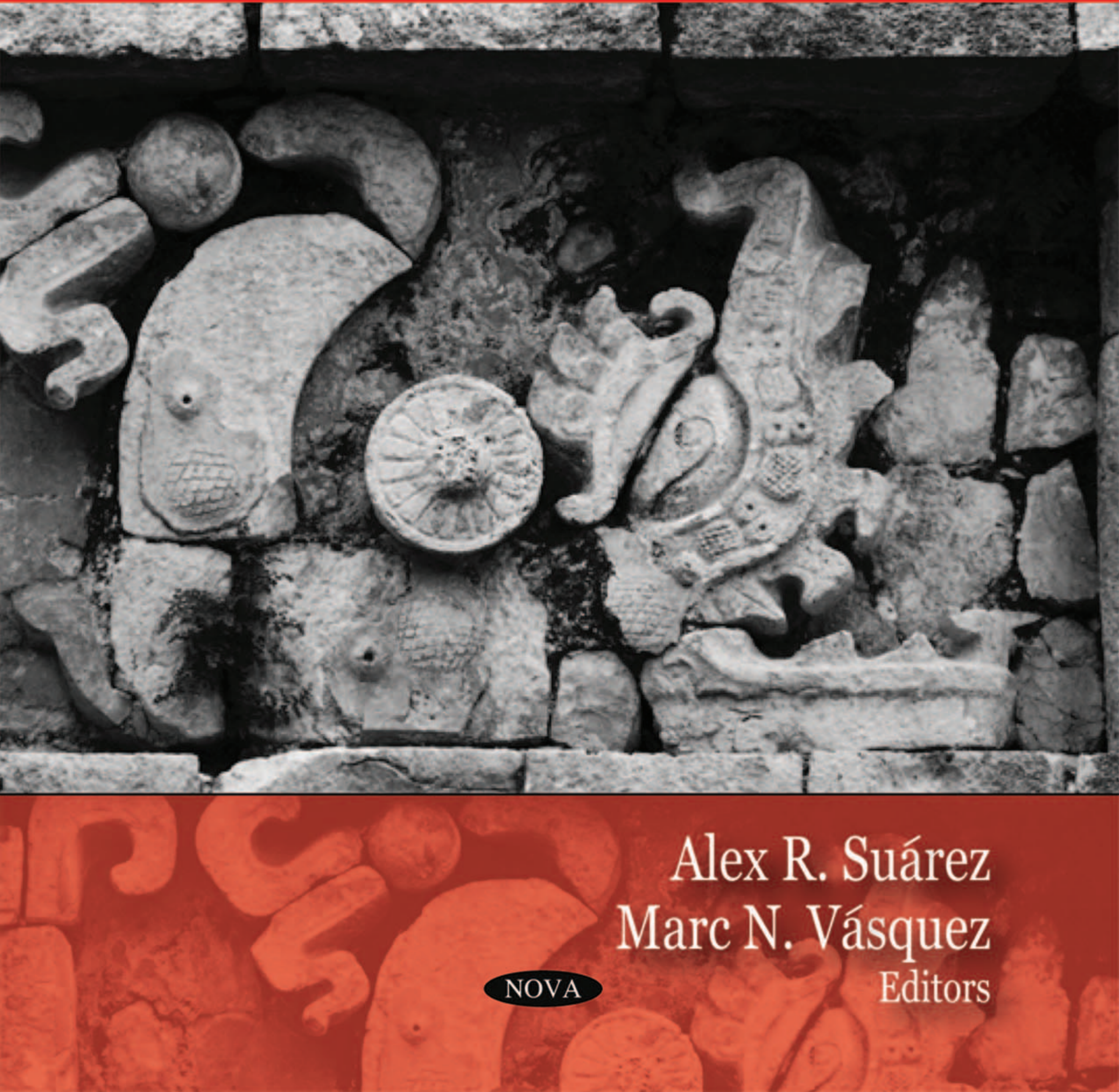
Archaeology Research Trends



Alex R. Suárez
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Editors

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CONTENTS

PREFACE

Archaeology studies human cultures through the recovery, documentation, analysis and interpretation of material remains and environmental data, including architecture, artifacts, features, biofacts, and landscapes. Because archaeology's aim is to understand mankind, it is a humanistic endeavor. The goals of archaelogy vary, and there is debate as to what its aims and responsibilities are. Some goals include the documentation and explanation of the origins and development of human cultures, understanding culture history, chronicling cultural evolution, and studying human behavior and ecology, for both prehistoric and historic societies. This new book presents important research in the field.

Chapter 1 – Formation processes are the natural and cultural processes that make up the archaeological record. Whereas natural formation processes are the environmental factors that influence the survival of the archaeological evidences, cultural formation processes include the accidental or deliberate human activities that can affect in a positive or negative way the archaeological record. Special attention should be given to the archaeological contexts associated with human skeletal remains, once natural phenomena can disguise or even be confused with cultural aspects, leading to misinterpretations of burial and activity patterns, as well as health, diet and nutritional status of humans in the past. The excavation of burial grounds lays down the basis on which to infer past funerary customs, and sometimes they represent the only evidence on which to reconstruct an extinct people’s origin, way of life and decline. The combination of the social position (burial structure, grave goods, position of the deceased) and the ritual (what happens before, during and after burial according to tradition) make up the funerary customs of a human group. These customs, together with bioarchaeological data such as sex, age, health and nutritional status serves as a basis to understand the demographic and social structure of past populations. Such an integrative research strategy requires close collaboration between human biologists and archaeologists and is totally different from the still prevailing tradition to relegate osteological data to the appendix of archaeological papers interpreting the significance of mortuary rituals.

The aim of this work is to alert archaeologists about the importance of clearly documenting and distinguishing natural and cultural factors to better understand formation processes not only related to human burials, but archaeological sites in general. In order to illustrate this, the authors identify and discuss these processes influencing the interpretation of burial patterns in a prehistoric Brazilian shellmound, named Jabuticabeira II, dated between 2890 ± 55 and 2186 ± 60 BP. This site is especially informative to illustrate the application of this approach since it contains many burials and is classified as a cemetery shellmound. This work also argues in favour of true multidisciplinary research where specialists such as bioarchaeologists participate in the decision processes of the exact location and strategy of excavation, coordinate sample collection of and documentation on burials, and, as usually already routine, carry out their specialized work in the laboratory.

Chapter 2 - The last 25 years have seen the development of a thriving literature on the archaeology of human-environment interactions. A review of the literature shows three distinct histories of work on human-environment interactions: “environmental archaeology” as represented by the Association for Environmental Archaeology; human paleoecology, which looks at human impacts on the environment from an anthropological viewpoint; and environmental studies, which uses archaeological data within the conservation biology literature. These bodies of work have explored different data sets, used different methods, and, by and large, come to very different conclusions about the nature of human-environment interactions both past and present. Despite the fact that their conclusions are often highly relevant to each other, there is very little cross-fertilization of theoretical or methodological approaches. This chapter critically reviews these bodies of work, assesses the current state of research, and discusses emerging trends in the archaeology of human-environment interactions.

Chapter 3 - This study examined congenital pathologies of 284 prehistoric California Amerinds to determine whether skeletal individuals exhibit multiple pathologies including excessive limb length asymmetries (i.e., greater than average asymmetries calculated from prehistoric populations) as reported in medical literature. Skeletal condition varied from fragmentary to complete (i.e., all major bones present). Pathological individuals were examined twice to ensure pathologies were congenital and avoid including asymmetries related to trauma.

Using conservative diagnoses, sixty individuals (21%) have congenital pathologies; half of them exhibit multiple pathologies (29/60). Excluding fragmentary individuals, 60% (28/47) of individuals have multiple pathologies; in complete skeletons, 79% (19/24) of individuals have multiple pathologies. Differences in pathology frequency within individuals compared to skeletal condition are significant (Chi-Square = 19.33; $P < 0.01$). One-third (20/60) of pathological individuals show asymmetry; half of these individuals have asymmetry in multiple sets of limbs. Multiple asymmetries are found more frequently in complete skeletons (Spearman’s *rho* = 0.479; $P < 0.001$).

This hunter-gatherer population has a fairly high rate of congenital pathologies possibly due to inbreeding. Pathologies are often minor, such as supernumerary teeth, spina bifida occulta, and bony growths. However, one individual has a cleft palate and four other pathologies. Fused bones, such as ribs, vertebrae, and foot phalanges, are also present. This study supports that individuals born with a congenital pathology often have other congenital pathologies. Anthropologists are disadvantaged in documenting congenital pathologies due to incomplete remains and the fragility of subadult remains.

Chapter 4 - Since the early stages of its domestication, the horse has been an important means of mobility for human populations. On the contrary, cattle, sheep and goat are more related to human early settlements. This is probably why the estimated date for the domestication of horse is set at a later time than the other species. From early times, and precisely because of their transportation capabilities, horses from distinct geographical regions have been crossbred which has led to the mixing of their genetic legacy. This has made it difficult to assign a genetic pattern to a specific geographical location and thus, to establish centers of domestication for this species. Because of this, horses are objects of interest for teams from a broad range of research fields. The processes that led to domestication and to the diversity of modern domestic populations are areas of focus for geneticists, evolutionists, archaeologists and anthropologists, among others. The identification of domestication centers of wild populations is important for the understanding of both human and livestock migrations and distribution as well as the impact of the first human settlements on local wild populations of livestock ancestors. These questions have been addressed in several studies for several species using not only archaeological data, but also molecular data obtained from archaeological specimens. The possibility of using DNA from archaeological remains and thus to analyze data from original sources which possibly were directly involved in the first steps of domestication is one of the major advantages of the application of molecular technology to Archaeology. Several molecular markers can be used to assess domestication processes, points and dates for several species. Mitochondrial DNA is the most commonly used marker to address migration, demography and phylogenetic relationships and the domestication process for today's domesticates, but sex chromosome related markers (such as SNPs) and whole genome sequencing have a bright future among researchers looking for answers related to human evolution and domestication as one of the consequences of this evolution. This is because of the recent developments of molecular technologies and because of the properties of the markers which are optimal for Ancient DNA analysis. This chapter aims to review what has been done to investigate domestication related issues and what can still be done to improve the knowledge that archaeological and molecular techniques have allowed so far. The authors aim to suggest future directions to be taken in Archaeological research using molecular approaches.

Chapter 5 - Architecture is a feature of cultural expression and the interpretation of the culture by means of its architecture allow us to obtain relevant information about this culture. The geometric and statistical analysis from obtained data by means of new technologies (georreferencied CAD plans and 3D models mainly) constitutes an important tool to obtain the basic features of design of the prehistoric constructions. These methods applied to daily architecture relates the use of buildings to structure social relations, and the changes of the geometric design and the metric parameters in prehistoric dwellings are an important indicator of social transformations, social complexity, emergence of social hierarchy and other social modifications. Also reveal settlement planning and urbanism concepts, and the changes produced in these concepts reveals the evolution in the prehistoric urbanism.

The results obtained provide that the inhabitants of prehistoric periods acquired concepts of descriptive geometry, and the used geometric features to design the prehistoric buildings emphasize that the construction was accomplished using a previous geometric and metric design with great accuracy, and encapsulates a more general perception of power and space. The existence of metric and geometric rules used in the architectural constructions proves the emergence of a basic mathematical thinking in prehistoric times.

Several examples from Prehistory to Roman times are provided.

Chapter 6 - The architectural heritage is the most cognizant element of the cultural heritage and considered as a major tourist attraction in the cultural heritage aspects. The value of any architectural heritage goes beyond its appearance to focus on its stability and on the consistency of all its components. The advancement of modeling and engineering analysis techniques helps to attain the required understanding of the morphology and the structural behavior of the construction. As early as civilization evolved, documentation of events, religion, culture and significant structures has been of utmost importance for further study and preservation. Therefore, the structural details with the graphical stress distribution for its main structural components may act as an essential engineering documentation for the building. An approach is the use of the structural software (SAP2000) to obtain the structural model of any historical building or its structural components depending on previously documented plans and sections and then analyzed. The obtained stress distribution contours could be useful to all personnel who may be involved in conservation and restoration problems. These documents serve as a tool to make structural information accessible to the archeologists or engineers during restoration to visualize the critical supporting structures that maintain stability for the building. Checking the documented stress contours for the structure will help reinforcing the structure where needed so as not to intrude upon the aesthetic and historical or archeological quality of the property by selecting the repair methods that are appropriate to the cultural context. The stress distribution contours in addition to other engineering documents can help thoroughly understanding the building in an effective, least destructive, most efficient and economical means. For complicated structural forms of architectural heritage that may cause a challenges in diagnosis and analysis, an experimental photoelastic method may be used to obtain a graphical stress distribution contours with clear optical identification of overstressed and understressed areas. From which, the intensity of stress at any point can be determined using lengthy mathematical calculations and should be scaled to indicate the behavior of the actual structure. This technique has been used widely in the past before the advancement of computer engineering analysis techniques. The choice between “experimental” and “analytical” techniques should be determined on a case-by-case basis depending on the complicity of the structural element and the difficulty of its modeling.

Chapter 7 - The information potential of micro-artefacts can assist in archaeological interpretation. This paper presents a combination of a non-linear method (i.e., the spherical self-organizing feature map) and a linear one (i.e., Spearman’s rho) that may improve the interpretation of micro-artefacts when investigating cultural site formation processes. An example is given on micro-artefact data from the Neolithic tell/extended site at Paliambela (Northern Greece).

Chapter 8 - The recent summer 2007 campaign of excavations of the Phoenician–Punic necropolis of Mount Sirai, located in the South-West part of Sardinia (Italy) has brought to light a number of tombs contextually attributed to a period from early VIth to the early Vth century B.C, which is simultaneous to the beginning of the Carthago influence in Sardinia.

In the interred burials recently brought to light the skeletal remains, sometimes of two superposed bodies, were discovered in a primary position and with fine anatomic connection. Some of the bones were visually stained, suggesting they were possibly subjected to a fire treatment.

In order to ascertain more objectively whether the bodies were subjected to burning, the bones from all the tombs were investigated by the X-ray powder diffraction (XRD) and Fourier Transform Infra-Red (FT-IR) spectroscopy techniques. After excluding the role of important diagenetic effects, from line broadening/sharpening analysis of hydroxylapatite in the bones according to the Rietveld method it was evaluated that the bodies were likely subjected to a regime of temperature from 300 to 700 °C. These data were supplemented and confirmed by an analysis of the splitting factor SF of apatite phosphate peaks in the Infrared spectrum of the bones. Our results point out to the existence of a rite intermediate between incineration and inhumation. This sort of “semi-combustion”, perhaps limited to the period of early Vth century B.C, appears to be peculiar just of this site.

Chapter 9 - Pattern recognition is of primary importance to the field of archaeology, given that recognizing patterns is the key to both understanding problems with our current beliefs about the past and the generation of new and better ideas to resolve them. This chapter discusses the use of multivariate statistics for data reduction and pattern recognition in large archaeological datasets. Most archaeological research is at least partially quantitative, but most of this research has traditionally focused on hypothesis testing and the calculation of probability statistics. While statistical hypothesis testing is an important aspect of scientific approaches to archaeological research, the field has largely overlooked the use of non-probability based statistical approaches to pattern recognition. The chapter begins with a brief discussion of the philosophy of science and the role of archaeological pattern recognition in the construction of accurate generalizations about the archaeological record based on material remains, the construction of hypotheses based on these generalizations, and the critical testing of hypotheses based on new and better understandings of archaeological patterning. This chapter then outlines the use of multivariate statistical approaches including factor analysis, principal components analysis, and multiple regression, which are powerful and under-utilized approaches to large archaeological datasets. The chapter illustrates the use of these techniques by discussing several important case study analyses of some major categories of materials and situations commonly encountered by archaeologists.

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Chapter 1

“NATURAL AND CULTURAL FORMATION PROCESSES ON THE ARCHAEOLOGICAL RECORD: A CASE STUDY REGARDING SKELETAL REMAINS FROM A BRAZILIAN SHELLMOUND”

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ABSTRACT

Formation processes are the natural and cultural processes that make up the archaeological record. Whereas natural formation processes are the environmental factors that influence the survival of the archaeological evidences, cultural formation processes include the accidental or deliberate human activities that can affect in a positive or negative way the archaeological record. Special attention should be given to the archaeological contexts associated with human skeletal remains, once natural phenomena can disguise or even be confused with cultural aspects, leading to misinterpretations of burial and activity patterns, as well as health, diet and nutritional status of humans in the past. The excavation of burial grounds lays down the basis on which to infer past funerary customs, and sometimes they represent the only evidence on which to reconstruct an extinct people’s origin, way of life and decline. The combination of the social position (burial structure, grave goods, position of the deceased) and the ritual (what happens before, during and after burial according to tradition) make up the funerary customs of a human group. These customs, together with bioarchaeological data such as sex, age, health and nutritional status serves as a basis to understand the demographic and social structure of past populations. Such an integrative research strategy requires close collaboration between human biologists and archaeologists and is

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totally different from the still prevailing tradition to relegate osteological data to the appendix of archaeological papers interpreting the significance of mortuary rituals.

The aim of this work is to alert archaeologists about the importance of clearly documenting and distinguishing natural and cultural factors to better understand formation processes not only related to human burials, but archaeological sites in general. In order to illustrate this, we identify and discuss these processes influencing the interpretation of burial patterns in a prehistoric Brazilian shellmound, named Jabuticabeira II, dated between 2890 ± 55 and 2186 ± 60 BP. This site is especially informative to illustrate the application of this approach since it contains many burials and is classified as a cemetery shellmound. This work also argues in favour of true multidisciplinary research where specialists such as bioarchaeologists participate in the decision processes of the exact location and strategy of excavation, coordinate sample collection of and documentation on burials, and, as usually already routine, carry out their specialized work in the laboratory.

Keywords: *Brazilian archaeology, bioarchaeology, taphonomy, burial pattern*

INTRODUCTION

What are Formation Processes of Archaeological Sites?

Formation processes are the natural and cultural processes that make up the archaeological record. The studies that are currently related to what is called “formation processes” were carried out by several authors since 1960 (Pyddoke 1961; Gladfelter 1977; Hassan 1978; Limbrey 1975; Renfrew 1976), but the idea was better accepted by the archaeological community after the works of Michael Schiffer (1972, 1975, 1976, 1983, 1987), who called the attention of archaeologists to the increasing need of integration between the Earth Sciences and Archaeology (Araujo, in press). Natural formation processes are the environmental processes that influence the survival of the archaeological record. Schiffer (1987:7) defined these processes as “any and all events and processes of the natural environment that impinge upon artefacts and archaeological deposits”. Cultural formation processes are defined as “the processes of human behaviour that affect or transform artefacts after their initial period of use in a given activity” (Schiffer 1987:7). In other words, cultural formation processes include the accidental or deliberate human activities that can affect in a positive or negative way the archaeological record.

Gifford (1980:105) stresses that the “key to elucidation of the past by studies of the present lies in assuming a comprehensive approach to the study of process and effect. By closely defining site formation processes, one can frame and test hypotheses concerning areas of knowledge which at present remain hazy”. Special attention should be given to the archaeological contexts associated with human skeletal remains, once the natural processes can disguise or even be confused with the cultural processes, leading to misinterpretations of burial and activity patterns, as well as health, diet and nutritional status of humans in the past. There are various instruments and approaches possible to aid differentiation of cultural and natural formation processes when dealing with burials. These are addressed in the following sections.

Observable Processes Today Can Explain Phenomena in the Past: Taphonomy

Literally meaning the "laws of burial", taphonomy presents several definitions. Previously seen exclusively as a branch of paleontology, nowadays, taphonomy is seen as a discipline itself, which studies the processes involved in the formation of the geological and archaeological record, issues worked on by experimental archaeologists. The basic epistemological framework of taphonomy is that of actualism, which means the explanation of past phenomena according to processes observable today. Therefore, observations in the present, which can be based on experiments on field or laboratory or on studies of the *in situ* formation of modern comparative assemblages, can be informative of the processes that created similar assemblages in the past (Stutz, 2003:132). One of the main criticisms concerning actualism is that it has to be assumed, not only because it cannot be tested directly, but also because it assumes that there are properties in the universe that have remained uniform in time and space. In this sense, conclusions have to be made based on induction because it is not possible to prove that the natural laws currently observed were the same in the past. Eventually, these generalizations based on actualism can lead to circular reasoning (Martin 1999:7). Lyman (1994: 69) criticizes the presence of analogies that only take into account similarities between the past and the present, ignoring the causal connections between process and observed phenomena. In fact, Stutz (2003:134) stresses that we have to understand why a certain process leads to a certain result. Nonetheless, Wylie (1985) argues that although these problems cannot be ignored, the use of analogy in archaeology can be done as long as certain guidelines are observed and when arguments about the importance of similarities between observed and inferred can be established.

Interestingly, although humans can be important taphonomic agents, there is a bias towards the idea that taphonomy mainly deals with the 'natural disturbance' of the archaeological record. This idea emerged probably because, in archaeology, the context of concern is generally human behaviour. Nonetheless, because humans form the archaeological site together with natural processes, they are very important taphonomic agents to a deposit's history (Lyman, 1994:33; Stutz, 2003:138).

Ethnographic Accounts, Formation Processes and Mortuary Ritual

The excavation of burial grounds often lays down the basis on which to infer past funerary customs. The combination of the social position (burial structure, grave goods, position of the deceased) and the ritual (what happens before, during and after burial according to tradition) make up the funerary customs of a human group. These customs, together with bioarchaeological data such as sex, age, health and nutritional status, serve as the basis to understand the demographic and social structure of past populations.

Gifford (1980) stresses that there is an overlapping in both theory and method regarding ethnoarchaeology and taphonomy due to a common concern with biological and geological processes forming deposits of prehistoric materials. However, the author says that the two fields differ in the sense that ethnoarchaeology is also concerned about the role of human behaviour in forming archaeological accumulations.

Based on ethnographic studies some authors claim that burial practices were part of the intangible domain of religious belief (Piggott, 1973). Nonetheless, Stutz (2003:320) states that there was a shift “from a referential focus to a focus on the practices, and that from a practice theoretical point of view the major questions about the mortuary rituals should not be what the actions meant, but what they consisted of. In the case of archaeology this is fortunate, since the traces of the practices are all we have left for our study. If the essence of the ritual is not in the verbal meaning but in the experience and practice of it, archaeology can actually get at some of the most fundamental aspects of it when the archaeologist studies the remains of the mortuary ritual he/she faces the result of *what people did with their dead”*. The author acknowledges the fact that mortuary practices involved elements that left no material trace to archaeologists, such as speech, song, dancing, and crying. However, the fact that the material remains of the mortuary practices, and the body itself are available for study, means that archaeologists have access to a significant part of the mortuary ritual (Stutz, 2003: 231) and therefore, can greatly contribute towards our understanding of the whole mortuary ritual.

Also based on ethnographic analysis, Ucko (1969) stated that there is no correlation between social structure and burial rites. On the other hand, for Childe (1945), there is a correlation of burial pattern and social functioning. He hypothesized that the more material progress is made, the less social energy is invested in the burial rituals. In contrast, the Archaeology of Death developed in the 1970´ postulated that mortuary practices are an expression of social reality, where social identity is an equivalent of social status (Goodenough, 1965, but see Gilman, 1983 for a different view). Binford (1971), counterbalancing the view of Childe, assumed that form and structure of mortuary practice are conditioned by the form and complexity of the society in question where the more complex the social structure, the more complex the burial ritual. Anyway, Gifford (1980) highlights that ethnoarchaeological studies provide an actualistic arena for framing, testing, and refitting general models of human behaviour and its material effects, thus allowing the researchers to go beyond the limits of strict analogy as an explanatory tool.

In decreasing isolation from western archaeological reasoning, Marxist approaches developed a scenario until the 1990s where burial sites are seen as deposits of social labour. Since funerary rituals denote the material conditions (in form of homage, payment of tributes or covering up of inequalities) of the society, their meaning can only be made explicit by studying also their living contexts (Lull, 2000).

One example of a materialistic view of mortuary practices is the one developed by Alekshin (1983). The basic informational units necessary to reconstruct and understand funerary rituals in the past, according to this view, include: a) conceptions of death and the other world, b) the development and succession of cultures, c) sex and age differences regarding wealth of grave offerings, d) social stratification on basis of number, type, material, rarity of grave offerings, e) form of marriage and family structure, that gain more and more informative potential as ancient DNA and other biodistance methods are used to identify kinship, and finally f) demographic and epidemiologic patterns. Other authors report different informational units, especially regarding the rich information source skeletal analyses can offer to reconstruct societies’ life in the past (Bartel, 1983), mainly in the light of recent advances in the detection of pathogen DNA, differential diagnosis of pathologies using microscopy, tomography and 3D reconstructions among others.

More recent advances stemming from this view consider three aspects crucial for studying funerary practices in the past (Lull, 2000): a) constructive characteristics of the burial containers, the raw materials and the technology employed; b) a systematic study of the human remains (including dietary patterns, pathologies, and demography); and c) the establishment of the social value of the grave goods.

Whenever available, the study of formation processes should include ethnographic accounts. However, some reports have proven that ethnography does not necessarily parallel archaeological evidences drawn from burial studies (Binford, 1971; Brown, 1971a, 1971b; Shennan, 1975; O´Shea, 1984). In fact, ethnographers concentrate on social phenomena that do not reflect material culture, whereas material culture is the only evidence archaeologist can rely upon to reconstruct social structure in the past (Alekshin, 1983). However, post-depositional processes may distort inferences from simplistic observation (Chapman and Randsborg, 1981) and sometimes counterintuitive ritual behaviour can influence archaeological interpretation (Hodder, 1982). Therefore an integrative approach based on bioarchaeological studies is necessary.

Integrative Approaches to Study Formation Processes: Bioarchaeologists at the Excavation and in the Laboratory

A key element in an integrative approach to study formation processes and mortuary analyses is the growing emphasis on bioarchaeological studies. Such an integrative research strategy requires close collaboration between human biologists and archaeologists and is totally different from the still prevailing tradition to relegate osteological data to the appendix of archaeological papers interpreting social significance of mortuary rituals (Gamble et al., 2001; Stutz, 2003:139).

When bioarchaeologists work in the laboratory as well as directly at the excavation, there are good chances to obtain enough data to reconstruct formation processes based not only on the skeletal material but also on the archaeological context involved and the features associated with the burial. Two examples show how:

The first example, a classical review of burial practices in Central and South America (Lowie, 1948), relies on some ethnographic reports, and shows a great variety of funerary customs often including the manipulation of the corpse. Before definite burial corpses were exposed or temporarily interred, then exhumed and scraped, bundled, pulverized, burned, drunk with alcoholic liquids, or dyed. Afterwards they may have been buried in urns, kept in baskets, hung in trees or houses, interred in individual or multiple burials, as whole skeletons or only consisting of certain parts of them. With the technologic advances available for bioarcheological studies today, most of these customs can be reconstructed even in the absence of ethnographic accounts.

The second example is the study by Nelson (1998), who describes extended funerary rituals among the Moches using skeletal evidences of the deceased and forensic data on decomposition in an arid environment. He analyzed those burials where the position and the preservation of the individual departed from the expected for bodies articulated at the time of burial. Considering decomposition processes specific for the dry climate in this region, and excluding post-depositional disturbances of geological and biological nature, Nelson concludes that these bodies must have been prepared before burial in such a manner as to preserve only the strongest ligaments. However, the individuals must have been buried in different stages of decomposition. The more disturbed the burial the more advanced must have been the state of putrefaction prior to burial. The deceased was manipulated or left to deliberate natural mummification, wrapped in cotton shroud (that would in some cases aid mummification) either shortly after death or when totally desiccated, followed by a long distance transport of the corpse. The body in the bundle was then lowered in different ways into differently constructed and elaborate tombs.

Thus it is clear from these examples that cultural as well as natural phenomena influencing the formation processes of burials can be detected by technological implements today available for bioarchaeologists working not only in the laboratory, but directly at the excavation. Details on the interaction of natural and cultural formation processes are addressed below.

Natural and the Cultural Processes Influencing Burials and Bones

The taphonomic influences acting on a corpse include a large number of factors. The external factors, such as time interval between death and burial, treatment of the body before inhumation, and the environment where it is buried, are all primarily cultural factors. Internal or natural factors include the cause of death, the state of the body at death, age, sex, body mass and existing, as well as past pathologies (Garland and Janaway, 1987). Both the cultural and natural factors can influence two, non-exclusive but very important aspects of a burial: the preservation and conservation of bone elements and the position of them at the time of excavation.

Bone is one of the most resistant biological materials, since it is the main calcified tissue in vertebrates (Schultz, 1997a). It is the main tissue that supports the weight of the body. Bone is formed by proteins (collagens) and minerals (hydroxyapatite), and is a living tissue that can repair and reshape itself in response to external pressures (White, 1991). Often, natural and cultural formation processes act upon the bone after the individual’s death, damaging it. However, as discussed below, some of these processes can actually favour the preservation of the bone material.

The deterioration of any buried material depends on two factors: the chemical nature of the material itself and the type of environment where it is buried (Cronyn, 1990). Therefore, the resistance of a bone element to the detrimental natural or cultural processes is determined by its density, its size and its shape, and it is mediated by the chemical or mechanical processes involved (Marean, 1991). Besides these natural factors, there are also cultural factors that affect the preservation, because cultural rules determine who will be buried, when, where and how it will happen. The place and the way to dispose of the individual will not just influence the position in the grave or pit, but also the preservation of the burial and its contents (Roksandic, 2002).

NATURAL FORMATION PROCESSES

The Process of Death

The definition of death is a complicated one. In this sense, Stutz (2003:142) quotes Bernard Knight (1991:12): "[T]here can be no single definition of death, since death is a process, not an event". The idea that death is a process and not a unique event makes sense not just because in western modern societies technology can keep a person alive through a "life support", but also because many body tissues, as well as cells and enzymes can remain viable for a certain time after the circulation has ceased (Mant, 1984). The cause of death and the condition of the body before death are some among several factors that can explain the individual variation in the post-mortem processes.

Usually, the first physical sign that follows death is a general relaxation of the muscle tone, resulting in the muscles becoming soft and the joints becoming flexible (Mant, 1984). At the same time, the body starts to cool because the metabolic activity of muscles and liver, which produce most of the body heat, are ceased. Of course, individual variation related to body weight and subcutaneous fat, as well as environmental variation, like atmospheric temperature and air circulation, will affect the rate of temperature decrease of the body (Mant, 1984). The blood settles in the body by gravity, mainly because it is still liquid, but not circulating anymore, causing the postmortem hypostasis.

In general, two to four hours after death, *rigor mortis* occur due to the release of actin and myosin from the muscles. Again, individual variation can occur, depending on how much of these elements were present in the muscle tissue. Very young or very old individuals, as well as those severely affected by illness, might never present *rigor mortis* (Knight, 1991:129). Usually this cadaveric rigidity gradually disappears after a peak around 12 hours after death. Stutz (2003:144) alerts to the fact that many times the process and timing of *rigor mortis* is misunderstood, leading to wrong interpretations of the mortuary ritual. Therefore, even when the mortuary ritual involves a primary burial, it is not possible to assume that arrangement of the body position took place prior to *rigor mortis*.

