

Figure 6.23 replicates Froehle et al.'s (2012) multivariate model. It shows the individuals from An Sơn and Hòa Diệm presented in Cluster 1 or on the periphery of Cluster 4. Cluster 1 represents a diet 100:0 C$_3$:C$_4$, C$_3$ protein. Cluster 4 represents a diet70:30 C$_3$:C$_4$, $\geq$65% C$_3$ protein (Froehle et al. 2012: 4 Table 1).

**Palaeodietary reconstruction**

Figure 6.24 presents the $\delta^{13}C_{\text{collagen}}$ and $\delta^{15}N_{\text{collagen}}$ values for the individuals from An Sơn and Hòa Diệm superimposed over the adjusted biogeographical baseline. It shows the distinction between An Sơn and Hòa Diệm indicative of the constituents of the protein in their diets.

Figure 6.25 presents the $\delta^{13}C_{\text{apatite}}$ and $\delta^{15}N_{\text{collagen}}$ values for the individuals from An Sơn and Hòa Diệm superimposed over the adjusted biogeographical baseline. It shows the distinction between An Sơn and Hòa Diệm indicative of the constituents of their whole diet.

Figure 6.26 presents the mean $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ values for the individuals from An Sơn and Hòa Diệm superimposed over the adjusted isotopic means for species of flora and fauna sourced from King (2008), which were identified zooarchaeologically or archaeobotanically present at the site of An Sơn.

Figure 6.27 presents the mean $\delta^{13}C_{\text{apatite}}$ and $\delta^{15}N_{\text{collagen}}$ values for the individuals from An Sơn and Hòa Diệm superimposed over the adjusted isotopic means for species of flora and fauna sourced from King (2008), which were identified zooarchaeologically or archaeobotanically present at the site of An Sơn.
There were 32 individuals that had $\delta^{13}$C_{apatite} values from bone (King 2008) and enamel (Bentley et al. 2005) for comparison. The mean $\Delta^{13}$C_{enamel-apatite-bone-apatite} was 0.1‰ ± 1.3‰ (data not shown). For the majority of individuals from Ban Chiang whose diets were not monoisotopic (< or > 4.4‰) (Figure 6.28) the protein portion of their diet ($\delta^{13}$C_{collagen}) was more depleted than their whole diet ($\delta^{13}$C_{apatite}) (assuming that their diet did not change between enamel formation and bone formation), that it was relatively stable over time.

Figure 6.22. Bivariate regression model presenting An Sơn and Hòa Diêm diets

Figure 6.23. Multivariate model presenting An Sơn and Hòa Diêm diets

Contextualising palaeodiet within Southeast Asia
Figure 6.24. $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ for An Sơn and Hòa Diệm superimposed over the biogeographic baseline based on data provided by King 2008.
Figure 6.25. $\delta^{15}$N$_{collagen}$ and $\delta^{13}$C$_{apatite}$ for An Son and Hòa Diệm superimposed over the biogeographic baseline based on data provided by King 2008.
6. Palaeodietary Analysis of An Sơn and Hòa Diêm

and that the increase in spacing (\(\Delta^{13}C_{\text{apatite-collagen}}\)) is due to an enrichment of \(\delta^{13}C_{\text{apatite}}\). This differs to An Sơn, where the \(\delta^{13}C_{\text{apatite}}\) is stable and the \(\delta^{13}C_{\text{collagen}}\) fluctuates (compare to Figure 6.10).

The following figures compare bone \(\delta^{13}C_{\text{collagen}}\) with bone \(\delta^{13}C_{\text{apatite}}\) (Figure 6.28) and then bone \(\delta^{13}C_{\text{collagen}}\) with enamel \(\delta^{13}C_{\text{apatite}}\) (Figure 6.29). The data for bone \(\delta^{13}C_{\text{collagen}}\) is the same for both graphs, however, the presentation varies because the \(\Delta^{13}C_{\text{apatite-collagen}}\) values are different as a product of the difference between enamel and bone \(\delta^{13}C_{\text{apatite}}\) values. Neither graph depicts diachronic changes. Figure 6.28 presents bone \(\delta^{13}C_{\text{collagen}} - \varepsilon \delta^{13}C_{\text{collagen-diet}}\) and bone \(\delta^{13}C_{\text{apatite}} - \varepsilon \delta^{13}C_{\text{apatite-diet}}\) plotted by \(\Delta^{13}C_{\text{apatite-collagen}}\). It shows at Ban Chiang \(\delta^{13}C_{\text{collagen}}\) is relatively stable, while \(\delta^{13}C_{\text{apatite}}\) is more variable. Figure 6.29 presents bone \(\delta^{13}C_{\text{collagen}} - \varepsilon \delta^{13}C_{\text{collagen-diet}}\) and enamel \(\delta^{13}C_{\text{apatite}} - \varepsilon \delta^{13}C_{\text{apatite-diet}}\) plotted by \(\Delta^{13}C_{\text{apatite}}\).
Figure 6.28. Bone $\delta^{13}C_{\text{collagen}}$ and bone $\delta^{13}C_{\text{apatite}}$ plotted by $\Delta^{13}C_{\text{apatite-collagen}}$ for Ban Chiang
Figure 6.29. Bone $\delta^{13}C_{\text{collagen}}$ and enamel $\delta^{13}C_{\text{apatite}}$ plotted by $\Delta^{13}C_{\text{apatite-collagen}}$ for Ban Chiang.
collagen. This demonstrates at Ban Chiang $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ from enamel are relatively stable. The two figures (Figures 6.28 and 6.29) demonstrate that the bone $\delta^{13}$C$_{\text{collagen}}$ and enamel $\delta^{13}$C$_{\text{apatite}}$ are not equivalent.

The only sites in mainland Southeast Asia that have comparable $\delta^{15}$N$_{\text{collagen}}$, $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ values are Núi Nấp from Vietnam, sourced from dentine and enamel (Bower et al. 2006) and Ban Chiang, Ban Lum Khao, Ban Na Di and Noen U-Loke from Thailand, sourced from bone (King 2008). Jiangzhai and Shijia from China provide comparable $\delta^{15}$N$_{\text{collagen}}$, $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{apatite}}$ values from bone (Pechenkina et al. 2005). Mán Bạc provides $\delta^{15}$N$_{\text{collagen}}$ and $\delta^{13}$C$_{\text{collagen}}$ values but $\delta^{13}$C$_{\text{apatite}}$ was not analysed (Minoru Yoneda pers. comm.).

Figure 6.30 presents the $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{15}$N$_{\text{collagen}}$ values from bone for Ban Chiang, Ban Lum Khao, Ban Na Di, Noen U-Loke, Jiangzhai and Shijia and the $\delta^{13}$C$_{\text{collagen}}$ and $\delta^{15}$N$_{\text{collagen}}$ values from dentine for An Sơn, Mán Bạc, Núi Nấp and Hòa Diệm. The $\delta^{13}$C$_{\text{collagen}}$ is slightly more depleted at the Vietnamese sites than the majority of individuals at the sites from Thailand and very depleted in comparison to the Chinese sites.

Figure 6.31 presents the $\delta^{13}$C$_{\text{apatite}}$ and $\delta^{15}$N$_{\text{collagen}}$ values from bone for Ban Chiang, Ban Lum Khao, Ban Na Di and Noen U-Loke and the $\delta^{13}$C$_{\text{apatite}}$ and $\delta^{15}$N$_{\text{collagen}}$ values from enamel and dentine respectively for An Sơn, Mán Bạc, Núi Nấp and Hòa Diệm. The $\delta^{13}$C$_{\text{apatite}}$ values from Núi Nấp are lower than An Sơn and the majority of individuals from the Thai sites. The $\delta^{13}$C$_{\text{apatite}}$ values from An Sơn are comparable with those from Thailand, while those from China are much higher in comparison.

The only sites in mainland Southeast Asia that have comparable $\delta^{13}$C$_{\text{apatite}}$ values are Núi Nấp and Cồn Cổ Ngựa from Vietnam (Bower et al. 2006: 85 Table 2) and Khok Phanom Di (Bentley et al. 2007), Ban Lum Khao (Bentley et al. 2009), Ban Chiang (Bentley et al. 2005) and Noen U-Loke (Cox et al. 2011) from Thailand. The $\delta^{13}$C$_{\text{apatite}}$ are all sourced from enamel.

Figure 6.32 illustrates the variation in enamel $\delta^{13}$C$_{\text{apatite}}$ among the Vietnamese and Thai sites. Khok Phanom Di and Hòa Diệm have the highest $\delta^{13}$C$_{\text{apatite}}$ values, Cồn Cổ Ngựa, An Sơn, Ban Chiang, Ban Lum Khao and Noen U-Loke have comparable values and Núi Nấp has the lowest values.

Figure 6.33 replicates Froehle et al.’s (2012) multivariate model. It shows the individuals from Vietnam and Thailand presented in Cluster 1 or Cluster 4. The individuals from the Chinese sites present in Cluster 2. Cluster 1 represents a diet 100:0 C$_{3}$:C$_{4}$, C$_{3}$ protein. Cluster 2 represents a diet 30:70 C$_{3}$:C$_{4}$, >50% C$_{4}$ protein. Cluster 4 represents a diet 70:30 C$_{3}$:C$_{4}$, ≥65% C$_{3}$ protein (Froehle et al. 2012: 4 Table 1).
Figure 6.30. δ¹³C_{collagen} and δ¹⁵N_{collagen} values for Southeast Asia and China.
Figure 6.31 δ¹³Capatite and δ¹⁵Ncollagen values for Southeast Asia and China
Discussion

This discussion focusses on a palaeodietary reconstruction for the individuals from An Sơn and Hòa Diệm using $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ from tooth dentine and $\delta^{13}C_{\text{apatite}}$ from tooth enamel to explore, interpret and reconstruct the diet more thoroughly. This was contextualised using the faunal data from Piper et al. (2014), the phytolith data from Tetsuro Udatsu (pers. comm.) and the stable isotope data from King (2008) as an interpretive biogeographical baseline.

The following discussion is structured in the same order as the results. To begin, an overview of the methodological approach and quality control protocols, entitled methodological and quality control justifications is presented. The second section, stable isotopes, discusses the raw stable isotope results for the individuals from An Sơn and Hòa Diệm in turn, and the implications of these. The third section, entitled multivariate dietary reconstruction models, discusses the results of the multivariate reconstruction models using the An Sơn and Hòa Diệm data. In the fourth section, palaeodietary reconstruction, each of the stable isotopes $\delta^{15}N_{\text{collagen}}$, $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ is presented and discussed in terms of its predictive power and contribution to the interpretation and reconstruction of the diet. The fifth section, entitled contextualising palaeodiet within Southeast Asia, discusses the data from An Sơn and Hòa Diệm in light of comparative data from other Southeast Asian assemblages to evaluate similarities in palaeodiet, contextualising the findings in a regional perspective. In the final section the key points in the reconstruction of the diet for An Sơn and Hòa Diệm are summarised.
Figure 6.33. Multivariate model presenting diets of the sites with $\delta^{15}N_{\text{collagen}}$, $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ values.
Methodological and quality control justifications

Dietary reconstruction is fraught with difficulties. It is essential to understand the fractionation process between ingested food and subsequent expression in consumer tissues, however, as it is not possible to conduct controlled feeding experiments on humans, finding an accurate analogue is problematic. Controlled feeding studies on different species of animals, conducted by various researchers, have found discrepancies in diet to tissue spacing in different tissues and animals, so how do we impose these on humans in dietary reconstruction? For the purposes of this analysis, where appropriate, rats were chosen over pigs as the analogue for humans in consideration of the extensive experimental feeding studies and animal modelling conducted on rats and for consistency in comparison with other sites. The limitations of this are acknowledged.

The enrichment between diet and tissues in $\delta^{13}C$ is also largely dependent on the constituents of the diet, if they are not known then making assumptions about the spacing can be problematic. While it was not possible to compare An Sơn and Hòa Diệm to the stable isotope data sourced from local flora and fauna, the results were contextualised with a consideration of the archaeological evidence.

It has been suggested that $\delta^{13}C_{\text{collagen}}$ from tooth dentine and bone may not be equivalent in their expressions of stable isotopes. It has also been suggested that $\delta^{13}C_{\text{apatite}}$ from tooth enamel and bone may not be equivalent. The latter was tested using the data from Ban Chiang and these were taken into consideration during this discussion.

Because southern Vietnam is a $C_3$ biome, with very few $C_4$ cultigens, the food web is relatively straightforward in one sense, although complex in that everything overlaps and identifying relative proportions of anything is not possible. This dietary reconstruction reveals the complexity of reconstructing human diet in a region where the majority of sources in the food web are $C_3$. Due to these issues, a broad, generalised discussion is applied here.