In most cases, *rigor mortis* disappears after 24 hours, giving way to corporeal flaccidity (Mant, 1984). This late phase of post-mortem changes in the body involves decomposition, which usually leads to the consumption of the soft tissues of the body. Due to the primary importance of this stage to the understanding of formation processes in the funerary record, the process of decomposition will be explored in more detail in the next part.

Decomposition, Disarticulation and Movement of Bones

The consequences of soft tissue decomposition, the sequence of disarticulation or disintegration of the connective tissues, and the potential range of displacement of the skeletal elements are natural processes which are some of the key factors in determining the state of the deceased after exhumation.

Lyman (1994:140) states that decomposition is a process divided into three or more stages, depending on the author. Basically, there is decay (decomposition of protein under aerobic conditions), putrefaction (bacterial breakdown of protein under anaerobic conditions) and autolysis (the digestion of cells by autolytic enzymes inside them).

Stutz (2003:145) stresses that archaeologists should be aware of how putrefaction and other processes related to decomposition occur, because this has important implications when considering how the body of the dead is handled by the living in human societies. Although aerobic fungi, insect larvae and adult insects will also contribute to the process of putrefaction, the activity of bacterial enzymes plays a major role in this process. In fact, after death, there is a spread of the anaerobic organisms that inhabited in the bowel *in vivo* throughout the body through the blood vessels. Due to the spatial proximity, the organs that are close to the intestines and more vascularised are affected first (Mant, 1984). In most of the cases the primary putrefaction signs (like marbling, when blue and purple lines appear over the trunk, neck and limbs) will occur between 48 and 72 hours after death (Mant, 1984), but again, this process will depend both on individual and environmental factors. For example, in a warm climate the signs of putrefaction will appear within few hours after death. After the first signs of putrefaction, the production of gases lead to marked changes of the appearance of the cadaver. The body begins to swell, especially in the face and abdomen. The gases increase the pressure inside the body, making the stomach contents being forced upward into the mouth or out of rectum, the lungs being forced upward and the decomposing blood escaping from mouth and nostrils. Gases pressure can also empty the bladder (Mant, 1984).

Saponification is the process in which the fat of the body is transformed into a hard fatty wax named adipocere. Obviously, it will occur in areas of the body with high concentration of fat. Because water is essential for the process of saponification, it contributes indirectly to the dehydration of muscles and internal organs, hindering the process of putrefaction (Mant, 1987). Because the dehydration of muscles prevents their putrefaction, saponification is considered a process very important in terms of preserving skeletal elements in articulation (Allison and Briggs, 1991:36).

Here it is important to say that disarticulation is the total reduction of soft tissues that surround and hold the bones together when the individual is alive. Therefore, even when each bone is in its right anatomical position, the skeleton is considered disarticulated, as long as there is no soft tissue connecting it. Usually this soft tissue removal (also known as skeletonization) occurs not only due to micro-organisms such as bacteria and fungi, but also to small organisms such as insects, and to medium and large organisms, such as vultures, hyenas, armadillos, and other scavenging carnivores (Lyman, 1994: 137).

Environmental conditions play an important role in terms of the speed with which putrefaction will occur. In general, the warmer the environment, the greater the bacterial growth and the quicker putrefaction will take place. Therefore, in colder conditions, there can be a gradual skeletonization of the cadaver, with the soft tissue persisting for about one to two years. On the other hand, in a warmer climate the skeletonization process can be completed within only a couple of weeks (Knight, 1991:41). Bodies in contact with air, when in a relatively warm place, will decompose faster than bodies buried on the ground or submerged in water.

In the same way that the environment plays an important role in increasing or decreasing the rate of putrefaction, cultural processes like clothing, shroud or any covering of the body can either stimulate or hinder this rate. In a first moment, covering would stimulate the process of putrefaction because it retards the cooling of the body, allowing bacteria to multiply. Later, the covering can decrease the rate of putrefaction because it prevents the access of insects to the body and stimulates the formation of adipocere (Stutz, 2003:147).

As said before, the rate of putrefaction also varies according to the spatial conditions of the internal organs. Therefore, organs close to the bacterial source of the bowel will putrefy faster than organs far from it. In this sense, muscular organs can be preserved for many months, and the ligaments and tendons of the joints will be one of the last elements to decompose (Polson 1955:15). In fact, the post mortem decompositional interval between death and disarticulation is highly influenced by the kind of joint and the nature of the ligaments holding the bones together (Lyman 1994:142). Usually the articulations that putrefy early are the ones between the phalanges of the feet, the bones of the hands, the cervical vertebrae, the costo-sternal articulations and the scapulo-thoraxic junction. On the other hand, the most robust articulations, which can persist for months to years, depending on the conditions, are those between atlas and the occipital, the lumbar vertebrae, the sacrum and the last lumbar vertebra, the sacrum and the ilium, the femur and the pelvis, the tarsal bones, and the articulations of knees and ankles (Duday et al., 1990).

After burial, the potential of post-depositional movement of a corpse and its bony elements as a result of the decomposition process depends obviously on its stage of decomposition. The more intact the corpse, the higher the potential degree of movements of the bones due to decomposition (Roksandic, 2002).

Another factor that influences the changes in situ of the original position of a corpse is the position in which the individual was deposited and the space available in which the movement can happen. Consequently, if bones are in a stable position in the burial, they will move just a little after the disarticulation of the skeleton. However, if the position of the body implies in an unstable position of the bones, once the soft tissues are decomposed, the bones will move according to the gravity and the spatial architecture of the burial. The empty space left around the corpse allows some changes in its position due to the gas concentration that occurs during the decomposition or due to the collapse of the articulations. Examples of these movements include fingers that spread on the abdomen and the aperture of arms or legs. Even if the burial is confined to a very small space in relation to the size of the individual, additional room appears after the soft tissue decomposition. In spite of this, the space of burial can vary accordingly to the presence of elements that delimit the room available in the grave, like stones put around the body, bodies tied up to fit in tiny baskets, and, of course, the infiltration of sediment adjacent to the corpse during the decomposition process (Roksandic, 2002). The filling of body cavities by the sediment can be progressive (slowly filling of body cavities) or differential (more filling in one than another body cavity) (Duday, 1985). Therefore, when the sediment directly covers the corpse, as soon as the decomposition begins, it can fill the body cavities. However, this kind of filling depends on the characteristics of the sediment (humidity, compactation, granulometric aspects, etc.).

Burial as a Taphonomic Process

Burial as a taphonomic process has not been studied in an extensive way in comparison with the biostratinomic processes (processes affecting the organic remains during deposition and before final burial) (Lyman, 1994:404). Straus (1990) argues that these processes were initially ignored because most of the archaeologists were more interested in building cultural chronologies than in understanding how deposition and formation were taking place in the archaeological record. Another possible explanation for this initial lack of interest was the fact that the better known taphonomic processes such as abrasion, weathering, and trampling occur at the sediment-air interface, therefore, they are mainly biostratinomic processes.

As Lyman (1994:411) highlighted in his book, the ritualistic disposal of conspecifics seems to be a unique feature of humans. Often, such disposal included purposeful burial, usually marked geologically by the presence of human remains in a stratigraphically distinct unit, usually a pit.

There is a common belief among taphonomists that if the bones (or corpses) are rapidly buried, this would buffer these remains from the several biostratinomic processes that might otherwise modify them. However, this does not mean that bones stop being modified by taphonomic processes after the burial. What happens is that the diagenetic processes that modify bones after burial are different from the biostratinomic processes (Lyman, 1994:413-114).

Diagenesis refers to the alterations that happen after burial (Lyman, 1994:417), and the diagenesis of bones can be affected by intrinsic factors of the specimen, such as size, porosity, chemical and molecular structure, and by extrinsic factors such as sediment pH, water and temperature regimes, and bacterial action (Von Endt and Ortner, 1984). There are some major factors that could influence the difference between the deposited assemblage and the buried assemblage. Clark and Kietzke (1967) suggested that the time interval between episodes of sedimentation, the thickness of sedimentary increments, the velocity of depositional forces in contact with bones (or corpses), the nature of the sediment (such as the amount of compaction and grain size), the post depositional action of roots and burrowing animals, and the permeability of the sediment and chemical nature of the permeating solutions could be some of these factors.

Soil Characteristics

Within some years after burial, the type of soil can affect the body in different ways. For example, heavy clay soils may stimulate the adipocere production and thus have a certain preservative effect, while very dry soils will tend to preserve the body while mummifying it (Stutz 2003:147). In a long term perspective, the soil characteristics are extremely relevant for the preservation of bones (Mant, 1953; 1987; Janssen, 1984; Henderson, 1987; Johansson, 1987), specially the pH. Soil pH usually varies between 4 and 9 (Knight, 1990), but occasionally can surpass these values. High or alkaline pH values are due to the presence of soil carbonates (Fitzpatrick, 1980), such as calcium or magnesium carbonates. An important property of carbonates is that they are easily soluble in water that presents carbon dioxide and, therefore, can be rapidly transported through the soil by the percolation of rain water or from water tables. Bones are usually better preserved in environments with neutral or slightly alkaline pH than in places with acid pH (Janaway, 2002). Waselkov (1987:149) alerts that “although shell middens are renowned for their enhanced bone preservation, the calcium-rich environment still allows transport in solution of exchangeable calcium from bone and shell”.

Post-Mortem Fractures and Deformations

Usually, the more deeply the corpse is buried the better is its preservation (Henderson, 1987), since low and stable temperatures, low gas diffusion and the inaccessibility of natural agents (such as animals, plants, erosion) hinder the rapid decay of the body. However, the pressure of extensive layers of soil upon a burial can result in distortion/deformation of bones (Brain, 1981; Janaway, 2002). Several factors affect the degree and kind of deformation, including the composition of the sediment, the original morphology, the elasticity and orientation, as well as mineralization and leaching (Lyman, 1994:425). The deeper the bones are buried, the greater is the weight of the sediment overlying. Besides this, the pore spaces between sedimentary particles become smaller and fewer, resulting in a greater bulk density and a higher compaction of the underlying sediments (Lyman, 1994:423).

It is frequently assumed that the action of sedimentary processes on bone results in abrasion of bone (Gifford, 1981). Although abrasion has not been rigorously defined, it is usually diagnosed by rounding of natural features or break surfaces of bone. Most of the taphonomic studies about abrasion of bone linked this to aqueous transport, although sandblasting of bone on a land surface or bioturbation (for example, trampling against an abrasive substrate by animals, Brain, 1967) cannot be ignored as abrasive agents. In the same way that bones react to other stresses at different rates, they would be differentially liable to damage by abrasive processes. It is possible that weathered bone would be more damaged by abrasion than fresh bone. In fact, Gifford (1981) stresses the high positive correlation between advanced stages of weathering and degree of abrasion in fossil bone. She also suggested that elements with greater proportion of spongy compared to compact bone would be more easily damaged by abrasion.

Erosive processes caused by the pressure of layers of sediment can also be mistaken by losses of bone tissue due to pathologic processes active during life time. Erosion, if acting during long periods of time, can completely destroy bone. Moreover, pressure resulting from sediment layers that cover the burial can cause fragmentation and dislocation of bones. Villa and Mahieu (1991) say that bones broken by the excessive weight of the sediment can be recognized by conjointing fragments lying in contact or adjacent to one another. They also argue that the fracture of bones lying on concave or convex surfaces can be explained by an increase in the bending forces applied to them.

But it is not only the surface features that module breakage of bone layed upon them. The shape of human bones also influences the mechanics of bone fracture, so the cranium is especially prone to break due to its globular shape, as is also the case for flat bones such as pelvis and scapula. Tubular bones (femur, tibia, fibula, radio and ulna) are a little more resistant to sediment pressure due to their elongated shape and their thicker cortical bone. Besides compression forces induced by overburden weight, other factors like feeding carnivores, trampling and factors related to climate such as subaereal weathering can also be listed as major causes of bone fracture.

Osseous fragmentation caused by natural processes (pseudopathologies) must clearly be distinguished from that caused by antemortem and /or perimortem causes (true pathologies). This is important, since the relative prevalence of certain types of ante and/or perimortem bone fractures are used to infer past behaviour, such as the degree of interpersonal violence, the frequency of accidental falls or the existence of idiopathic fractures, such as vertebral fractures following tuberculosis.

Size, Sex and Age at Death

Bone size is also a very relevant factor that affects the vulnerability of bone decay. Waldron (1987) says that the phalanges and the small tarsal bones are less preserved than the other bones of the skeleton and can disappear completely, as a consequence of the large surface (acted upon by the decay agents) in relation to the volume. However, depending on the burial context, these small bones can be the best preserved ones, since their small size avoids breakage (Currey, 1984; Darwent and Lyman, 2002). Nonetheless, the small size favours the dispersion and consequent loss of these bones (Waldron, 1987) through natural agents like small animals and roots, and cultural formation processes (e.g., “secondary burials”, as discussed below). Behrensmeyer (1978) observed that smaller mammal bones weather at faster rates than do those of larger mammals, although not all bones of the same individual weather at the same time. Again, it is the relation of surface area to volume that determines also the natural break down rate of bones (Gifford, 1981).

Bone density is also a factor that influences bone preservation. The proportion between cortical and trabecular bone varies accordingly to the type of bone and plays an important role in the differential decomposition of the skeleton. Although the basic organic and inorganic makeup of mammalian bone is not highly variable, the wide range of functions of different elements results in a great diversity in the structural variability of bone tissue, which will influence the resistance of different skeletal elements to destructive forces. Obviously, thicker compact bone resists damage better than thin bone, since the ratio of bone tissue per unit of volume is positively correlated with its resistance to stress. Therefore, compact bone, with its high ratio of bone tissue per unit of volume, resists localized stress better than cancelous, or spongy bone, with its low ratio of bone tissue to volume. However, compact bone readily transmits stress causing fractures that may propagate more extensively than cancellous bone (Gifford, 1981).

Age and sex of the individual also affect bone diagenesis. Women tend to be more gracile than men, and children have thinner and smaller bones than adults, whereas in older individuals, bones can be less dense due to osteoporotic processes, and therefore more prone to decay (Janaway, 2002). There are only a few studies on decomposition of juvenile skeletons but practical experience shows that juvenile skeletal remains are less prone to preserve than adult remains (Hill, 1980; Crist et al., 1997), mainly because of their smaller size and lower density that facilitate dispersion and even complete ingestion by scavengers (Morton and Lord, 2002). This differential preservation of juvenile skeletal remains in comparison with adult remains was also confirmed by Gordon and Buikstra (1981). The authors found a strong negative correlation between the sediment pH from which the bones were recovered and the frequency of ontogenically mature bones preserved within particular preservational categories, meaning that even if the pH value is adequate for bone preservation, juvenile bones preserve less well that bones from mature individuals. However, Hill (1980) alerts that some old individuals present a tendency to resorb bone and that this also may influence the susceptibility of bones to damage.

Nevertheless, the lack of a high proportion of a certain age group in a cemetery is not necessarily due to the differential preservation of these remains. Basically, there are four major factors that influence how much a given funerary sample represents the demographic distribution of the corresponding living group (Waldron, 1994). The first is the proportion and distribution of individuals buried in the cemetery. An example would be that a given group buries juveniles somewhere else than adults. Thus, this factor results from a clearly cultural process. The second factor is a natural process, because it refers to the proportion of individuals that, once buried, are preserved. The last two factors are related to the proportion of individuals that are found and that are exhumed during archaeological excavation.

Bioturbation

Apart from intrinsic factors of the human bones themselves (such as size, sex and age), extrinsic factures caused by other living beings (like plants and animals) are natural processes that affect the preservation of human skeletal remains. These are collectively called bioturbation. Floral turbation involves all the natural processes related to the action of plants on the archaeological record, most of them caused by roots. In fact, the presence of roots in burials is not rare. The principal cause probably is the decomposition of the corpse that releases important nutrients for root growth (Rodriguez and Bass, 1985). The roots can act in two different ways upon the bones: through physical effect and through chemical destruction (Botella et al., 1999). The physical effect results from the growth of the root that may travel through the medullary canals and split sturdy long bone shafts, or penetrate through the cortex causing holes. This chemical destruction of bone is caused by the liberation of acids released by the roots and can leave dendritic patterns of shallow grooves on bone surfaces (Behrenmeyer, 1978). The presence of root etching indicates that the bone existed in a plant-supporting sedimentary environment for at least part of its history. The marks that the roots leave on bone may sometimes be mistaken by the unaware as pathologies such as trepanation, bullet injuries, or infectious disease (Schultz, 1997b; Saul and Saul, 2002). In the case of lichen, their presence indicates a period of at least partial exposure without much disturbance (Cook, 1986).

Besides plants, animals also can be important agents of bioturbation. Hungry scavengers may excavate bones and cause their fragmentation and dislocation, also being responsible for the “creation” of pseudopathologies or pseudotraumas (Haglund, 1997a; b; Haskell et al., 1997; Merbs, 1997; Murad, 1997; Rodriguez, 1997; Ubelaker, 1997; Symes et al., 2002). Mammals and insects are the animals more often associated with bioturbation of burials for feeding purposes (Henderson, 1987).

Although quite common in North American archaeology and forensic sciences (Morse, 1983; Krogman and Iscan, 1986; Haglung et al., 1989; Berryman, 2002), studies about natural processes related to mammal and insect action in tropical regions are scarce (for an exception, see Araujo, 1995; Araujo and Marcelino, 2003). Mammals like rodents and armadillos can move the bones from their original contexts, can originate marks that may be potentially mistaken with pathological processes that occurred during life and may completely destroy the bones through chewing (Sorg, 1985; Patel, 1994).

Insect activity depends on the burial’s condition, the season, latitude and longitude (Erzinclioglu, 1983; Rodriguez and Bass, 1983; Catts and Haskell, 1990; Schultz, 1997b; VanLaerthoven and Anderson, 1999; Anderson and Cervenka, 2002). Some experiments show that animal carcasses not buried can be completely skeletonised in just 96 hours of intense activity of insect larvae (Haskell et al., 1997), therefore insects as agents of soft tissue removal, can be very important for the decomposition process. Coe (1980) describes that in a wet season in Kenya, dermestid beetles removed the skin and sinews of an elephant carcass at the astonishing rate of 8kg per day. Soil covering is not a totally effective barrier against insect larvae, although it can inhibit it partially (Nuorteva, 1977), since the infestation can initiate before burial or because the saprophagous insects have adapted senses for corpse localization. Lyman (1994:393) highlights that Derry (1911) was the first to report on the gnawing action of insects resulting in damage to bones, although Smith (1908) also described gnawing damage found in human bones related to beetles, after discarding this damage as an antemortem pathological condition. While Derry (1911) and Smith (1908) described grooves gnawed by moth larvae and beetles, Watson and Abbey (1986) found that Australian termites gnaw bone and create "scratches" in bone surfaces. Holes found in fossil bovid bones were reported by Kitching (1980) as caused by dermestid beetles.

Lyman (1994:142) argues that it is important to note that some insects do eat bone tissue (Behrensmeyer 1978), while others move bones from their original position (Shipman and Walker, 1980). However, because small-scale removers like insects are less likely to separate a bone and soft tissue package from a carcass and then move that package, the role of animals as agents that can move bones was better studied in large-scale agents like mammals and birds (Lyman, 1994:142). On the other hand, the removal of soft tissue and the movement of bones resulting from the action of large-scale agents happen simultaneously, making the distinction between skeletonization and disarticulation very difficult and sometimes impossible.

Obviously, the potential for transport of skeletal elements by animals varies accordingly to its appeal to them. Therefore, the amount of muscle and fat associated with, or blood and marrow contained in, a bone are very important factors that will reflect also in the frequency with which it will be subject to damage and transport by such animals (Gifford, 1981).

Rodents are the best known gnawers of bone (Miller, 1969), favouring bone that is somewhat weathered and free from fat and sinew. It is very important to distinguish these marks from those related to cultural processes, like defleshing, disarticulation, or even cannibalism. Rodent tooth marks on bone surfaces are described as channels, grooves or parallel striations (Johnson, 1985; Sorg, 1985). However, sometimes it is not possible to find the characteristic parallel grooves indicating the rodent action, especially on spongy (trabecular) bone and on small bones, like metacarpals, metatarsals and phalanges, where the cortex is thin (Haglund, 1997b). Therefore, the identification of those marks is not always possible. The pattern of tooth marks left by carnivores is even more complicated, because the marks are usually less specific and more irregular (Haglund, 1997b). Carnivore tooth marks can indicate the time of exposure of the corpse before complete skeletonization, being the most often gnawed element those with little overlying soft tissue (Hurlburt, 2000).

Weathering

Weathering is the process by which the original components of bone are separated and destroyed by physical and chemical agents operating on the bone in situ, either on the surface or within the soil zone (Behrenmeyer, 1978). This process can result not only in splits and cracks that develop between collagen fibers, but also in the separation of bones of the skull along sutures, and teeth falling out of their alveoli (Lyman, 1994:358). Chemical weathering begins on the bone surface and progresses into the bone tissue mass (Bromage, 1984). Although bones weather in both surface and subsurface contexts (Behrenmeyer, 1978), the distinction between subaereal (surface) and subsurface weathering have not been studied in detail. The fact that buried bones seem to weather much slower than exposed ones, does not mean that they are free from this process (Lyman, 1994:360).

The importance of this discussion for bioarchaeological studies can be highlighted in cases where the funerary ritual does not involve the burial of the corpse, or involves it in a later stage. Humidity, temperature, and pH in the immediate environment of a bone are some of the factors that can influence the rates at which weathering occurs (Behrenmeyer, 1978). This could explain why one end of a single bone can weather at a much faster rate than the other. Bone exposed to direct sunlight weathers more swiftly than those in shaded areas, including those shaded by vegetation (Gifford, 1981).

The variation in the structural density of different bones results in a different rate of weathering (Behrenmeyer, 1978). Besides this, even bones from animals of similar constitution, size or taxa will weather at different rates due to constructional differences (Gifford 1981). It is well known that the weathering process is more intense when the bone is freed from the soft tissues. Therefore, the timing when bones from the same individual were exposed and the exposure duration could explain the variation of weathering between bones from the same individual (Lyman, 1994:363). Unfortunately, most of the studies involving weathering are based on non-human remains, making inferences quite difficult in terms of funerary studies.

Weathering acts along lines of structural weakness in the bone, resulting in a fine network of “split lines” over time. Coe (1980) describes that the bones and teeth begin to crack (and flake, in the case of bones) within five weeks of death when they were submitted to a diurnal temperature range of 35^{o}C. Apparently the range of temperature that the bones are exposed can be ameliorated by covering (in this case, the author was considering vegetation covering, but in the case of human remains, it is possible to consider a hut, cloths or baskets as covering elements). This observation was confirmed by Behrensmeyer and Boaz (1980), who describe that except for the teeth of recently dead individuals, the only uncracked tooth observed were either those unexposed to the air in semiburied crania or mandibles. In the same way, Hill (1980) says that unburied bones shielded by vegetation, are more likely to survive than are those exposed to harsher conditions.

Water Exposition and Calcium Deposits

The action of water can be directly (while raining) or indirectly (through percolation). Calcium deposits are formed when the atmospheric carbon dioxide is dissolved by water producing carbonic acid. This decreases pH. Rain water, which is acid, reacts with calcium carbonate, producing calcium bicarbonate. The calcium bicarbonate dissolved by rain drops falls on the soil and when the partial pressure of carbon dioxide is diminished, it is transformed again into calcium carbonate (Botella et al., 1999). Calcium carbonate often is distributed as a layer upon the bones, protecting them from other natural processes. However, if there is too much overlapping of these layers, the bones can be totally covered by them. If bone fragments are dislocated before the deposition of calcium carbonate layers, they become agglutinated in a messy way, sometimes preventing their reconstruction and analysis. Calcium deposition also precludes the visualization of bone surfaces, making paleopathological analyses impossible. Besides the macroscopic deposition of calcium, there are also microscopic depositions that incorporate calcium carbonate on the bone matrix. In the latter, it is not always possible to detect the deposition of calcium macroscopically.

Fungi, Bacteria and Algae

Regardless the role of micro-organisms in the decomposition process, important biological alteration of bone can be caused mainly by algae, fungi, and bacteria (Davis, 1997; Schultz, 1997b; Jans et al., 2004).

Algae are, together with other organism, reported to be responsible for microscopic focal destructions (MFD) of bone (Davis, 1997). These MFD are small holes or hypermineralized nodules. They alter histomorphological features of bone, and may facilitate decomposition of bone and thus prevent fossilization. Fossilization was thought to occur to bone not attacked by bioerosion, but a systematic study of fossil bone revealed that about one third on them did show evidences of microbial attack (Trueman and Martill, 2002). Nevertheless, the resulting bioerosion in fossilised bone affects only rare specimens and if, affects only diminute areas of the bony tissue. It appears, thus, that bioerosion is a very early post mortem process that rapidly destroys bone and that bioerosion can be haltered through chemical inhibition resulting from different still unknown processes of microbes attacking mainly collagen (Trueman and Martill, 2002).

Apparently, fungi penetrate bone within 30 days after exposure (Marchiafava et al., 1974), creating MFD of 1 to 8 micron in diameter, in an attempt to gain access to collagen. Surrounding these tunnels, there is a redeposition of hidroxyapatite, which can be very useful in order to differentiate these post-mortem processes from pathological ones (Hackett, 1981; Piepenbrink, 1986). It is relatively easy to identify fungal action on bones when they leave irregular usually green (sometimes also black or white) patches and spots on the bone surfaces (Botella et al., 1999). However, in some instances the fungal action can only be distinguished from bacterial attack by histological analyses on the basis of size differences in the tunnels left by them (Hackett, 1981; Jans et al., 2004). Additionally, when the tunnels created by fungal action gradually coalesce to form large patches of resorbed cortical bone, it can be easily mistaken by the unaware as remodelling and bone loss that happened when the individual was alive.

In contrast to the usually macroscopically identifiable fungal action on bone, bacteria leave tiny tunnels of 5-10 micrometer in diameter only detectable through microscopic analyses, as early as months to many decades after death (Jans et al., 2004). This resulting porosity then accelerates bone decomposition through other agents such as water percolation and roots, and thus reduces the chances of biomolecular research, such as ancient DNA analyses (Bar et al., 1988). Histology and mercury intrusion porosity metrics on bones of 41 archaeological sites with different environmental characteristics revealed microbial attacks in as much as 68% of samples (Jans et al., 2004). Primary burials are more likely to be attacked by bacteria, indicating their action during putrefaction. Secondary burials, in contrast, are more likely to show better conservation. However, fungal attack can occur at any time during burial and until excavation and depends on the surrounding environment (darkness and humidity favouring their growth).

The reduction in the structural density and increase of the porosity of the bone (Hanson and Buikstra, 1987; Bell, 1990) caused by the small tunnels created by fungal and bacterial activity may exacerbate the effects of diagenetic processes such as crushing from sediment overburden weight (Garland, 1987).

CULTURAL FORMATION PROCESSES

Primary and Secondary Burials

One of the most important cultural formation processes is the arrangement of a burial because it has relevant consequences on bone preservation. Basically, the arrangement of a burial can be classified as primary and secondary. The primary arrangement refers to the initial place where the corpse shortly after death is left. If the initial arrangement is the same as the final one, it is classified as a primary burial. On the other hand, secondary burials are those where the human remains are removed from their initial place to be definitely inhumed either in the same place or somewhere else. This happens when the individual is buried, exhumed and then buried again or when the corpse is left exposed until the partial or total skeletonization and only then is interred. Charnels are defined according to O'Shea (1984:37) as rooms used to accumulate the remains of the dead, often in a multistage program of disposal that may include a period of primary "interment", not always below ground (Nelson et al., 1992).

Although the presence of secondary burial can be quite easily identified when the reburial includes just the largest bones (Duday, 1978), the loss of small bones[‡] can also indicate that the primary disposal of the individual was different from the final one, and that in some moment between the primary and the final disposal, these small bones were lost. Accordingly, when juveniles are involved in a secondary burial, the loss of bones is quite common, depending on the stage of decomposition. However, not always the identification of primary or secondary burials is straightforward. Even when all bones are present and in anatomical position, one cannot rule out a secondary burial in the sense that the corpse could have been removed from an initial to a final place of burial before the complete decomposition and subsequent disarticulation took place (Roksandic, 2002). Nonetheless, corpses wrapped in textiles or bound together with the aid of ropes and baskets can be removed from their initial places without loss of bones. Consequently, no indication about this displacement would be left over for the bioarchaeologist to identify, except the possible movement of bones due to the decomposition of soft tissues.

It is important to note that even in a primary and undisturbed burial, not all the bones of the skeleton will necessarily occupy the same position as they did in the cadaver before skeletonization. There will always be a (slight or great) difference between the original *in vivo* position of the skeleton and what archaeologists discover in the exhumation. This can be explained by the decomposition of soft tissues, which affects the balance of the bones in two ways: due to the lack of articulation of these bones and due to the presence of empty spaces left after the decomposition of these soft tissues (Stutz, 2003: 150-151). Although decomposition and the subsequent movement of bones is a natural process, it will be strongly

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[‡] The loss of small bones can also happen as a consequence of natural formation processes, as already discussed.

influenced by cultural factors, including the structure and size of the grave, as well as the way that the corpse is placed (sitting, on its back, on the lateral side, etc) into it.

Besides the anatomical position, the way that the skeleton was laid down into the burial pit can also give important clues about what could have happened before skeletonization. In fact, acute angles of arms and legs indicate manipulation of the body before burial, once some of these angles are impossible to attain while the soft tissue of the corpse is still intact. In addition, dismemberment at the time of death, under most circumstances, would leave parallel cut marks especially at the greater and lesser trochanter and the greater tubercle and medial epicondile of the humerus (Marshall, 1989; Nelson et al., 1992), although depending on the stage of decomposition dismemberment can be done more easily and not necessarily leaving marks on bones. Bleached and friable bones, presenting longitudinal cracking can suggest that they were exposed to the elements for quite a long period (Nelson et al., 1992), suggesting that the final burial did not take place immediately after death.

Usually secondary burials evoke moral and social obligation during which death does not occur and is not perceived as a moment in time, but is a drawn out process. In some groups, the dead person is still considered as a part of society and the spatial proximity between the living and the corpse in treatment for secondary burial, put the mourning persons apart from society. For the Dayak of Kalimantan in Indonesia, for example, the soul only definitely detaches from the corpse when the body is ready for secondary interment and the mourners have carried out their obligations. The second interment has three main functions in this Indonesian group: bury the remains, ensure the soul access to the land of the death, and free the living from the obligations of mourning. The secondary burial is a collective affair, in the contrary to the temporary burial (Hertz, 2006).

Cannibalism

Probably one of the most polemic cultural processes involving death is the practice of cannibalism. Cannibalism has disturbed and fascinated researchers since a long time. There are numerous ethnographic as well as prehistoric evidences on cannibalism all over the world. Only in southwest North America there are about 30, mostly Anasazi Pueblo sites (400-1350 AD) with anthropogenic bone modification interpreted as signs of cannibalism (Hurlburt, 2000). Behavioural inferences were drawn upon different signatures left on osteological collection of these Anasazi sites, based on taphonomy, demography, ethnohistorical accounts, and analogy. There are seven basic criteria that can aid cannibalism identification: pot polishing, perimortem breakage, burning, anvil abrasions, cut marks, underrepresentation of vertebrae (White, 1992; Turner and Turner, 1999) and similarities with butchering marks on faunal bones. Due to the disarticulation and defleshing marks secondary burials can in some rare cases resemble cannibalism (Hurlburt, 2000).