$\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ were sourced from dentine and $\delta^{13}C_{\text{apatite}}$ from enamel. An interpretation of palaeodiet using both $\delta^{13}C_{\text{collagen}}$ and $\delta^{13}C_{\text{apatite}}$ provide the opportunity to identify ‘invisible’ dietary elements containing low or no protein. Teeth are often the tissue of choice for isotopic analysis. Enamel has a stable composition, it is constructed of densely arranged prisms of large crystal size, it has low organic content and porosity; and it is resistant to diagenetic processes and microbial influences (Lee-Thorp and Sealy 2008; Tütken and Vennemann 2011). Teeth do not remodel “[s]econdary dentine may be deposited at the margins of the pulp cavity throughout life, but constitutes a small fraction of dentine volume, and can be removed” (Wright and Schwarcz 1999: 1160) so teeth capture a static representation of diet. Bone tissue continuously remodels throughout life,
providing a cumulative representation of diet, however, there is some suggestion that the postadolescent turnover of bone is considerably slower than previously calculated (Hedges et al. 2007). The collagen quality of the dentine was assessed using three protocols, samples were accepted on the condition that they met the required collagen yield, the required %C and %N and the C:N ratio was between 2.9-3.6. Samples which met the first two criteria but had a C:N of 3.6-4.5 were also accepted with the following justification. The variation between the stable isotopic values for An Sơn and Hòa Diêm are as expected for the different environments in which they lived. The respective enamel $\delta^{13}$C$_{apatite}$ and dentine $\delta^{13}$C$_{collagen}$ from the same individuals express the expected spacing. Finally, as discussed earlier, it has been accepted that none of the quality control criteria alone stand to provide a definitive measure of collagen quality and recently several studies have suggested that the range for C:N should be extended (Harbeck and Grupe 2009).

Stable isotopes

This section discusses the raw stable isotope results for the individuals from An Sơn and Hòa Diêm in turn, and the implications of these. The data for $\delta^{15}$N$_{collagen}$ indicating trophic level effects from protein consumption, $\delta^{13}$C$_{collagen}$ indicating protein consumption, $\delta^{13}$C$_{apatite}$ indicating whole diet and $\Delta^{13}$C$_{apatite-collagen}$ indicating information on protein to whole diet equivalence are discussed for each site respectively. Where possible, these are examined over time and by sex. Finally, in summary An Sơn and Hòa Diêm are compared to illustrate any differences between the sites. This information provides the foundation on which the later interpretation of palaeodiet is based.

A diet comprised largely of terrestrial animal protein would have anticipated $\delta^{15}$N values of 5-10‰, while a diet comprised of mainly marine or freshwater animal protein would be expected to have values between 10-22‰. In areas where C$_4$ plants are not consumed as a staple, a purely terrestrial diet would have $\delta^{13}$C$_{collagen}$ values of -20‰ while a diet focussed on marine resources would be expected to have a $\delta^{13}$C$_{collagen}$ value of -12‰ (Mays 1997; Richards and Hedges 1999).

The average $\delta^{15}$N$_{collagen}$ at An Sơn is 10.7‰, which is indicative of a diet comprised of terrestrial C$_3$ protein. The average $\delta^{15}$N$_{collagen}$ at Hòa Diêm is 12.9‰, which is indicative of a marine influence in protein consumption. The average $\delta^{13}$C$_{collagen}$ value at An Sơn is -19.6‰, which is indicative of consumption of terrestrial C$_3$ protein. The average $\delta^{13}$C$_{collagen}$ value at Hòa Diêm -16.4‰ which is indicative of a marine influence in protein consumption. The average $\delta^{13}$C$_{apatite}$ at An Sơn is -13.4‰, which is indicative of a terrestrial C$_3$ diet, supplemented with C$_3$ plants. The average $\delta^{13}$C$_{apatite}$ at Hòa Diêm is -12.5‰, which is indicative of a marine diet, supplemented with C$_3$ plants.

There is a positive correlation between the $\delta^{13}$C$_{collagen}$ and $\delta^{15}$N$_{collagen}$ values at An Sơn.
(Figure 6.6), which you would expect from a population consuming terrestrial C\textsubscript{3} resources and riverine protein. High δ\textsuperscript{15}N\textsubscript{collagen} values of individuals suggest consumption of protein sources high in the trophic level of the foodweb. Relatively low δ\textsuperscript{13}C\textsubscript{collagen} values suggest the diet was supplemented by terrestrial animals consuming C\textsubscript{3} resources. The wider range of δ\textsuperscript{13}C values for δ\textsuperscript{13}C\textsubscript{collagen} (Figure 6.6) than δ\textsuperscript{13}C\textsubscript{apatite} (Figure 6.7) when plotted against δ\textsuperscript{15}N\textsubscript{collagen} suggest a wider range in carbon values for protein foods than carbohydrate foods. The very small variation in δ\textsuperscript{13}C\textsubscript{apatite} suggests homogeneity in plant food consumption for the inhabitants of An Sơn, that they were possibly focussed on one major staple crop, probably rice. δ\textsuperscript{13}C\textsubscript{apatite} is weakly positively correlated with δ\textsuperscript{15}N\textsubscript{collagen} (Figure 6.7) and δ\textsuperscript{13}C\textsubscript{collagen} (Figure 6.8) at An Sơn, which is expected if there are differences in the trophic level of foods consumed by different individuals in the same sample (Prowse et al. 2005; Wright and Schwarcz 1996). If this is the case, a correlation should be found between Δ\textsuperscript{13}C\textsubscript{apatite-collagen} and δ\textsuperscript{15}N\textsubscript{collagen} (Wright and Schwarcz 1996).

There is an inverse correlation between Δ\textsuperscript{13}C\textsubscript{apatite-collagen} and δ\textsuperscript{15}N\textsubscript{collagen} (Figure 6.9), as δ\textsuperscript{15}N\textsubscript{collagen} decreases with increasing Δ\textsuperscript{13}C\textsubscript{apatite-collagen}, which highlights the differences in the trophic levels of food consumed between individuals (Kellner and Schoeninger 2007; Lee-Thorp 1989) and indicates the protein carbon source in the diet was predominantly higher in trophic level for individuals with high δ\textsuperscript{15}N values. The Δ\textsuperscript{13}C\textsubscript{apatite-collagen} values are higher than 4.4‰ for all individuals from An Sơn, when the δ\textsuperscript{13}C\textsubscript{apatite} - ε δ\textsuperscript{13}C\textsubscript{collagen-diet} and δ\textsuperscript{13}C\textsubscript{apatite} - ε δ\textsuperscript{13}C\textsubscript{apatite-diet} values are plotted by Δ\textsuperscript{13}C\textsubscript{apatite-collagen} (Figure 6.10) it indicates the diet was not monoisotopic, the protein portion of the diet and the whole diet were not equivalent. This suggests that the protein δ\textsuperscript{13}C values of the diet were more negative than the whole diet. The Δ\textsuperscript{13}C\textsubscript{apatite-collagen} values are very stable and consistent. This indicates that where there is a lower Δ\textsuperscript{13}C\textsubscript{apatite-collagen} the protein consumed is higher in the trophic food chain and more enriched in δ\textsuperscript{13}C\textsubscript{collagen} and δ\textsuperscript{15}N\textsubscript{collagen}, while where there is a larger Δ\textsuperscript{13}C\textsubscript{apatite-collagen} the protein consumed is more depleted in δ\textsuperscript{13}C\textsubscript{collagen} and δ\textsuperscript{15}N\textsubscript{collagen}. This probably indicates a differential consumption of riverine vs terrestrial protein among inhabitants, with a consistent staple carbohydrate.

There is a strong positive correlation between δ\textsuperscript{13}C\textsubscript{collagen} and δ\textsuperscript{15}N\textsubscript{collagen} at Hòa Diệm (Figure 6.11), which suggests food sources with higher δ\textsuperscript{15}N also have higher δ\textsuperscript{13}C values, so the higher in the trophic level the protein source the more enriched the δ\textsuperscript{13}C\textsubscript{collagen}. It was only possible to obtain δ\textsuperscript{13}C\textsubscript{apatite} values from three individuals from Hòa Diệm and only one of those individuals had a δ\textsuperscript{13}C\textsubscript{collagen} value. The Δ\textsuperscript{13}C\textsubscript{apatite-collagen} value for the individual was 4.6‰, suggesting an almost monoisotopic diet (protein slightly depleted compared to whole diet), for this individual at least. It was not possible to comment further on the diet spacing for Hòa Diệm. Acknowledging the potential problems of adjusting the apatite by 9.4‰, it is interesting that the indicators suggest that the diet of An Sơn is not monoisotopic, that the protein portion of the diet is more depleted than the whole diet, indicating the food sources in their diet that contained little protein, such as carbohydrates,
must have been more enriched in δ¹³C than the protein sources, and for the one individual from Hòa Diêm, the values are suggestive of a nearly monoisotopic diet. Because the δ¹³C in their diet is enriched due to the marine input, this would suggest that the low protein sources of their diet are similarly enriched. However, this observation is wholly reliant on the assumption that the δ¹³C apatite is enriched by 9.4‰.

At An Sơn there was no consistent pattern in δ¹⁵N collagen (Figure 6.12) or δ¹³C collagen (Figure 6.13) over time, however, δ¹³C apatite (Figure 6.14) was very stable with a slight enrichment over time. The consistency in δ¹³C apatite values at An Sơn suggests that the whole diet of the individuals was relatively stable. It was not possible to examine changes over time at Hòa Diêm due to limited dates available.

There were no significant differences between the sexes at An Sơn for δ¹³C collagen (Figure 6.15), δ¹⁵N collagen (Figure 6.16), δ¹³C apatite (Figure 6.17) or ∆¹³C apatite-collagen (Figure 6.18). It was not possible to make any comment about sex differences in diet at Hòa Diêm. Further, because there was only one individual with a δ¹³C apatite value, differences in diet spacing could not be evaluated.

The individuals from An Sơn and Hòa Diêm cluster as distinct groups. An Sơn has significantly lower δ¹⁵N collagen values, with a narrower range; and significantly lower δ¹³C collagen values, with a narrower range than Hòa Diêm (Figure 6.19). An Sơn had a tight range of δ¹³C apatite values suggesting that among the majority of individuals there was little variation in diet. There was only one individual from Hòa Diêm who had a δ¹³C apatite value, so it is difficult to know whether it is representative of other individuals from the site. The apatite value was significantly higher for the individual from Hòa Diêm than the individuals from An Sơn as expected (Figure 6.20). The differences between the average δ¹³C collagen values at An Sơn and Hòa Diêm is 3.2, while the differences in the δ¹³C apatite values is only 0.9. The difference in δ¹³C collagen is a reflection of the different protein sources, terrestrial/riverine vs marine environment, while the similarity in δ¹³C apatite suggests that the whole diet is relatively similar, suggesting that the consumption of carbohydrates is similar.

The stable isotopes of these individuals are a direct result of their environment and the foods they were consuming. The individuals at An Sơn were likely consuming a terrestrial based protein diet, supplemented with C₃ plants, the ∆¹³C apatite-collagen values indicate the protein portion of the diet was more depleted than the whole diet, so it is possible that they were consuming some C₄ plants in their diet also. The enrichment in the δ¹⁴N collagen and collagen of the individuals at Hòa Diêm was due to their marine influenced diet, consuming animals with higher trophic food chains and enriched sources of carbon. The ∆¹³C apatite-collagen value for the individual from Hòa Diêm is almost monoisotopic, this suggests that the protein portion of the diet and the whole diet were almost equivalent. Given that their protein was enriched in ¹³C with a marine influence, this suggests that their whole
diet must have been similarly enriched, so it is possible that they were consuming some C₄ plants in their diet also. Given the marked difference in the δ¹³C collagen values between the An Sơn and Hòa Diêm individuals, based on their different environments, but the similarity in the δ¹³C apatite values, despite the different environments, this is plausible.

Multivariate dietary reconstruction models

This section discusses the results of the multivariate reconstruction models using the raw An Sơn and Hòa Diêm data. The two models that were used to further elucidate the diet of An Sơn and Hòa Diêm are discussed in turn. Both offers an independent alternative assessment to either corroborate or refute expected outcomes. In each model the dietary ‘position’ of individuals is presented using the raw data to infer the contribution of different constituents in the diet. Where appropriate, analogies are drawn between the position of the animals the models are developed from and the individuals from An Sơn and Hòa Diêm. The results and the possible implications of this in terms of the diet are discussed.

Using Froehle et al.’s (2010) bivariate regression model, the majority of individuals from An Sơn fall just above the C₃ protein line, the individual from Hòa Diêm falls between the C₃ and C₄/marine protein lines. None of the individuals are positioned at the extreme 100% C₃ diet end of either of the respective C₃ or C₄ protein regression lines (Figure 6.22). The position of the An Sơn individuals near the C₃ protein line is expected, as a consequence of the terrestrial and riverine protein in their diet; their position along δ¹³C apatite axis is indicative of their whole diet, the contribution of C₃ to C₄ including non-protein foods in their diet. When examining their position on the δ¹³C apatite axis relative to the animals on which the model was based (Froehle et al. 2010: 2669 Figure 5), the individuals from An Sơn are comparable to the rodent fed diet 5E from Ambrose and Norr (1993) and the swine fed diet 8 from Howland et al. (2003) (Froehle et al. 2010: 2663 Table 1). The diet of these animals was quite different, the rodents ate 100% C₃ protein with 100% C₄ non-protein and the pigs ate 100% C₃ protein and 100% C₄ non-protein. The protein portion of the whole diet of these two experimental diets, diet 5E and diet 8 was different, 70% and 20% of the whole diet, respectively (Froehle et al. 2010: 2663 Table 1). This reinforces the concept that the effect of 100% C₄ non-protein, where a large proportion of the diet is C₃ protein, will be very subtle. In a high protein diet, the effects of C₄ low protein foods are even more obscured. The position of the individual from Hòa Diêm, between the C₃ and C₄/marine protein lines, is expected as a consequence of the marine influence in their diet but suggests they were also reliant on C₃ terrestrial protein which is consistent with Sawada’s (2012) observations. There are no comparable animal diets in the same position as the individual from Hòa Diêm.

Froehle et al.’s multivariate model (2012), shows the individuals from An Sơn and Hòa
Diệm presented in Cluster 1 or Cluster 4 (Figure 6.23). Cluster 1 represents a diet 100:0 \((C_3:C_4); C_3\) protein. Cluster 4 represents a diet 70:30 \((C_3:C_4); \geq 65\% \ C_3\) protein (Froehle et al. 2012: 4 Table 1). Both of these models independently support the evidence from the raw data for the diet at An Sơn and Hòa Diệm. The diet at An Sơn was focused on \(C_3\) protein, which was supplemented by \(C_3\) and \(C_4\) non or low protein foods, the latter, which was enriched in \(\delta^{13}C\) enriched the whole diet. The diet at Hòa Diệm was supplemented by marine protein, although only represented by one individual, it is interesting that the diet is also shown to be almost monoisotopic, if slightly depleted compared to the whole diet. This suggests that the whole diet of all individuals from An Sơn and Hòa Diệm were more enriched than the protein portion of their diet. The limitations of these models, as discussed earlier, is that they were constructed using the swine and rodent data from controlled feeding studies which sampled bone collagen and apatite, data from enamel apatite was not included (Froehle et al. 2010, 2012).

**Palaeodietary reconstruction**

In this section each of the stable isotopes \(\delta^{15}N_{\text{collagen}}\), \(\delta^{13}C_{\text{collagen}}\) and \(\delta^{13}C_{\text{apatite}}\) is presented and discussed in terms of its predictive power and contribution to the interpretation and reconstruction of the diet. These are discussed within the context of the archaeological evidence, the fauna from Piper et al. (2014) and the phytolith data from Tetsuro Udatsu (pers. comm.), using the data from King (2008) as an interpretive biogeographic baseline. This final stage uses the raw data presented as the building blocks for the palaeodietary reconstruction and interpretation.

There is no nitrogen in carbohydrates and fats (Ambrose et al. 1997; Lassar-Cohn 1908; Sanders and Emery 2003), therefore the \(\delta^{15}N_{\text{collagen}}\) of consumer tissues are mainly a reflection of dietary protein. \(\delta^{15}N_{\text{collagen}}\) can be used to determine the contribution of foods with different trophic levels in the foodweb (DeNiro and Epstein 1978). This is relevant in terrestrial environments between herbivorous and carnivorous animals, where carnivorous animals have higher \(\delta^{15}N\) values due to their consumption of other animals; but also in marine environments, where the foodwebs have a greater number of trophic levels. Marine plants are also usually enriched 4‰ in \(\delta^{15}N\) over terrestrial plants (Ambrose 1993; Schoeninger and DeNiro 1984), which contributes, in addition to the longer trophic chain, to higher \(\delta^{15}N\) values in marine animals than terrestrial ones. Therefore, \(\delta^{15}N_{\text{collagen}}\) can be used to understand the contribution of herbivorous to carnivorous animal protein consumed in the diet, and the contribution of terrestrial to marine animal protein consumed in the diet.

The \(\delta^{15}N_{\text{collagen}}\) of consumer tissues is a reflection of dietary protein, plus the enrichment from the trophic level effect of 3-4‰ (Minagawa and Wada 1984; Schoeninger and DeNiro 1984). The most common taxa identified during the 2009 excavation of An Sơn...
were turtles, domestic dogs, domestic pigs, snakeheads, swamp eels and climbing perch. Turtles are mixed aquatic and terrestrial species, which are largely omnivorous and will eat insects, worms, fish, crustaceans, carrion and fruit (Franklin and Killpack 2007). The diet of domestic dogs and pigs is omnivorous and would be largely based on what the community were feeding them, or what they could scavenge from what was thrown away. Snakehead, swamp eel and climbing perch are all benthopelagic, inhabiting freshwater or brackish environments. All have the ability to survive out of water for a period of time and all are largely carnivorous. Climbing perch feed on aquatic plant vegetation, invertebrates and larvae (Pethiyagoda 1991). Swamp eels feed on detritus, fishes, worms, crustaceans, and other small aquatic invertebrates (Yamamoto and Tagawa 2000). Snakeheads are known to feed on plankton, aquatic insects, earthworms, tadpoles, crustaceans, fish, frogs, snakes and in rare cases rats (Allen 1991; Rahman 1989). These species all have high trophic level food webs and easily explain the high δ¹⁵N₉.collagen at An Sơn.

When the individuals from An Sơn were superimposed on the foodweb (adjusted by +3‰ for δ¹⁵N₉.collagen), the individuals are positioned above the C₃ herbivores and among the fish and the majority of the terrestrial omnivores, in δ¹⁵N₉.collagen values, indicating they were an important part of the diet (Figure 6.24). When examining the position of the individuals from An Sơn in relation to the mean of particular animals known to be important in the diet, the δ¹⁵N₉.collagen values of An Sơn were higher than the domestic pig, eel and fish (Figure 6.26). The δ¹⁵N₉.collagen values at Hòa Diệm are even higher than at An Sơn, although no data is available on the specific constituents of the Hòa Diệm diet, because of the locality of the site, it is assumed that there was a marine influence, which explains the higher δ¹⁵N₉.collagen.

δ¹³C₉.collagen of consumer tissues are mainly a reflection of dietary protein in an individual with an adequate intake of protein. δ¹³C₉.collagen can be used to determine the contribution of terrestrial C₃ or C₄ or marine resources. Terrestrial C₃ or C₄ animals have distinctive non-overlapping δ¹³C₉.collagen values due to their consumption of plants photosynthesising atmospheric CO₂ using different pathways, while marine animals, due to their consumption of plants incorporating dissolved bicarbonate from the sea during photosynthesis, sit intermediate to C₃ or C₄ animals, more enriched than C₃ and more depleted than C₄ (Chisholm et al. 1982; Dufour et al. 1999; Tauber 1981). Defining the δ¹³C₉.collagen values of freshwater animals is more difficult, due to their consumption of plants with variable carbon sources, CO₂ from the atmosphere and water, organic carbon from terrestrial detritus, and carbon and bicarbonate from the environment. The variability in freshwater fish is found among different species, but also the same species in different locations and even in different parts of the same location (Dufour et al. 1999; Katzenberg and Weber 1999; Yoder 2010). Domestic dogs and pigs are terrestrial omnivores, with low δ¹³C₉.collagen values, turtles are terrestrial/aquatic, while freshwater riverine snakeheads, swamp eels and climbing perch would have variable δ¹³C₉.collagen.
The δ13Ccollagen of consumer tissues is mainly a reflection of dietary protein, plus the fractionation $\Delta^{13}$Ccollagen-diet. The $\Delta^{13}$Ccollagen-diet is 5‰ on a monoisotopic diet where the protein and non-protein components have identical δ13C values. When the individuals from An Sơn were superimposed on the food web (adjusted by +5‰ for δ13Ccollagen) they were shown to be more depleted in δ13Ccollagen than the C₃ herbivores, fish, and most of the terrestrial omnivores (Figure 6.24). The marine influence at Hòa Diêm explains their high δ13Ccollagen values.

When examining the position of the individuals from An Sơn in relation to the mean of particular animals known to be important in the diet from the faunal remains found in the archaeological record, the δ13Ccollagen of An Sơn are more depleted than the turtles, domestic dog, domestic pig, and fish (Figure 6.26), this is contrary again to what is expected. A possible reason for this is that the stable isotope data for potential fauna used from King (2008) to develop a comparative food web for diet is inappropriate, as discussed below.

δ13Capatite represents the whole diet, including low protein foods which may alter the δ13C value of δ13Capatite which would otherwise be invisible if assessing diet based on δ13Ccollagen alone (Ambrose et al. 1997; Lee-Thorp 2008). An examination of the phytoliths from soil samples from the 2009 An Sơn excavation provides some evidence for the presence of potential low protein carbohydrate sources that may have been included in the diet. From the phytoliths present, the subfamily Bambusoideae were most common followed by the tribes Andropogoneae and Paniceae, and genus Oryza and Phragmites (See Chapter Two Table 2.5). Paniceae and Andropogoneae use the C₄ photosynthetic pathway. There are several examples of edible foods, belonging to these tribes, which could have contributed to the diet of inhabitants of prehistoric Vietnam. Sugar cane and Job’s Tears (Coix lacryma-jobi) are species within the respective genera Saccharum and Coix within the tribe Andropogoneae. Rice (Oryza sativa) is a species within the genus Oryza within the tribe Oryzeae. Foxtail millet (Setaria italica) and Proso millet (Panicum miliaceum), are species within the respective genera Setaria and Panicum within the tribe Paniceae. These two species of millet have been the most commonly found in archaeological sites in Southeast Asia (Weber et al. 2010). The question of to what proportion these plants were present at site, as endemic native plants, for their use as animal fodder, for their domestic use, or for consumption in the human diet is not a question we can answer at this stage.

The δ13Capatite of consumer tissues is a reflection of the whole diet, plus the fractionation $\Delta^{13}$Capatite-collagen. The $\Delta^{13}$Capatite-collagen is 9.4‰ regardless of the constituents of the diet. When the individuals from An Sơn were superimposed on the food web (adjusted by +9.4‰ for δ13Capatite), their position reflects the input of protein, carbohydrates and low protein foods in the diet (Figures 6.25 and 6.27). What this obscures is the relationship between δ13Capatite and δ13Ccollagen. Using the values of 9.4‰ and 5‰ to test if the diet was monoisotopic, the $\Delta^{13}$Capatite-collagen values for the individuals from An Sơn were all >4.4 (Figure 6.10),
suggesting the protein portion of the diet was depleted compared to the whole diet. If the individuals were primarily consuming terrestrial/riverine animals consuming a C$_3$ diet and C$_3$ plants why would the diet not be monoisotopic? The answer must lie in a low protein food. Millet or Job’s Tears are low protein C$_4$ sources that may have been consumed and the phytolith evidence from An Sơn supports this as a possibility.