It is important to state that even if one or more of the basic criteria on cannibalism are met, there are no evidences that human flesh has ever been part of subsistence strategies and thus for nutrition purposes. Evidences usually point to ritualistic situations when cannibalism was practiced.

Where to Bury the Dead

Although the physical characteristics of the place where the individuals are buried will influence the preservation of the corpse, the place where someone is buried is determined by a cultural choice. Therefore, although pH and humidity, among others are key factors for the preservation or not of the body, these factors will be influenced and often manipulated (as in the case of deliberated practices that modify the physical characteristics of the burial place) by people. This manipulation can accelerate the decomposition process (like cremation or watering the grave – Ramos, 1951:181-182) or can reduce smelly odours and aid preservation of bones (when the corpse is covered with lime, for example).

Aims

The aim of this chapter, besides presenting a review of the literature about formation processes involving human remains in general, is to identify and discuss the natural as well as the cultural formation processes influencing the interpretation of burial patterns in a prehistoric Brazilian shellmound. Therefore we chose the site Jabuticabeira II, a site especially informative for this approach since it contains mainly burials and therefore is classified as a cemetery shellmound. Furthermore it should alert archaeologists about the importance of documenting and distinguishing these factors clearly to better understand formation processes of archaeological sites in general. This should be undertaken in situ as well as in laboratory. This work also argues in favour of true multidisciplinary research where specialists such as bioarchaeologists participate in the decision processes of the exact location and strategy of excavation, coordinate sample collection of and documentation on burials, and, as usually already routine, carry out their specialized work in the laboratory.

MATERIAL AND METHODS

Archaeological Background: Brazilian Shellmounds and the Case of Jabuticabeira II

Brazilian shellmounds are archaeological sites that can be found in almost the entire coast, especially the Southern regions. Although more than one thousand of these sites have been catalogued, not many were systematically studied yet (Gaspar, 1998). Most of these shellmounds are dated to between 5,000 to 1,000 years BP (Lima, 1999-2000), and the great number of them, the long period of time and large area of occupation, associated with the huge size of many of these sites (reaching up to 70 m in height), suggests that these populations were very well adapted to the coastal environment (De Blasis et al., 2007). Because of their use for the extraction of lime, the Portuguese colonists knew the Brazilian shellmounds already in the Sixteenth century, but these sites have only been a target for archaeological studies from the Nineteenth century onwards (Lacerda, 1885). Apart from craniometrical studies, most of the research carried out on skeletal remains to date is restricted to the description of pathologies in single sites (Salles Cunha, 1959; 1963a; 1963b;

Araujo, 1969; 1970; Mello e Alvim et al., 1991; Mello e Alvim and Gomes, 1992). Recently, archaeological excavations in shellmounds and the reassessment of osteological collections housed in museums have been more systematic, allowing more meaningful analyses of population history at specific sites or regions (Mendonça de Souza, 1995; Storto et al., 1999; Wesolowski, 2000; Scheel-Ybert et al., 2003; Rodrigues-Carvalho, 2004; Hubbe, 2005; Neves and Okumura, 2005; Okumura and Eggers, 2005; Filippini and Eggers, 2005-2006; Bartolomucci, 2006; Marinho et al., 2006; Okumura, 2007; Okumura et al., 2007; Wesolowski, 2007).

The skeletal material analyzed in this chapter was exhumed from burials at the Brazilian shellmound Jabuticabeira II, one of 68 shellmounds located close to Camacho Lake, Jaguaruna, Santa Catarina State, Brazil (Figure 1). More than 40 radiocarbon dates indicate that this site was built between 2890 ± 55 and 2186 ± 60 BP (De Blasis et al., 1998; Gaspar et al., 1999; Fish et al., 2000). The part that remained of the site after the mining activities measures about 400 x 250 x 6 meters.

The osteological material from Jabuticabeira II derives from profiles and horizontal excavations, showing a long and continuous depositional history of recurrent burial and mortuary activities as well as the lack of habitation structures. The high number and great density of burials, most of which lay out with shells and covered over by a layer of sand mixed with shells, suggest that the utilization of this shellmound as cemetery was linked to its construction process (De Blasis et al., 1998; Fish et al., 2000).

Primary and secondary burials are distributed over most of the locations excavated, presenting hearths, post holes, as well as lithic artefacts, beads, fish remains (interpreted as offerings for the dead and food for the living, depending on completeness and state of conservation of their skeletons), and red pigment (De Blasis et al., 1998; Edwards et al., 2001; Klokler 2001).

Based on the mean number of burials per cubic meter excavated until then, Fish et al. (2000) estimated that an astonishing number of about 40,000 individuals must have been buried in this site. Even if this is an overestimate, it suggests a large number of people living nearby Jabuticabeira II, possibly sharing a social identity and getting together for the construction of and the rituals carried out at this site.

The material described here consists of the remains of a minimum number of 89 individuals (using the criteria established by White, 1991) excavated from the site Jabuticabeira II during three field campaigns in 1997, 1998 and 1999.

The state of conservation of some of the individuals is far from being ideal. In many cases there are only a few skeletal elements.

Curation and Analyses

The curation was carried out in the laboratory according to internationally accepted criteria. The distinction between juveniles and adults was based on classical osteological features, like the fusion of spheno-occipital suture, the degree of epiphyseal closure, tooth formation and eruption (Ubelaker, 1989) and the size of the long bones (Johnston, 1962). Adult individuals were sexed based on pelvic and cranial morphology (Buikstra and Ubelaker, 1994). More details on age and sex distribution as well as a palaeopathological analysis on these individuals can be found in Okumura and Eggers (2005).

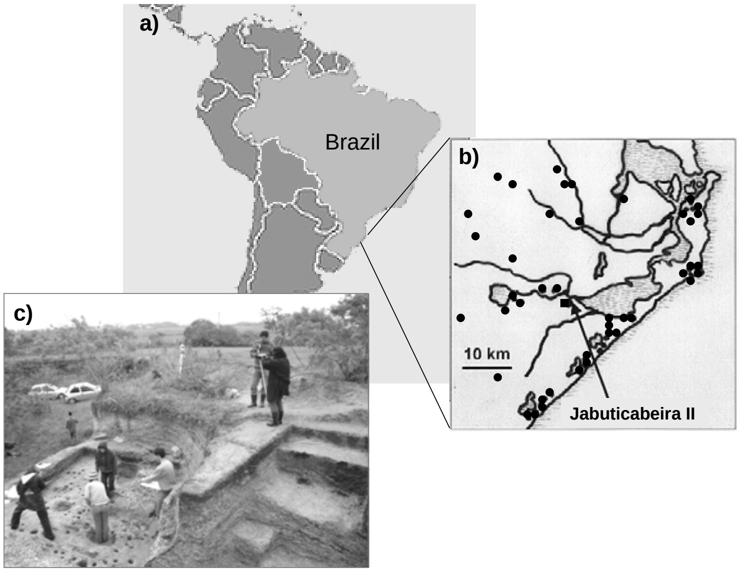

Figure 1. Map showing Brazil (a), the geographical location of the Jabuticabeira II site amongst many other shellmounds (b), and a general overview of it (c).

The analysis of natural and cultural processes was carried out macroscopically. Due to the fragmentary character of the sample, not all individuals were included in every analysis. Burial forms and photographs taken in the field were also used to access information for the analysis.

RESULTS

Evidences of Natural Formation Processes

Due to the great concentration of shells, the soil pH of shellmounds is usually higher than that found in other tropical soils, neutralizing their acidic destructivity and allowing the conservation of human remains. The fact that the majority of Brazilian skeletal remains were exhumed from shellmounds (Okumura et al., 2007) supports the notion that the soil alcalinization in these sites is a natural formation process that allows the preservation of human remains. However, the accumulation of shells in shellmounds is a cultural phenomenon, since these were accumulated on purpose by the dwellers while constructing the site (Gaspar and De Blasis, 1992; Gaspar, 1998; 2000; Fish et al., 2000).

Calcium deposition is often found on skeletons buried in shellmounds, due to the calcium rich environment provided by the abundance of shells. This kind of deposition can sometimes prevent the surface visualization, not allowing the analyses of pathologies that affect the surface of the bones. An advanced mineralized state of a skeleton exhumed in Jabuticabeira II was described by Edwards et al. (2001), showing evidences that the calcium carbonate was being incorporated into the phosphatic hydroxyapatite. Therefore, the mineralization process happens through the absorption of carbonaceous material into the inorganic matrix on sites previously occupied by the collagen component.

Raman spectroscopy analysis on a forearm of this highly mineralised individual revealed a layer of limewash (Edwards et al., 2001). This could be the product of heating shells to 700-900 °C and applying the produced lime onto the corpse. If molluscs are heated to high temperature calcium oxide is released; this reacts with sodium bicarbonate solutions in the midden soil to form powdered calcium carbonate to precipitate on the shells (Waselkov, 1987). Whether this procedure was intentional, in order to avoid putrefaction smells and attraction of flies and scavengers is not known. Therefore, in the same way that the soil alkalinisation was a natural process related to a cultural habit, the consequences of the spread of lime on the corpses is a natural process that could be linked to a cultural one.

The presence of human bones deformed due to sediment pressure is quite common in shellmounds, due to the mountain shape and huge size as well as the presence of burials in every stratigraphic layer. Although there is no evidence of artificial cranial deformation in vivo among these shellmound dwellers, it is very important to distinguish intentional deformations from the ones that occurred after death, as a result of a natural process. In Jabuticabeita II, at least one individual presenting a postmortem cranial deformation was recovered and although recent construction material was covering this burial, it is more likely that cranial natural deformation occurred while the bone was still fresh (recently deceased).

Among the skeletal material from Jabuticabeira II, evidences of weathering or water exposition are extremely rare but numerous bones show fractures caused by post-mortem natural processes, while antemortem and perimortem fractures, indicating accidents and violence are extremely scarce. In a sample of 21 adults that presented enough bones to be analysed, seven presented traumas, but none classically related to interpersonal violence (Okumura and Eggers, 2005).

The human remains described previously (Okumura and Eggers, 2005) reveal that about one third of the individuals died before 21 years of age, a proportion that agrees with the percentage observed in other prehistoric cemeteries (Waldron, 1994), meaning that, a priori, the natural and cultural processes related to the differential bone preservation between adults and juveniles did not distort the original (and expected) demographic composition of these group.

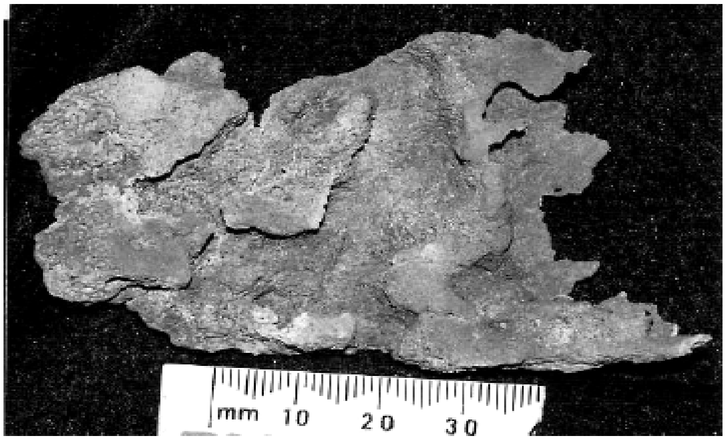

Figure 2. Example of a natural process related to insect action in bone material. See the extensive bone loss on the endocranium.

Photo: Wagner Sousa e Silva

Figure 3. Rodent marks on ulna of a mid-adult female.

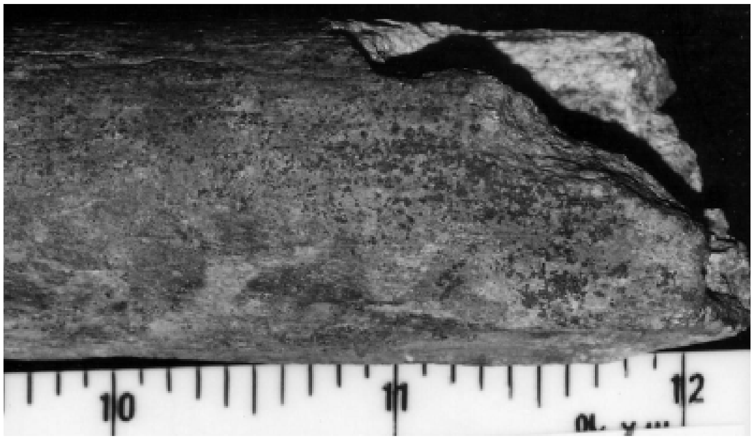

Figure 4. Black spots caused by fungi on long bone fragment of a young adult.

Another demographic parameter concerns sex distribution. The fact that both sexes are represented in a very similar proportion and that all age classes are represented in the osteological collection of Jabuticabeira II (Okumura and Eggers, 2005), indicates that no strong selection processes (being they cultural or natural) acted on the people buried and exhumed. It is important to stress that the exhumed individuals, apart from indicating no selection processes regarding age or sex of whom was buried, are, at the same time, an example of recent selection processes (such as the decision of which part of the site to excavate and which of the individuals recorded to exhume).

The presence of roots was observed and documented (although not systematically) in many occasions during the curatorial process of the human skeletal material from Jabuticabeira II. Furthermore, another evidence of bioturbation was identified among the individuals analysed. An adult of undetermined sex presented an extremely modified surface of the inner table of the cranium, with extensive bone loss. In some regions, all that was left from the cranium was the outer table.

Figure 5. Locus 2. The tightly flexed skeletons were layed down on shell beds (such as at top left) in small, non-intruding burials surrounded by postholes. Some burials were covered with stones.

Pathological processes, such as meningitis, can be confounded with this bone loss. However, a detailed examination of the cranium revealed that the damage was possibly caused by insects (Figure 2).

The ulna of a mid-adult female found in a hyperflexed position, depicted on Figure 3 is a good example for the action of rodents, showing shallow and short parallel grooves. The presence of superficial fungi was also observed. One example is a long bone fragment of a young adult of undetermined sex, with clear black spots of fungi with no associated macroscopic alteration (Figure 4).

Evidences of Cultural Formation Processes

After initial field campaigns focussed on the stratigraphic analysis of the profiles, Locus 2 was chosen for horizontal decoupage aimed at investigating funerary rituals. Locus 2 is a stratigraphically well defined funerary area, with dark organic sediment and shells, presenting faunal remains, numerous burials with extremely flexed individuals of all age categories and both sexes lay down on whole shell beds and covered with shells and hearths containing fish as offering and feast remains, and surrounded by many postholes (Figure 5). All 12 burials from Locus 2 are neatly delimited from each other through vestiges of wooden posts surrounding the graves. These posts probably helped to avoid the intrusion of new burials in old ones and to prevent scavengers to reach the deceased (indeed gnawing marks are very rare in the Jabuticabeira II bones). Additionally, small shellmounds covered each of the individual burials, and groups of burials too. Two human bones, one from a burial located at the basis and another one from a burial at the top of this 25cm thick funerary layer were dated to 2,340 ± 50 and 2,320 ± 50 BP respectively (Beta 188381 and Beta 188382 - De Blasis et al., 2004). The concomitance of these dates suggested that the individuals buried in this area were linked to each other by some kind of affinity, be it biological or cultural or both. However, dental and cranial non-metric data, as well as osteoarthrosis frequencies and patterns revealed no significant differences between the individuals exhumed from Locus 2 in comparison to those exhumed from other areas of this same site (Filippini 2004; Petronilho, 2005; Bartolomucci, 2006).

Figure 6. Possible defleshment marks left on the pelvis of a young individual.

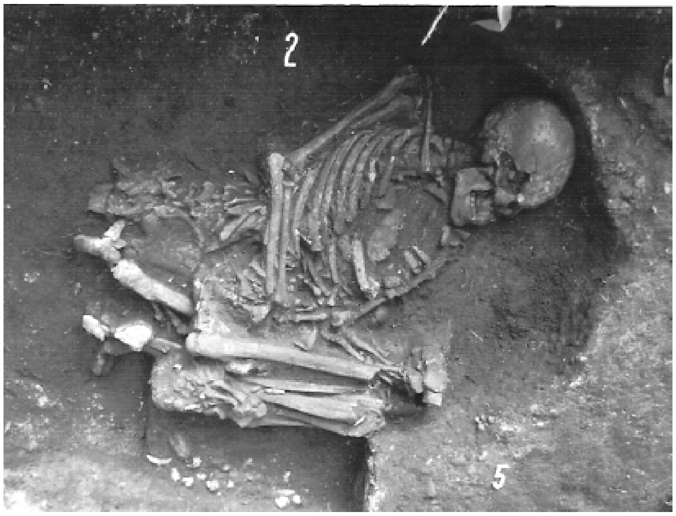

Figure 7. General aspect of Burial 26B. The very acute angles of the lower limbs suggest a period between death and burial long enough for the soft tissue to deteriorate.

Curiously, preliminary data on stable isotopes reveal that the individuals from Locus 2 had a diet richer in proteins than those excavated elsewhere at Jabuticabeira II (Richards et al., 2007).

The majority of Locus 2 burials in Jabuticabeira II contained complete or nearly complete skeletons. Most of these bones are not bleached, not friable, and exhibit no longitudinal cracking and as such do not suggest that they were exposed for the elements for a very long time (Nelson et al., 1992). However, the presence of very acute angles on lower limbs, probably made with the help of ropes, strings or bundles in some burials especially at Locus 2 indicates that some of the corpses were exposed until decomposition of most soft tissue in a place different than that chosen for final burial. Another possibility would be the intentional defleshment carried out by members of the group (as discussed in Fish et al., 2000), leaving cut or scraping marks (Marshall, 1989; Nelson et al., 1992), similar to those seen in Figure 6. However, among the 89 individuals analyzed, this is the only one with evidences of such type, rendering defleshment, if any, a rare ritual among the people buried in Jabuticabeira II. On the other hand, as seen in Figure 7, very acute angles of the lower limbs probably could not be obtained while the soft tissues were still on the corpse. These so called hyperflexed skeletons (and in fact secondary and not primary burials) are frequent in Jabuticabeira II and since defleshing marks are extremely rare or absent, deceased bodies must have been left to deteriorate naturally before secondary interment.

Another evidence of cultural mark left on the bones from the Jabuticabeira II shellmound, are small starshaped antropogenic marks, possibly of anthropogenic origin, such as that seen in Figure 8. Since these marks are tiny and localized, and since no hard implement was found associated to them, a natural cause for their occurrence can be excluded. These marks certainly do not resemble rodent marks, and although they are not the typical marks related to defleshment, we hypothesise that they represent marks carved onto the bones during preparation of the deceased for secondary burial.

Secondary burials can lead to absence of small bones, that can be deliberately ignored (when the burial includes just the largest bones) or accidentally lost (Duday, 1978). This process is more common in the secondary burial of juveniles. A case described in detail by Okumura and Eggers (2005) shows a secondary double burial of a six-month old infant and a three-year-old child. In this case, the skeleton of the older child was relatively complete, presenting more than 50% of the bones, while the youngest child presented just a few long bones.

The presence of pigments associated with funerary rituals which stain bones is relatively frequent in shellmound burials. This was also often observed in Jabuticabeira II. Raman spectroscopy studies on a pigment covered forearm revealed that it was pure red haematite (instead of the most often used mixture of pigments known as ochre) applied over a layer of limewash onto the corpse (Edwards et al., 2001), as seen in Figure 9.

DISCUSSION

Natural and cultural formation processes are usually inter-related, because cultural choices in mortuary rituals strongly affect natural formation processes. This influence or alteration can be clearly seen in Brazilian shellmounds, where the accumulation of shells, a cultural practice (Gaspar and De Blasis, 1992; Gaspar, 1998; 2000; Fish et al., 2000), changes the natural tropical acid pH of the soil. In the same way, the mineralization that occurs in some skeletons in these sites can also be linked to the cultural practice of accumulating shells. The limewash applied onto the deceased body (Edwards et al., 2001) is another example of cultural practice that alters the environment where the body is buried.

The importance of recognizing and distinguishing natural formation processes from cultural ones is essential when dealing with skeletal samples, especially in palaeopathological studies. In fact, deformed bones due to sediment pressure can be misdiagnosed as cultural practices, such as artificial deformations performed during growth, or can be confounded with true pathologies (like bended legs in rickets, etc). Also, it is essential to separate pre, peri and post mortem fractures that can be a reliable indicator of accidents and interpersonal violence.

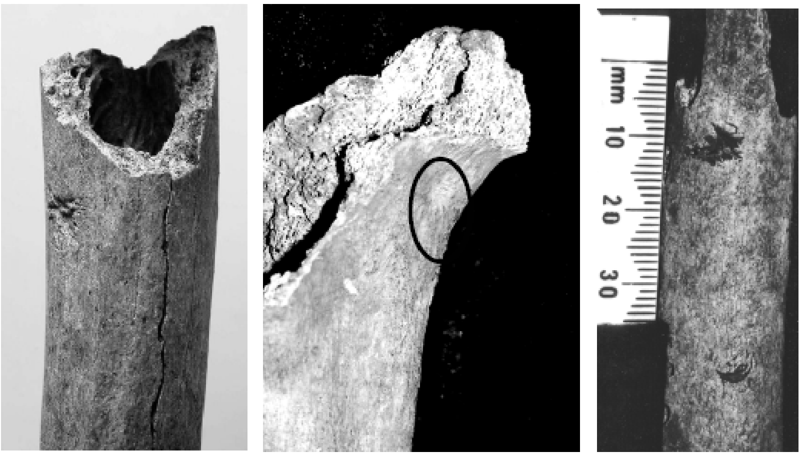

Photo: Wagner Sousa e Silva

Figure 8. Starshaped carved mark found in a few long bones.

Figure 9. Massive layer of red pigment on humerus.

The rarity of trauma, be they accidental or violent in nature, observed in Jabuticabeira II was also reported for other Brazilian shellmounds, indicating rare conflicts between groups, in spite of the proximity of living and dwelling areas inferred through the existence of nearby contemporaneous shellmounds (Mendonça de Souza, 1995; Lessa and Medeiros, 2001; Lessa, 2005; Okumura and Eggers, 2005; De Blasis et al., 2007).

Clearly, the same mortuary context can be representative of different funerary behaviours. For example, tightly flexed individuals can, a priori, be indicative of: a) an extended funerary ritual where the body, already partially decomposed is interred in a secondary burial; b) the deceased may alternatively have been actively defleshed, put in bundles and only then buried; or c) the manipulation of a primary inhumation in the same place, moving long bones to a different position. In these cases, sometimes it is impossible for a bioarchaeologist to distinguish among these possibilities, although some features observed in the burial can indicate which possibility is the more likely one. For example, secondary burials can involve weathering, carnivore gnawing, dismemberment, and/or defleshment. However, to characterize a secondary burial certain features must be excluded, such as perimortem trauma, intentional percussion breakage, or evidences of cooking. On the other hand, while cannibalism may resemble secondary burials, extensive carnivore gnawing could exclude cannibalism.

The high frequency of hyperflexed complete individuals in Locus 2 from Jabuticabeira II suggests secondary burial, where the corpses must have been left to decompose naturally until the lack of soft tissue allowed the individual to be wrapped or tied very tightly and then buried. Obviously, the fact that the lower limbs were found forming acute angles in the grave does not necessarily mean that the decomposing bodies were tied together or wrapped, but this is a possibility that should not be ignored. The absence of friable and cracked bones as well as the rarity of rodent marks suggests that the decomposition took place in a sheltered place and that the definite burial was performed as soon as it was possible to hyperflex the limbs. Also, the absence of systematic cut marks makes it very unlikely that rituals of defleshment or cannibalism were performed.

Although there are no extant Brazilian groups which can be culturally associated with shellmound builders, some ethnographic accounts can be used in order to support or inspire models about the mortuary ritual of these coastal groups. Specifically in the case of Jabuticabeira II, as mentioned above, the burial pattern at Locus 2 is of secondary burials with hyperflexed individuals on top of whom little individual mounds of shell were put shortly after final interment. Besides this, groups of burials were also covered by a bigger mound, contributing to the construction (or increase) of the main mound. The cultural practice related to individual mounds on top of burials was described in ethnographic accounts for Brazilian Kaingang (Lozano, 1873-1874:423), although the mounds where build with sediment, and not with shells. Also, the fact that Locus 2, a quite small area of about 25m^2, presented a considerable amount of burials (about 0.5 per m^2) and none of them where intruding into each other, strongly supports the idea that the posts found around the burials could be used to delimit the burial space. This cultural practice was also reported in ethnographic accounts on contemporaneous Brazilian indigenous groups that presented the same custom. These include again the Kaingang who delimited their cemetery using wooden posts (Baldus, 1979:20), but also the Botocudo who erected a small cabin or shed above the burials (Métraux, 1946; Saint-Hilaire, 1838; Manizer, 1919), the Mbaya who buried their dead in mortuary huts where each family owed a piece of ground demarked by posts (Métraux, 1948), the Kamayura who surrounded the burial place with a low fence (Métraux, 1948), the Guayaki who used to build a miniature hut over the grave (Métraux and Baldus, 1946), and the Tupinamba who sometimes suspended the corpses in hammocks over a pit lined out with posts and covered with branches (Métraux, 1948). This widespread cultural practice documented in ethnographic reports can help to propose and test new models about the funerary practices of ancient shellmound groups.

The picture that emerges taking the abovementioned observations into account is that the funerary practices in Jabuticabeira II probably lasted for several weeks (until the soft tissue on the deceased body decomposed). In case the deceased was put to naturally decompose in a closed charnel with no access of scavengers and rodents, the shellbed, the lime, as well as the offerings (such as mortars and shell bead strings) had to be prepared. The wood for the posts that later surrounded each burial had to be selected, transported and prepared. The pure hematite had to be collected and the fish for the offering needed to be caught. Finally, when all these arrangements were ready, the group of people who participated in the preparation of the secondary burial gathered nearby the burial and participated, perhaps in the presence of other people of the community, at an interment ritual. At this occasion the remaining bones (with some of the strongest ligaments still intact) were transported to the final burial place, where they were bundled or hung up between the posts on top of the shell bed, and surrounded by funerary offerings. At a certain point the bones must have been laid down and covered with some heaps of shell. On top of this little shellmound a ceremonial fire, using already dead wood (Scheel-Ybert et al., 2003) was lit. Judging from the burned fishbone, however, this fire also was used to prepare a meal. Only after this complex funerary ritual the mourning people were released to reassume their normal life (if the ethnographic accounts on secondary burial can be applied to this archaeological context).

This picture, although compelling, needs to be confirmed through various new analyses. This will be the subject of a future work, since the dilemma of the bioarchaeologist is how to consider all the evidence together to reconstruct behaviour and formation processes. Only very careful examination can result in the identification of those processes. And this should be carried out in collaboration with specialists from other areas, gathering data on osteology, archaeological context, anthracology, geology, demographic composition, taphonomy, associated artefacts and ethnohistoric accounts (Hurbult, 2000).

CONCLUSION

The understanding of natural and cultural formation processes and the discrimination between them are essential for any kind of morphological, palaeopathological, dietary or demographic analysis performed on human skeletal remains. This demands a more intense participation of bioarchaeologists in the recovering and recording of human skeletal remains and their respective burial settings. In this chapter, we limited our discussion to the natural and cultural processes related to the funerary ritual of the Jabuticabeira II cemetery shellmound. In this case the construction of the shellmound itself is intimately associated with the funerary rituals, since consecutive layers of little individual shellmounds on top of burials contributed in an important way to the make up of the entire mound. However, each funerary context must be analyzed in its own particularity; therefore, distinct funerary contexts probably must take into account the understanding of other natural and cultural processes that were not mentioned here.

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Chapter 2

THE ARCHAEOLOGY OF HUMAN-ENVIRONMENT INTERACTIONS: HISTORY AND CURRENT TRENDS

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ABSTRACT

The last 25 years have seen the development of a thriving literature on the archaeology of human-environment interactions. A review of the literature shows three distinct histories of work on human-environment interactions: "environmental archaeology" as represented by the Association for Environmental Archaeology; human paleoecology, which looks at human impacts on the environment from an anthropological viewpoint; and environmental studies, which uses archaeological data within the conservation biology literature. These bodies of work have explored different data sets, used different methods, and, by and large, come to very different conclusions about the nature of human-environment interactions both past and present. Despite the fact that their conclusions are often highly relevant to each other, there is very little cross-fertilization of theoretical or methodological approaches. This chapter critically reviews these bodies of work, assesses the current state of research, and discusses emerging trends in the archaeology of human-environment interactions.

INTRODUCTION

> … [G]iven the impact of Quaternary climate changes on plant and animal communities, on sea level, on rivers, on lakes, and on all other components of the environment, human prehistory must be inextricably linked to Quaternary environmental changes, although the degree and *nature* of the linkages are hotly debated….Coping with or even (more recently) distancing ourselves from Quaternary environments and environmental changes is arguably a key aspect of human prehistory and evolution. Archaeology is thus one of the Quaternary

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> sciences and, therefore, understanding the record of the Quaternary and some basic principles of the Quaternary geosciences is an important part of archaeology…. (Holliday 2001: 3-4)

> Thus, as ecologists initiate new research projects and address environmental concerns, as conservationists turn to protect or restore species, as the larger population tries to understand the wildlife in its backyards, let us not forget to look back to understand the forces and changes that shape the ecosystems we seek to understand…. [P]ast processes in the landscape condition the present and loom as legacies in modern and future landscapes. For us to succeed in our science, our environmental interpretations and predictions, and our management objectives we must heed the past. (Foster 2000: 29)

Statements such as these two, asserting the importance of both environmental studies in archaeology and archaeology in environmental studies, have become increasingly common in the literature over the past twenty-five years. Archaeologists often pin the development of recent interest in human-environment interactions to the emergence of an environmental movement in the 1970s (Fieller, Gilbertson et al. 1985; Trigger 1989; Evans and O'Connor 1999; Dincauze 2000; McIntosh, Tainter et al. 2000); ecologists who are interested in the effects of prehistoric human impact on present environments generally claim an even more recent genesis (Meffe and Carroll 1997; Peterson, Allen et al. 1998; Foster 2000; Holland 2000; i.e., Burgi and Russell 2001). When one examines the literature closely, however, it quickly becomes evident that prehistoric human-environment interactions have been a topic of scholarly attention for over a century, both in the ecological community (Thoreau 1860; Nash 1967; Runte 1987) and among archaeologists (Grayson 1984; Trigger 1989; Willey and Sabloff 1993).