Inferring that the animal and plants sampled in prehistoric and modern Thailand are synonymous with those in prehistoric and modern Vietnam is problematic, but given the limitations of financial constraints it was the only avenue to pursue. Given the similarities in climate, humidity, temperature and insolation it is assumed that the plants are comparable and that the animals that forage on these plants are comparable. However, a consideration of the contrary is important. The zooarchaeological evidence does suggest that there are some differences in the focus of domesticity and animal husbandry at An Sơn in comparison to Thailand. In particular, the subsistence strategy at An Sơn seems focussed primarily on dog and pig husbandry and river fishing, supplemented by hunting (Bellwood et al. 2011; Piper et al. 2014), while other areas in Neolithic Thailand seemed to have more of a focus on hunting (Piper et al. 2014). The diets of these domesticated animals at An Sơn would have been determined by the community that housed and fed them; this presumably would have been of a similar scope to that available in Thailand, given the similarity in available foodstuffs. However, there is some suggestion that dogs and pigs were treated differently at An Sơn to what has been reported for other sites in Thailand. There was no evidence found for special treatment at An Sơn, for example, burials of dogs indicating emotional investment in the animals, or inclusion of pigs in burials (Piper et al. 2014), suggesting that pigs and dogs were treated differently at An Sơn to what has been reported at other sites in Thailand. If there was some marked difference in treatment, symbolism or status of these animals, they may have had a diet different to the animals from Thailand, which would deem the values for those animals incomparable for Vietnam. Domesticated dogs may have been specifically kept for consumption at An Sơn. Several lines of evidence attest to this in that most of the remains were juvenile and show evidence for butchery marks; the site itself was also lacking other animal remains with gnawing marks from dogs and coprolites featuring small bones, usually associated with wild dogs roaming around the community (Piper et al. 2014).

Contextualising palaeodiet within Southeast Asia

This section discusses the data from An Sơn and Hòa Diệm in light of comparative data from other Southeast Asian assemblages to evaluate similarities in palaeodiet, contextualising the findings from a regional perspective. Firstly, the implications of the enamel δ$^{13}$C$_{apatite}$ and bone δ$^{13}$C$_{apatite}$ data for the individuals from Ban Chiang are discussed. Secondly, the patterning among the sites of δ$^{15}$N$_{collagen}$ and δ$^{13}$C$_{collagen}$, either from bone or dentine, and the possible implications of this are examined. Thirdly, the patterning among the sites of
The mean $\Delta^{13}C_{\text{enamel aperture-bone apatite}}$ using published data from Ban Chiang (Bentley et al. 2005; King 2008) was 0.1‰ ± 1.3‰. There was a very small mean enrichment in enamel $^{13}C_{\text{apatite}}$ over bone $^{13}C_{\text{apatite}}$; however, there was no evidence for a consistent or significant enrichment between the two tissues. This is contrary to what Warinner and Tuross (2009) found in their swine experiment, however, it supports Loftus and Sealy’s (2012) findings that there is no evidence for a consistent fixed enrichment between $^{13}C_{\text{apatite}}$ sourced from bone or enamel in humans.

Ban Chiang was also used to examine dietary spacing as a comparison to An Sơn and Hòa Diệm. The analysis showed that for the majority of individuals at Ban Chiang, the protein portion of their diet ($^{13}C_{\text{collagen}}$) was more depleted than their whole diet ($^{13}C_{\text{apatite}}$). This is consistent with what was seen at An Sơn (Figure 6.10). However, at Ban Chiang, protein ($^{13}C_{\text{collagen}}$) was relatively stable over time, the increase in spacing ($\Delta^{13}C_{\text{apatite-collagen}}$) was due to an enrichment of $^{13}C_{\text{apatite}}$ (Figure 6.28). The longer temporal sequence and bigger sample size at Ban Chiang demonstrates more variation in diet, but definitely shows a source of enrichment from carbohydrates in the whole diet ($^{13}C_{\text{apatite}}$).

The comparison of bone $^{13}C_{\text{collagen}}$ with bone $^{13}C_{\text{apatite}}$ and then bone $^{13}C_{\text{collagen}}$ with enamel $^{13}C_{\text{apatite}}$ respectively for Ban Chiang (Figures 6.28 and 6.29) demonstrated that the bone $^{13}C_{\text{apatite}}$ and enamel $^{13}C_{\text{apatite}}$ are not equivalent. This finding is in agreement with Loftus and Sealy (2012: 6) who also suggested that the two tissues are not equivalent: “it seems that $\Delta^{13}C_{\text{collagen-apatite}}$ cannot simply be equated with $\Delta^{13}C_{\text{apatite-collagen}}$.” Van der Merwe et al. (2003) also found that dentine $^{13}C_{\text{collagen}}$ was 1‰ more enriched than bone $^{13}C_{\text{collagen}}$, but that was not able to be tested.

When comparing the Vietnamese sites to other sites in Southeast Asia with comparable $^{15}N_{\text{collagen}}$ and $^{13}C_{\text{collagen}}$ values (Figure 6.30), the $^{15}N_{\text{collagen}}$ values of coastal Hòa Diệm and Mán Bạc are higher than the other inland sites. The $^{15}N_{\text{collagen}}$ values of An Sơn and Núi Nấp, an Iron Age site for northern Vietnam, are similar to the other Southeast Asian sites. There are several factors that can enrich $^{15}N_{\text{collagen}}$: consumption of animals with high trophic levels in their food web and consumption of drought adapted animals. Given the ecological setting of Southeast Asia, consumption of drought adapted animals is unlikely to have an effect on the $^{15}N_{\text{collagen}}$ of the individuals, so the $^{15}N_{\text{collagen}}$ is representative of the trophic level of the food they consumed in the food chain. The relative similarity in $^{15}N_{\text{collagen}}$ among all the sites, except Hòa Diệm and Mán Bạc which is explained by the marine influence in their diet, suggests the diets were all based on animals with similar trophic food webs. The sites from China provide a comparative
sample of individuals who are argued to have subsisted on domesticated animals which subsisted on C₄ plants, lowering the trophic level expression on the δ¹⁵Ncollagen values of the individuals (Pechenkina et al. 2005).

The values of An Sơn and Núi Nấp are more depleted in δ¹³Ccollagen than the Thai sites, while the values for Hòa Diêm and Mán Bạc are explained by the marine influence in their diet. The sites from China provide a comparative sample of individuals who are argued to have subsisted on domesticated animals which subsisted on C₄ plants, enriching the δ¹³Ccollagen of the individuals. There are several factors that can enrich δ¹³C; these could include trophic level affects from consuming other animals, consuming marine or riverine animals, consuming grazing animals, consuming C₄ plants, consuming plants from higher altitudes or consuming plants from cleared areas. In consideration of the environment, for the Vietnamese and Thai sites and excluding Hòa Diêm, consuming plants from higher altitudes or marine animals is unlikely to affect the values. In consideration of the routing of protein to the respective tissues, factors influencing a shift in δ¹³Ccollagen are likely to be associated with protein consumption, so possibly consumption of more animals, riverine or grazing animals.

It is possible that the inhabitants of the Thai sites consumed more meat than at the Vietnamese sites, enriching their δ¹³Ccollagen slightly. It is difficult to know whether consuming riverine protein would deplete or enrich the δ¹³Ccollagen of individuals since there is such a large amount of variation among riverine animals. When analysing the archaeological samples of water buffalo, the Cervus species of deer and some of the Muntiacus species of deer from Thai sites, King (2008) found that the δ¹³Ccollagen values of their diet indicated the animals were consuming C₄ crops as a staple source of food. There was no evidence for buffalo found at An Sơn in 2009 but Cervus and Muntiacus species of deer were present, although not in great quantities. It is not possible to speculate on whether the deer had a similar diet to the deer from the archaeological sites in Thailand, but it is a possibility. If the individuals from the Thai sites were consuming these buffalo and deer in greater quantities than at the Vietnamese sites, which is suggested from archaeological faunal evidence (Higham and Thosarat 1998; Piper et al. 2014), it could have contributed to the enrichment of their δ¹³Ccollagen.

It is also possible that there is a difference in the δ¹³Ccollagen values between the Vietnamese and Thai sites due to the tissues analysed, if the tissues are not equivalent in their representation of diet. The values at the Vietnamese sites reflect the δ¹³Ccollagen in dentine, while the Thai sites reflect the δ¹³Ccollagen in bone, this is, however, unlikely to explain the enrichment in the Thai sites compared to the Vietnamese sites, as other research has shown that dentine δ¹³Ccollagen is slightly enriched over bone δ¹³Ccollagen (van der Merwe et al. 2003).
When comparing Southeast Asian assemblages with $\delta^{13}\text{C}_{\text{apatite}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ values (Figure 6.31) or only $\delta^{13}\text{C}_{\text{apatite}}$ values (Figure 6.32) Khok Phanom Di and Hòa Diệm have the highest $\delta^{13}\text{C}_{\text{apatite}}$ values (Figure 6.32), consistent with the marine environments of the sites, Cồn Cổ Ngựa, An Sơn, Ban Chiang, Ban Lum Khao and Noen U-Loke have comparable values and Núi Náp has the lowest values. The sites from China provide a comparative sample of individuals who are argued to have subsisted on the staple millet, a C$_4$ plant and domesticated animals which subsisted on C$_4$ plants, enriching the $\delta^{13}\text{C}_{\text{apatite}}$ of these individuals.

The $\delta^{13}\text{C}_{\text{apatite}}$ values at Cồn Cổ Ngựa are higher than at Núi Náp, Bower et al. (2006) suggested, based on the Ba: Sr ratios, that Cồn Cổ Ngựa had a higher proportion of marine animals in their diet than at Núi Náp. The high $\delta^{13}\text{C}_{\text{apatite}}$ values of Hòa Diệm are consistent with the expected enrichment in $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ indicative of marine input in the diet. Unfortunately it was not possible to assess this for Khok Phanom Di or Cồn Cổ Ngựa as $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ were not analysed or attempts at analysis were unsuccessful.

The $\delta^{13}\text{C}_{\text{collagen}}$ values from Núi Náp suggest that like An Sơn, the protein portion of the diet was predominantly C$_3$ terrestrial (Figure 6.30). However, when examining the $\delta^{13}\text{C}_{\text{apatite}}$ values (Figure 6.31) it is clear that the $\delta^{13}\text{C}_{\text{collagen}}$ obscures a low protein contribution to the diet of Núi Náp, which is significantly depleted in $\delta^{13}\text{C}$. This supports the suggestion by Bower et al. (2006) that rice was a significant and staple crop in the diet of the individuals at Núi Náp.

The average $\Delta^{13}\text{C}_{\text{apatite-collagen}}$ for the three individuals from Núi Náp was 3.3‰ (data not shown), suggesting the protein portion of the diet was more enriched in $\delta^{13}\text{C}_{\text{collagen}}$ than the whole diet, which further supports a diet focussed on a staple carbohydrate of C$_3$ rice (depleted in $\delta^{13}\text{C}$). If the depleted $\delta^{13}\text{C}_{\text{apatite}}$ at Núi Náp is a product of the consumption of a staple diet of rice, why does Noen U-Loke, temporally similar and renowned for the copious amount of rice found in burials at the site, not have similar values to Núi Náp? Unfortunately it is not possible to further investigate this without $\delta^{13}\text{C}_{\text{collagen}}$ and $\delta^{15}\text{N}_{\text{collagen}}$ data.

Factors influencing a shift in $\delta^{13}\text{C}_{\text{apatite}}$ values are likely to be associated with the whole diet, so more sensitive to carbohydrate and intake of low protein foods, possibly consumption of C$_4$ plants or consumption of plants from cleared areas. The possibility of the contribution of C$_4$ plants in the diet, to explain enrichment in carbon values over time, has been discussed by Krigbaum (2003; 2005) and King (2008) conducting work in Island and Mainland Southeast respectively, but both argue that a more likely explanation is the increased reliance on crops grown in more open conditions. This makes sense in the explanation of the enrichment in carbon over time in the case of Island Southeast Asia, between the preNeolithic and Neolithic sites, with a shift from foraging for resources from
the forest to more open horticultural and agricultural practices in the Neolithic (Krigbaum 2003; Krigbaum 2005). The Thai sites examined by King (2008), however, all have evidence for established agricultural practice, so an enrichment in $\delta^{13}C$ over time would need to be attributed to something other than open air agriculture in cleared areas. The consumption of $C_4$ plants is a possible cause of the enrichment of the whole diet compared to the protein portion of the diet (Figure 6.31). If the inhabitants of the Vietnamese and Thai sites were consuming a source of $C_4$, through consumption of millet or Job’s Tears, this would explain the enrichment of the whole diet in relation to the protein portion of the diet, with a high $\Delta^{13}C_{\text{apatite-collagen}}$ difference. This interpretation is further strengthened by the use of the multivariate model for the sites with available $\delta^{13}C_{\text{collagen}}$, $\delta^{13}C_{\text{apatite}}$ and $\delta^{15}N_{\text{collagen}}$ values (Figure 6.33). It is possible that Núi Náp, representing an Iron Age site had developed a more pure reliance on the consumption of rice. The other possibility is that there was some diagenetic contamination of the samples from Núi Náp. Although XRD was performed on samples of enamel from Núi Náp to assess the integrity of the tissue, it is possible that the enamel $\delta^{13}C_{\text{apatite}}$ in the teeth was diagenetically altered through the uptake of environmental carbon from groundwater from the karstic environment, as has been observed elsewhere (Wright and Schwarcz 1996).