The ways in which changing environments affected humans, and the ways in which humans changed their environments, have been of interest to archaeologists since the origins of the discipline. In 18th and 19th century Europe, archaeology was considered a part of geology and the "natural sciences" (Willey and Sabloff 1993; Stein 2000). John Lubbock (1865) created his periods of European prehistory by stratigraphically correlating archaeological remains and the extinct fauna of the Pleistocene. For some time, the environmental changes that accompanied the end of the Pleistocene were thought to be so traumatic for foragers living in Europe at the Pleistocene-Holocene transition that they suffered a huge population crash (Childe 1925; Daniel 1950; Clark 1980), a clear case of environmental cause-and-effect. The development of human ability to transform environments, specifically in regards to agriculture—considered a hallmark of "civilization"—was a hot topic in the early 20th century, as it is now (Childe 1925; Trigger 1989). Researchers who today advocate integration of archaeological/historical studies and conservation biology (Denevan 1992; Kay 1994; Lyman 1996; Kay 1998; Foster 2000; Butler 2001; Grayson 2001; Pitcher 2001; Yochim 2001; Redman 2005; Costanza, Graumlich et al. 2007) might be surprised to learn that as early as the 19th century, scientists argued that archaeology and a diachronic approach had the potential to contribute to wildlife management and biological studies (Wintemberg 1919).

Although many of the issues that were of interest to earlier archaeologists remain the subject of debates today, some scholars assert that the ways in which these questions are framed and understood have changed.

Table 1. Some definitions of goals from authors using different approaches to the study of prehistoric human-environment interactions

"Environmental archaeology is a wide and multi-disciplinary science which seeks to understand past ecology -- with emphasis on man's role -- and past human economy and living conditions. Its sources of evidence are diverse but the main stream of the subject is founded upon analysis of the remains of plants and animals and the sediments in which they are buried."
-Kenward et. al 1984, cited on the AEA Web site (http://www.envarch.net/)

"… [T]he primary goal of environmental archaeology should be to define the characteristics and processes of the biophysical environment that provide a matrix for and interact with socioeconomic systems…."
(Butzer 1982)

"[Environmental archaeology] arose from widespread concern with environmental issues…and from consequent rapid development of techniques to delineate, describe, and explain past and present ecological systems…."
(Reitz, Newsom et al. 1996)

"[Environmental archaeology] is an area of archaeology that lies very firmly within the realms of the natural sciences, more specifically biological and earth sciences….The term 'environmental archaeology' is seen by many as a convenience to collectively describe a group of archaeological studies carried out using biological and geological materials…."
(Wilkinson and Stevens 2003)

"The study of how human groups survived in particular environments: the examination of why these survival methods changed through time."
(review in O'Connor 2001)

"Study of past environments, with particular emphasis on man's impact on the landscape."
(review in O'Connor 2001)

"Historical ecology or landscape history is study of past ecosystems by charting the change in landscapes over time. Thus, evidence for the historical interrelatedness of humans and environments may be read in the landscape....changing human attitudes may also be identified and their effects studied."
(Crumley 1994)

"Environmental archaeology is the study of past human environments, traditionally from archaeological investigations, sections, and boreholes but increasingly from written sources, and the relationship between humans and those environments."
(Evans 2003)

"… [T]o seek a better understanding of the interaction between society and the environment, to use that knowledge to preserve, nurture, and perhaps even improve on what we value in the environment, and, further, to ensure that our future actions are consistent with these goals. These interactions can best be understood from a perspective that takes those long-term dynamics into account…"
(Redman 2005)

The development of conservation biology as a discipline in and of its own right (Meffe and Carroll 1997), the growth of environmentally-related, methodically-defined subdisciplines such as zooarchaeology, paleoethnobotany, and geoarchaeology (Dincauze 2000), and a growing interest in human impacts on surrounding environments (Grayson 2001) have contributed to the development of what some archaeologists call "human paleoecology"; but was this really a revolutionary event that caused a radical break from previous approaches? Such a question is difficult to assess, because the history of archaeological inquiry into prehistoric human-environment interactions is marked by such a wide variety of approaches. In this chapter, I explore this history to address the above question, and consider the future for an archaeology of human-environment interactions.

Although there are almost as many approaches to studying prehistoric human-environment interactions as there are researchers (see table 1), interest in this topic can be broken down into three main categories, each of which is increasingly restricted in scope. In Great Britain, archaeologists interested in environment often call themselves "environmental archaeologists," and focus primarily on methodological developments and paleoenvironmental reconstruction; some North Americans have been involved with this school as well. In North America, archaeology concerned with environmental issues has been dominated by the more theory-based "human paleoecologists," who focus on the ways in which human-environment relationships shaped prehistoric cultures, and recently have been particularly interested in issues of "global environmental change" (Driver 2001; Redman, James et al. 2004; Kirch 2005). Finally, there are ecologists and conservation biologists (sometimes archaeologists) who use archaeological data to make arguments within ecology (Martin and Szuter 1999; Lyman 2006; Etnier 2007; Frazier 2007). In recent years, the last two categories have become far less distinct, with many researchers publishing the same results for different audiences.

The past 15 years have also been marked by a growth of theory-driven work in human-environment interactions. In particular, two bodies of theory – optimal foraging theory (Stephens and Krebs 1986) and resilience theory (Holling 1973; Gunderson and Holling 2002) – are frequently employed in the current literature. Both bodies of theory are "borrowed" from ecology, and archaeologists using them frequently publish in both the archaeological and ecological literature.

"NATURAL SCIENCE" AND ARCHAEOLOGY

Archaeology had its beginnings as one aspect of what was then termed "natural science" or "earth science." In the 18th century, natural scientists began using geological stratigraphy, paleontology, and archaeology to answer questions about the antiquity of the earth (Grayson 1983; Trigger 1989; Willey and Sabloff 1993; Stein 2000). As Stein (2000) explains:

> Associations among extinct fauna, primitive artifacts, and stratigraphically superimposed layers were sought, but these eighteenth century scholars were generalists, not specialists. The disciplines that were much later to become separate and distinct entities shared, at this moment, the same history. Archaeology, stratigraphy, paleontology, and geology began simultaneously as earth science. (18)

In the beginning, the focus was on stratigraphic correlation; with no “absolute” dating methods, the establishment of the antiquity of humans relied heavily on the ability of these “natural scientists” to establish the contemporeneity of extinct mammals (paleontology), glacial landscapes (palynology, geology), and prehistoric humans (archaeology). Researchers were primarily interested in establishing a chronology, but also participated in what today we might call paleoenvironmental reconstruction—trying to understand what past landscapes looked like. Their approach was what today might be labeled both interdisciplinary (involving personnel from and methods of a variety of academic disciplines) and problem-oriented (focused on a particular research question, in this case, the antiquity of humans) environmental research.

By the mid-19th century, the antiquity of humans was widely accepted in the scientific community (Lyell 1863). With the publication of *On the Origin of Species* (Darwin 1859) and contemporaneous interest in cultural evolution, questions of human antiquity turned in a new direction: demonstrating the “progress” of the human species through time, and developing unilinear evolutionary schemes of human development. Questions of environment here took on an entirely new character, as the degree to which societies “controlled” their environment was one of the hallmarks of “civilization” (see Lubbock 1865; Tylor 1865; Morgan 1877).

> The important fact that mankind commenced at the bottom of the scale and worked up, is revealed in an expressive manner by their successive arts of subsistence. Upon their skill in this direction, the whole question of human supremacy on the earth depended. Mankind are the only beings who may be said to have gained an absolute control over the production of food; which at the outset they did not posses above other animals….It is accordingly probably that the great epochs of human progress have been identified, more or less directly, with the enlargement of the sources of subsistence. (Morgan 1877: 19)

Again, this research was thoroughly interdisciplinary, with archaeological, paleontological, geological, and ethnographic data all being used together to make arguments about the degree to which various cultures had “progressed.”

19th century evolutionary anthropologists, however, had a significant problem: clearly, not all peoples in the world had progressed to the same level. As an explanatory mechanism, some of these theorists adopted a perspective of environmental determinism (i.e., Semple 1903; Semple 1911; Huntington 1914; Huntington 1915; Semple 1931). Huntington suggested that climate determined why some cultures raced along evolutionary trajectories while others slowed down; warmer climates slowed progress while colder ones advanced it (Huntington 1915). Semple’s formulation of environmental determinism was rather more complex, taking into account a variety of environmental variables in addition to climate, and postulating a variety of potential results from environment (Semple 1903). In many ways, Semple’s heavily interdisciplinary research—technically a geographer, she drew from history, archaeology, anthropology, geology, and biology, among others—foreshadows Jared Diamond’s (1997; 2005) work on environment and human history.

Both unilinear evolution and environmental determinism produced a fierce backlash, and were justly criticized for being overly simplistic; the backlash was particularly violent in the United States, where the Boasian approach dominated. The Boasians argued strongly that history, not environment, explains cultural differences. Thus archaeologists in the early 20th century tended to be in one of two camps: either they were adherents of environmental determinism, or they avoided environment altogether. Julian Steward described these latter: "Environment is relegated to a purely secondary and passive role. It is considered prohibitive or permissive, but not creative" (1955: 35).

While environment continued to be presented as a (more or less important) factor in determining culture, the integrated approach to archaeology, paleontology, and geology disappeared at the beginning of the 20th century. Specialization in individual topics became more common, and many of the interdisciplinary roots of inquiry into human antiquity were forgotten. Archaeology became a discipline in its own right, rather than a part of "earth science" (Trigger 1989; Stein 2000; Holliday 2001). In addition (in part following divisions within cultural anthropology), environmental research in archaeology acquired distinct continental differences at this time (Trigger 1989; Watson 1997; Pearsall 2000). In Europe, methodology and reconstructions of past environments became the foci of research. In North America, archaeologists were more theoretically oriented, attempting to understand the causes and meanings of human adaptations to particular environments. Ecologists, meanwhile, focused on human-caused environmental changes.

ENVIRONMENTAL ARCHAEOLOGY

As noted above, in Europe the study of prehistoric human-environment interactions focused on paleoenvironmental reconstruction and on methodology. This stemmed in part from the "gap" or "hiatus" debate mentioned earlier and Grahame Clark's reaction to it (Mithen 1999; see essay 2 for detailed discussion of this issue). The apparent disjunction between the Paleolithic and Neolithic led some researchers to conclude that the end of the glacial period caused Paleolithic hunters to die. As the large herds of animals died out, the theory went, so did the people who hunted them; Europe was then repopulated by peoples from the Near East who brought domesticated plants and animals with them (see review in Daniel 1950). As more research was conducted, and assemblages intermediate in age between the Paleolithic and Neolithic emerged, this position became less and less tenable. As evidence against a "gap" mounted, the theory was reworked with continued emphasis on the way changing environmental conditions affected remnant Paleolithic hunters (Childe 1925). Mesolithic peoples were seen as scarce, as having returned to a barbaric state after the shock of changing environment.

Although curiously absent from many of the timelines put forth in "environmental archaeology" texts (Evans and O'Connor 1999; O'Connor 2001; Evans 2003; Wilkinson and Stevens 2003, but see Dincauze 2000 and Mithen 1999), Grahame Clark's (1932; 1936; 1939) reactions to Childe and subsequent excavations at Star Carr (1954; 1972) had a huge effect on the development of interdisciplinary paleoenvironmental work, particularly in Great Britain. Clark argued against the hypothesis that there was no substantial Mesolithic occupation of Europe (1980). At Star Carr, he assembled a team of archaeologists, faunal analysts, palynologists, and geologists to reconstruct the interaction between the Mesolithic occupants of the site and their surrounding environment.

> It soon became evident that the most promising way of gaining an adequate picture of the achievements of the inhabitants of Europe between the end of the Ice Age and the adoption of

> a Neolithic way of life was to adopt an ecological approach and deploy the full armoury of Quaternary research. (Clark 1980: 38)

This multidisciplinary approach set a standard to which environmentally-inclined archaeologists still aspire today (Mithen 1999; Dincauze 2000).

Clark's excavations at Star Carr established a new protocol: no longer were archaeologists generalists, rather archaeological projects employed a team of specialists to focus on different aspects of the archaeological record. One could argue that it was from Clark's excavations that the archaeological subdisciplines of zooarchaeology, archaeobotany or paleoethnobotany, and geoarchaeology graduated into subdisciplinary specialties of their own.

> Since the 1950s it has been a fundamental tenet of Mesolithic studies that human behaviour cannot be understood without knowledge of the environment within which it takes place….[I]t was Clark that pioneered the development of a multidisciplinary approach to the past. The establishment of the Fenland Research Committee in Cambridge during the 1930s brought together Clark and a range of specialists from disciplines including botany, geology, geomorphology and historical geography. The multidisciplinary spirit of this group became institutionalized in Cambridge in 1948 by the founding of the Sub-department of Quaternary Research which then played a central role in the first major excavation of a Mesolithic site in Britain—Star Carr, Yorkshire. And it is the long history of research related to Star Carr that is perhaps the most effective demonstration of both the need and ability for 'cultural' and 'environmental' approaches to be thoroughly integrated. (Mithen 1999: 477)

The environmental archaeology subdisciplines were born at Star Carr. Although few sites since have been excavated with massive multidisciplinary teams such as the one Clark assembled (Dincauze 2000), an interest in reconstructing both paleoenvironments and considering how humans used those environments has been a driving force behind research in geoarchaeology, paleoethnobotany, and zooarchaeology.

Early work in these three environmental subfields was largely divergent in the years immediately following the excavations at Star Carr; boundaries within the subdisciplines were being sorted out. Most work focused on paleoenvironmental reconstruction, or on methodological developments (Shackley 1981). Site formation processes and taphonomy became major interests (Butzer 1982). In the 1970s, the environmental movement outside archaeology fostered rapid development of the environmental subdisciplines within archaeology; what Shackley (1981) terms "the limp environmental appendix model" became widespread. While Star Carr inspired many to include environmental data in site reports, this was generally done by tacking reports by a number of specialists on to the end of the monograph, and never addressing the data in the actual reporting of the site.

By the late 1970s and early 1980s, this compartmentalization was widely recognized as a problem, and calls for integration became widespread (i.e., Shackley 1981; Butzer 1982). As a response to the calls for integration, archaeoenvironmental specialists in Great Britain joined forces to establish a subdiscipline called "environmental archaeology," and as part of this effort, founded an organization called the Association for Environmental Archaeology in 1979 (see http://www.envarch.net for a detailed history). The membership was made up of archaeologists working in the various environmental subfields, and their communications focused on methodological concerns and on descriptive work, rather than on theory; this is not surprising as the available theory at the time was overly complex and thus not very helpful. Today the "environmental archaeology" subdiscipline and the Association for Environmental Archaeology (AEA) continue work in this vein. The AEA publishes a journal called *Environmental Archaeology,* and has put forth a series of books and reports attempting to define the subfield. A perusal of their journal establishes why; there is little to bind these archaeologists together other than the fact that they use methods drawn from "environmental sciences" (i.e., zoology, biology, geology) to understand "human-environment interactions."

The "environmental archaeologists" of today are thus a loosely grouped set of zooarchaeologists, archaeobotanists, and geoarchaeologists who initially defined their subdiscipline as a set of methodological techniques for studying the past (Evans 1978; Shackley 1981). Many members have apparently become dissatisfied by this methodological approach, and have endorsed a theoretical approach, focused on "human-environment interactions" (Luff and Rowley-Conwy 1994; Reitz, Newsom et al. 1996; Evans and O'Connor 1999; Reitz and Wing 1999; Dincauze 2000; Albarella 2001; O'Connor 2001). Others suggest the solution can be found in the incorporation of social theory (Evans 2003; Wilkinson and Stevens 2003). Most work, however, still seems to be method-based and only loosely tied together (Reitz, Newsom et al. 1996; Albarella 2001; O'Connor 2001). As a one paper suggests, "…[E]nvironmental archaeology suffers from too many identities, and a lack of consensus about which face to present to the world" (O'Connor 2001: 19).

JULIAN STEWARD AND HUMAN PALEOECOLOGY

If British "environmental archaeology" began with Star Carr, one could argue that "human paleoecology" in North America, the other trajectory taken by archaeologists interested in human-environment interactions, derives from the work of cultural ecologist Julian Steward. Steward, better known as an ethnologist than as an archaeologist (but see, for example, Steward 1937; Steward 1937), nevertheless had an important effect on the development of the study of environment in prehistory, particularly in the United States. He developed a school of anthropological inquiry that he called "cultural ecology," which focused on understanding the ways that cultures adapt to environmental differences (Steward 1955). He and Seltzer (1938) argued that archaeology should play a large role in the ecological analysis of human behavior, but that new data (rather than the previous focus on typology) would be necessary for them to do so: data on subsistence, population, and settlement.

> Any culture must, of course, rest upon a basic economy which is adapted to its environment. This adaptation is human ecology. To varying degrees, it produces a configuration that interrelates a large number of elements; e.g., food getting, storing, grinding, and cooking. A description of it would, so far as data permit, make explicit the relative importance and kind of horticulture, fishing, or hunting and gathering; the relation of these traits to soils, altitudes, rainfall, flora, and fauna, that is, to the natural landscape. It would ascertain whether particular types of economy did or did not correlate with certain environments, and whether unlike economies occurred in the same environment. It would also make explicit the kind of villages, evidence of clustering or lack of clustering of houses,

> number and distribution of villages in an area, and inferences about population density and stability. (Steward and Setzler 1938: 7-8)

Steward was responding to the typical archaeological report of the day, which focused on describing typologies and stylistic variation rather than on explaining human behavior. In apparent frustration with this, Steward and Setzler wrote “One wonders whether the frequent limitation of interest to measurements and tabulation of data and refinements of techniques is an unwillingness to grapple with the problems of objectives” (1938: 6). Their efforts, however, resulted in productive new fields of archaeological inquiry: encouraged by Steward, archaeological research on the origins of agriculture, settlement patterns, and the meaning of changing patterns of subsistence advanced dramatically.

Steward (along with the contemporaneous work by Clark at Star Carr) encouraged and inspired large multidisciplinary archaeological projects attacking theoretically-based problems of human adaptation. The most famous are Willey’s Virú Valley project (1974), Braidwood’s expedition to Iraq (1974), and MacNeish’s work in Mexico (1974). All these projects were concerned not just with describing paleoenvironments, but with understanding how humans adapted to the paleoenvironments in which they lived.

This ecological focus continued in North American archaeology; by the time of Binford and the start of the “New Archaeology,” however, the archaeology of human-environment interactions in the New World was suffering from a lack of attention to methodological problems; an interest in pursuing the “big questions” had left methods obsolete. The study of what Trigger calls “middle range theory” during this time—of site formation processes and taphonomy—began to help the methods catch up with the more well-developed theory that had evolved in response to Steward’s work (Trigger 1989). A focus on quantitative methods, the development of the flotation technique for paleoethnobotany (Streuver 1968; Pearsall 2000), taphonomy (i.e., Thomas 1971), and a growing emphasis on geoarchaeology stemmed from a recognition that understanding how a site was formed was imperative if one wanted to extract behavioral information from that site (Binford and Binford 1968; Watson, LeBlanc et al. 1971; Schiffer 1975).

In the early 1970s the study of the environment within archaeology underwent several shifts. One was related to the development of the environmental movement, which stressed the ways in which humans could negatively affect their environments; a specific aspect of this was the assertion that human population could grow out of control and have significant results on surrounding environments (Boserup 1965; Ehrlich 1968). Another was the search for public relevance for archaeology, which caused some to make the argument that understanding past human impacts was important for the present (Fritz 1973; Martin and Plog 1973; for example, Dymond 1974). All this, plus a reaction against some of the more simplistic schemes in which environment was seen as causal, led to the development of systems theory.

Systems theory was borrowed from biology’s “general systems theory” (Bertalanffy 1968). Early systems-theory archaeologists conceived of human culture as a system, the behavior of which could be modeled by mapping feedback between the various parts. Led by Flannery (1968), archaeologists used computer programs to model the potential variables (often environmental) that led to archaeological change. The results of all this work were primarily complex flow charts, which were both hard to read and descriptive rather than explanatory. The complexity of variables involved made it virtually impossible to draw any concrete conclusions about how change came about. By the 1980s, it was largely abandoned as an approach to archaeology (Trigger 1989).

In the last decade, however, systems theory in archaeology has been reborn in the form of resilience theory (Gunderson and Holling 2002; Redman 2005). Resilience theory centers on a figure-eight diagram of a four-stage "adaptive cycle"; the four stages, through which socio-environmental systems are said to pass, are exploitation, conservation, release and reorganization (Holling and Gunderson 2002). Resilience theory thus simplifies the earlier flow charts, makes a systems approach easier to operationalize, and, proponents point out, "emphasizes the inevitability of both stability and transformation" (Redman 2005: 72). Resilience theory is relatively new on the scene in archaeology; thus far, researchers using this paradigm have produced work which seems more descriptive than explanatory (i.e., Redman and Kinzig 2003; Delcourt and Delcourt 2004; Nelson, Hegmon et al. 2006; Peeples, Barton et al. 2006). Time will tell if resilience theory is here to stay in archaeology, or if it is a passing fad.

By contrast, the research tradition of human behavioral ecology—which also made its debut in the 1970s, and borrowed from a biological theoretical tradition—has gained archaeological adherents slowly and steadily since it was first introduced (Winterhalder and Smith 2000). Human behavioral ecology uses models, originally developed to analyze the behavior of non-human animals, to study human behavioral diversity (Smith 1983; Kaplan and Hill 1992; Winterhalder and Smith 2000). These models have been successfully adapted to address issues of prey choice, dietary shifts, and responses to exogenous environmental change, among other topics (O'Connell, Hawkes et al. 1988; Layton, Foley et al. 1991; Smith 1991; Hawkes and O'Connell 1992; Winterhalder and Goland 1993; Bliege Bird, Bird et al. 1995; Kelly 1995; Bird and Bliege Bird 1997; Winterhalder and Lu 1997; Bird and O'Connell 2006; Lupo 2007).

From the earliest days of this research agenda, some archaeologists have worked to adapt models designed for ethnographic time to archaeological time, with increasing success (see discussions in Grayson and Delpech 1998; Grayson and Cannon 1999; Winterhalder and Smith 2000). Archaeological work on human behavioral ecological topics has grown steadily since the 1970s (Winterhalder and Smith 2000). This approach has brought robust theory and an ecological approach to a wide variety of classic archaeological questions: for example, residential mobility and settlement patterns (Kelly 1995; Zeanah 2000; Waters 2006), transport costs (O'Connell, Hawkes et al. 1988; Metcalf and Barlow 1992), resource intensification (for instance, Bettinger 1991; Broughton 1997; Broughton 1999; Grayson and Cannon 1999; Grayson, Delpech et al. 2001; Nagaoka 2002; Butler and Campbell 2004; James 2004; Nagaoka 2006), domestication and agriculture (Cannon 2000; Kohler 2004), trade and resource sharing (Rautman 1996; O'Connell, Hawkes et al. 1999), and "showing off" and the sexual division of labor (Broughton and Bayham 2003; Hildebrandt and McGuire 2003). In recent years, human behavioral ecology has provided a perspective from which archaeologists have been able to explore prehistoric conservation, impacts on the environment, and landscape management.

PLEISTOCENE EXTINCTIONS, ENVIRONMENTAL STUDIES, AND DIACHRONIC RESEARCH

Of the three main approaches to prehistoric human-environment interactions, the environmental studies approach is often considered the most recent; authors tend to cite an origin in the late 1980s for this line of research (Denevan 1992; Kay 1994; Lyman 1996; Kirch 1997; Kay 1998; i.e., Burgi and Russell 2001). Although this is true in many ways, there is at least one major exception: the "Pleistocene overkill" hypothesis dates to the nineteenth century (see discussion in Grayson 1984). Even prior to the widespread acceptance of human antiquity, researchers suggested that human hunting could be responsible for the extinctions of the suite of mammals that died out at the end of the Pleistocene; once the scientific community was largely in accord that humans and the Pleistocene fauna had co-existed, this suggestion was widely accepted. Grayson writes:

> … [T]he overkill hypothesis gained adherents because other hypotheses seemed inadequate. At the same time, a human role in the extinctions helped lessen the impact of the new realization that people had coexisted with Pleistocene mammals: extinction due to human activities was very clearly a part of the modern world….Those who remained convinced that the vicissitudes of the earth's surface had been of sufficient magnitude to account for the extinctions continued to reject the overkill hypothesis. (1984: 34)

The current argument about whether climate change is enough to account for the rash of extinctions that occurred at the end of the Pleistocene thus has a long history.

However, more data—both about climate change and about human impacts on animal populations—was available when Paul Martin put forth his argument that a wave of Paleoindian hunters was responsible for the extinction of 35 genera of mammals at the end of the North American Pleistocene (Martin 1958; Martin 1967), and thus his argument was more complete. Martin's work inspired a huge response, both in the archaeological and the biological community; the debate over whether humans caused Pleistocene extinctions in North America (and in other places too, for instance Siberia) continues to rage. Interestingly enough, this debate, from its beginnings, involved both archaeologists and environmental scientists. Archaeologists often support climate change as an explanatory mechanism; environmental scientists seem far more likely to support the overkill hypothesis or a mixed explanation.

I will not review the argument over Pleistocene extinctions here (see Grayson 1984; Martin and Klein 1984; Beck 1996; Grayson 2001; Surovell, Waguespack et al. 2005; Grayson 2007); however, this debate has been of great importance in the development of archaeology as a part of conservation biology. This was one of the first arguments since the development of ecology as a field of research that involved archaeological data in a discussion of significance to environmental science; it brings up all the questions central to debate in this field today: under what conditions can humans cause extinctions? Can hunter-gatherers cause extinctions through hunting, or are the current wave of extinctions the result of massively increased population, improved technology, what some might call the "growth of the human footprint"? Not only does the Pleistocene overkill argument involve archaeological data, it has involved a wide number of archaeologists, many of whom have broadened their outlook to consider the historic and prehistoric aspects of conservation biology-based questions from around the world.

Conservation biology-oriented archaeologists have considered questions about human impacts on the environment in a variety of different ways. One of the most important developments in this subfield has been the incorporation of human behavioral ecology (see discussion in the previous section), specifically optimal foraging theory, into investigations of impacts of prehistoric peoples on their environments. Optimal foraging theory has provided both a theoretical framework and testable hypotheses about how humans might impact environments (Grayson and Cannon 1999). Many archaeologists have demonstrated that resource depression, or a situation in which the activities of a predator result in reduced capture rates of prey by that predator (Charnov, Orians et al. 1976), is omnipresent in the archaeological record (e.g., Broughton 1997; Janetski 1997; Cannon 2000; Stiner, Munro et al. 2000; Butler 2001; Nagaoka 2001; Stiner 2001; Butler and Campbell 2004).

Although much of the conservation-oriented literature has involved studies of resource depression, other human effects on environment have been studied as well: animal translocation, for one, has been demonstrated to have had a large effect on prehistoric biotas. The extinctions debates (now numerous, applying to various locales) continue on, with differential success in island (Simmons 1992; Steadman 1995; Simmons 1999; Burney, James et al. 2001; Kirch 2005; Fitzpatrick and Keegan 2007) and continental settings (Grayson 1989; Grayson 1991; McDonald and Brown 1992; Beck 1996; Stahl 1996; Surovell, Waguespack et al. 2005; Firestone, West et al. 2007). Finally, resilience theory seems to be especially prominent in the conservation literature on archaeology (e.g., Redman and Kinzig 2003; Folke 2006; Peeples, Barton et al. 2006; Costanza, Graumlich et al. 2007); this is perhaps not surprising, given resilience theory’s origins in ecology.

Yet another avenue of research on prehistoric impacts concerns landscape transformation, generally through burning, erosion, and/or agriculture-mediated vegetation change (Piperno, Bush et al. 1990; Balee 1993; Aronsson 1994; Amorosi, Buckland et al. 1997; Hörnber, Östlund et al. 1999; Niklasson and Granström 2000; Frazier 2007). Interestingly enough, this area of study has inspired far more work among ethnobotanically-inclined cultural anthropologists (Anderson 1991; Blackburn and Anderson 1993; Peacock and Turner 2000) than among archaeologists, and the language used to describe the impacts is also startlingly different: what is referred to as “landscape management” in the anthropological literature is called “landscape degradation” by some archaeologists.

The archaeological focus on the various ways in which prehistoric humans have impacted their environments has produced literature far too extensive to cite here (Lyman 1996; Kirch 1997; Grayson 2001; Kirch 2005; but see Costanza, Graumlich et al. 2007). One interesting aspect of the literature of archaeology of human impacts that they cite is that, although many archaeologists (Wintemberg 1919; Fritz 1973; Martin and Plog 1973; Lyman 1996; Grayson and Cannon 1999; Martin and Szuter 1999; Pitcher 2001; Redman 2005) have argued that diachronic studies are a necessary component of understanding how current environments should be managed to preserve biological diversity in the face of “global environmental change,” only relatively recently have articles on the importance of a diachronic effect begun to be published in the ecology literature (Peterson, Allen et al. 1998; Foster 2000; Holland 2000; Burgi and Russell 2001; Kirch 2005; Lyman 2006; Costanza, Graumlich et al. 2007; Emery 2007; Etnier 2007; Frazier 2007). Perhaps, as both Kirch (1997) and Grayson (2001) suggest, this indicates that the conservation community is changing.

DISCUSSION

This chapter argues that in many ways the questions about human-environment interactions in prehistory currently prominent in archaeology are not new, but rephrase older concerns in a new light. From its origins, archaeology has been concerned with how humans interact with the environment, although the ways in which archaeology has approached environmental issues have varied significantly through time. Archaeological-environmental research has ranged from broad questions about human reactions to environment, to more archaeologically-focused investigations of paleoenvironmental reconstruction, to a recent focus on integration with biological sciences (particularly conservation biology).

A careful review of the history of archaeological interest in human-environment interactions, however, shows not a continual rephrasing of questions to match current approaches, but rather an increasing focus of questions and precision of answers. From asking the broadest questions about how environment affects humans, archaeologists have come to ask more focused questions using theory from a variety of sources (Steward, systems theory, human behavioral ecology), and with the current focus on conservation, have focused their questions still further. The accumulation of archaeological data and refinement of archaeological method in the last century has made more, and better, archaeological data available. Theory in anthropology, ecology, and archaeology has also become more sophisticated over the years, providing environmentally-oriented archaeologists with the tools to successfully tackle a more interesting and increasingly focused array of questions. While archaeological investigations into human-environment interactions still vary dramatically in scope, theoretical orientation, and method, a subset of such investigations are considering questions that are more focused—and thus more possible to answer correctly.

In her textbook, “Environmental Archaeology,” Dincauze (2000) makes the argument that the goals of paleoenvironmental studies can be split into three categories: historical (i.e., “environmental archaeology”), theoretical and philosophical (“human paleoecology”), and policy (“environmental studies”). Dincauze remarks on the lack of integration and coherence between researchers in all these fields. Certainly, environmentally-oriented archaeological research, as the review above demonstrates, varies widely in method, goals, and scope, and I find it unlikely that this will change. Without work on method and paleoenvironmental reconstruction, the more focused work on theoretical and policy-oriented research will not succeed (e.g., Driver 2001).

That said, while I acknowledge that broad methodological and descriptive works are important, there is little room for substantial change in this field. In particular, the “environmental archaeology” recovered from textbooks and the Association for Environmental Archaeology seems to have stagnated with the struggle to make this school of research more theory-driven and rigorous (Driver, 2001; O'Connor, 2001). While further development of methods has the potential to contribute to this area, such contributions seem unlikely given the current state of affairs. Methodological refinements and useful paleoenvironmental data have been more profitably produced by the more theoretically-driven approaches to prehistoric human-environment interactions of late (O'Connor 2001).

“Human paleoecology,” on the other hand, has flourished since it has taken advantage of the theory provided by human behavioral ecology. This theoretical direction has led this line of inquiry to more or less merge with that part of archaeology that has been interested in conservation biology and anthropogenic landscapes, an exciting field of inquiry that has grown massively over the last twenty years are so. Thus far, archaeologists have been so busy arguing that their data is important to conservation biology, however, that there has been little work devoted to making concrete policy recommendations. Pitcher (2001) is an interesting exception, though not written by an archaeologist. Archaeologists have argued persuasively that archaeological training is necessary to understand and interpret archaeological data; thus, it is time now for archaeologists to start making the leap from merely providing background information to drawing conclusions about how to proceed in the light of global environmental change.

Of course, to do this archaeologists will need to be educated in policy-making; this is, however, a logical outgrowth of the conservation-based work that archaeologists have been doing for the past twenty years. Education for such archaeologists would have to include a background in conservation biology science and policy; rather than being archaeologists with environmental interests, such archaeologists will be environmental scientists who study archaeology.

A related but potentially more academic recommendation involves the development of new methods. More knowledge of work being conducted in environmental studies would be of great use to archaeologists interested in conservation issues. Although conservation has not been widely observed in ethnographic small-scale populations (Hames 1991; Redford and Stearman 1993; Bodmer, Eisenberg et al. 1997; Alvard 1998; Alvard 2000; Smith and Wishnie 2000), both sustainable practices and landscape management have (Anderson 1991; Blackburn and Anderson 1993; Moreno and Villafuerte 1995; for example, Alvard 2000; Peacock and Turner 2000). Archaeologists, however, have primarily documented “negative” impacts on environments—because that is what archaeologists (and conservation biologists) have been looking for. Ethnographers have developed scenarios under which conservation, sustainable practices, and landscape management may occur (Alvard 1998; Smith and Wishnie 2000). Observing any of these prehistorically will be difficult, unless we develop strategies to do so, archaeologists may not be observing the whole picture. Testing for neutral or “positive” prehistoric human impacts will require the development of new methods; nonetheless, it is imperative for archaeologists to determine if the record of human impacts we have been presenting to the world is, in fact, biased.

Another aspect of research that is increasingly important concerns the feedback between exogenous climate change and human impacts on biological diversity. With the threat of global warming, it is important to understand the effects that human impacts will have on a landscape that is already changing dramatically. Now that human impacts have been well-established, we need to take a deeper look at the record and understand true human-environment interactions: situations where exogenous changes are affecting humans and humans are changing their environments. Some of the recent work on climate (Rautman 1996; Dean 2000; Gunn and Folan 2000; Hassan 2000; Johnson 2000; McIntosh, Tainter et al. 2000; Tainter 2000; van der Leeuw 2000; Fish and Fish 2004; Dean and Doyel 2006) and in historical ecology (Crumley 1994; Crumley 2000; Fitzpatrick and Keegan 2007) is a promising start in this area.

CONCLUSION

This chapter has not reviewed all the literature or even all the schools of thought related to archaeology and environment; there is far too much material. Instead, I have attempted to place the divergent array of literature on "human-environment interactions" into broad, telescoping categories that emphasize their origins in older questions. I expect that new research foci will develop in future years. However, the recent developments in archaeology of human behavioral ecology and particularly in conservation biology and archaeology suggest that topics will remain productive areas of research for years to come.

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Chapter 3

WHEN IT RAINS IT POURS: MULTIPLE CONGENITAL PATHOLOGIES IN SINGLE INDIVIDUALS

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ABSTRACT

This study examined congenital pathologies of 284 prehistoric California Amerinds to determine whether skeletal individuals exhibit multiple pathologies including excessive limb length asymmetries (i.e., greater than average asymmetries calculated from prehistoric populations) as reported in medical literature. Skeletal condition varied from fragmentary to complete (i.e., all major bones present). Pathological individuals were examined twice to ensure pathologies were congenital and avoid including asymmetries related to trauma.

Using conservative diagnoses, sixty individuals (21%) have congenital pathologies; half of them exhibit multiple pathologies (29/60). Excluding fragmentary individuals, 60% (28/47) of individuals have multiple pathologies; in complete skeletons, 79% (19/24) of individuals have multiple pathologies. Differences in pathology frequency within individuals compared to skeletal condition are significant (Chi-Square = 19.33; $P < 0.01$). One-third (20/60) of pathological individuals show asymmetry; half of these individuals have asymmetry in multiple sets of limbs. Multiple asymmetries are found more frequently in complete skeletons (Spearman's *rho* = 0.479; $P < 0.001$).

This hunter-gatherer population has a fairly high rate of congenital pathologies possibly due to inbreeding. Pathologies are often minor, such as supernumerary teeth, spina bifida occulta, and bony growths. However, one individual has a cleft palate and four other pathologies. Fused bones, such as ribs, vertebrae, and foot phalanges, are also present. This study supports that individuals born with a congenital pathology often have other congenital pathologies. Anthropologists are disadvantaged in documenting congenital pathologies due to incomplete remains and the fragility of subadult remains.

INTRODUCTION

Much of current anthropological research on skeletal remains involves using living populations to understand and reconstruct the lives of prehistoric populations; ethnographic accords of hunter-gatherers and reconstructions of prehistoric hunter-gatherers is a typical example. Examining sports medicine literature and the injuries of athletes has also been used to understand the injuries prehistoric populations. One example comes from Trinkaus (1995) who compared the injuries sustained by Neanderthals and various competitive sports players. Trinkaus found that professional rodeo athletes were most similar in their injuries to Neanderthals. He, therefore, concluded that Neanderthal injuries were the result of close contact with large animals in hunting endeavors that would be comparable to the close contact with large animals bull and bronco riders experience in rodeos. Another example comes from studies of spondylolysis, which are back fractures resulting from activity. Recent studies find a correlation with spondylolysis to sports that require extensive use of one upper limb side, such as cricket, baseball, and tennis (Merbs, 1996). Many of these activities involve hyperextension of the hip and torsion of the back, such as in swinging a bat and throwing a ball. Furthermore, musculoskeletal stress markers, which are locations of bones where muscles attach and increase in robusticity with use of specific muscles, have been measured in skeletal populations and activities have been reconstructed using sports literature in conjunction with artifacts. The California population examined in this study, for example, was also examined for musculoskeletal stress marker variation. I found that males had larger musculoskeletal stress markers than females (even after controlling for body size) in the pectoralis and the latissimus dorsi muscles, which are usually associated with throwing or pitching motions as in baseball (Weiss, 2007). These motions mapped onto the artifactual evidence of hunting suggests that males were throwing spears rather than pitching balls, but the effect on the arm is the same since the motion is similar. Other examples of using present populations to understand and reconstruct past populations' lives are abundant in the cross-sectional bone strength (e.g., Cowgill & Hagar, 2007; Mays, 2001; Weiss, 2003), limb bone asymmetry (e.g., Rhodes & Knüsel, 2005; Rhodes, 2006; Wanner et al., 2007), and osteoarthritis studies (for a review of this literature see Weiss & Jurmain 2007). The above detailed examples and the hundreds more that have been published in anthropology journals show promising results for reconstructing the past using present peoples.

On the other hand, recent studies have arisen that highlight the difficulty of using present populations with data and reconstructing the past. Some of these difficulties arise due to the nature of modern populations, such as in the case of using femoral head size to calculate body mass or weight. Modern peoples have a great deal of variation in body mass and this variation is not accurately reflected in the femoral head size; thus, the use athletes' and other fit individuals' femoral sizes and body masses have been proposed as a good fit for prehistoric population body mass reconstructions (Ruff, 2000). Another example comes from the osteoarthritis literature; there is good evidence now that individuals with extra body weight have more arthritis in their weight bearing limbs than do slimmer individuals (Weiss & Jurmain, 2007). In prehistoric populations, conversely, osteoarthritis of weight bearing joints seems to have a negative correlation with body mass (Weiss, 2006). Females, moreover, have greater osteoarthritis in weight bearing joints than do males. Thus, we must ask ourselves whether the extra weight on females is actually increasing osteoarthritis on small joints because they have less area to spread the forces bearing down on them. So, weight and size are interacting in the onset of osteoarthritis. We also see a disconnect with modern populations and spondylolysis in which spondylolysis seems to be correlated with greater flexibility in modern populations and females are more flexible than males, but males of prehistoric populations have greater frequencies of spondylolysis than do females (e.g. Merbs, 1996, Weiss, in press). In order to complicate things further, anthropologists have had difficulty obtaining comparative data in living peoples of musculoskeletal stress markers, bone strength, and other non-injury related activity indicators since much of the data on present populations is only collected when individuals go to the hospital due to the experience of pain.

To further obscure the situation, severe pathologies are rarely found in skeletal collections of prehistoric populations due to the early death of individuals with severe pathologies (which is in part due to the lack of modern medicine in these populations) coupled with the taphonomy of infant and child bodies, which makes their remains extremely rare regardless of their health (e.g., Bello et al., 2006; Guy et al., 1997). A good example of these confounding difficulties arises from the study of spinal defects. Spina bifida occulta is found in many prehistoric populations and has been hypothesized to relate to a high frequency of the severe forms of spina bifida, spina bifida cystica and spina bifida aperta, found in modern populations (Hall & Solehdin, 1998; Jorde et al., 1983). It seems that all forms of spina bifida are in part a result of genes and in part a lack of folate in maternal diets (Hall & Solehdin, 1998; Jorde et al., 1983). Spina bifida cystica is often lethal at birth and, thus, extremely rare in skeletal populations. In modern populations spina bifida occulta is not diagnosed and we have no accurate idea of its frequency, although the percentage is given at around 15-20% in modern populations based on a few studies (Jorde et al., 1983). Additionally, scientists are not sure of the connection between spina bifida occulta and more severe cases of spina bifida (Hall & Solehdin, 1998; Jorde et al., 1983). On the other hand, in skeletal populations individuals with spina bifida cystica would have died shortly after birth and the remains are likely not to survive the thousands of years of diagenesis (Ferembach, 1963). For skeletal populations, ergo, the consideration and documentation of minor pathologies is essential.

In modern populations, the medical literature is rife with syndromes that can be defined as multiple congenital pathologies that occur together and related to a single cause, some of these are Down syndrome, Turner Syndrome, and Klippel-Feil Syndrome. New research, furthermore, has shown that individuals born with the help of fertility drugs and procedures face multiple anomalies that are usually related to the hormones given to the mother and multiple births, such Beckwith-Wiedemann syndrome that is associated with abdominal-wall defects, hypoglycemia, ear abnormalities, and tumors (Halliday et al., 2004) and craniosynostosis that is associated with premature suture closure of the skull, low IQ, and small brain size (Reefhuis et al., 2003). The latest child cancer research also has found a correlation with physical anomalies in children and their likeliness of getting cancer; for example, Gorlin syndrome, which includes an abnormally broad face and organ deformities, has been linked with a greater risk of basal cell carcinoma (Merks et al., 2008). Subadults with cancer had more minor pathologies, such as asymmetrical limbs and curved spines, than those without cancer (Merks et al., 2008). Seemingly different ailments, hence, have genetic links that cause multiple pathologies in single individuals. Research on neural tube defects has also consistently found that individuals born with a neural tube defect often display other defects (Hall & Solehdin, 1998). Finally, alcohol, drugs, and inbreeding cause multiple birth defects in single individuals; fetal alcohol syndrome, for example, includes small gestational size, small eye openings, poor coordination, low IQ, and hyperactivity (Centers for Disease Control and Prevention Website). In summary, in modern populations, most individuals born with congenital pathologies have many anomalies and they rarely exhibit just one anomaly.

Anthropologists have not ignored the study of congenital pathologies, but they publish studies often focused on a single type of pathology, such as spina bifida. For example, El-Din and El Banna (2006) examined congenital anomalies of the spine in ancient and modern Egypt. They found that the cases of spina bifida occulta were low in ancient Egyptian skeletal populations with a frequency of about 3%, but they found it difficult to assess a modern comparative since spina bifida occulta was not recorded in studies of modern Egyptians. Another example stems from Merbs (2004) study of Inuit skeletal remains; he looked at vertebral developmental errors of several populations of Canadian Inuits. Merbs found that sagittal clefting, which can cause curvature of the back and severe back pain, and spina bifida occur more frequently together in one individual than do clefting and segmentation errors, which is when there is massive fusion of vertebrae and is sometimes associated with Klippel-Feil syndrome, in a single person. Klippel-Feil syndrome is also linked with renal, cardiovascular, and otology abnormalities. Merbs (2004) study is one of the few studies in the anthropological literature that link specific pathologies with other pathologies on a population scale. Merbs (2002) also found a connection between unilateral spondylolysis and spina bifida, suggesting that the congenital pathology may be in part the cause of the unilateral spondylolysis. An early study by Bennett (1972) tied the high frequency of spina bifida occulta in Modoc Indians to inbreeding, but no other pathologies were noted.

Other anthropologists publish on single individuals with pathologies in case studies (e.g., Anderson, 2003; Formicola & Buzhilova, 2004; Malgosa et al., 1996; Molto, 2000). Case and coworkers (2006), for instance, examined extra digits (or polydactyl) in two Prehistoric American Southwest individuals. Mann and colleagues (1998) examined an adult female from Moundville, Alabama dating from 1200 to 1400 AD with a fused humerus and radius and a missing ulna. They also examined the crania and other remaining elements, but the evidence was fragmentary and they did not find additional pathologies. Phillips and Sivilich (2006) provide a case study of a prehistoric Native American from Indiana dated to 500 to 1000 AD with a cleft palate. The individual, a female between the ages of 20 and 30, had several pathological legions that suggest a cleft hard palate and an affected nasal region. Furthermore, the individual appears to have infected sinuses and dental caries. The authors point to the difficulty in comparing this individual with modern individuals since they are likely to receive medical attention prior to adulthood; the disparity in lifestyle due to medical progress makes reconstructing the prehistoric individual’s quality of life difficult. Two additional articles are case studies that have found multiple pathologies in single individuals; Dickel and Doran (1989) examined an individual from Florida with severe neural tube defect. The Florida female lived about 7,500 years BP and died at the age of about 15 years old; she had spina bifida aperta (running through her thoracic vertebrae and likely causing immobility). Secondary pathologies were also found, such as enlarged nutrient foramen (sometimes associated with Gaucher disease that causes renal and blood disorders), disuse atrophy of the limbs, vertebral curvature, and cone-shaped epiphyses of the hand phalanges. The authors note how remarkable it is that this female survived till her teens and that she was likely cared for by her community. Another study found 30,000 year old Slovakian burials of well-preserved skeletal remains that had deformities of femur, fibula, radius, and ulna, along with scoliosis and misshapen vertebral spines (Masnicová & Beňus, 2003). The authors suggest that these anomalies can be linked to various possible syndromes, such as chonodrodysplasia calcification puncata (an inherited bone disorder).

As one can see, the anthropological literature is lacking examinations and reports of overall pathologies and multiple pathologies in single individuals on a population scale. This may in large part be due to the nature of our data. An exception to this absence is a broad study examining congenital pathologies in Slovakia 11th and 12th Century skeletons that examined over 300 skeletons. Spina bifida, the most frequent pathology, was found in 24% of the population, while other pathologies occurred rarely, such as premature synotosis of a coronal suture in a juvenile and nasal bone hypoplasia in another individual. However, no multiple pathologies in single individuals were noted in this study.

This current chapter is an effort to merge the two types of studies in the anthropological literature mentioned above while determining whether a prehistoric population's frequency and pattern of congenital pathologies is similar to those we find in modern populations. If the prehistoric population has a similar pattern of pathologies (i.e., multiple anomalies in single individuals), then we can use modern populations to understand and reconstruct what it may have meant for prehistoric populations to cope with individuals with congenital pathologies. Although this is an ambitious project, the first step is to examine the patterns of congenital defects and compare it to those in medical literature. In modern populations, as mentioned above, the clinical literature has abundant cases of syndromes (e.g., Klippel-Feil Syndrome), which are basically multiple congenital pathologies that occur together and related to a single cause. Nonetheless, multiple defects in single individuals may be in large part a relatively new development due to the environment and the misuse and use of medicines. Or the documentation of multiple pathologies may be difficult in the skeletal populations due to the lack of survival to adulthood in pathological individuals and the loss of information from soft tissue.

This current study will help anthropologists to determine whether using just skeletal material we can document population occurrence of syndromes in prehistory as we do in present populations. Presences of multiple congenital pathologies in single individuals will also aid anthropologists to be more certain in the reconstruction of past populations with the use of modern populations as models when congenital pathologies are considered. Cautiously, however, I note that skeletal samples are far from ideal for diagnosing pathologies. Because the condition of remains varies from one population to the next it is important to determine whether this will be a factor in reconstructing congenital health of populations. This study attempts to answer whether there will be a significant different in observing pathologies when the skeletal remains are not complete; thus, aiding anthropologists to avoid the trap fall of reconstructing a picture of healthier individuals due to the lack of complete skeletons. It is perhaps obvious that anthropologists who examine skeletal remains are at a disadvantage in understanding congenital pathologies due to their low frequency in many populations, the uneven preservation of remains, and the lack of soft tissue. Finally, most anthropological studies concerning congenital anomalies focus on single case studies; case studies have been abandoned in other areas of anthropology due to the lack of statistical ability and the absence of hypothesis testing. This study, therefore, will provide a model of examining and documenting demographics of congenital pathologies, which will hopefully be useful to other anthropologists studying large well-preserved skeletal populations. To simplify my goals, I state my hypotheses in testable questions: (1) even in skeletal populations, individuals with congenital pathologies have multiple defects (and, therefore, modern populations can be used as good models in reconstructing past populations' health); (2) complete skeletons offer a significantly greater ability to find multiple pathologies in single individuals (which should make anthropologists careful of reconstructing a healthy population when the data is not available); and, (3) pathologies are also correlated with greater asymmetries of limbs that would indicate an effect on growth (since severe pathologies will be hard to find, minor anomalies are important to document).

MATERIALS

The skeletal sample consists of 284 individuals ranging from infancy to 50 years of age from a California site (CA-Ala-329) located on the southeastern side of the San Francisco Bay dating from 2180 to 250 yrs BP (which is pre-European contact) housed at San José State University Anthropological Collection. Jurmain (1990) aged and sexed individuals according to standard osteological procedures. Jurmain (1990) reported ages in ranges of five to ten years. As an aside, the preservation of this collection is excellent.

The Ryan Mound Site (CA-Ala-329) contained numerous indicators of rich environmental resources (Leventhal, 1993). The site contained large quantities shellfish, waterfowl, and mammal bones (Leventhal, 1993). Additionally, Amerinds utilized acorns, berries, and seeds as indicated by the numbers of mortars, pestles, and refuse found around the site (Leventhal, 1993). Obsidian points, along with shafts and other types of hooks and harpoons, were in abundance at CA-Ala-329; most of these artifacts (especially the obsidian points) were associated with male burials (Leventhal, 1993). This possibly indicates the emphasis on hunting as a male activity whereas females were more likely to be buried with pestles and cobblestone (Leventhal, 1993).

The Amerinds from CA-Ala-329 were hunter-gatherers with a heavy reliance on acorns and supplemented by hunted foods (Jurmain, 1990, 1993; Leventhal, 1993). Although the time span is great, there seems to have been cultural continuity as indicated by similarities in mortuary practices and artifacts (Leventhal, 1993).

The remains at CA-Ala-329 represent high lineage or wealthy individuals from various villages. Villagers were not isolated from other villagers as indicated by lack of artifactual and mortuary differences (Leventhal, 1993). A downside to the population density was the high levels of interpersonal aggression (Jurmain, 1988; Jurmain & Bellefemine, 1997). From the skeletal remains and archaeological material, it is known that these Amerinds used shafted obsidian points in hunting and aggressive acts (Jurmain, 1988, 1990, 1993; Jurmain & Bellefemine, 1997; Leventhal, 1993).

METHODS

In this study, I examined congenital pathologies of 284 prehistoric California Amerinds to determine whether skeletal individuals exhibit multiple pathologies plus excessive limb length asymmetries. Skeletal condition varied from fragmentary to complete (i.e., all major bones present). Pathological individuals were examined twice to ensure pathologies were congenital and avoid including asymmetries related to trauma. Diagnosis of pathologies were conservative, any pathology that could possibly have been caused by trauma was excluded.

For each individual, data were recorded on sex (male, female, and indeterminate) and age (Infant = Younger than 2 years-old; Child = 2 through 10 years-old; Teen-Age = ll through 16 years-old; Young Adult = 17 through 24 years-old; Adult = 25 through 39 years-old; Old Adult = Older than 40 years). Also, the condition of the remains was recorded on the a three point scale: 1) complete = all major bones are present and at least 80% complete or intact; 2) partially complete = at least 50% of the major bones are present and at least 50% complete or intact; 3) fragmentary = less than 50% of the major bones are present and less than 50% complete or intact. Asymmetry was recorded as being present or absent (i.e., one standard deviation or greater than average asymmetries calculated from prehistoric populations from my own dissertation data and previously published materials); the number of bones affected by asymmetry, and the bones that displayed asymmetry. Asymmetry was considered due to the recent research that suggests asymmetry is linked with other diseases (Merks et al., 2008). Finally, number and type of pathology was noted for each individual.

The data was entered into a SPSS spreadsheet. Frequencies were calculated for pathologies and multiple pathologies. Non-parametric Chi-square tests were run to test for significant differences in distribution of pathologies between the skeletal condition (fragmentary, partially complete, and complete), the sexes, and age groups. Furthermore, pathologies were correlated using a two-tailed non-parametric Spearman test with asymmetry. Significance was set at $P = 0.05$.

RESULTS

Out of 284 individuals, sixty individuals (21%) have congenital pathologies; nearly half of the individuals with pathologies exhibit multiple pathologies (29/60). When fragmentary individuals are excluded, then 28 out of 46 (60%) of the pathological individuals have multiple pathologies; and, when only considering complete skeletons, 19 out of 24 (79%) of the pathological individuals have multiple pathologies (Table 1). Differences in pathology frequency within individuals compared to skeletal condition are significant (Chi-Square = 19.33; $P < 0.01$ and Spearman's *rho* = 0.554; $P < 0.001$).

Table 1. Skeletal condition cross-tabulated with number of pathologies (N = 60).

Skeletal Condition	Number of Pathologies					Total
	1	2	3	4	5	
Complete	5	11	7	0	1	24
Partially Complete	14	6	3	0	0	23
Fragmentary	12	1	0	0	0	13
Total	31	18	10	0	1	60

Examining the interaction with asymmetry, one-third (20/60) of pathological individuals show asymmetry (Spearman's *rho* = 0.484; P < 0.001); half of these individuals have asymmetry in multiple sets of limbs. Asymmetries are found mainly in complete skeletons (Chi-Square = 13.79; P < 0.001) and this significance is also borne out in the correlation coefficient (skeletal condition and asymmetry correlate at Spearman's *rho* = 0.479; P < 0.001) (Table 2). But, there are no significant results regarding asymmetry and the number of bone sets that display asymmetry.

Table 2. Skeletal condition cross-tabulated with asymmetry (N = 60).

Skeletal Condition	Asymmetry		Total
	Absence	Presence	
Complete	10	14	24
Partially Complete	17	6	23
Fragmentary	13	0	13
Total	40	20	60

With regards to sex differences, only one marginally significant finding occurs. There are no significant differences in skeletal condition and sex (Chi-Square = 2.41, n.s.). There are also no sex differences in number of pathologies per individual (Chi-Square = 4.23, n.s.). There is a marginal sex difference in asymmetry with females exhibiting more asymmetry than males (Chi-Square = 5.73, P = 0.057) (Table 3).

Table 3. Sex differences cross-tabulated with asymmetry (N = 60).

Sex	Asymmetry		Total
	Absence	Presence	
Male	23	8	31
Female	12	12	24
Indeterminate	5	0	5
Total	39	20	59

With regards to age differences, no significant differences in skeletal condition and age (Chi-Square = 12.33, n.s.). There are also no age differences in number of pathologies per individual (Chi-Square = 9.57, n.s.). There are no age differences in asymmetry (Chi-Square = 4.47, n.s.).

CONCLUSION

This California hunter-gatherer population has a fairly high rate of congenital pathologies possibly due to inbreeding. Supernumerary teeth, which are frequent in the current population, and spina bifida occulta, which is the most common pathology found in the current study, both have been linked to inbreeding (e.g., Bennett, 1972; Lovett & Gatrell, 1988; Mahaney et al., 1990). Inbreeding may have been due to the elite status of these individuals and could also suggest that many of the skeletal remains came from a more narrowly defined time range than the entire population.

This study supports the first hypothesis that individuals born with a congenital pathology often have other congenital pathologies, which is what we find in the current medical literature. Syndromes are not only an effect of modern environments; individuals experienced cleft palates with numerous other pathologies, vertebral pathologies, Klippel-Feil syndrome, and possibly other now well-documented syndromes. In the current population, one individual had fused cervical vertebrae, sacralization, and a sagittal vertebral cleft; this person may have had Klippel-Feil syndrome (Fig. 1). Another adult individual had an abnormally small external auditory meatus (possibly linked to hearing difficulties), sacralization, and spina bifida occulta. Other examples are abundant and those individuals with any pathology were likely to have more than one pathology, such as the individual with spina bifida, tibial shaft deformation, and upper limb asymmetry (Fig. 2). Anthropologists should try to link multiple pathologies in single individuals to modern syndromes in order to better understand the past individual’s health. However, we also must be cautious to avoid over diagnosis when the skeletal remains are not indicative enough of any particular ailment. In sum, for hypothesis one, modern populations can be used as good models in reconstructing past populations’ health and the link between multiple pathologies holds for the past and present. It seems that when it rains, it pours. Individuals who are born healthy either have no pathologies or these are so minor as not to be reflected in the skeletal remains.

The second hypothesis is also supported; complete skeletons offer a significantly greater ability to find multiple pathologies in single individuals than do incomplete or fragmentary remains. Anthropologists must be careful in reconstructing a healthy population when the data is not available. Anthropologists are disadvantaged in documenting congenital pathologies due to incomplete remains and the fragility of subadult remains, which may be why we see so few severe pathologies. Most researchers who work with skeletal remains are well aware of the disadvantages in diagnosing pathologies (Mann et al., 1998) and many of provide useful information on the lack of data for infants and subadults who are most likely to have evidence of severe pathologies (Bello et al., 2006; Guy et al., 1997). Nevertheless, some past populations took care of their severely pathological individuals and they lived into their teens or later (e.g., Dickel & Doran, 1989). It appears that this may also be the case with the individual in the currently examined California population with the cleft palate, supernumerary teeth, lumbarization, and upper limb asymmetry (Fig. 3).

Finally, the third hypothesis is supported as well; pathologies are also correlated with greater asymmetries of limbs that would indicate an effect on growth. It seems that asymmetry is related to pathological occurrence; this may relate to how pathology influences growth of individuals. Merks and colleagues (2008) documented this finding with childhood cancer patients, but it may be true for many other pathologies. Anthropologists should be aware of excessive asymmetry not linked to injury as one way to measure a population’s health. Asymmetry of skeletal remains is an indicator of poor health and should be noted when examining individuals.

Figure 1: Burial 71 an adult male with fused cervical vertebrae (pictured above), sagittal cleft, and sacralization.

Figure 2: Burial 103 an adult male with spina bifida (displayed above), asymmetry of the upper limbs, and tibial shaft deformation.

Figure 3: Burial 92 a 20-24 year old female with a cleft palate and supernumerary teeth (pictured above). She also displayed asymmetry and lumbarization.

As a final thought, case studies should not be abandoned in this field, especially when the probability of finding numerous individuals with specific pathologies is low, but these case studies can be complimented with an overall examination of the population. Furthermore, less severe pathologies of the population should not be ignored. Perhaps cases of severe pathologies are found in populations with greater than average minor pathologies, suggesting that these two are related.

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Chapter 4

ARCHAEOLOGY AND ANCIENT DNA: ASSESSING DOMESTICATION

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ABSTRACT

Since the early stages of its domestication, the horse has been an important means of mobility for human populations. On the contrary, cattle, sheep and goat are more related to human early settlements. This is probably why the estimated date for the domestication of horse is set at a later time than the other species. From early times, and precisely because of their transportation capabilities, horses from distinct geographical regions have been crossbred which has led to the mixing of their genetic legacy. This has made it difficult to assign a genetic pattern to a specific geographical location and thus, to establish centers of domestication for this species. Because of this, horses are objects of interest for teams from a broad range of research fields. The processes that led to domestication and to the diversity of modern domestic populations are areas of focus for geneticists, evolutionists, archaeologists and anthropologists, among others. The identification of domestication centers of wild populations is important for the understanding of both human and livestock migrations and distribution as well as the impact of the first human settlements on local wild populations of livestock ancestors. These questions have been addressed in several studies for several species using not only archaeological data, but also molecular data obtained from archaeological specimens. The possibility of using DNA from archaeological remains and thus to analyze data from original sources which possibly were directly involved in the first steps of domestication is one of the major advantages of the application of molecular technology to Archaeology. Several molecular markers can be used to assess domestication processes,

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points and dates for several species. Mitochondrial DNA is the most commonly used marker to address migration, demography and phylogenetic relationships and the domestication process for today's domesticates, but sex chromosome related markers (such as SNPs) and whole genome sequencing have a bright future among researchers looking for answers related to human evolution and domestication as one of the consequences of this evolution. This is because of the recent developments of molecular technologies and because of the properties of the markers which are optimal for Ancient DNA analysis. This chapter aims to review what has been done to investigate domestication related issues and what can still be done to improve the knowledge that archaeological and molecular techniques have allowed so far. We aim to suggest future directions to be taken in Archaeological research using molecular approaches.

INTRODUCTION

Archaeology and Molecular Genetics have been uniting efforts in order to address several issues related to the evolution of extinct and extant animal and plant species. The main difficulties felt by archaeologists, when addressing species domestication and dating of scenarios, is the diversity of morphological forms and the contaminations inherent to the sample collection processes (which is one of the main factors producing erroneous dating results even when using the recent AMS methodology [1]). We will be addressing the contamination issues later in this chapter.

According to several authors, variable morphological traits in fossil forms do not necessarily correspond to different species and special caution must be used when classifying a morphological type as a different taxonomical unit [2-4]. For instance, it is widely accepted that the genetic variability currently known for true horses has derived long before modern breeds have evolved and perhaps even before the first horse domestication events [5-8]. Molecular genetics technologies applied to archaeology are helping to solve some of the Systematics problems encountered by archaeologists and anthropologists who otherwise could only rely on archaeological remains, sometimes highly damaged. A good example of the importance of the close collaboration between Archaeology and Molecular Genetics is the study of Human Evolution. This field of research is being addressed with the help of Ancient DNA (aDNA) technologies by several teams [9-11] and these technologies are even permitting the sequencing of the Neanderthal genome [12, 13], which constitutes a major breakthrough to the study of the demographic and evolutionary history of mankind. It does make sense to say that ancient genomics is born [14].