It is also possible that there is a difference in the $\delta^{13}C_{\text{apatite}}$ values between the Vietnamese and Thai sites due to the tissues analysed, if the tissues are not equivalent in their representation of diet. The values at the Vietnamese sites reflecting the $\delta^{13}C_{\text{apatite}}$ in enamel, as opposed to the Thai sites reflecting the $\delta^{13}C_{\text{apatite}}$ in bone, this is however, unlikely to explain the enrichment in the Thai sites compared to the Vietnamese sites. This study and other research has shown that enamel $\delta^{13}C_{\text{apatite}}$ is slightly enriched over bone $\delta^{13}C_{\text{apatite}}$ (Loftus and Sealy 2012; Warinner and Tuross 2009) and subsequent analyses of the $\delta^{13}C_{\text{apatite}}$ in tooth enamel from some of the same Thai assemblages show the same patterning (Bentley et al. 2009; Bentley et al. 2005; Cox et al. 2011).

**Summary**

The results of the stable isotopes $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ from tooth dentine and $\delta^{13}C_{\text{apatite}}$ from tooth enamel, were presented to allow a comprehensive assessment of the diet of the individuals from An Sơn and Hòa Diệm. These were contextualised using zooarchaeological and phytolith data from the 2009 An Sơn excavation. The results were explored in relation to published stable isotope data for Southeast Asian flora and fauna as an interpretive biogeographical foundation. The results of the stable isotope analysis and the contextual information were congruent and further supported using multivariate dietary reconstruction.

These data suggest that the subsistence economy of the inhabitants from An Sơn comprised a dominant carbohydrate source, rice, and variety of animal protein sources including
different species of terrestrial animals and riverine fish. Although only Sawada’s data (2012) on the mammalian remains was available for Hòa Diêm, an assumption was made that their diets would have been largely similar, with the addition of marine resources.

Using rats as an analogue the stable isotope data for An Sơn and Hòa Diêm suggest that the whole diet was more enriched than the protein portion of the diet, which is interesting because it would suggest that a low protein resource, enriched in δ¹³C, must have been consumed to affect the results in such a way. The possibility of the inclusion of millet in the diet, either consumed wholegrain or by proxy through the consumption of animals grazing on the crop was discussed.

Finally the stable isotope data for An Sơn and Hòa Diêm were examined in relation to published data from other Southeast Asian and Chinese sites and reasons for possible similarities and differences were discussed. The palaeodietary reconstruction is consistent with the expected outcomes from the local environmental information and suggests a comparable diet to other sites in Southeast Asia. This discussion has focussed on an evaluation of these findings and their implications and contributes to our knowledge of diet in southern Vietnam, drawing on regional comparisons to encompass prehistoric Southeast Asia.

Having discussed palaeodiet at An Sơn the following chapter provides an overall synthesis of the chapters, and some conclusions and future direction.
Chapter Seven:  
Conclusions

This thesis sought to investigate the lifeways of two prehistoric Vietnamese communities, An Sơn from southern Vietnam and Hòa Diêm from the south central coast of Vietnam, representing two temporally distinct periods. Three distinct themes were used to assess the health and behaviour of these people 1) health as an indicator of childhood stress 2) oral health and extramasticatory modifications and 3) palaeodiet. The interpretation of these factors takes into consideration the local natural and cultural environments; drawing comparisons and further contextualising the findings within a wider Southeast Asia bioarchaeological framework. These themes were discussed with reference to four metathemes which played out in the separate sections of the thesis, but are clearly ultimately linked to one another in complex ways. The metathemes include population history, connectivity, the Neolithic Demographic Transition and the Osteological Paradox. The following discussion synthesises and expands on these findings.

Population history

Although representing temporally distinctive cultural periods of Vietnam, both An Sơn and Hòa Diêm represent populations that were engaged in the processes associated with demic diffusion and as a result represent genetically pluralistic communities. The inhabitants of An Sơn preserved some genetic traits (dental metrics) from the original indigenous Southeast Asian populations (Australo-Melanesians), but also demonstrate genetic input (cranial metrics) from Northeast Asia, while Hòa Diêm preserved some genetic traits (cranial and dental metrics) from Northeast Asia, but includes some genetic input from Island Southeast Asia (cranial and dental nonmetrics).

It appears that craniometrics, along with dental metrics and nonmetrics, provide the opportunity to distinguish the population affinity of different groups that represent distinct temporal populations very well. All three methods have been successfully used to distinguish early Southeast Asians and modern Southeast Asians, with most samples separating into two distinct clusters. One cluster includes Australo-Melanesian, Australian, Pleistocene and early Holocene populations while the other represents modern Southeast Asian populations (Matsumura et al. 2011a; Matsumura et al. 2012; Matsumura and Oxenham 2014; Matsumura et al. 2008a; Matsumura et al. 2011b; Matsumura et al. 2015).

In terms of the population history of Southeast Asia, it seems quite common that populations craniometrically dichotomise quite well into distinct clusters, while dentally, whether it be metrics or nonmetrics, the separation is not as clear. This occurs with several populations, for example, An Sơn, Hòa Diêm, Mán Bạc and Ban Chiang, where cranially
they present an affinity with modern Southeast Asian populations (Matsumura et al. 2015), but dentally they retain some indigenous traits and are positioned in the middle of the two extreme population clusters (Matsumura et al. 2011a; Matsumura and Oxenham 2014).

Matsumura and Oxenham (2014) argue that for dental nonmetrics this heterogeneity represents a clinal adoption of dental features which is influenced by the contribution, speed, timing and direction of genetic admixture ultimately derived from northern populations (present day central and southern China). This explains the heterogeneous pattern observed in the morphology of the dentition of Southeast Asians, but it does not explain why craniometrically a population may appear morphologically modern Southeast Asian but have a different affinity dentally. How does one reconcile these different data?

Both craniometrics and dental nonmetrics are polygenic variables, meaning their heritability is more complex than simple Mendelian inheritance (Scott and Turner 2000; Von Cramon-Taubadel 2014). As more than one locus is responsible, ultimately their genotypic expression does not translate directly into their phenotypic expression. Population variation in cranial shape and dental nonmetrics are a reflection of changes in allele frequencies and can be attributed to four key microevolutionary neutral genetic variables, selection, flow, drift, and mutation (Relethford and Blangero 1990; Von Cramon-Taubadel 2014). Populations experiencing a greater degree of gene flow from outside would show more heterozygosity, observable in a larger than expected deviation from the centroid of allele frequencies of their population. On the other hand, populations experiencing lower levels of gene flow from outside would show less heterozygosity, observable in a smaller than expected deviation from the centroid of allele frequencies of their population (Relethford and Blangero 1990).

There are several potential reasons that could explain inconsistencies observed between the different analyses exploring human variability in ancient Southeast Asia. It may be a sampling bias, as the different methods have different sensitivities, or differences in the protocols employed by different studies for inclusion and exclusion of certain traits or comparative samples. Matsumura (e.g. Matsumura et al. 2011a; Matsumura et al. 2012; Matsumura and Oxenham 2014; Matsumura et al. 2008a; Matsumura et al. 2011b; Matsumura et al. 2015) only includes males in the sample for the cranial and dental morphometric analyses, while both males and females are included in the samples for dental nonmetric analyses. For metric analyses, typically only males are measured and included in the samples because of the effect that secondary sexual characteristics have in the skull and dentition of males due to sexual dimorphism, so most of the comparative samples are only represented by males. However, dental nonmetrics are less sexually dimorphic than craniometrics, so females can be included. Small sample sizes can be used for dental metric data, but dental nonmetric data are more sensitive and small sample
sizes can skew the data so assemblages that are underrepresented are often aggregated with a loss of geographic specificity (Matsumura et al. 2011a; Matsumura et al. 2012; Matsumura and Oxenham 2014; Matsumura et al. 2008a; Matsumura et al. 2011b; Matsumura et al. 2015).

These differences observed among cranial and dental characteristics may reflect differential patterns of inheritance. The teeth may reflect a deeper genetic history, while craniometrics may be more sensitive to recent genetic contributions. The differences may reflect a differential influence of environmental effects. Or alternatively, perhaps cranial and dental traits have differential modes of inheritance influenced from either parent. A recent paper suggested that craniometrics are more influenced by mitochondrial DNA while cranial nonmetrics are more influenced by Y chromosome DNA and that they could potentially be used as proxies for DNA (Herrera et al. 2014). This finding potentially has important implications in the interpretation of population affinity and migration. If phenotypes are directly influenced by genotypes specific to one or the other sex this could have implications when assessing and interpreting data. It could potentially assist in explaining discordant results among the same population between two different datasets, craniometrics and dental nonmetrics for instance, or help in explaining why at some sites the craniometrics demonstrate statistical intrapopulation variation while the dental nonmetrics of the same sample population can be invariable. And again sample bias could also potentially play a role, if researchers are only targeting males in a sample to avoid such issues as sexual dimorphism they may unintentionally be selecting for, misrepresenting or inflating, genotypic and by proxy phenotypic, expressions in populations.

Although dental metrics and nonmetrics had to be dropped from Herrera et al.'s (2014) study due to small sample sizes, hopefully in the future the relationship between the dentition and genetics will be further explored. The individuals from whom the cranial metric and nonmetric data were derived were not the same as those from whom the genetic data were derived, therefore any correlation could only be a minimum estimate (Herrera et al. 2014). However, in Southeast Asia, Mán Bạc provides evidence that supports this concept (Oxenham pers. comm.), with matching craniometric and DNA data (Oxenham et al. 2011b). While the correlation among craniometrics and mitochondrial DNA and cranial nonmetrics and Y chromosome DNA suggest possible male or female dominated inheritance, it could also suggest that the correlated data are susceptible to the same evolutionary forces (Herrera et al. 2014).

Both cranial and dental morphometrics and dental nonmetrics are used to characterise populations, assess population affinity and assist in population comparisons. While the genetic influence on tooth morphology is argued by some to be stronger than that of osteological features (White et al. 2012), the polygenic nature and heritability of these traits is very complex and all are prone to epigenetic and environmental influences in their
expression (Ricaut et al. 2010; Stojanowski and Johnson 2014). No skeletal or dental morphological trait should ever perfectly correlate with DNA, and indeed environmental plasticity prevents this from occurring (Herrera et al. 2014).

The population affinities of An Sơn support the notion of genetic exchange between local indigenous and migrating populations as a result of rapid population movement from the north in a southerly direction, perhaps using coastal routes or river systems from at least 2000BCE. The population affinities of Hòa Diêm supports the concept of genetic exchange between local northeast Asians and Island Southeast Asians 850BCE - 250CE. These observations play directly into what we know about connectivity and the complexity of inter and intra-regional population mobility in the past.

**Connectivity**

The geography of Vietnam, situated on the peripheral margin of continental Southeast Asia, is particularly accessible, interposed between Island Southeast Asia in the South China Sea to the east and Mainland Southeast Asia to the west. However, the Trường Sơn mountain range circumscribes the central highlands and serves as somewhat of a barrier with Laos. Geography and river systems probably largely dictated the movement of people and facilitated and influenced connectivity and connections among different groups and communities. Northern Vietnam is the recipient of the Red River, descending from China’s Yunnan province, while southern Vietnam is the recipient of the Mekong River; descending from the Tibetan plateau. The upper Mekong Basin also extends into Yunnan in China, with the lower Mekong Basin winding through many contemporary countries in Southeast Asia.

During the Neolithic Demographic Transition, 2100-1100BCE, following the rapid population movement of Northeast Asians into Southeast Asia, the bioarchaeological record demonstrates a strong commonality among sites all across the region in terms of their subsistence practices, their mortuary practices and their material culture. In particular, there is a wide distribution of communities with similar incised and impressed detailing expressed on their pottery that has been argued to follow several different routes as part of the larger Southeast Asian Interaction Sphere during the Neolithic (Higham et al. 2011; Rispoli 2007).

An Sơn, occupied c.2100-1050BCE, represents one of these Neolithic sites, the burials of which date to between 1600-1050BCE. Although An Sơn can be described as part of the larger Southeast Asian Interaction Sphere, with incised and impressed pottery designs, the painted motifs and ‘S’ shaped incised motifs were not part of their stylistic repertoire. They had a preference for banded roulette stamping and curvilinear and geometric incisions in their pottery (Sarjeant 2014a). The variability in the pottery styles at An Sơn are argued
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to represent a trickledown effect where the original repertoire of ceramic traditions seen in other Neolithic sites was diluted by the time it reached southern Vietnam, representing the ‘end of the line’ (Sarjeant 2014a). An Sơn is argued to represent part of the ‘greater Mekong’ cultural network (Bellwood et al. 2011) that linked sites along the Mekong and its main tributaries as part of the wider Southeast Asian Interaction Sphere. The ceramic assemblage at An Sơn maintained some ties to the Northeast, but also reflects their own conception and Neolithic identity which evolved locally and independently. This evidence for connectivity supports the evidence for the population history of the An Sơn people.