Ancient DNA has the advantage of disclosing information that was not available until relatively recently. This is very useful for various areas of interest within Molecular Archaeology and Anthropology, but particularly helpful to address several questions still unresolved concerning livestock and plant domestication. Regarding the origins of *Equus caballus*, several authors have based their conclusions solely on morphological data and/or molecular data exclusively from modern DNA [2-4, 15-19]. However, for instance, only by combining aDNA and modern DNA data was it possible to determine a date range for modern horse mtDNA control region lineage origins in closer agreement to the one based on archaeological evidence [8]. Similarly, only with the use of aDNA was it possible for researchers [5, 7, 8] to confirm what zooarchaeologists [2, 18] already suspected: morphological variability does not necessarily indicate speciation or even a subdivision into different taxonomical units lower in the systematics hierarchy (namely, breed). Morphological differentiation of fossil (extinct) equids is rather a product of adaptation to paleoclimatic conditions and respective existing vegetation.

Many review articles can be found in the scientific press that address genetic, economical and cultural aspects of domestication [20, 21], and not so many focus the relationships between research teams in Archaeology and Genetics. Zeder and colleagues [22], for instance, make a very interesting and thorough list of both archaeological and genetic markers that help scientists identifying domestication events. The same authors, edited the book “Documenting Domestication - New Genetic and Archaeological Paradigms” [23], whose contributors make a valuable effort gathering a few studies documenting both plant and animal domestication from either archaeological and genetics points of view. However, the cases analysed using archaeological data were not the same as the genetics data and thus a comparison cannot be made. This is what we still observe frequently: archaeological and genetics studies still belong to rather parallel universes, while cooperative work is still not frequent [23]. Other reviews which address domestication are focused exclusively on the genetic focus of the question [21, 24-26]. Our objective in the current chapter is mainly to portrait the evolution of the investigation of livestock domestication from the point of view of both genetics and archaeology providing a comparison, when possible, of the results obtained regarding dates and locations. We also aim to report the latest developments in molecular technologies which can be used to aid corroborating or even complement archaeological findings.

DOMESTICATION: ARCHAEOLOGY AND GENETICS (MODERN AND ANCIENT DNA)

It is possible to establish an approximate period in time and a likely location for the domestication of some species based on archaeological and molecular evidence. For instance, using modern mtDNA variation, Savolainen et al. (2002) [27] have found genetic evidence for the East Asian origin of modern domestic dogs at approximately 15,000 y BP (years before the present). The archaeological records place the earliest dog domestication evidence at approximately 14,000 y BP, in Germany [28]. Although the locations are quite different, the dates are relatively coincident if we have in mind earlier findings based on molecular data which pointed to a much earlier domestication event [29-31]. Interestingly, up to the date of publication of this chapter, there was no work done with aDNA from dog archaeological remains, but we are convinced that if that kind of material is used, the time of the first dog domestication events will be even more accurate.

Cattle and sheep seem to show a similar pattern of structure and distribution of mtDNA variation with evidence that leads to think of one to three domestication events (Africa, East Asia and the Fertile Crescent) from two or three wild ancestor species and little mobility after the domestication events [25, 32, 33]. For cattle, the estimated time for the first domestication event is 9,000-10,000 y BP and there have been identified three different ancestors for the European, African and Indian modern domestic populations [34, 35]. The oldest unequivocal archaeological evidence for cattle domestication was found in Algeria and it is approximately 6,530 y BP [36]. There is earlier indirect evidence of in the Eastern Sahara that places the earliest domestication event at approximately 9,000 y BP [37], however, this evidence is regarded as dubious by some researchers [38]. The location for the oldest archaeological findings supporting the existence of domestic cattle coincides with one of the domestication locations proposed by molecular data – North Africa [34]. But it does not coincide with the dates proposed by the same type of data (especially if we do not consider the dubious evidence for early domestication in the Eastern Sahara. Ancient DNA analysis still did not permit the finding of the earliest domestication date, mainly because of the apparently complex pattern of domestication [34] and also because of the low number of archaeological samples which yielded authentic aDNA [39-41] (we will return to the authenticity issue posed by aDNA). Here we feel compelled to stress the value of collaboration between archaeologists and geneticist: archaeology can only be based on physical evidence, that is, the presence of archaeological remains. Genetics, supported by statistics and bioinformatics (modeling of molecular evolution) can go further. More so with the possibility of the use of aDNA, that can provide a better insight on the ancestral lineages of our study object. Of course, molecular data must be carefully analyzed and interpreted but it is still a powerful tool when used accurately. For domestic sheep the most likely origin is located in the Fertile Crescent and the domestication events leading to lineage divergence may have occurred in different times, the oldest of all having been estimated from both archaeological and molecular data as being approximately 9,000 years old [42-44].

Goats seem to have been the first wild herbivores to be domesticated [25]. However, the patterns of distribution of mtDNA variation seem to follow those found in the horse, indicating great mobility and thus suggesting the important role goats had in human migrations [33]. The first domestic goats seem to have been raised 10,000 y BP with the incorporation of several wild ancestor lineages [32, 45] in the Fertile Crescent [25]. The archaeological record agrees with this date estimate for the earliest goat domestication event since the unequivocal evidence for this event was found in the Fertile Crescent [46]. However, archaeological studies did classify the Fertile Crescent as the only domestication centre for goats. Again, this is where archaeology greatly benefits from the collaboration with genetics: three different domestication events were detected for goats at three independent dates and there are signs that lead to think that Asia and Europe may have also foster goat domestication events [32]. Luikart and colleagues have used both modern and aDNA from museum specimens.

The donkey seems to have been one of the latest species to have been domesticated, similar to the horse [47]. The archaeological record sets the domestication of donkey at approximately 5,000 y BP, at a not consensual location [48]. Remains have been found in a domestic scenario in three distinct locations with different but relatively close dates: Sudan – 5,000 y BP [23]; Iran – 4,800 y BP [49]; Syria – 4,300 y BP [50]. Although the exact location for maybe two domestication events is still not clear, recent genetic data points to Northeastern Africa as a likely candidate [47, 51].

For the horse, things are not so well defined as for other domesticates. So far it has not been possible to establish an approximate date for the first domestication event and the locations for possible subsequent multiple domestication events have also not been established, although Eastern Asia is a likely candidate, as well as Western Europe [52] and the Iberian Peninsula [53, 54]. It should be noted that it was thought and accepted for a long time that there had only been one domestication event for the horse with subsequent spread of domesticated forms due to increased mobility of this species [7]. However, it was established by Jansen et al. [8] that this was not the case and that there were several independent domestication events. Although the Kurgan Culture theory places the earliest horse domestication events somewhere between 7,000 and 6,500 y BP, the most consensual and unequivocal archaeological traces of horse domestication (for traction and for riding) were found throughout Europe and in the Near East dating from the end of the fourth millennium BP [48, 52, 55, 56]. These findings comprise cave paintings or clear associations between entire skeletons of horses, riding artefacts and utensils such as bitted bridles and nose rings working as bridles as well as chariots, from the Eurasian steppes, to the Iberian Peninsula [48, 52, 56-58].

Whether or not the Iberian Peninsula has fostered independent horse domestication events is a matter of debate [59, 60]. Rupestrian illustrations have been found in more than one archaeological site of Southern Spanish territory (e.g. Cueva de La Loja Alta - Jimena de La Frontera, Cádiz, Andalucía, Spain, and Yacimiento de La Peña del Escrito – Villar del Humo, Cuenca, Castilla-la-Mancha, Spain) which depict what appears to be a domestication scene: a horse lead by a man with a rope. These schematic cave paintings are characteristic of the Spanish Levant. The chronology of this period is not consensual however it is usually placed between the eighth millennium BP and the end of the Bronze Age, approximately 2800 y BP (VIIIth century B.C. [57, 61-63]).

Scenes which constitute evidence of domestication only started to appear from the fourth millennium BP in the Spanish Levant art period [57]. Thus, domestication in the Iberian Peninsula seems to be a reality, whether it occurred independently or associated to other domestication events in other parts of the Old World [7, 8], as opposed to domesticated horses being brought by other peoples. According to d'Andrade [55], the horse was used in the Iberian Peninsula since early in the global domestication history of the horse. The author claims that since the beginning of the fourth millennium BP, the horse was already ridden in Iberian territory based on bronze weapons from the Bell-Beaker context, with a typology that is known as only being used by soldiers riding horses.

Based on historical archived documents, d'Andrade [55] suggests that Iberian horses, widely appreciated for their resilience and usability, have been used in war since early times. A Garrano like form was used until the Middle Ages. In this period there existed already the larger horses from the Southern Iberian Peninsula, equivalent to what is known today as the Pura Raza Español and the Lusitano. These were considered the best war horses in Europe and started to be widely used in other European countries to ameliorate the cavalry effectives since 600 y BP (XVIth century BP [55, 64]). McGahern et al. [65] were able to detect a light but evident tendency for a geographical patterning of horse mtDNA variation, which may help interpret the archaeological findings available as well as the patterns of horse domestication and post-domestication mobility.

Using molecular data and including aDNA data, either previously published or obtained by the authors, Seco-Morais et al. [53] were able to determine that the Iberian Peninsula is indeed a likely candidate for a domestication event. Further significant evidence regarding the Iberian Peninsula as an Ice Age refugium and a putative domestication centre is being gathered by Seco-Morais et al. (unpublished data). This is another situation where molecular genetics may complement and help clarify the debate between archaeologist regarding the domestication locations and dates proposed by the available archaeological remains.

PECULIARITIES OF aDNA ANALYSIS AND CRITERIA OF AUTHENTICITY

Because of its unique features, aDNA cannot be used without caution. It is indeed a powerful source of potential information, but if used carelessly, like any other molecular studies, really, can lead to erroneous interpretations. Although molecular technologies have evolved rapidly and are now sensitive enough to permit the analysis of highly fragmented and otherwise damaged DNA, the analysis of biomolecules extracted post-mortem and after a long period of exposure to environmental conditions, is such a delicate procedure that it requires several criteria of authenticity to be applied before the results obtained can be declared ready for publication. For obvious reasons, working with human aDNA is far more critical than working with ancient biomolecules from other species for which primers can be designed and tested for specificity and sensitivity without the risk of contamination from anyone handling the sample.

There are a number of problems that can be encountered and are enhanced when analysing aDNA. Several authors have dedicated their research to assess the effects of each of these problems on the output of aDNA analysis. One of the problems most frequently addressed, besides contamination, which can be controlled to a certain extent, is post-mortem damage. When an organism dies, its DNA rapidly degrades through the action of endogenous endonucleases [66, 67]. However, postmortem damage is not exclusively caused by natural cellular decay. It is also greatly influenced by the taphonomic processes undergone by the sample. Environmental factors such as temperature, humidity, pH value, organic substances (humic and fluvic acids), and general degree of microorganisms present in the soil (in case of archaeological findings embedded in it) [68, 69] are important influences on the final condition of endogenous aDNA. When unprotected by cellular repair mechanisms, DNA is a chemically unstable molecule which decays spontaneously mainly through hydrolysis and oxidation [70]. Postmortem damage is one of the factors affecting correct interpretation of sequence data [68, 69, 71-74]. Nowadays it is possible to quantify this type of damage to obviate misinterpretation in the analysis of haplotypes and alleles: cloning is the most commonly use one [73].

Another problem that can greatly affect complete carry out of aDNA analysis is the amount of template present. Under extreme circumstances, aDNA amplification (using the Polymerase Chain Reaction – PCR) may depart from amounts of template as small as one single strand of one single molecule. This is particularly critical when the target template is a microsatellite (STR) locus, because when only a single strand from a single template molecule is present, heterozygous individuals may erroneously be interpreted as homozygous [75]. There are currently effective quantification methods that can be used to assess the amount of authentic DNA template, such as Real-Time Quantitative PCR (qPCR) [75, 76].

Several authors have tried to assess the relationship between state of specimen preservation (after taphonomic processes) and the likelihood of retrieval of amplifiable DNA from archaeological material [77-79]. The analysis of ancient biomolecules can be an expensive and time consuming process and it would be helpful to have a way to predict whether an archaeological sample will be a good source of viable authentic DNA. Amino acid analysis such as the determination of the total number of amino acids preserved in a specimen as well as the composition and extent of racemisation is the most extensively studied [80, 81].

Other indicators such as preservation of the histological structure [82] and quality of protein preservation [83] in the specimen have also been studied for this purpose. However, there are still no consensual conclusions as to which is the most effective method that can be used to predict the viability of endogenous DNA [81, 84]. As the amount of sample to be used as source of aDNA for analysis is often limited [53, 85, 86], and while there is no certainty as of which methods are the most reliable to assess aDNA viability, most authors prefer to consider these as general guidelines rather than follow them as strict rules. Because of its peculiar characteristics, aDNA analysis is bound to vary from specimen to specimen. Thus studies involving this type of molecule should be evaluated case by case for authenticity of the results issued.

Since the first experiments with DNA from museum specimens [87], the authenticity criteria to be applied to aDNA work have gradually become stricter although still under debate. Most of these criteria are essentially designed with the objective of testing the data for possible artefacts caused by contamination and/or postmortem damage.

A characteristic of aDNA is that postmortem degradation by endogenous endonucleases and taphonomy tend to reduce DNA molecules to very short fragments [66, 67]. Often, it becomes unfeasible to amplify fragments longer than 100 base pairs (bp) [53]. This characteristic is useful as a criterion of authenticity as the successful amplification of fragments longer than 400 bp should be treated with caution because longer fragments are likely to be a source of contamination.

It is generally accepted that aDNA survives in specimens up to several thousands of years [70]. However, the first publications with the claim of the first Dinosaur sequences from the Cretaceous [88] is, at least, doubtful. Hedges et al. [89] have refuted the unlikely results as being a chimeric product of contaminant DNA. An estimate has been made of the time that would take for hydrolytic damage to destroy all DNA that could be amplified consistently and it is 100,000 years at physiological salt concentrations, neutral pH and at a temperature of 15 ºC [90, 91].

A list of 10 criteria to test the authenticity of aDNA has been published by Poinar in 2003 [92] in an attempt to set a number of strict rules to be employed in aDNA work. Such list includes: a) Physical isolation of the work area; b) PCR control amplifications (aliquoted reagents and water, without DNA added sample); c) Molecular behaviour test (fragments larger than 1000 bp are to be addressed critically and possible contamination stressed); d) Quantitation; e) Reproducibility (from the same and different DNA extracts of the same specimen); f) Cloning (to rule out contaminant DNA and assess damage induced errors); g) Independent replication (different laboratories, different analysts); h) Biochemical preservation (analysis of amino acids, fatty acid oxidation or lipid peroxidation – the later two being advisable in the case of forensic samples where protein residues may still be in excellent condition and lead to biased conclusions regarding the preservation of endogenous DNA); i) Phylogenetic sense (to avoid claims such as the ones by Woodward et al. [88]).

Other criteria have been suggested recently (DNA8 Conference, 16-19 November, 2006, Łódz, Poland), which simplify the criteria proposed by Poinar [92]. Such new criteria comprise: a) Swabbing of work areas and use the swab in a PCR reaction for environmental control; b) Methodological replication - extraction (rather than having the samples sent over to a different laboratory, use different methods to achieve the same results. May be a problem if soil composition – in case of specimens embedded in soil – contains PCR inhibitors that can only be removed with one extraction method); c) Sample collection – for human material, it may be critical that the researchers that are going to handle the samples in the laboratory collect the samples in the field to facilitate contamination identification; d) Independent replication can be claimed if the researcher handling the samples in the laboratory goes, in person, to a different facility and perform the work him/herself.

In 2005, Gilbert and colleagues [93], in a review about aDNA studies published so far, and about the excessive criticism involved in the peer review process undergone by this type of study, said that some of the results obtained are likely to be accurate and that ancient DNA studies should be evaluated for authenticity on a case-by-case basis.

MOLECULAR MARKERS

Molecular markers can be considered as target DNA portions with variations or polymorphisms which permit the extraction of information. This information can then be interpreted in light of the existing knowledge of mutation rates, inheritance mechanisms, and location within the genome. The utility of molecular markers comprises many applications, including sex identification (archaeological and forensic samples), evolutionary studies, species identification and domestication.

Mitochondrial DNA (mtDNA): The mitochondrial genome is organized in a circular molecule and is, under normal circumstances, transmitted to following generations through maternal inheritance. Through the regular mechanism only the female mitochondria contribute to the genome of the embryo, and all members of a maternal lineage will be allocated into a common haplogroup [94]. The mitochondria harbour only a small part of the whole genome. In humans, each mitochondrial genome has approximately 16,570 bp [94] whereas one donkey mitochondria encloses 16,670 bp [19] and the horse mitochondrial genome is near 16,660 bp long (not absolute, due to the pronounced presence of heteroplasmy[3] [96].

Within mtDNA markers, the most commonly used for phylogeny inferences and divergence dates (commonly used to infer about domestication) are the coding regions 12S RNA and 16S RNA genes [97-100] and Cytochrome b [97, 101] and the non-coding regions Hyper-Variable Region I (HVRI), Hyper-Variable Region II (HVRII) from the control region of the mitochondrial D-loop [39, 44, 65, 94, 99, 100, 102-107]. Whereas coding regions are better suited for interspecific studies, non-coding regions, for their high variability, are more commonly used when studying more closely related populations [94]. Other applications of mtDNA include forensics cases such as the identification of otherwise unidentifiable victims [108], exclusion of suspects [109] and other cases of public interest such as the identification of the members of the Romanov family [110]. In the long list of applications for mtDNA, animal forensics is also an emerging field with vital importance. The identification of subspecies using mtDNA has proven itself of great use in illegal butchering and trading of endangered fauna cases [94, 111]. Domestication of animal species is also a subject which finds its most preferred molecular tool in mtDNA analysis. As discussed above, several

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[3] If mitochondrial DNA from the sperm enters the oocyte at the moment of fertilization, the developing individual is likely to reveal a mitochondrial DNA mosaic in its mitochondria, and the respective sequence polymorphism is called heteroplasmy. Other forms of heteroplasmy may occur: by maternal inheritance or by mutation along the development of the individual 95. Lightowlers, R., et al., Mammalian mitochondrial genetics: hereditary, heteroplasmy and disease. Trends Genet., 1997. 13: p. 450-455. (Lightowlers et al. 1997).

authors have made use of it to address domestication times and origin locations for several populations such as cattle [33-35], sheep [44, 112] and goat [25, 32, 45], horse [5, 7, 8, 65, 113] and donkey [51] and dog [29, 102, 114].

Autosomal microsatellites (Short Tandem Repeats-STRs): Microsatellites (or Short Tandem Repeats - STRs) are non-coding portions of the nuclear animal and plant genomes. STRs are present in both autosomal and sex chromosomes [94]. Autosomal STRs enable the genetic typing of individuals and consequent identification relative to others, closely related. By definition, STRs are short DNA fragments (up to approximately 400 bp) composed by tandemly repeated units of 1 to 5 bp [115]. For their great variability, STRs are widely used for estimating demographic parameters, genetic structure and variability of both natural and domestic closely related populations [116-126] as well as for parentage tests for management plans [127-129]. STRs are, therefore, strong tools to aid in conservation strategies of small, endangered populations, wild or domesticated [130]. Other useful applications of STR analysis include detection of fraud in gaming and fishing competitions [131] and forensics cases [94]. In rare but well achieved studies, STRs have also been used to address domestication issues [24, 132]. Sex determination can also be undertaken by using sex specific STRs located either on the Y or the X chromosomes. Usually, sex determination is more reliable when used in a multiplex panel with the amelogenin gene, because of identified artefacts when using amelogenin alone [94]. Typing of STRs can also be rather useful in specific circumstances, such as the identification of historical documents written in several types of parchment. Since parchment could be made of several different types of animal skin, sometimes the meaning of the text alone is not enough to unequivocally assign a parchment fragment to the document of origin [94].

mtDNA versus autosomal STRs in aDNA analysis: In general, STRs are more suitable than mtDNA for demographic studies, assessment of introgression levels within populations and genetic diversity [133, 134]. Although STRs can also be used to assess genetic relationships and phylogenies between closely related populations [135, 136], mtDNA is still the chosen molecular marker to infer origins of populations, founder lineages and evolution times in small animal groups, such as humans as well as endangered and domesticated populations [45, 51, 137-140], as the diversity characteristic to mtDNA reflects, in many instances, the time since the last event of genetic shift due to selective pressures [134, 141].

The use of STRs for aDNA analysis could have a great potential. Defined for their small amplicon size, these markers would be likely candidates for use with degraded and fragmented DNA [69, 94, 142]. However, when aDNA is implied, mtDNA is still widely preferred over microsatellites for two main reasons: (1) the number of copies of mtDNA (103-104 copies per cell [95]) is present in larger quantities than nuclear DNA based markers and consequently, the chances of the presence of undamaged molecules also increase and (2) aDNA fragmented and damaged nature makes STR typing and interpretation a difficult task because of different allele sizing and stuttering artefacts [142, 143]. Technical issues related to DNA degradation and its interference with STR analysis in aDNA are still being addressed [142, 143] and need further verification for consistency and secure application.

The amelogenin gene: The amelogenin gene is, for example, widely used for sexing of archaeological samples and otherwise unidentifiable forensic samples [144, 145]. The amelogenin gene is a single-copy gene that can be found in both the Y chromosome and the X chromosome. Since the intron 1 of the gene presents a 6 bp deletion on the human X chromosome, the amplification product is a single fragment with 106 bp for females and two fragments of 106 and 112 bp for males [94].

Single Nucleotide Polymorphisms (SNPs): The recently discovered SNPs can be used for paternity testing but are more commonly applied to population genetics [146, 147]. SNPs are single nucleotide sites containing more than one nucleotide (G, A, T or C) that is present in the population [147]. As they require only a 20 bp primer to bind to the template and permit the detection of the nucleotide immediately adjacent, only very short portions of the genome are required for each SNP detection [147, 148], which makes SNPs particularly adequate to use with aDNA. In addition, SNPs can be potentially found throughout the whole genome, unlike STRs or mtDNA [146]. Ultimately, SNPs could potentially replace mtDNA sequencing in aDNA analysis, if diagnostic polymorphisms are known. SNPs can be used and a high throughput and relatively low-cost method to complement and authenticate results from otherwise confusing and controversial data provided by other molecular markers [148].

The Y chromosome: Semino and colleagues [149] have already made use of Y-chromosome based haplotypes to infer about human migrations and their data is consistent with two Paleolithic and one Neolithic migratory episodes. Furthermore, Mannen et al. [104] and Andreung et al. [150] have also applied Y chromosome haplotypes to clarify origins and genetic diversity of cattle and the Y chromosome of horse is now being thoroughly scrutinized for polymorphic SNPs [151]. Many researchers have proposed the use of Y-chromosome based markers (such as SNPs) to further clarify the origins and genetic diversity of several species [25, 152].

ANCIENT DNA UNRAVELLED

The success of aDNA analysis depends greatly upon the removal of PCR inhibitors that may be present upon initial extraction steps [77]. This is to say that the choice of the extraction method will determine the success of a study involving aDNA.

With the development and optimization of molecular techniques, several methods have been published and the choice becomes more and more critical. The focus of the following overview will be turned to methods developed for DNA retrieval from bone and teeth because that seems to be the most common source of aDNA. Because of the aforementioned unique features of aDNA, there are almost as many different methods as there are publications [53, 86, 94, 153-155]. Extraction methods are chosen bearing in mind the nature of the burial environment of the archaeological material to be analysed as well as the amount of sample that can be used [77, 155]. As burial conditions can vary greatly from site to site, methods can differ even within the same laboratory [94].

It appears, from recent research, that freshly excavated bones retrieve the best quality endogenous DNA probably because of the effects of the standard washing procedures for fossil bones routinely used by archeologists and paleontologists, combined with relatively high temperatures in post-excavation storage rooms [156]. The authors stress the need for closer collaboration between geneticists and archaeologists in order to plan the selection of a few samples from an excavation site if the study is to retrieve significant molecular data to complement the archaeological context.

The most commonly used extraction methods are the Silica based method [157] and the Phenol extraction [158], with variations and optimizations according to the aforementioned constraints [40, 53, 94, 153, 159, 160]. Recently developed methods allow to researchers to retrieve DNA from highly deteriorated sources such as bones by total demineralisation [161].

Pre-sequencing amplification methods also determine the success of aDNA analysis. If postmortem damage and the persistence of inhibitors even after post-extraction purification are present to a great extent, PCR reactions can still be inhibited. Of course, there is still no way of knowing whether there are inhibitors present and it is difficult to determine the amount of template present in the reaction, however the knowledge of general aDNA features aforementioned will help.

The most common step used for the construction of larger targets for sequencing from highly fragmented DNA is the overlapping fragments approach [9, 53, 160, 162-165]. This approach consists of amplifying several adjacent fragments using overlapping primers. This is to say that the primer from the second target fragment will start in a region before the end of the first target fragment [94]. The two main advantages of this technique as pointed out by Hummel (2003) are that (1) the primers can be designed and used independently without being limited to the same optimal reaction conditions (e.g. Annealing temperature) and (2) that the overlapping PCR is applicable to both direct sequencing and clone sequencing.

The multiplex approach is also used, although less frequently, among teams who work with aDNA [166, 167]. This approach has the advantage of using the minimum amount of sample possible because many target non-overlapping fragments can be amplified in the same reaction mix. Also, because all the fragments are amplified in a single reaction and from a single aliquot of template DNA, authentication potential is enhanced [94]. However, this method cannot be used when cloning of PCR products is involved in the authentication process. Since cloning is still a crucial criterion of authenticity [66, 68, 92, 143, 168, 169], this approach is not as widely used as the overlapping fragments method described above.

Sequencing methods have also improved over time and there are now alternatives to the original Sanger method [170], still preferred by Noonan et al. [171] for their Neanderthal genome sequencing project, which is based on the use of fluorescent chain-terminating nucleotide analogues and further visualization through either gel or capillary electrophoresis (the earlier has become obsolete with the emerging of capillary electrophoresis sequencers). The new method dispenses electrophoresis, labelled primers and labelled nucleotides [172]. It is based on the detection of released pyrophosphate (PPi) during DNA synthesis. The visible light generated in a succession of enzymatic reactions is proportional to the number of incorporated nucleotides [172]. The overall reaction from polymerase extension to light detection takes place within 3–4 sec at room temperature. One pmol of DNA in a pyrosequencing reaction yields 6×1011 ATP molecules which, in turn, generate more than 6×109 photons at a wavelength of 560 nanometres. This amount of light is easily detected by a charge-coupled device camera (CCD) camera [172].

Green et al. [13] have used a modified pyrosequencing method preceded by a new emulsion method for DNA amplification called the parallel 454 sequencing [173]. This method consists essentially of generating random libraries of DNA fragments by shearing an entire genome and isolating single DNA molecules by limiting dilution. Specifically the entire genome is randomly fragmented, specialized common adapters are added to the fragments, which are then captured on their own beads and, within the droplets of an emulsion, the individual fragment is clonally amplified.

The pyrosequencing approach has a higher throughput than the Sanger sequencing method [12-14, 172]. It does show a read error rate superior to that exhibited by the Sanger method [171]. However, with the correction methods developed by Green et al. [13], the novel method can be readily applied to high throughput projects such as the sequencing of large portions of genomes, which would have a much higher cost with the traditional Sanger method [172].

The new sequencing methodology has also permitted to study thoroughly the post-mortem damage to aDNA molecules and to establish patterns and mutational hotspots in order to modulate and predict this kind of damage [174]. This will be most promising to the future of Ancient Genomics and Archaeology.

Sequencing can be used to identify markers within a given genome. After these markers have been identified and studied within the population for variability, they can be used to retrieve information. Such is the case of SNPs. The minisequencing SNaPshot^{TM} reaction has recently been tested on human aDNA and it proved to be an effective way of putting SNPs to use in aDNA research [175]. SNPs were also put to the test and proved to be highly suited for aDNA analysis.

We are also convinced that the application of the new technologies to the screening of new polymorphic markers in the Y chromosome of several domestic animal species (such as horse, donkey, goat, sheep and so on) will provide a better insight to their origins and global domestication scenario as well as to clarify a few aspects of human migrations throughout time. By applying the found markers to aDNA, perhaps the big picture will be visible to all researchers who will then have the task of revealing it to people outside scientific communities.

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Chapter 5

METRIC AND GEOMETRIC METHODS APPLIED TO THE ANALYSIS OF ARCHITECTURAL DESIGN. URBANISM CHANGES AND THE EMERGENCE OF MATHEMATICAL THINKING

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ABSTRACT

Architecture is a feature of cultural expression and the interpretation of the culture by means of its architecture allow us to obtain relevant information about this culture. The geometric and statistical analysis from obtained data by means of new technologies (georreferencied CAD plans and 3D models mainly) constitutes an important tool to obtain the basic features of design of the prehistoric constructions. These methods applied to daily architecture relates the use of buildings to structure social relations, and the changes of the geometric design and the metric parameters in prehistoric dwellings are an important indicator of social transformations, social complexity, emergence of social hierarchy and other social modifications. Also reveal settlement planning and urbanism concepts, and the changes produced in these concepts reveals the evolution in the prehistoric urbanism.

The results obtained provide that the inhabitants of prehistoric periods acquired concepts of descriptive geometry, and the used geometric features to design the prehistoric buildings emphasize that the construction was accomplished using a previous geometric and metric design with great accuracy, and encapsulates a more general perception of power and space. The existence of metric and geometric rules used in the architectural constructions proves the emergence of a basic mathematical thinking in prehistoric times.

Several examples from Prehistory to Roman times are provided.

Keywords: *2D, 3D, architectural design, geometry, mathematics, metric*

The architecture of prehistoric settlements constitutes an element of prime importance to analyze prehistoric societies, since all communities have their own ways of perceiving the world, and this plays a fundamental part in shaping the building environment. The diversity and the specialization of scenarios occur in the complex societies, and architecture is a physical expression of power, wealth, social structure, symbolism, identity, etc. (Rapoport, 1990). The architectural structure and the concepts used in the construction of space are a basic factor to know the development of a society because social complexity determines the organization of constructed space, especially at the level of segmentation, and, as a society becomes more complex, behavior/use of space and material culture/architecture becomes more compartmentalized, more segmented (Chapman, 1990; Kent 1990). Furthermore, some authors argue that the structures of Çatalhöyük and other cities were constructed as examples of a tiered cosmology comprising three interacting levels: an upper and a lower realm and, between them, the level of daily life (Lewis-Williams, 2004).