During the Iron Age, 500BCE-500CE, at least two large archaeologically visible interaction spheres were operating around the South China Sea, solidifying connectivity between Mainland and Island Southeast Asia. The first was the distribution of Đồng Sơn drums from northern Vietnam, connecting Mainland Southeast Asia, and the southern islands of Indonesia (but absent in Taiwan, the Philippines and most of Borneo). The second was the distribution of Sa Huỳnh-Kalanay pottery, which did extend to include the Philippines and most of Borneo. The distribution of jewellery, particularly lingling-o penannular earrings and bicephalous animal earrings/pendants, often manufactured from Fengtian nephrite sourced from Taiwan and Mindoro jade sourced from the central Philippines, were traded over a large area of the Sa Huỳnh-Kalanay Sphere.

Hòa Diệm, occupied c.850-250CE, with burials dating to c.200BCE-250CE, represents part of the southern tradition of the late Sa Huỳnh culture (Lâm 2011), but also represents participation in the Sa Huỳnh-Kalanay Interaction Sphere. Pottery in the earlier layers at Hòa Diệm, with distinctive curvilinear incised patterns infilled with punctate stamping, parallel the older widespread tradition witnessed among Island Southeast Asian Iron Age jar burial sites (Flavel 2006; Hung et al. 2013), earlier Sa Huỳnh and Kalanay sites (Favereau 2015). The pottery in the later layers reflect shell impressions without graphite which is seen at Kalanay, and although shell impressions are also a feature of earlier Sa Huỳnh sites they were infilled with graphite, finally rotated pivoting incision also features at Hòa Diệm, a feature which is argued to come from the Philippines (Favereau 2015). These stylistic features of the pottery assemblage at Hòa Diệm reflects the transitional period of the site, where it maintained some features characteristic of the typical Sa Huỳnh, but later in its occupation it developed some strong and recurrent ties to the central Philippines. This evidence for connectivity supports the evidence for the reconstructed population history of the Hòa Diệm people.

The widespread and archaeologically visible geographic distribution of a number of different cultural and behavioural practices and material culture provides us with an insight into the many networks that were operating during prehistory. Although many of these are temporally specific, there is evidence of enduring traditions and connections which suggest shared identity to a well circumscribed larger shared community transcending
both geographic time and space. Although representing temporally distinctive cultural periods of Vietnam, both An Sơn and Hòa Diêm were both a part of wider interaction spheres with neighbouring communities.

The role that these interaction spheres had on An Sơn and Hòa Diêm provides a good opportunity to investigate diet at these sites and how they compare to other sites in the region. The subsistence economy at An Sơn has been described as based on rice cultivation with the management of domestic pigs and dogs with a strong focus on fishing within local rivers, supplemented with the hunting of a range of terrestrial and aquatic mammals and reptiles (Bellwood et al. 2011; Piper et al. 2014). The subsistence economy at Hòa Diêm was probably focussed on marine resources, fishing for aquatic fish and mammals and collecting shellfish, supplemented by the management of domestic cattle/water buffalo and pigs (Sawada 2012).

The stable isotopes $\delta^{15}N_{\text{collagen}}$ and $\delta^{13}C_{\text{collagen}}$ from tooth dentine and $\delta^{13}C_{\text{apatite}}$ from tooth enamel at An Sơn and Hòa Diêm were used to provide a more nuanced understanding of palaeodiet. The results were contextualised using published Southeast Asian floral and faunal isotope data as a palaeodietary baseline and other published Southeast Asian assemblages for which comparative dietary isotopes were available. $\delta^{15}N_{\text{collagen}}$ reflects animal protein consumption providing information on trophic level effects, $\delta^{13}C_{\text{collagen}}$ reflects the contribution of terrestrial $C_3$ or $C_4$ or marine animal protein, and $\delta^{13}C_{\text{apatite}}$ reflects the whole diet. Using $\delta^{13}C_{\text{apatite}}$ and $\delta^{13}C_{\text{collagen}}$ provided an opportunity to examine the protein portion of the diet as a function of the whole diet of individuals from these sites. Because Southeast Asia is largely a $C_3$ biome, with few $C_4$ plants incorporated into the diet, it has previously been assumed that any variation or change in $\delta^{13}C$ were probably indicative of temporal changes in agriculture, for example, from foraging in understory plants to open air agriculture.

The $\delta^{15}N_{\text{collagen}}/\delta^{13}C_{\text{collagen}}$ data for the sites were quite homogenous, suggesting that there were common sources of protein being consumed by these individuals that were at a similar level in the trophic foodweb. However, these results did vary as expected by site location as a function of the inhabitant’s access to marine sources at coastal sites or their focus on more terrestrial and riverine sources at inland sites. The $\delta^{13}C_{\text{apatite}}$ data were more dispersed indicating that the whole diet was more variable among the sites than the protein sources. The $\delta^{13}C_{\text{collagen}}$ suggests that the protein the individuals were eating was more depleted than the whole diet ($\delta^{13}C_{\text{apatite}}$), indicating that a low protein food, potentially the $C_4$ plants millet or Job’s Tears, enriched in $\delta^{13}C$, contributed to the whole diet. The palaeodietary reconstruction was consistent with the expected outcomes from the local environmental information and suggests a comparable diet to other sites in Mainland Southeast Asia. However, the results indicated a fundamental shift is required in the interpretation of potential $C_4$ sources in the diet and highlights the necessity of
The Neolithic Demographic Transition

Following the population history in the region and the migration of northeast Asians into Southeast Asia, the subsequent period presents the key characteristics of a Neolithic Demographic Transition. This period witnessed an explosion in population growth and fertility largely fuelled by factors such as the establishment of sedentary communities by those with a knowledge of agriculture and domestication, providing a constant and sustainable supply of food conducive to shorter birthing intervals. Although a decline in oral health has been documented in many prehistoric sites in many regions of the world during the Neolithic Demographic Transition and the adoption and intensification of agriculture, Southeast Asia has appeared to be an exception. Bioarchaeological investigations of oral health in Southeast Asia have recorded an improvement during the intensification of agriculture, discordant with what is observed in other areas of the world. Interpretations of why this may be the case have focussed on the fact that rice is not a cariogenic crop, or on the later development of social complexity in the area or the later production of large scale agriculture. Interpretations of sex differences have largely been explained by focussing on traditional dietary behavioural models, sexual division of labour, and differential access to food or different oral behaviours.

Synthesising the oral health results from An Sơn and Hòa Diêm with recently published data from Mán Bạc substantially increased an understanding of the Neolithic Demographic Transitional period. Contextualising this within a regional context provided the opportunity to reinterpret the oral health of Southeast Asia. The results of the oral health analyses suggest that the currently held consensus among many Southeast Asia bioarchaeologists that oral health did not decline with the adoption and intensification of agriculture in Southeast Asia is no longer viable. It has been demonstrated, using a larger sample of sites representing the Neolithic period in Southeast Asia, that there was a decline in oral health during the Neolithic Demographic Transition, but this is largely influenced by a decline in female oral health during this period. The main reason for this decline in oral health is related to elevated levels of fertility and a clinically demonstrated predisposition to poor oral health exacerbated by pregnancy, rather than diet or behaviour which have been the favoured explanations in the past.

The temporal changes in oral health over time follow the expectations using the predictions of the Neolithic Demographic Transition as a framework. In agricultural spread zones, a pattern would be seen where fertility increased and as a consequence of this so too would caries prevalence. After around 1000 years with a stabilisation or decrease in fertility (Bocquet-Appel 2011) there would be a directly associated decrease in caries...
prevalence among females. At Cồn Cô Ngựa, a preNeolithic site, caries rates were low, although females still had a higher prevalence of caries. At the Neolithic sites of An Sơn, Khok Phanom Di and Mán Bạc, caries rates were highest, statistically significantly so in females. At the Bronze Age sites of Ban Lum Khao and Ban Na Di and the Iron Age site of Noen U-Loke caries rates were lower, although females still have a higher prevalence.

The Osteological Paradox

These metathemes discussed so far, suggesting a significant degree of demic diffusion characterising the population history of the region, in addition to a complex but important degree of intra and interregional connectivity during both the Neolithic Demographic Transition and the Iron Age, must be taken into consideration when synthesising and contextualising health in the region. In terms of the comparative samples used, care was taken to choose assemblages that were reliably dated, well researched and published, and to ensure that each spanned one temporal period to avoid issues discussed earlier, such as time averaging (DeWitte and Stojanowski 2015). Using comparative series which are simple in terms of being heterarchical and culturally and biologically homogenous, representing several generations, minimises the impact of heterogeneous frailty which can result from underlying genetic variation, and be a consequence of nonstationarity (DeWitte and Stojanowski 2015). The evidence from the population history work suggests that these sites would unfortunately not have been culturally and biologically homogenous, but the evidence for connectivity makes them relevant for regional comparisons. During the Neolithic Demographic Transition the sampled populations would also not have been stationary; they would have been growing and both the diffusion and admixture would contribute an unknown level of heterogeneous frailty. However, using demographic modelling, such as $P_{5}$ values to estimate population growth based on subadult mortality, gives us some insight into the degree of nonstationarity of the Neolithic sites of interest.

The question as to how to interpret the nonspecific indicators of childhood health is a difficult one. One way to deal with this is to examine adult health as a direct consequence of childhood stress in consideration of the underlying strength or frailty of the individuals concerned, with the assumption that the frailest individuals would have died in childhood. Therefore, looking at childhood indicators of health in adults provides an indication of childhood morbidity and ultimately adult age as an indication of mortality. The childhood stressors manifesting in the form of stature, linear enamel hypoplasia and cribra orbitalia have been interpreted as a sign of the ability of the individual to sustain and overcome stress (however caused) as a function of their underlying susceptibility. The fact that they developed manifestations of stress indicated that they were ill during their childhood, that they survived it and lived to adulthood suggested they were not frail. A reduction in the manifestation of stress among a population was interpreted as a reduction in stress overall in comparison to another population.
The results of the analysis of physiological health as an indicator of childhood stress suggest that there were no significant changes in female stature over time, however, there was in males. The likely interpretation for this is that male children, more predisposed to infectious disease and less buffered to environmental stresses, consequentially suffered reduced attained stature because catch-up growth was inadequate to compensate for growth retardation during the Neolithic Demographic Transition. The increase in stature during the Bronze and Iron Ages suggests that with improved conditions individuals were better able to overcome any growth faltering during childhood with subsequent catch-up growth. This prompts the question as to why females were not effected in the same way given the arguments for higher fertility and pregnancies during the Neolithic Demographic Transition: why was female stature not affected, given that it is argued that the age of first pregnancy has an effect on attained stature (Vercellotti and Piperata 2012)? Given it has been argued that growth faltering during 2 and 3 years (Eveleth and Tanner 1990; Martorell 1995) will have the most impact on attained stature and the observation that age of first pregnancy also has a significant impact on attained stature, the observed relative homogeneity in female stature over time is potentially due to the majority of females in each temporal period all giving birth during adolescence. In such a model, females during the Neolithic Demographic Transition would not be more adversely affected than those in the other temporal periods in terms of attained stature, as the age at first pregnancy is argued to effect attained stature rather than the number of children given birth to. The issue regarding the actual mean number of births in each period could, however, play into the general health and wellbeing of females as adults and their susceptibility to illness and underlying frailty in adulthood.

The results suggest that for linear enamel hypoplasia the preNeolithic site Cồn Cổ Ngựa and the Neolithic sites of Mán Bạc, Khok Phanom Di and An Sơn had higher frequencies than the Bronze Age sites of Ban Lum Khao and Ban Na Di and the Iron Age site of Noen U-Loke. In terms of cribra orbitalia, there was a similar prevalence of cribra orbitalia at preNeolithic Cồn Cổ Ngựa and Neolithic An Sơn and Mán Bạc, however, it was only significantly higher at Cồn Cổ Ngựa in comparison to Khok Phanom Di and Hòa Diêm. While these temporal differences could be a reflection of different recording protocols, or hidden heterogeneity among populations that are the recipients of demic diffusion, it could also be interpreted as representing real changes in systemic stress over time.

There is a complex interplay between a range of intrinsic and extrinsic factors that have an effect on the variation witnessed among human populations in their susceptibility and expression of various forms of stress as a direct result of their phenotypic or developmental plasticity to social, nutritional and environmental factors (Kuzawa and Bragg 2012). The synergistic relationship between inadequate nutrition, impaired immunocompetence and infectious disease have a profound effect on morbidity and mortality (Stinson 2012), which is influenced by the age and sex of the individual, their unique physiology, biology,
life histories and life cycles and the timing, severity, duration and frequency of these environmental insults. These factors make interpreting health a challenging and exciting undertaking. The following section describes some possible future direction for broad temporal observations of health in Southeast Asia.

A synthesis and future directions

The Neolithic Demographic Transition is “seen as perhaps the single most significant social, cultural and biological transition since the origin of our species” (Stock and Pinhasi 2011: 1). The changes during this period included a move toward sedentism and a stable and reliable source of food; while an increase in fertility and a decrease in birthing intervals and mortality in general led to an increase in population growth. Despite these outwardly beneficial changes, health is generally considered to decline during the Neolithic Demographic Transition with the introduction and intensification of agriculture (Cohen and Armelagos 1984; Cohen and Crane-Kramer 2007; Steckel and Rose 2002). The deterioration in health with the introduction to agriculture is most often attributed to a decrease in the variation and nutritional value of food, where there was a move from a diverse and nutritionally enriched diet among hunter gatherers to one that was focussed on one major staple with agriculturalists. Other common factors suggested are associated with increased sedentism and include problems with sanitation and hygiene, increased transmission of virulent pathogens and exposure to zoonotic diseases (Stock and Pinhasi 2011) or the first epidemiological transition (Armelagos et al. 2005). Bioarchaeologists generally interpret these within a biocultural framework, taking into consideration the natural and cultural environment and physiological and biological resistance or susceptibility to stress. But what are bioarchaeologists actually looking at as evidence of poor health with the adoption and intensification of agriculture? Stature, cribra orbitalia and linear enamel hypoplasia are nonspecific indicators of systemic childhood stress and childhood illnesses. Oral health measures including caries, antemortem tooth loss, alveolar lesions and periodontal disease, although cumulative from the eruption of the permanent dentition, are indicators of adult oral health and are often used as indicators of general health. Although there are definite correlates between oral pathology and ill health they are not necessarily synonymous; as discussed earlier in this thesis they are attributable to a range of different aetiologies which are then further conflated given the synergistic relationships among them. Osteoarthritis, periostitis and trauma are argued to be mostly reflective of adult behavioural markers. Although it is emphasised and impressed upon bioarchaeologists to use multiple indicators of stress to assess overall health, are these indicators of stress being conflated rather than being used to address specific periods of the human life cycle?

It seems that most researchers have a tendency to interpret any evidence for a decline in health, or ‘poor health’, as evidence for intensification of agriculture, no matter
when it occurs. There is a vast amount of literature describing the negative effects of the introduction and intensification of agriculture all around the globe (Cohen and Armelagos 1984; Cohen and Crane-Kramer 2007; Steckel and Rose 2002), however, no one seems to focus on what happened directly after the Neolithic Demographic Transition. Traditionally, in Southeast Asia once again the region has appeared to indicate inconsistencies when compared to the global trends of a decline in general health with what is perceived to reflect an introduction and intensification of agriculture (Domett 2001; Douglas and Pietrusewsky 2007; Oxenham 2006). Reasons for this have included the maintenance of a rich and varied diet, including a range of terrestrial and aquatic protein sources, complemented by rice agriculture (Pietrusewsky and Douglas 2002b; Tayles and Oxenham 2006). The palaeodietary reconstructions from the region supports this. However, as with the oral health data, new data from several Neolithic Southeast Asian assemblages and a more nuanced understanding of the population history of the region suggests that fully functioning agriculturalists moved into the region during the Neolithic and it is these individuals that have the ‘worst’ health.

Recent studies from Southeast Asia focussed on the site of Ban Non Wat in Thailand provide the ideal sample to examine changes in health over time, from the Neolithic through to the Iron Age. Bioarchaeological publications on Ban Non Wat (Clark 2014; Clark et al. 2014) have slowly been emerging, however, the authors have focussed on changes circumscribed by microtemporal periods. Rather than just assessing health changes over time, they have assessed health changes over time from the Neolithic to the Early Bronze, the middle Bronze and the late Bronze Ages. The recent focus on understanding and tightening our knowledge of the chronology of Southeast Asia has demonstrated that the Bronze Age in the region only lasted about 600 years (Higham et al. 2011), and it seems that this is a fairly small time period in which to analyse and provide broad statements about changes in health over time. If you look at the data at Ban Non Wat, you see an improvement in stature and linear enamel hypoplasia from the Neolithic to the Bronze Age. This arguably matches what is seen at a regional level. There was relatively poor health during the Neolithic, for a range of different reasons, probably partially ascribable to the often cited effects of increased sedentism: crowding, increased communicable infections and increased zoonoses. However, these only appear to have a negative effect on individuals during the Neolithic. In contrast, during the Bronze and Iron Ages, there is clear improvement in health. So how does one explain this improvement in health? It is hard to gauge whether this improvement in health is demonstrated at other sites around the world as, indicated previously, researchers have a tendency to still interpret the changes seen during this period as ascribable to changes in the intensification of agriculture. Possible reasons for an improvement in health in the Bronze Age and later would include such factors as changes in social complexity and a broader dietary breadth.

How are we to interpret a positive change in health over time in the context of arguments
that the decline in health during the Neolithic was due to sedentism, crowding, increased communicable infections and increased zoonoses? The population history of Southeast Asia demonstrates migration of northeast Asians into and throughout Southeast Asia. The migration of people from one region to another brings with it not only new people but also new pathogens into a region with its own vectors and disease reservoirs (Harkins and Stone 2015). Could these be explained by human evolution in response to their interaction with commensal organisms and pathogens? Or pathogen evolution in response to changes in human biology as a consequence of cultural and technological developments? (Harkins and Stone 2015). Would such factors suddenly cease to be of relevance in the following temporal periods? Yes, one could argue that changes in social complexity and hygiene may partially ameliorate their effects, but is that a satisfactory explanation?

While such factors no doubt had an effect on these populations during the Neolithic Demographic Transition, are they adequate to explain causation? The one thing that these sites have in common, irrespective of their location, is arguably a rise in fertility. Bocquet-Appel and Naji (2006) argue that during the Neolithic Demographic Transition there would have been a peak in fertility that lasted between 500-700 years after which it levelled off. It has already been suggested that fertility could play a significant role in the almost universal pattern observed in poorer oral health among females. Could a rise in fertility be a significant contributing factor in the decline of other health indicators observed with the introduction and intensification of agriculture? Females under stressful conditions often mature and reproduce earlier (Kuzawa and Bragg 2012). As suggested above, the common indicators of ‘health’ often include stature, linear enamel hypoplasia and cribra orbitalia which reflect childhood health. Human adaptation to the environment is influenced in utero in response to hormonal or nutrient cues of past environmental maternal experience (Kuzawa and Bragg 2012; Kuzawa and Quinn 2009). “It is this environmental variability that necessitates plasticity in growth, development, reproduction, and other components of a species’ life history strategy” (Kuzawa and Bragg 2012: S377). Could this developmental plasticity or intergenerational phenotypic inertia (Kuzawa and Bragg 2012) be responsible for the high frequency of linear enamel hypoplasia and cribra orbitalia and changes witnessed in stature in adults during the Neolithic Demographic Transition as a reflection of their environmental adaptation or programming during their developmental period? Could the subsequent health improvements, in the Bronze and Iron Ages in Southeast Asia, be a reflection of a reduction in maternal stress as fertility decreased over time? Clearly much more bioarchaeological research is required in Southeast Asia (and globally) in order to address these important questions. Further, there is a demonstrated need for bioarchaeologists to engage with other biological, behavioural and evolutionary models if we are to advance our understanding of health and disease in the past.
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Appendix 1:

An Sơn Burial Descriptions

78ASH1M1

Age: 10-15 years
Orientation: West-East
Pit: H1
Square: -
Layer: -
Depth: 85cm

This individual was an adolescent. The head was oriented west. The burial was supine extended with the arms by the sides. The skull was relatively intact, however, the postcranial skeleton was not well preserved. There were no associated grave goods (Lê, 1978a; Lê, 1978b, 1978c). This skeleton is currently on display in the museum in the Long An Provincial Museum. The age estimate comes from the information card associated with the exhibit. This individual was not included in this analysis.

78ASH1M2

Sex: -
Age: -
Orientation: Southwest-Northeast
Pit: H1
Square: -
Layer: -
Depth: 1.15m

The individual was an adult, however, there was no specific data on age or sex. The head was oriented southwest. The burial was supine extended with the upper and lower limbs extended. The skull was relatively intact, however, the postcranial skeleton was not well preserved. There were two ‘wavy rim’ bowls associated with the individual (Lê, 1978a; Lê, 1978b, 1978c). This individual was not included in this analysis.

78ASH1M3

Sex: -
Age: -
Orientation: Southwest-Northeast
Pit: H1
This individual was a child, however, there was no specific data on age. The head was oriented southwest. The skull was relatively well preserved, however, the postcranial skeleton was not well preserved and only faint traces could be seen. There was one shouldered jar, one bowl and two small pots associated with the burial (Lê, 1978a; Lê, 1978b, 1978c). This individual was not included in this analysis.

**04ASH1M1**

Age: 1-4 years

**Orientation:** Southwest-Northeast

**Pit:** H1

**Square:** -

**Layer:** -

**Depth of skull:** -

This individual was buried in a supine, extended position with the hands by the sides and the left lower limb bent outward slightly. The head was oriented southwest. There were no grave goods associated with this burial. There was a layer of broken pottery, a stone tool and several pieces of animal bone and teeth including a big turtle’s carapace mounded over the burial (Phạm et al. 2006), however, it is not possible to know whether these materials were intentional or just in the grave fill.

**04ASH2M1**

Age: <1

**Orientation:** Southwest-Northeast

**Pit:** H2

**Square:** -

**Layer:** -

**Depth of skull:** -

This individual was buried in a supine, extended position, slightly on its right side, with the upper limbs flexed over the chest area. The skull was not well preserved but appeared to be lying on the right side. The head was oriented southwest (Phạm et al. 2006). There were no grave goods found associated with this burial, however, a worked fish bone artefact was found during the cleaning of the skull in the lab.
Appendix 1

04ASH2M2
Age: -
Orientation: Southwest-Northeast
Pit: H2
Square: -
Layer: -
Depth of skull: -
This individual was a perinate. The head was oriented southwest. It was poorly preserved and very little remained of the skeleton, there were only a few fragments of cranial material and some post cranial fragments (Phạm et al. 2006). This individual was not available for analysis.

04ASH3M1
Sex: Male
Age: 30-39
Orientation: Northeast-Southwest
Pit: H3
Square: G1
Layer: -
Depth of skull: -
This individual was buried in an extended supine position with its upper and lower limbs extended. The hands were placed by the sides. The head was oriented northeast. The skeleton was well preserved. There were many pieces of pottery scattered above and around the cranium, so it is possible that there was a pot placed above the head. The individual was wearing beads around the neck and both wrists, which consisted of four different types. There were eight pottery vessels associated with the burial. One small pot was beside the right femur beyond the right hand, two bowls were placed on the lateral sides of the femora, two pots were placed between the lower limbs, one bowl was lateral to the right foot, one pot was placed between the feet and had fish bone inside it, the final vessel was a ‘wavy rim’ bowl found underneath the thoracic region. There was one shouldered adze with the two pots between the lower limbs. The stratigraphy suggested there may have been a mound over the burial (Phạm et al. 2006).

04ASH3M2
Sex: Female
Age: Adult
Orientation: -
Pit: H3
This individual was only represented by a well preserved calvarium, there was no maxilla, mandible or post cranial remains associated with it. It was positioned between two large pieces of turtle carapace (Phạm et al. 2006).

04ASH3M3

Sex: Male
Age: 40-49
Orientation: Northeast-Southwest
Pit: H3
Square: C2-C3
Layer: -
Depth of skull: -

This individual was lying in an extended supine position, with its upper and lower limbs extended. The head was oriented northeast and lying on the right side. The hands were beside the body, under the pelvis. The right leg was lying on the lateral side and flexed, the lower portion crossing the left lower limb, which was straight but incomplete below the knee. The skeleton was well preserved. It appears the individual was buried on top of a deliberately placed sherd sheet. There were no pottery vessels associated with the individual, however, there was a shouldered adze beyond the left shoulder (Phạm et al. 2006).