In prehistoric times, architecture was part of mathematics and the two disciplines were indistinguishable. Architecture was strongly associated with geometry and metric features, and these ideas evolved a particular perception of the world. Therefore, the planning of great constructions (fortifications, monuments and even that of whole settlements) often encapsulates a more general perception of space, which is shaped by the function and the symbolism as much as the topography (Bradley, 1998). The construction of buildings required the ability to plan and skill in engineering, implying skilled builders (Trigger, 1990). The archaeological record provides numerous examples of architectural structures with design and construction very well adapted to the principles and rules of elemental mathematics and geometry. Geometry is found in many places, as the Mediterranean Middle East, the great megalithic constructions at Stonehenge, the complex fortified settlements in south-eastern Spain, the pyramids of Egypt, the Greek and Roman buildings, the Inca and Aztec temples and cities, etc. (Brunes, 1967; Blackwell, 1984; Hardaker, 2001; Wright, 2000). These constructions show great geometric knowledge that had been necessarily acquired by means of the transmission from a previous culture through time and space. The great quantity of architectural evidence, including structures designed based on the circle and regular polygons, suggests the existence of a common tradition. This is the same type of geometry that appears in a great quantity of archaeological sites, from China to the Mediterranean and the British Islands including simple structures with sacred and calendar interpretations (De Jong, 1988; Hartwell, 1998).

Geometry imposes constraints on space due to the geometrical properties of space and the geometrical foundations of design. Measurement was used for applied geometry in which lengths and even sublengths required measurement, but always by construction (Kapraff, 2002). Metric and geometric studies associated with architectural concepts are very important tools to analyze prehistoric communities and bring their own perspective to bear. The planning of monuments or even entire settlements includes a more general perception of space, determined by mythology, topography, taking of place, and social hierarchy, among other factors. These quantitative aspects can be detected throughout the construction, showing that an individual or individuals followed a pre-established design and coordinated the construction in every detail, demonstrating the existence of a basic constructive pattern of a cultural type (Esquivel and Navas, 2007).

Computation of metric parameters is difficult due to the bad preservation of the remains with poorly preserved structures, exacerbated by the irregularities and collapses in the walls over time. It is common to compute a single measurement to describe the complete design (for example, to assign the value to the radius of a circular prehistoric structure is used a single measure as the real radius), but this procedure lacks precision and depends on the points used for the measurement. However, metric parameters need be calculated with great accuracy and reliability to ensure good results. Statistical techniques help to avoid this problem by taking random samples of the preserved zones and applying inferential statistical procedures to obtain reliable values. This methodology gives good results in prehistoric structures, which are usually damaged, and other structures that have undergone severe damages.

Metric and geometric analyses of buildings constitute a major tool to obtain available archaeological information, and the new technological tools provide more detailed research with greater accuracy and shorter labor time. The most recent technological tools are focused mainly to georreferencied data, and its archaeological application is focused on artifacts and architectural structures.

2D CAD MODELING

CAD (Computer Assisted Design) software has the great potential in archaeological and architectural research since it can record the geometry and the metric parameters of their objects and develop and display 2D or 3D models. These models may be viewed from any point of view with any size, in perspective, isometric or axonometric drawings, as well as traditional plans and elevations at scale 1:1 or other scales. Furthermore, scaled dimensional information can be retrieved from the model, providing access to the geometry of the subject with the precision commensurate with the data registered. This software provides a powerful tool to analyze 2D archaeological plans of structures by means of a Cartesian relative coordinate system with an arbitrary point of origin (0,0) determined by the development of the excavation. The most usual system of coordinates is constituted by two orthogonal axes (X and Y axes) using the meter as the metric unit with the Y axis pointing north. This origin can be displaced to establish a new origin point and coordinates system such as UTM, allowing the linking of various plans, the measuring using metrics units, and so forth. CAD software provides highly accurate spatial results (Calter, 2000; Eiteljorg, 2002 and 2007). The geometric and metric capabilities of this software constitute the basis to carry out further analyses, and the conjunction with inferential statistical methods allows us to obtain the mathematical and geometric design in architectural construction. Also, it is possible to construct detailed virtual models of monuments (e.g. the Erechtheion at the Acropolis of Athens) adding the results of a diachronic examination including the time dimension (Blomerus and Lesk, 2007).

Many Egyptian, Greek, and Roman structures are well preserved, allowing accurate measuring (Psimoulis and Stiros, 2003), but the prehistoric constructions present serious problems in determining their metric parameters, because of:

- Poor state of conservation due to the stone with clay construction. This building method produces walls, terraces, bridges, roads, boundaries, and so on, but is prone to collapsing.

- Landslides alter walls and thus the original architectural design.
- The successive use of structures over the time gives rise to alterations in the original design.

These problems preclude the taking of a single measurement, for example the radius of a circular structure using the distance between the center and one point of the circle, because this measurement depends of the state of preservation of the structure. That is, a measurement of the radius at another point might give another value and, therefore, this measurement lacks confidence. A feasible method is based on statistical sampling using a random sample of measurements in each structure in order to obtain reliable results, such as confidence intervals, by means of statistical inference, a comparison of means by statistical tests to compute the differences between metric parameters of two or more structures, the analysis of symmetry with respect to an axis by means of coupled random samples, the study of standardization by means of the values of statistical coefficient of variation, etc. (Sokal and Rohlf, 1983; Venables and Ripley, 2002. Also, it is possible to compute the fit to mathematical models by testing a sample of parameters from the constructed structure in a poor state of conservation and the parameters obtained from a ideal and supposed geometric structure (Psimoulis and Stiros, 2004). Also, it can be determined whether mathematical models such as circle or ellipses are feasible for the current constructed adjusting geometrical curves applied to partial remains using a functional and a stochastic model fitted by least squares (Ziebart et al., 2007).

In prehistoric constructions the most commonly used figures are the circle and the ellipse, the regular hexagon, the equilateral triangle and the rectangle, besides axial symmetry. This perhaps due to the need for feasible designs to execute with elementary tools such as sticks and rope. Thus, the architectonic constructions have geometric simplicity and the builders understood basic principles of elemental geometry, and with these geometric figures the builders achieved elegant symmetries. Some authors suggest that these construction models serve as an intermediary between the unity and harmony of the natural world and the capability of the humans to perceive this order (Seymour, 1988; Kappraff, 1991).

THE ANALYSIS OF LOS MILLARES COPPER AGE SETTLEMENT (SANTA FE DE MONDUJAR, ALMERIA, ANDALUSIA)

Los Millares is a large settlement located on a promontory between the Andarax River to the north and the smaller Rambla of Huéchar river to the east; the south and south-west flanks are formed by a plain without natural defenses but have thirteen defensive forts, named "fortínes", located in the more prominent altitudes. The settlement has three wall lines: line A is the outermost one with small external and internal circular structures, while lines B and C have internal circular structures, and an inner citadel. The entrance is fortified and very elaborate by means of a barbican and the external wall has defensive bastions. All structures were built in three constructive phases with stones of various sizes (mean length of 0.40-0.50 m). There are 80 passage graves outside the area enclosed by the three walls (Arribas et al., 1985) (Figure 1).

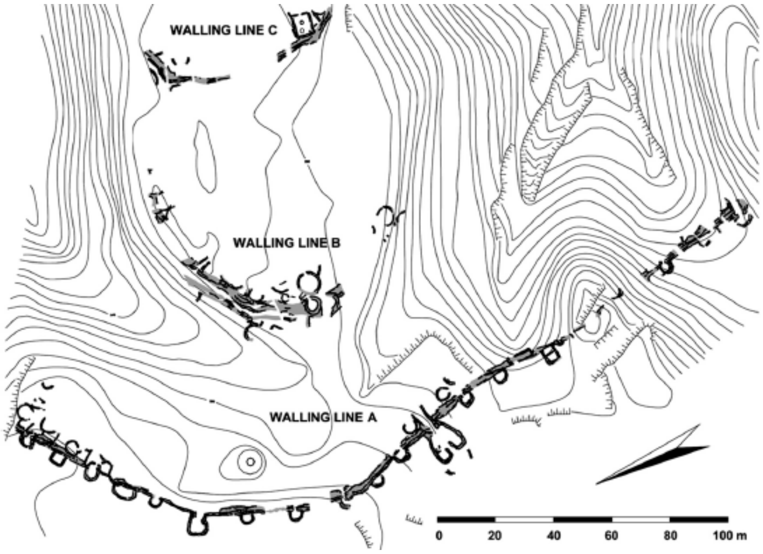

Figure 1. Map of Los Millares showing the excavated settlement area.

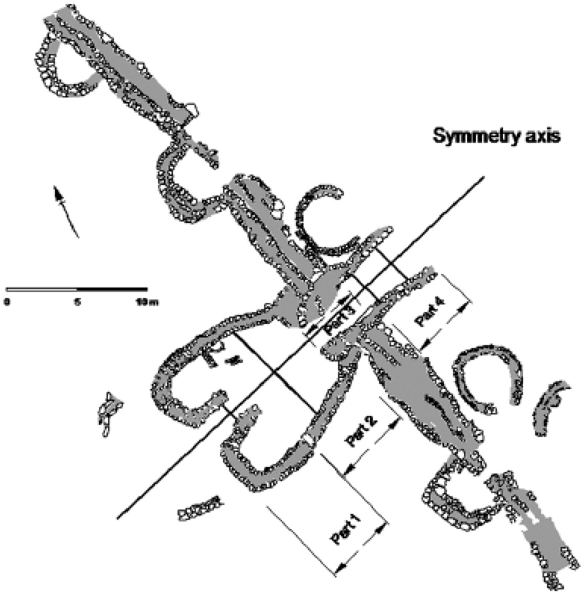

Figure 2. Map of barbican including ideal geometric figures.

Wall line A follows the irregularities of terrain, having circular, rectangular and elliptic bastions. The statistical study provides an important result: the mean radius is 1.07 m for external circles versus 1.69 m for interior circles, and the most plausible explanation is that external structures are smaller because this shape is more resistant from a defensive point of view. In wall line B, all circles have a radius greater than 2 meters, maybe due to these circles are internal and used as dwellings. The difference between the two wall lines may be due to social differences between the inhabitants of the two areas, those of wall line B having a higher social status. Also, the mean widths of structures in wall line A are larger than those in wall line B (in B, all structures have mean widths of <1 m), and the t-Student's statistical test applied to a random sample indicates that the difference between the external and inner structures in wall line A is almost the same as that in wall line B, although external and internal structures in line A are wider than those in line B. These results confirm the hypothesis that wall line A has more defensive features than wall B, and the difference in mean width between external and internal structures is similar in both lines, showing a well-defined construction pattern. Finally, the skill of builders is contrasted by means of the coefficient of variation C.V. ($\sigma/\bar{x}$) with values ranging from 5.13% to 14.55%, providing great accuracy and standardization in width.

A defensive and monumental barbican 8 meters long constitutes the entrance of settlement and is formed by two curvilinear branches with the same shape, size, and width. Drawing an ideal West-East axis aligned with the entrance path to the settlement, the distance between each symmetrical point with respect to this theoretical line of two random samples were analyzed by means of the non-parametric Mann-Whitney test for dependent samples, providing no significant differences between the two sets of points ($\alpha<0.05$). This theoretical line is a symmetry axis that divides the barbican into two equal areas and embodies the underlying complex geometric concept used in its construction. That is, the geometrical symmetry along an axis indicates the level of mathematical understanding of the builders. Therefore, the width varies according to the four basic well-defined parts: 1) the part that includes the two circular structures at the entrance, 2) the part that progressively narrows towards the narrowest part, 3) the narrowest part, and 4) the part that widens and opens up into the settlement interior. The analyses using random samples in each part show a uniform width in each section, with values in the coefficient variation ranging from 6% to 13%, again reflecting the mathematical knowledge and the care of the builders. Also, the two towers in the beginning had similar metric, geometric, and design features.

The design of this structure was carried out with great accuracy, following a well-determined geometric model based on symmetry, perfection in the laying out the paths, and accurate metric measurements. Architectonically, this structure is complex (Bradley, 1998), having an essential feature with regard to the settlement as a whole: it is perfectly symmetrical around an ideal west-east axis almost aligned with the presumed entrance path to the settlement. Many researchers propose that Los Millares and similar sites are part of a wider process of ‘‘creating place’’, constructing a significant symbol that expresses and reinforces the identity of the local population (Bradley, 1998; Champion et al., 1984; Jorge, 1999; Whittle, 1996).

The analysis of the Fortín 1, the most complex of all constituted by two concentric circles 44 meters in diameter with two constructive phases, indicates great accuracy in location of centers because the difference between the coordinates of the centers is $\Delta X=26.27$ cm. and $\Delta Y=10.42$ cm., and the difference between the width of the wall at inner enclosure is 12 cm. Also, the circular bastions have radius homogeneous, independently of their situation in the interior enclosure or in the exterior, and the rectangular bastions have similar to each other. Bastions are symmetrical with respect to east-west symmetry axis in both circles of wall. These results reinforces that there are very precise constructive rules applied to the walls of the enclosures, by showing a geometrically sophisticated and complex design with circles, rectangles, ellipses, a hexagon, symmetry, and well-defined metric parameters (Figure 3).

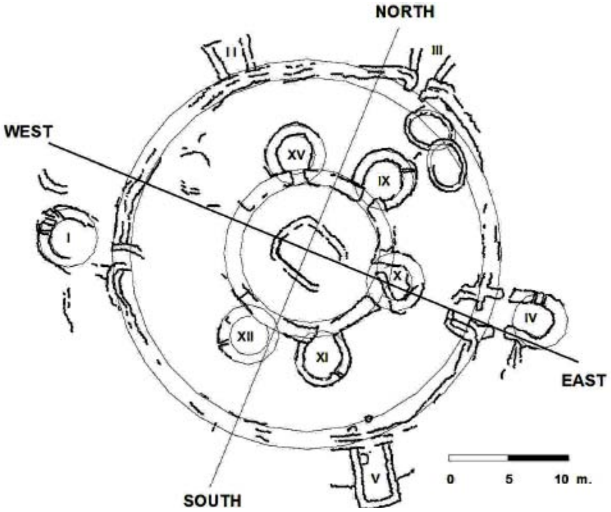

Figure 3. Map of Fortín 1 showing geometric figures.

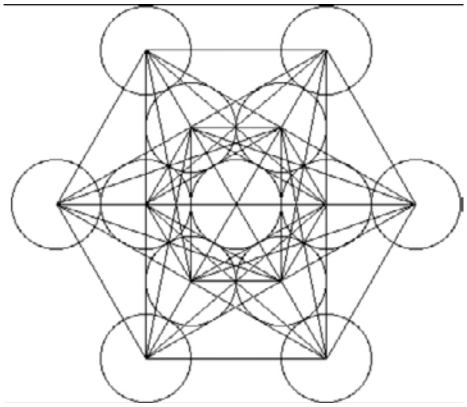

Figure 4. Metatron Platonic Solid Cube.

The Fortín 1 was constructed over time using sophisticated design patterns , demonstrating the builders had exhaustive knowledge of geometric procedures besides metric and geometric features (Esquivel and Navas, 2005). In fact, the prehistoric people during the III millennium BC held some mathematical knowledge perhaps because forms, sizes, metric parameters, and the proportions derived from the circle frequently appear in nature (Blackwell, 1984; Kappraff, 1991). This design seems to be a simplified version of the ideal design of the Metatron Cube, a geometric figure composed of two-dimensional images of the Platonic Solids and other primary forms (Figure 4), but Pythagoras (572-496 BC) and Plato (428-347 BC) lived long after the third III millennium.

Some authors suggest that these models are an intermediary between the unity and harmony of the natural world and the capability of the humans to perceive this order (Seymour, 1988; De Jong, 1988; Kappraff, 2000). Such mathematical concepts were discovered because the circle constitutes an important symbol that served as the basis for countless defensive, domestic and ceremonial architectural structures, and originated a type of easily handled proportional geometry (Brunes, 1967; Blackwell, 1984; Sherrat, 1990; Weigand, 1995). The use of the geometry in the constructions extends to many areas (Kappraff, 2002; Bernardini, 2004) and the appearance of the geometric and mathematical thinking in the European Mediterranean area in prehistoric times constitute a key result (Esquivel and Navas, 2005 and 2007).

3D MODELS FROM 2D PLANS. ENERGY AND EARTHQUAKE-RESISTANT ANALYSIS

CAD software can be used to construct 3D geometric models using the values of height of each vertical architectonic structure, and the three spatial dimensions (X,Y,Z) of basic constructive elements reveal metric parameters as volumes. Division into minor architectural components allows us to use the plan of monuments or settlements as the basis for analysis, and provides the computation of metric and geometric parameters (weight, volume, etc.) of each basic unit of construction such as stone blocks, cover stones, columns, and lintels. Taking into account all the basic architectural units, it is possible to estimate the parameters of groups of constructive linked blocks such as entrance, walls, etc., and compute the parameters for each block and the overall parameters in the building.

A noteworthy result is the calculation of the volume of structures and the internal empty of the building, these being indexes of effort expended by the community. Therefore, using the specific gravity (weight by volume unity), it is possible to estimate the masses and weight of stones that comprise the structure. These results can reveal the labour invested in the construction of structures and a quantitative energy analysis makes it possible to estimate the physical and social parameters of the construction (Abrams, 1994; Abrams and Bolland, 1999). Based on the observations by Erasmus (1965) a usual estimation is that two person/hours (PH) were required to construct one cubic meter of stones, and according to the digging experiments by Erasmus, an eight-hour working day is assumed (Bernardini, 2004). Also, knowledge of source of construction materials allows us to estimate the person-hours involved in their construction and the number of laborers and durations of construction. In addition, other important matters must also be analyzed, such as the ‘‘labor catchment area’’ or the territory from which people must be drawn to provide the required number of workers, the number of days per year devoted to communal projects, the parameters concerning the transport of materials, etc. must be carried out also. These analyses demonstrate the importance of the scale of social parameters and social interaction (Bernardini, 2004).

Another important issue to investigate is the earthquake resistence analysis of buildings. The quantitative model provided by 3D CAD software enables us to evaluate the earthquake resistance of constructions and the engineering knowledge of prehistoric architects to construct earthquake-proof buildings based on the architectonic and geometric design. This is an important feature to study the collapse of buildings due to earthquakes stress. Recent archaeology contributes to the study of earthquake activity by identifying the damage caused by historical earthquakes, although the archaeological evidence for an earthquake is not always clear or unambiguous (Ambraseys, 2006). Other studies seek to analyze the occurrence of great earthquakes or groups of earthquakes occurring in areas having major fault lines. This offers evidence for the hypothesis that a number of the sites were partly or totally destroyed, and earthquakes even destroyed entire societies. These studies have been performed in major areas as the eastern Mediterranean region (Ambraseys and Jackson, 1998), revealing that earthquakes and earthquakes storms occurred in the Late Bronze Age Aegean and eastern Mediterranean (Nur, 2000). Also have been studied earthquakes occurred in well-located archaeological areas, such as Thera during the Late Bronze Age (Cioni et al., 2000), and the Minoan palaces on Crete were abandoned probably because of changes in the groundwater supply induced by earthquakes (Gorokhovich, 2005).

Architectonically, two crucial topics are the analysis of the earthquake-resistant construction and the engineering features of the buildings and other constructions. The construction of buildings adapted to seismic risks has many unknown variables, ranging from the earthquake features to the characteristics of the buildings. The structural features of earthquake-resistant buildings can be stated by seven basic metric and geometric principles related to proportionality, symmetry and the distribution of loads principles in order to prevent overstresses anywhere in the load-carrying structure (Kirikov, 1992). These principles can be tested through 3D CAD models, indicating that antiseismic features were carried out reflecting the mathematical and engineering knowledge of the builders. Probably this knowledge was empirical, acquired by construction experience, and the prehistoric builders perhaps did not plan for the resistance of earthquakes but rather they obeyed general principles meant to maintain the integrity of structure, evaluating the combined action of such natural effects as wind, snow, and earthquakes, etc.

The metric and geometric analyses provide key social features also. That is, a study of the change in the design and construction of architectonic structures reveals shifts in the perception of the world. Constructive changes in fortifications or dolmens indicate modifications in the traditions but maintaining certain principles such as circular shapes (Bradley, 1998). The maintenance of the same geometric principles until Later Bronze Age suggests similar archetypes to organize different structures, perhaps indicating the use of similar symbolic code as the primitive designs of monuments.

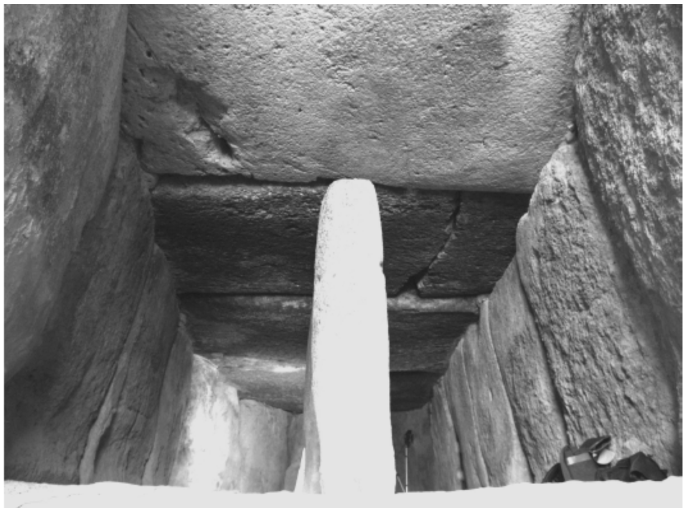

Figure 5. Chamber of dolmen of Menga (courtesy of the Research Proyect “Nuevas Investigaciones en los dólmenes de Antequera, Málaga)”.

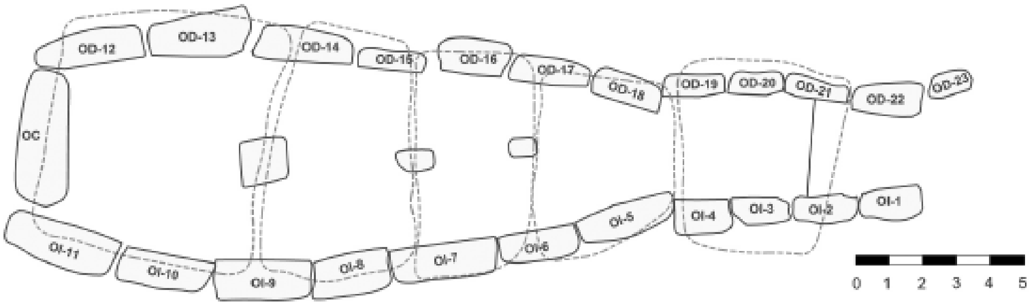

Figure 6. The plan of Menga dolmen shows the differences between the left and right sides. Shaded lines are for the cover slabs.

MENGA DOLMEN (ANTEQUERA, MALAGA, ANDALUSIA)

The neolithic Dolmen of Menga belongs to the megalithic group located in a strategic area of Antequera (Málaga, Andalusia) between the Guadalquivir Valley and the Granada Basin. It is a large gallery 24.81 m long and 2.87 m height (internal measurements) and is formed by colossal stones with an corridor and an oval chamber covered by a barrow 38 m in diameter. This monument is very similar to other European megaliths with large stones that provide singular features with respect to most dolmens (for example, the cover slabs range from 50,000 Kg. and 150,000 Kg) (Figure 5).

The 2D plan shows differences between the two sides along the longitudinal axis: viewed from the entrance, the mean width of the slabs on the left side (0.9563 m.) is greater than the other (0.7975 m.), and the coefficient of variation is smaller in the left lateral (CV=16%) than on the right (CV=26%). These results point to an intentional construction maybe due to such factors as the working of the stones or the decision to conclude the construction quickly (Figure 6).

Application of the t-Student's statistical test to the length of the vertical stones reveals that the differences between the stones in the chamber (mean 2.48 m.) and the corridor (mean 1.69 m.) are statistically significant ($\alpha<0.05$), the vertical stones in the chamber being longer than in the corridor. This result demonstrates that the constructive design was focused to establish a major differentiation between the chamber and the corridor using different metric parameters. Furthermore, the nonparametric Wilcoxon test applied the vertical length matched stones with respect to the symmetry axis indicates no statistically significant differences between the left and right sides of the chamber, or of the corridor. Also, the Pearson correlation coefficient shows ($r=0.77$) the existence of a basic constructive proportionality between the width and the length of the vertical stones. These results demonstrate that the geometric design and the metric features include an evident division between chamber and corridor, and the builders applied a basic but essential mathematical knowledge.

The use of the 2D plan and the mean height of each vertical stones and cover slabs provided a 3D ideal model by the elevation of 2D CAD objects; this showed an entire view of the design, reflecting the monumentality of dolmen (Figure 7). This feature shows that its scale and elaboration exceed of requirements of the practical functions of a building, and its great scale and the expertise of skilled specialists are striking. Probably the splendor of such buildings reinforces the status of rulers, of the political state or of their protective gods (Trigger, 1990). Other authors propose that the energy spent on architecture is positively related to the hierarchical complexity of political system, constituting an expression that architectural complexity is synonymous with positions of power (Parker Pearson and Richards, 1994).

This model offers us 3D displays of the monument from many perspectives, enabling an architectural energy analysis. The modifications carried out by the inhabitants of Antequera had modified the landscape substantially and allows us to deduce important energy information, such as the distance to the quarry, the processes for procuring the blocks of stone, the method of transport from the quarry to the dolmen, the previous earthwork labor, the laying of foundations, the method of lifting the cover slabs. These considerations allow us to estimate the volume and the weight of the entire dolmen and each single structure, as well as the volume of the inner empty vanish also, but it is not possible to compute the number of hours or days of labor, the number of workers, etc.

The volume of vertical slabs varies with respect to the chamber and the corridor, ranging mostly from 5 m^3 to 9 m^3, and highlights the vertical slab located at the end having 17.48 m^3. The volume of cover slabs is greater, ranging from 22.30 m^3 to 38.31 m^3, while the slab at the end is colossal in volume (78.48 m^3). The estimation of entire volume is 345.85 m^3 including the central pillars. This quantity of stone explains the difficulty of accepting the theory of the constructive method by which the inner space is filled with sand, the covering slabs are then dragged by sleds, and finally the sand is cleared away because the energy spent is too big.

Using the specific gravity of each stone (two types of chalky rocks and sedimentary rocks), we can calculate the entire weight of the material as 725.36 Tm, and the end cover slab has a colossal weight of 156.96 Tm. The great weight of the cover reveals that, in the construction, weight was used as the principle to maintain the stability of buildings rather than cement, and the weight contributes to the structural stability of monument (an improved technique of this constructive method was used by the Egyptians).

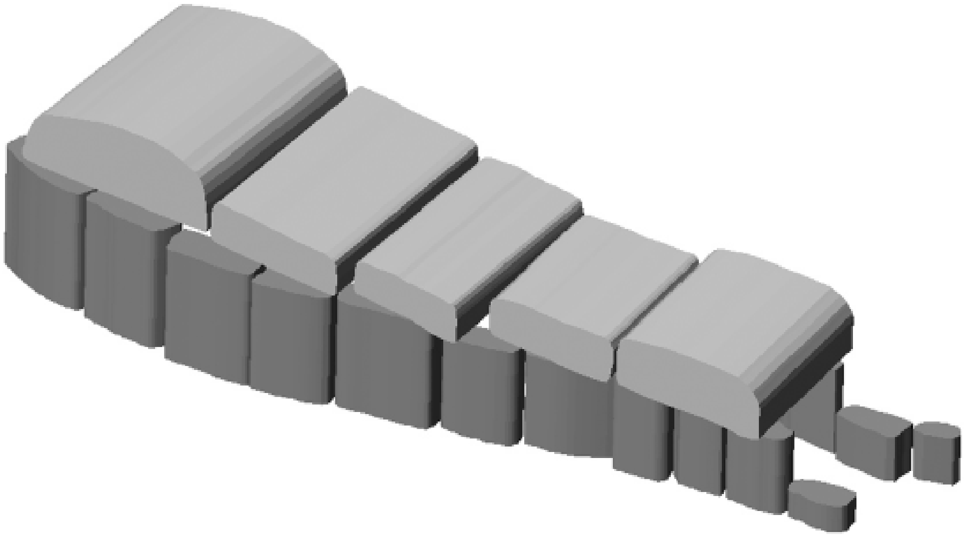

Figure 7. View of 3D ideal model developed from the 2D plan.

Using the previous results, we can estimate the pressure supported by each vertical slab and each pillar of this monument due to the weight of the cover slabs. All the vertical slabs of chamber support similar values of pressure: statistical methods give 8.37 Tm/m^2 mean pressures and a coefficient of variation of almost zero CV=3.76%, demonstrating an important mathematical and engineering knowledge. The pressures are not dependent on the dimensions of vertical slabs in the chamber, pointing to the skill of the builders that used the architectural technique with great accuracy to distribute the pressure evenly. However, the pressure induced by the central cover slab only is twice that of the chamber (16.056 Tm/m^2), a surprising value that has no explanation.

The colossal features of this monument, the careful geometric design and construction, the northern orientation that differs markedly with respect to the nearby dolmens in Antequera oriented eastwards, the great open area surrounding them and the view of the fields of Antequera basin (more than 700,000 km^2 area) imply that the functionality of the Menga Dolmen may be have symbolic features, taking of place, identity, etc..

3D MATHEMATICAL MODELS FROM LASER SCANNER TECHNOLOGY

Emergence of 3D laser scanning has provided a new technological tool for archaeological research to construct geometric models in digitalizing objects of different sizes (settlement structures, sphinxes, statues, etc.). Most recent works have been focused on modeling structures in the excavation of archaeological sites, either of only one zone (Doneus and Neubauer, 2005) or of the complete excavation (Gaisecker, 2005), as in the computerized reconstruction and the structural analysis of a house built with whale bones in Thule at the end of the 12th century (Levi and Dawson, 2005) or the reproduction of the tomb of Seti I (Lowe, 2005).

The high-definition 3D laser scanner allows us to collect 3D data from a given volume in a systematic, automated manner, at a relatively high rate, in near real time using a laser ray to establish the 3D surface coordinates. Traditional methods such as theodolites, total stations and the more modern GPS technology provide accurate but relatively slow and cumbersome methods for gathering spatial data.

Three-dimensional scanning technologies are generally based on one of three methods having different technical characteristics and operational modes (Boehler, Heinz and Marbs, 2001): time of flight (the instrument emits a laser pulse measuring the time of flight, from which the distance to the object can be determined), phase comparison (the instrument emits a beam of light with a known frequency and phase and by comparing the emitted phases to the returned phases the distance to the object can also be determined), and triangulation (this system uses two sensors which simultaneously record the reflected laser pulse and determines the distance). The physical basis of 3D scanner laser is the following: with the velocity of light (c=300,000 km/s) and measuring the time t used by a laser pulse to revert from object, the distance d it is possible to determine using the expression $d = \frac{c \cdot t}{2}$. Therefore, the accuracy of device is constrained by the accuracy in measuring the time t. By scanning the entire object, we can compute the three-dimensional X,Y,Z coordinates of the points using a UTM global coordinate system or our own coordinate system.

Figure 8. Panoramic view of theatre showing preserved areas.

The recording of three-dimensional X,Y,Z coordinates produces a cloud of points including the basic features of images as color, brightness, hue, and saturation in RGB format. Later, computational methods are focused on building a 3D surface formed by triangles constructed by vertical and horizontal sweepings of contiguous points. This process has many problems because three points can be detected consecutively by the scanner but located far away. Also, the distance in each detection between consecutive points varies according to the distance and the angle between the monument and the scanner. The first approach to solve this problem is usually to limit the surface area of each triangle so that it should not surpass a specified limit, and thus large triangles are avoided. Another criterion concerns maintaining a smaller proportion between the edges of each triangle in order to avoid having triangles with great deformation that lead to computational artifacts. A third criteria involves keeping the angle between the triangle and the scanner close to 90º, providing to remove faces that seem correct by size but the are not detected by scanner this face (Esquivel et al. 2008, in press). Other computer processes including registration of meshes, debugging (fill holes, wrong intersections, overlapped zones), etc. are needed to establish the entire virtual model.