04ASH3M4

Age: 10-15 years
Orientation: North-South
Pit: H3
Square: A’3-A’4
Layer: -
Depth of skull: -

This individual was lying in an extended supine position 5cm above 04ASH3M7. The head was oriented north. The skeleton was very poorly preserved (Phạm et al. 2006). There was one pottery vessel associated with this individual beside the left femur, however, it may have been associated with 04ASH3M7.
04ASH3M5
Sex: Female
Age: 50+ years
Orientation: Northeast-Southwest
Pit: H3
Square: C1
Layer: -
Depth of skull: -
This individual was lying in a supine extended position, with its upper and lower limbs extended. The hands were beside the body, under the pelvis. The head was oriented northeast. The individual was relatively well preserved. It appears the individual was buried on top of a deliberately placed sherd sheet. There was one pottery vessel associated with the burial, placed lateral to the right foot (Phạm et al. 2006).

04ASH3M6
Age: 5-9 years
Orientation: East-West
Pit: H3
Square: D3
Layer: -
Depth of skull: -
This individual was lying in an extended supine position, with its upper and right lower limbs extended (the left was not preserved). The head was oriented east. The skeleton was very poorly preserved. It appears the individual was buried on top of a deliberately placed sherd sheet. There were no other associated grave goods in the burial (Phạm et al. 2006).

04ASH3M7
Sex: Female
Age: Adult
Orientation: North-South
Pit: H3
Square: A’3-A’4
Layer: -
Depth of skull: -
This individual was lying in an extended supine position 5cm below 04ASH3M4. The head was oriented north. The skeleton was very poorly preserved with only the shafts
of the long bones remaining. Three pottery vessels were associated with this burial, one between the lower portion of the lower limbs, one over the left femur and one over the left hand and forearm, the latter two pottery vessels were not studied (Phạm et al. 2006).

04ASH3M8
Sex: Male
Age: 20-29 years
Orientation: North-South
Pit: H3
Square: III
Layer: -
Depth of skull: -
This individual was lying in an extended supine position, with their upper and lower limbs extended. The head was oriented north. The preservation was variable, the cranium was damaged, the long bones were well preserved, but the left thoracic region and pelvis was not. It appears the individual was buried on top of a deliberately placed sherd sheet. There was a pot beside the left hand. There was also a fragment of bracelet found beside the right femur (Phạm et al. 2006).

04ASH3M9
Sex: -
Age: -
Pit: H3
Square: B5
Layer: -
Depth of skull: -
This was recorded as an individual burial, however, there were no diagnostic features to suggest it was a burial. It was recorded as very poorly preserved with associated cranial fragments (Pham et al. 2006). This individual was not available for analysis.

04ASH3M10
Age: 15-19 years
Orientation: Northwest-Southeast
Pit: H3
Square: II-III
Layer: -
Depth of skull: -

This individual was lying in an extended supine position with their upper and lower limbs extended. The hands were positioned beside the pelvis. The head was oriented northwest, and lying on the left side. There were three pottery vessels associated with the burial, two small pots, one positioned lateral to the right distal femur and one positioned medial to the distal right tibia and one ‘serrated rim’ bowl on top of the proximal right tibia (Phạm et al. 2006).

04ASH3M11

Sex: -
Age: -
Pit: H3
Square: B3
Layer: -
Depth of skull: -

This was designated as an individual burial. Two finger bones were recorded as being associated with a pottery vessel (Phạm et al. 2006). They were not available for study.

04ASH3M12

Sex: -
Age: -
Pit: H3
Square: A2
Layer: -
Depth of skull: -

This was designated as an individual burial. One long bone shaft was recorded as being associated with a cluster of pottery fragments (Phạm et al. 2006). It was not available for study.

04ASH3M13

Sex: Male
Age: 30-49 years
Orientation: North-South
Pit: H3
Square: B2
Layer: -
Depth of skull: -

This individual was lying in an extended supine position, with their upper and lower limbs extended. The hands were placed either side of the pelvis. The head was oriented north. The individual was relatively well preserved. It appears the individual was buried on top of a deliberately placed sherd sheet. There were five pottery vessels associated with this individual. There was one small pot and one small bowl between the knees, two 'wavy rim' bowls, one complete and positioned between the femora, one broken and positioned lateral to the right femur and one large dish with a broken rim positioned over the right tibia. There was also a shouldered adze positioned beyond the left hand lateral to the left femur (Phạm et al. 2006).

04ASH3M14
Age: 15-19 years
Orientation: Northeast-Southwest
Pit: H3
Square: A1-A2,’A1’-A2
Layer: -

Depth of skull: -

This individual was lying in an extended supine position, with their upper and lower limbs extended. The hands were positioned beside the pelvis. The feet were lying on the lateral sides. The skeleton was fairly well preserved. The head was oriented northeast. There was one pottery vessel associated with the burial, it was a ‘serrated rim’ bowl positioned between the lower limbs, adjacent to the left knee (Phạm et al. 2006).

04ASH3M15
Age: -
Orientation: Northeast-Southwest
Pit: H3
Square: B2-C2
Layer: -

Depth of skull: -

This individual was a child, however, there was no specific data on age. The individual was lying in an extended supine position with the upper limbs extended. The lower right limb was flexed, the lower left was incomplete. The postcranial skeleton was well preserved but the cranium was not. The head was oriented northeast. There was one pottery vessel associated with this burial, a small pot which was positioned beyond the right flexed lower limb. It appears the individual was buried on top of a deliberately placed sherd sheet (Phạm et al. 2006). This individual was not available for analysis.
04ASH3M16
Age: 1-4 years
Orientation: Northeast-Southwest
Pit: H3
Square: C3-C4
Layer: -
Depth of skull: -
This individual was probably supine extended, however, the skeleton was incomplete, only part of the thoracic region, which was very poorly preserved, and part of the skull remained. The head was oriented to the northeast. The individual was placed on top of pottery fragments. There were no grave goods associated with this individual (Phạm et al. 2006).

04ASH3M17
Sex: Female
Age: 20-29 years
Orientation: Northeast-Southwest
Pit: H3
Square: A1-'A1
Layer: -
Depth of skull: -
This individual was lying in an extended supine position, with their upper and lower limbs extended. The hands were positioned beside the pelvis. The feet were together. The head was oriented northeast and lying on the right side. The skeleton was well preserved. There was one complete pottery vessel and a few fragments of another associated with this burial, the complete vessel was a ‘wavy rim’ bowl placed over the distal right femur (Phạm et al. 2006).

07ASH1M1
Age: 1-4 years
Orientation: North-South
Pit: H1
Square: B2
Layer: 5
Depth of skull: -
This individual was lying in an extended supine position, with their upper limbs extended
and their lower limbs loosely flexed to the right. The feet were clustered together and a few elements were concreted onto the right tibia. The head was oriented north. The skeleton was well preserved. There were no grave goods associated with this burial (Đặng et al. 2008).

**07ASH1M2**

**Age:** 1-4 years  
**Orientation:** North-South  
**Pit:** H1  
**Square:** A2  
**Layer:** 5  
**Depth of skull:** -  
This individual was lying in an extended supine position, but was very poorly preserved and only represented by some cranial, clavicle and pelvis fragments and a fragment of the mandible and maxilla. The head was oriented north. There were no grave goods associated with this burial (Đặng et al. 2008).

**07ASH1M3a**

**Sex:** Female  
**Age:** 20-29 years  
**Orientation:** Northeast-Southwest  
**Pit:** H1  
**Square:** C2-C3  
**Layer:** 4  
**Depth of skull:** -  
This individual was lying in an extended supine position, with their lower limbs extended, the feet had fallen back over the tibiae. Their upper limbs were flexed, the left tightly with the hand on the scapula, the left loosely, the forearm crossing the thoracic region with the hand beyond the left distal humerus. The head was oriented northeast. The skeleton was very well preserved. This individual was pregnant with 07ASH1M3b (Willis and Oxenham 2013a). The individual was lying on pottery fragments. There were a few beads in the cervical area and a clay pellet over the left knee (Đặng et al. 2008).

**07ASH1M3b**

**Age:** <1 year  
**Pit:** H1  
**Square:** C2
Layer: 4

Depth of skull: -

This individual was identified from photographs of the 2007 excavation season and confirmed during the cleaning of the bulk lifted thoracic region of 07ASH1M3a during data collection (Willis and Oxenham 2013a).

07ASH1M4

Age: 1-4 years

Pit: H1

Square: -

Layer: 5

Depth of skull: -

This individual is only represented by a partial mandible. There was no information regarding the square it came from.

09ASH1M1

Sex: Female

Age: 40-49 years

Pit: H1

Square: A2

Layer: 6

Depth of skull: 157m below datum

This individual was only represented by the cranium, there was no mandible or post cranial remains associated with it. It was lying on the right side facing west. The cranium was complete and in very good condition with no evidence of damage suggestive of a disturbance of a burial. The left M1, M2 and M3 were missing postmortem, but were not associated with the cranium. This suggests the teeth had fallen out post decomposition where the individual was initially decomposing and that the cranium represents an intentional secondary burial. The cranium was located in the cultural layer and as a result there were many pottery fragments and bone fragments associated with it. It appeared to be lying on an intentionally placed, isolated cluster of pottery fragments, a sherd sheet, which also featured a dog mandible. These items may have been intentionally placed as grave goods.

09ASH1M2

Sex: Female

Age: 20-29 years
**09ASH1M3**

**Sex:** Male  
**Age:** 30-39 years  
**Orientation:** Northeast-Southwest  
**Pit:** H1  
**Square:** A2-A3, B3-B4  
**Layer:** 11  
**Depth of skull:** 2.03m below datum

This individual was almost complete, however, the right side had been disturbed and removed by the later interment of 09ASH1M4a. The head was oriented northeast. The individual had variable preservation, the facial region and maxilla of the skull were crushed and poorly preserved and the articular epiphyses of all of the long bones were degraded. The individual was buried supine. There were two pottery vessels associated with the individual, both were ‘wavy rim’ bowls. One was placed over the proximal right tibia and cut in half with the placement of 09ASH1M4a and one placed over the distal tibiae and calcanei. There were intentionally placed sherds of pottery under the skull. There was one unshouldered adze possibly associated with this burial found in square B3.

**09ASH1M4**

**Age:** 3-5 years  
**Orientation:** Northeast-Southwest  
**Pit:** H1
Square: A2-A3, B2-B3

Layer: 11

Depth of skull: 2.05m below datum

This child was almost complete but had variable preservation with the articular epiphyses degraded and the hands and feet completely degraded. The head was oriented northeast. There was one ‘serrated rim’ pot placed to the right of the tibiae. There were intentionally placed sherds of pottery under the skull. This burial cut through 09ASH1M3a indicating a later interment.

09ASH2M1

Age: <42 weeks

Orientation: Southeast-Northwest

Pit: H2

Square: B4

Layer: 4.1

Depth of skull: 2.00m below datum

This neonate was complete and very well preserved. The head was oriented southeast. There were no grave goods associated with it.

09ASH2M2

Age: <42 weeks

Orientation: Northeast-Southwest

Pit: H2

Square: E1-E2

Layer: 4.1

Depth of skull: 1.99m below datum

This neonate was almost complete, however, the cranium had been crushed by pottery and there was some disturbance to the postcranial skeleton. The left distal radius was missing, the left tibia and foot were disturbed and displaced beyond the left femur, the right ulna and femur were missing, and the right tibia, fibula and foot were disturbed and displaced in articulation to the right of the pot. The right pubis, ischium and a metatarsal were found under the pot. This suggests that the distal postcranial area and pot were disturbed shortly after the individual was interred as some elements were still in articulation. The head was oriented northeast. There was one pot associated with this individual and two shell beads found in the chest area.
**09ASH2M3**

**Age:** 12-15 years

**Orientation:** Northeast-Southwest

**Pit:** H2

**Square:** D2, E2-E3

**Layer:** 5

**Depth of skull:** 2.25m below datum

This adolescent is complete and very well preserved. The grave cut of this individual was perfectly preserved in the sterile alluvium. There were three pots associated with this burial, two were ‘wavy rim’ bowls, one over the right femur and hand, one over the left distal femur and proximal tibia and one placed between the tibiae and calcanei, there was also two pieces of stone, a shell and a shouldered adze beside the right proximal tibia and there were 13 shell beads found in the chest area. There was also a stone tool beyond the head, however this was at a higher level than the base of the grave so was likely in the grave fill.