The model established is georreferencied because each point is represented by its X,Y,Z coordinates 1:1 scale. This result provides many useful archaeological features, such as:

- Drawings of plans and sections of archaeological structures with the accuracy provided the laser scanner (the most usual laser scanners provide errors smaller than 3 cm). These drawings can be produced by specifying of desired height, and thus showing many plans as horizontal sections.
- Measurements of the geometric features such as angles, perimeters, distances, surfaces, and volumes of the entire model or selected zones, providing important quantitative information such as the volume of stones used, the volume of the earthwork, the contrast between characteristic measurements of similar zones, metric basic parameters of the design, etc.

- Virtual reconstructions of modified or damaged parts, offering a virtual and dynamic image of the building that can be used for conservation and design of a multimedia system (Cosmas et al., 2001).
- Construction to conservation facsimiles in silicone or other materials, to balance cultural tourism with the needs of conservation, producing high-fidelity facsimiles of monuments (Lowe, 2005).

Many cultural applications to Culture have been carried out using 3D laser scanner technology, including interactive display applications, remote interactive 3D display, interactive virtual reality systems, archival recording, sculptural and architectural building elements, replication applications, etc. (Taylor, et al., 2005). In this study, we used a laser scanner to gather metric and geometric information from a Roman theatre.

3D MATHEMATICAL MODEL OF A ROMAN THEATRE AT ACINIPO (RONDA, MALAGA, ANDALUSIA)

The Roman city of Acinipo is a settlement (Ronda, Málaga, Andalusia) located over an Iberian oppidum, being a geographic and strategic site, 12 km. from the present-day city of Ronda. Also there are substantial remains from Neolithic, Bronze Age (Later Bronze Age mainly) and the Iberian culture. The settlement acquires major importance in the Roman period between the first and second centuries A.D., having terraced buildings, monumental entrances, defensive circular and rectangular towers, cyclopean walls and public buildings such as baths, a forum, and a theatre. The theatre has been excavated almost entirely in the rock (hole in the ground, gradins, proscenium, lateral open entrance and lateral closed entrance) except for the scenario and external constructions composed of stone blocks. Other zones, such as the upper gradins and the back zone, are not excavated (Figure 8).

Scanning, digitalization, and the 3D model construction were undertaken in the context of the research project “Automated Generation Applied to 3D Modeling to Preservation and Diffusion of Historic Heritage TIC-401”.

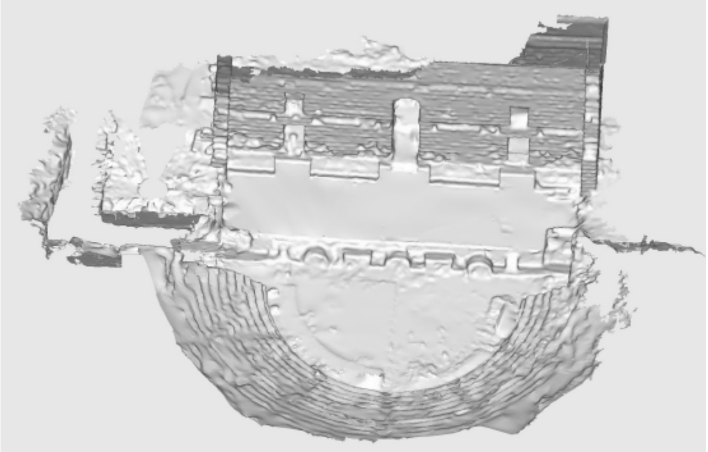

Figure 9. Virtual model of the theatre.

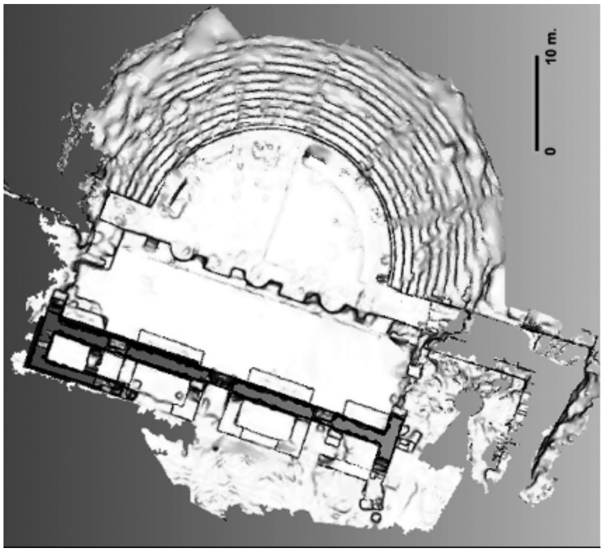

Figure 10. Plan of the theatre.

The author is mathematician and archaeologist, and belongs to this research team with computer-graphics researchers. We used a 3D Laser Measuring System composed of a Callidus CP 3200 laser scanner equipped with a CCD digital camera and a PC controller, using 0.25º horizontal and vertical resolution.

Two models were produced using the view captured. The first one is composed of 1,000,000 triangles having a mean error of 5 cm, enabling us to make suitable drawings and measures. The second one will have 15,000,000 triangles with a mean error of 1 cm and it will need an upgraded computer to manage it.

Another drawing including a complete plan (Figure 10) and the measurements of structures can be derived from the virtual model. Also, the virtual modeling will be used to carry out the reconstruction of the theatre.

Quantitative metric analyses have been made to determine the underlying geometry. First, the entire theatre has a planar symmetry with respect to a vertical plane orthogonal to the wall of scenario that divides the scenario into two equal parts. The symmetric structures have similar measurements: the mean radius of proscenium arc is $\bar{x} = 1.27$ m, $\sigma = 0.03$ and CV=0.02%, and the rectangular structures are 2.56 and 2.57 m long and 1.45 and 1.44 m wide. The width of the external rectangular structures embedded in the external range belong the interval 1.16-1.18 m, and the width of orthogonal walls ranges between 0.91 and 0.93 m. The two rectangular structures on the scenario nearest to the great gate measure 5.45 m and 5.47 m, and 145 m and 1.44 m in width. However, the structures in the coins have similar measurements among them but shorter in length (3.78 m. and 3.84 m.) and greater in width (1.52 m. and 1.49 m.) than the other. This design is usual and follows similar parameters as other theatres. The building verifies the resistant earthquake construction principles established by Kirikov (Kirikov, 1992).

The gradins are parallel arcs of circles and were excavated in the rock with a 160.52º span. A central stair is located on the gradins along the symmetry axis with the central gate, and there are two symmetric stairs with respect this axis on each side with similar angular amplitude ($\bar{x} = 26.9^{\circ}, \sigma = 0.73$, CV=2.7%), and another two stairs located on the ends with 21° amplitude also. There are eleven rows of undamaged seats, but other rows are perceived and the distance between each consecutive line of seats ranges between 0.76 m. and 0.80 m. The t-Student's test gives statistically significant differences between these values ($\bar{x} = 7.19$ m. and CV=7.1%), but these differences fit to a normal distribution N(7.19, 0.623), providing randomness in the data set. Taking into account the visible and marked erosion of stones, previous estimations demonstrate the existence of an elaborate geometric design carefully carried out by the architects and artisans that excavated the proscenium, the gradins, stairs on gradins and the lateral entrances on the rocks. Also, the equal distances between the arrays of seats point out that there were no privileges with respect to the comfort of the seats, but probably most important people sat in other seats, such as the destroyed ones over the covered entrances.

The Romans had major mathematical and geometric knowledge that their builders applied to the public buildings. The theatre of Acinipo reveals a careful architectural design and construction in a minor area, showing the great importance that the Roman rulers given to the public buildings, probably to reflect the power of Roman civilization.

CONCLUSIONS

Architecture provides answers to material and spiritual needs of the people, and monumental architecture is associated with complex societies. Over time, construction design appears steadily more important and the public constructions (walls, dolmens, etc.) become more elaborated and differentiated (Trigger, 1990) and the planning of monuments and even that of whole settlements includes a more general perception of space, whether determined by mythology, topography, taking of place, or social hierarchy, etc.. Also the perfection of construction, the labor involved, the great volume of stones used, the careful construction, the geometric design using regular figures, and the symmetric features all reveal defense, power status, resources control, identity, and so on. Finally, the splendor of the edifices may proclaim and reinforces the status of rulers, of their protective gods, and the political entity (Trigger 1990).

The architectural features demonstrate that the builders or "architects" knew basic metric concepts with great accuracy and made precise measurements. In prehistoric times, the metric and geometric parameters of building were applied probably by using a rope of a given length and multiples and submultiples. The builders knew basic geometric figures as circles, rectangles and ellipses, as well as other more sophisticated concepts such as the symmetry that require a higher level of mathematical concept. Repeatedly applying the basic mathematical operations of additions, subtractions, multiplications, and divisions, and they gave rise to construction metrics and the mathematical thought of prehistoric people.

The use of new digital technologies (2D y 3D measurement) provides major tools to carry out measurements with greater accuracy than other methods. Software and hardware tools provide such archaeological information on the design, metrics, mathematical concepts used, skilled and careful construction, aesthetic harmony of structures, etc. These applications require high-quality digitizing systems to record the sizes and archaeological materials as well as a variety of display and data-processing systems. Also, the statistical methods applied to the measurements provide underlying results showing standardization, symbolism, power, constructive pattern of cultural type, and so forth, indicating the emergence of mathematical concepts in prehistoric times. These mathematical concepts expanded over time until the emergence of Greek geometers that systematized geometry. These quantitative aspects emerged in the entire construction, showing that an individual or individuals carried out a previously established design and they coordinated the construction to the most minimum details.

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Chapter 6

STRESS DIAGRAMS AS A STRUCTURAL DOCUMENTATION OF AN ARCHITECTURAL HERITAGE

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ABSTRACT

The architectural heritage is the most cognizant element of the cultural heritage and considered as a major tourist attraction in the cultural heritage aspects. The value of any architectural heritage goes beyond its appearance to focus on its stability and on the consistency of all its components. The advancement of modeling and engineering analysis techniques helps to attain the required understanding of the morphology and the structural behavior of the construction. As early as civilization evolved, documentation of events, religion, culture and significant structures has been of utmost importance for further study and preservation. Therefore, the structural details with the graphical stress distribution for its main structural components may act as an essential engineering documentation for the building. An approach is the use of the structural software (SAP2000) to obtain the structural model of any historical building or its structural components depending on previously documented plans and sections and then analyzed. The obtained stress distribution contours could be useful to all personnel who may be involved in conservation and restoration problems. These documents serve as a tool to make structural information accessible to the archeologists or engineers during restoration to visualize the critical supporting structures that maintain stability for the building. Checking the documented stress contours for the structure will help reinforcing the structure where needed so as not to intrude upon the aesthetic and historical or archeological quality of the property by selecting the repair methods that are appropriate to the cultural context. The stress distribution contours in addition to other engineering documents can help thoroughly understanding the building in an effective, least destructive, most efficient and economical means. For complicated structural forms of architectural heritage that may cause a challenges in diagnosis and analysis, an experimental photoelastic method may be used to obtain a graphical stress distribution contours with clear optical identification of overstressed and understressed areas. From which, the intensity of stress at any point can be determined using lengthy mathematical calculations and should be scaled to indicate the behavior of the actual structure. This technique has been used widely in the past before the advancement of computer engineering analysis techniques. The choice between “experimental” and “analytical” techniques should be determined on a case-by-case basis depending on the complicity of the structural element and the difficulty of its modeling.

INTRODUCTION

Right from the beginning of the ancient civilizations, documentation of events, religion, culture and significant structures has been of extreme importance for further study and preservation. Built heritage seems to represent all the technical and architectural knowledge of the place. It is the product of the interaction of people, place and time. Figure1 represents schematically the interaction layers of built heritage. Every building should be engaged in a dialog with the history, beliefs and needs of a particular place and time. Place refers to the natural environment characteristics which gives rise to the architectural characteristics, and people refers to the users, builders, modifiers and to their culture and values, while time refers to past, present and future. The structural form of buildings is the geometrical configuration of the space involved by the structure forming the building envelope, usually defined by height, distance from its neighboring constructions and by projections. It represents a defined volume in the environment. That volumetric envelope is then somehow covered with a material (brick, plaster, wood, stone, cement, etc.) and generally of specified colors called the skin of the building. Various capacities of different materials, internal detailing of cross-sections, the manner and sequence of construction and the dimensions of the structure can cause different structural actions in similar overall geometry of the structures depending on the structural system used. Therefore, the geometrical configuration is only one aspect of the structural form [1].

The need to maintain safety for the world architectural heritage is becoming more and more widely acknowledged since it is mostly affected by modern development and growth. [2]. Based on the recognition that architectural heritage is one of mankind's priceless and irreplaceable possessions and that its loss through deterioration or disappearance, deprives the heritage of all the people of the world, stability should have the priority to think of. An architectural heritage has values which go beyond the facilities which it provides. In many cases these values derived from its physical characteristics, including those of its structure. The main factors that increase the value of any architectural heritage are the stability of its structure, the history and finally its over all appearance. All stability actions increase the requirements for a structural documentation to be referred to before any field work. Figure2. represents these factors in a triangular shape with the stability factor as the base of the triangle. In many cases, emergency stabilization is necessary to ensure that a structure does not continue to deteriorate prior to a final treatment or to ensure the safety of investigators, or visitors. Although severe cases might call for structural remedies, in more common situations, preliminary stabilization would be undertaken on a maintenance level for temporary stabilizing structural elements. Alteration of the structural characteristics cause reduction in the value of the building. Therefore, conservation, restoration, strengthening or even reconstruction of an architectural heritage requires comprehensive documentation of the buildings. Information regarding history, architecture, archeology, engineering and culture must be collected and organized to assure the accomplishment of stabilization with minimum alteration to any structural element. Therefore, the investigation of the structure requires an interdisciplinary approach that goes beyond simple technical considerations because any specific information may be obtained from overlapping of distinct areas. As an example historical research can discover phenomena involving structural behavior while historical problems may be solved by considering structural information. Therefore it is important that a team of varied skills and adequate experience take the responsibility of evaluating the building. Knowledge of the structure requires information on its historical origin, on its constructional techniques, on the processes of decay and damage, on alteration that have been made and finally on its present condition. [3]

Usually the documentation techniques are based on the significance of the building. Documentation may be limited to the exterior façades, while in some cases the significant interior architectural features and non-visible structural details would also be documented. The full documentation is essential in many cases to enable buildings restoration and maintain immediate structural stabilization if required. Relying on the value triangular assessment shape of an architectural heritage which consider the value of the architectural heritage is due to its stability, a full documentation for all valuable architectural heritages wherever they present should be conducted. In additions, samples of the construction materials should be tested for some mechanical and chemical properties. While documenting distinctive architectural, features which characterize a building or structure should be annotated clearly to be treated with sensitivity by concerned personal.

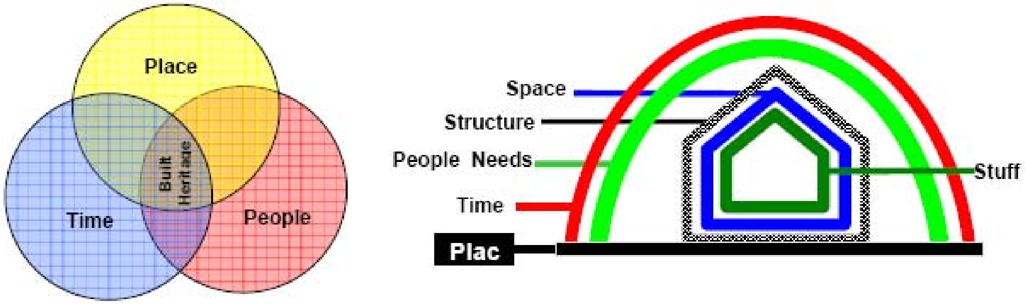


Figure 1. Interaction layers of built heritage.

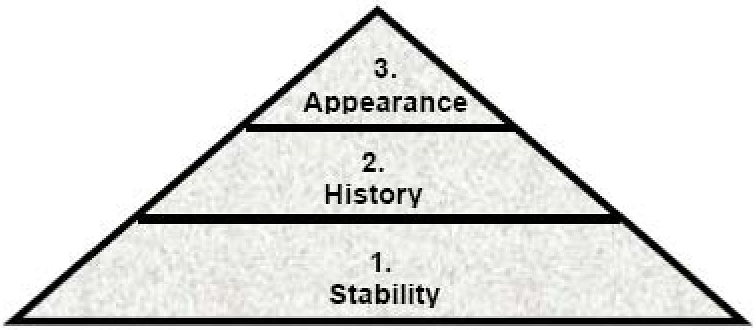


Figure 2. The value triangular assessment shape of an architectural heritage.

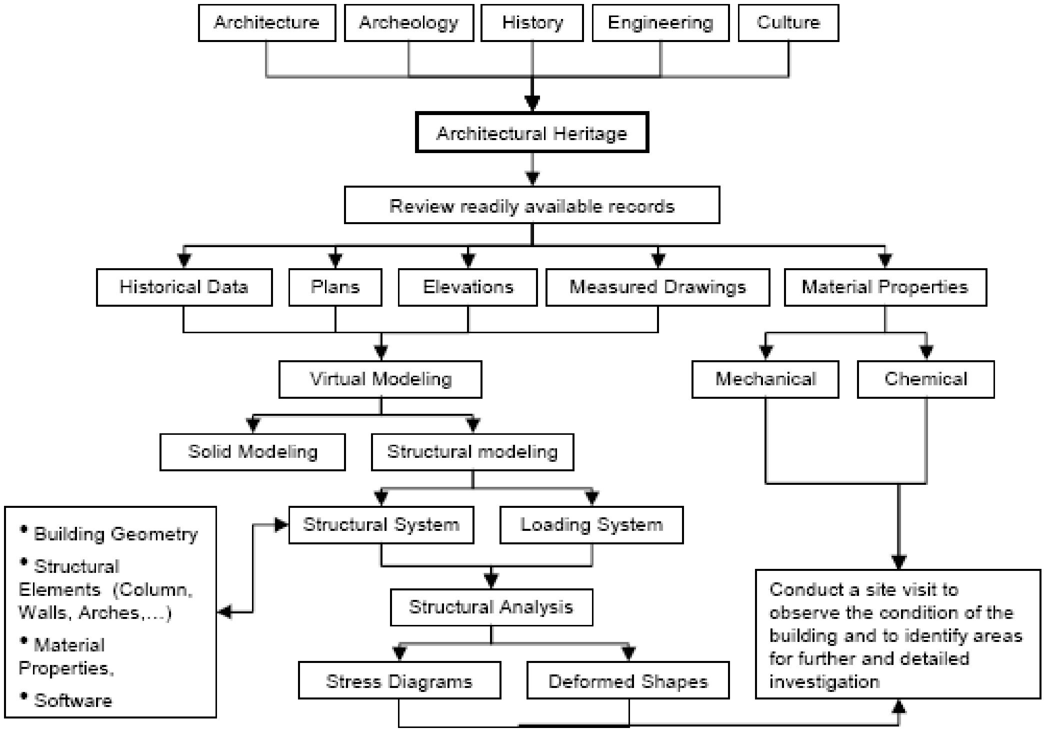


Figure 3. Flow chart of the documents required for assessment of an architectural heritage.

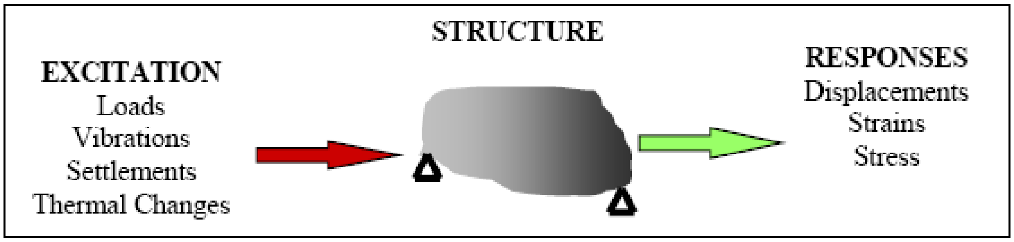


Figure 4. Simplified structural system.

ENGINEERING DOCUMENTATION

Architecture is an interdisciplinary field which combines mathematics, science, engineering, art, technology, social sciences, politics, and history. Accordingly all the related information for any historical building should be documented to every tiny detail to be used for protecting and preserving archeological buildings during stabilization, preservation, rehabilitation, restoration or reconstruction. Therefore, documentation is a detailed record, in the form of a report, images, models, test results, measured drawings, photographs or other written document, of the architectural heritage. Treatment techniques that should be followed based on collective, conclusions of an entire professional team. The architectural heritage may be diagnosed using qualitative and quantitative approaches. The qualitative approach being mainly based on direct visual observation of the structural damage and material decay as well as historical and archaeological studies, while the quantitative approach mainly based on material and structural tests, monitoring and structural analysis. [3] As this study focuses on the importance of the structural documentation, the flow chart in Figure 3 shows the records required for structural analysis and stress distribution output diagrams in a sequence to be followed before conducting a site visit to observe the condition of the building and identify areas for further and detailed investigation. Putting findings and conclusions in an accessible form helps those who are planning treatment. This study is illustrating the importance of the structural engineering documentation that may help in the assessment of the stability of the structure.

Figure 4 shows a simplified representation of a structural system indicating that the behavior of any structure is influenced by three main factors: the geometrical shape of the structural elements with their proper end conditions, the construction materials and the imposed forces.

If a rehabilitation of an archeological architecture is planned, careful structural and architectural investigation-together with archeological and historical studies provides a firm foundation for this goal. Architectural and engineering documentation are taken as a main foundation to rely on. They provide the knowledge that is necessary for any action to be taken for that building, and to avoid any improper, conflicting, ambiguous, or confusing requirements. Where the engineering documents can help thoroughly understand the building. Methods and techniques of structural documentation should be chosen for later accessibility to obtain the needed information in the most efficient way, and to manipulate and navigate through the most critical structural elements.

VIRTUAL MODELING

Virtual modeling is a digital description of an object that can represent its shape accurately and reliably using computer platform. A 3D virtual model used to represent objects in order to convey information in a visual way. Models are the main channel for visualizing, specifying, constructing, and documenting architecture. The so obtained models can be rendered to simulate the material color and texture and should be suitable to be used efficiently in different contexts. The model of architectural heritage in particular can be viewed with virtual reality to concerned personnel including investigators, historians, designers and engineers for further studies.

There are two types of modeling:

a. Architectural Solid Modeling

The architectural heritage virtual model of its geometry and skin can be a pictorial evidences that help archeology to study present, altered or even totally destroyed archeological architecture. Modeling depends mainly on other two dimensional (2D) records like detailed plans, elevations, sections and photographs. As computers becoming more powerful, the model generation of an architectural heritage will be easier and can be rendered to the exact material, color and texture. For any missing information or incorrect scales and mismatching measurements a further investigation can be followed through site survey, or interpreted with other existing buildings of the same architectural style. Literary evidences from history and written description of the building may play a great role in modeling and assisting in visualizing missing data. The next step towards modeling is the selection of the appropriate software for translating the orthographic projections into three dimensional (3D) digital representations. AutoCAD software can be used for 2D drawing and then exported to the 3D MAX modeling software.

The accuracy of the model depends on the initial input and capabilities of the particular software used in creating it. A virtual model can be very accurate depending on the requirements and application that it may be used for. When it is for visual presentation only the accuracy may be less than it the model will be used for other purposes. Higher model accuracy can result in finer details and features but usually at the expense of higher memory requirements.

With the Aid of CAD the following can be achieved [4]:

- 3D accurately dimensioned models can be constructed
- Surface and materials can be added to 3D solid models
- Lighting of 3D solid models can be included in scenes to produce a whole range of lighting effects, including color
- The resulting 3D models in scenes including the lighting can be rendered to produce realistic photo like representations of solid models with the aid of cameras incorporated within 3D scenes

b. Structural Modeling

Architectural design and visualization have been in a rapid and continuous change in the past decades due to the development in computer hardware and software technologies. Structural functions and principles are one of the essential components of preservation of architectural heritage. Architectural knowledge of the historical structural system is based on understanding the on time traditional building techniques which is considered as an essential task for protecting cultural heritage As the real structure cannot be analyzed and it can only be load-tested to determine its response, therefore, tools are required to model and to analyze the structure taking advantage of the detailed 2D drawings in addition to 3D model. Pre-survey of both the site and the building should guide the interdisciplinary team to select the most representative structural model. Historical data covering the entire life of the structure including both changes to its form and structural system should be gathered to assess structural modeling. The advanced computer utilities provide new horizons for the definition of the structural function of any historical structure. Almost in all engineering fields, Finite Element Analysis (FEA) plays an important vital role in modeling, and analysis of structures in addition to researches and design. It provides precise solutions and accomplishes cheaper and quicker results as compared to large laboratory experiments. Knowing that any structure can be considered as an assemblage of physical components called members such as slabs, beams, columns, Footings, etc. Then the physical members can be modeled by using one or more conceptual components called elements (1D elements, 2D element, 3D elements). Which may be frame element, plate element, shell element, solid element, etc. In complex structures, it is important to determine the level of simplification that will preserve realistic results in advance of the modeling effort. FEA can be used to examine the entire structure constructed of any material of known mechanical properties. It also explores overall performance of the total structure or individual elements. Within this framework, the strongest benefit of FEA appears in the analysis of historic structures. The geometry can be idealized in different ways, namely, by considering the structure to be made of linear elements, 2D elements, shell elements or fully 3D elements. The graphical outputs of FEA contribute to the ability of interpretation of result and can be easily understandable even for non-engineering personnel. Varied techniques are available for the structural modeling of actual structures. The geometry of the structure may be input either through the structural analysis program interface, or by importing a model from a computer-aided drafting program. Decisions on material properties, element types, meshing, boundary conditions, and loading conditions result from careful review of the structure in the field and of the literature on the particular construction method employed. As Material characteristics are the basic parameters for any calculation, detailed investigation should be carried out to be get precisely. This can be obtained by consulting reference material, by conducting tests on specimens of material extracted from the structure (semi destructive), and by methods of non-destructive evaluation. The principal material properties required for structural modeling are the compressive strength, tensile strength, density, modulus of elasticity and Poisson's ratio. Support conditions, have great influence on the computed results. For true representation of the structural behavior of the actual system in the FE model, boundary conditions must be represented as closely as possible to the actual conditions of the structure. The boundary conditions are dependent on physical properties and configuration of the historic materials. In many cases the choices are imposed by the analyst’s intuition.

The results of the analysis need to be interpreted in conjunction with a detailed inspection of the condition of the structure. Therefore, architects, architectural historians, restoration specialists and archaeologists can also be involved in the analysis of structural problems of historical buildings, where analysis is the point by point study of how architecture components of a building work in relation to any other part. 2D modeling of the structural parts and details instead of 3D modeling of the complete structure may simplify interpreting the results and minimize the effort of modeling. The deformed shape, graphical stresses and force distributions expose considerably true structural behavior of the structure in consideration, making it possible to visually detect stresses in various locations and then helping to reach simple and logical generalizations about the building stability. Any alteration can be studied on the model before selecting the technique on reality causing minimum damage to the building.

The importance of structural analysis of historical buildings is shown by Robert Mark [5] by using an optical stress experimental technique to analyze a Gothic structure showing the stress distribution under simulated wind loading. By the advancement of computer structural modeling the analysis of complex structures become feasible and simpler than the experimental technique. The actual behavior of the structure is usually highly complex and many simplifications have to be made in order to model it. To achieve a refined structural model, material behavior has to be simulated properly, supports and connection of elements have to be modeled and the loading has to be defined , [6],[7].

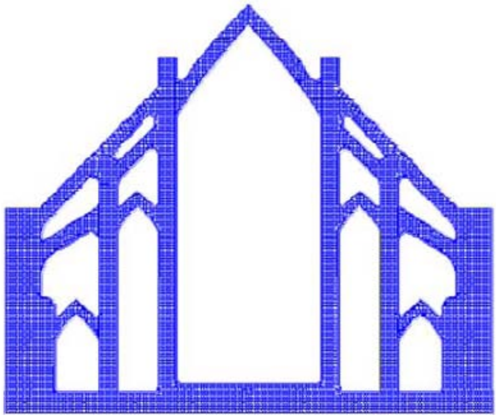


Figure 5. Structural model using 2D finite elements.

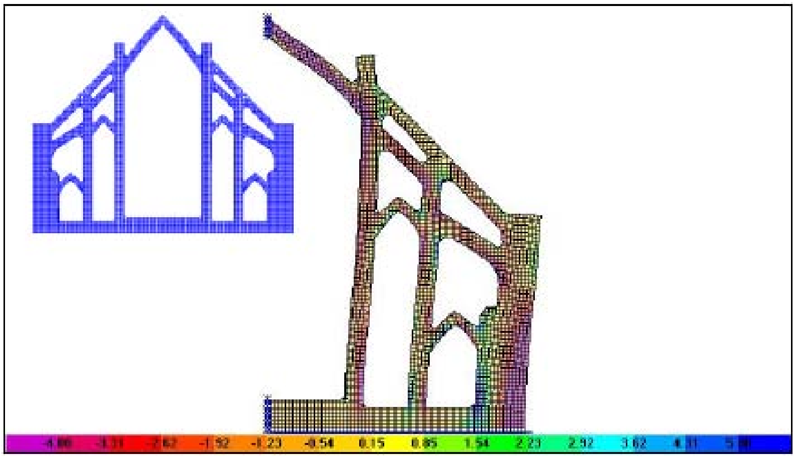
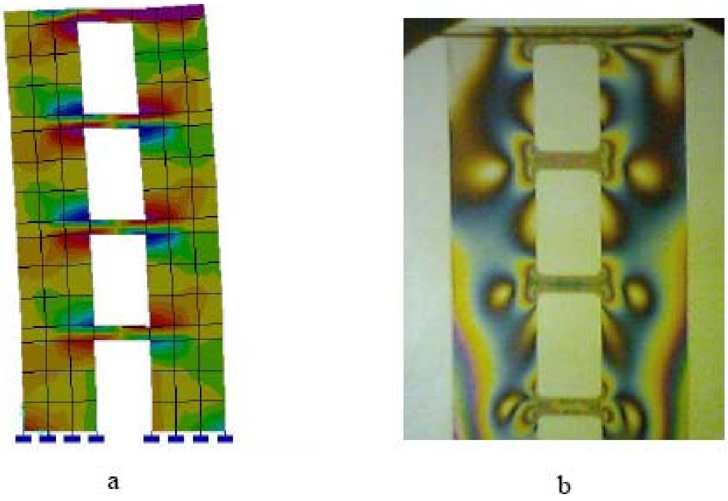


Figure 6. Stress intensity distribution on the deformed configuration of structural elements of a gothic building modeled and stressed by dead weight loading.

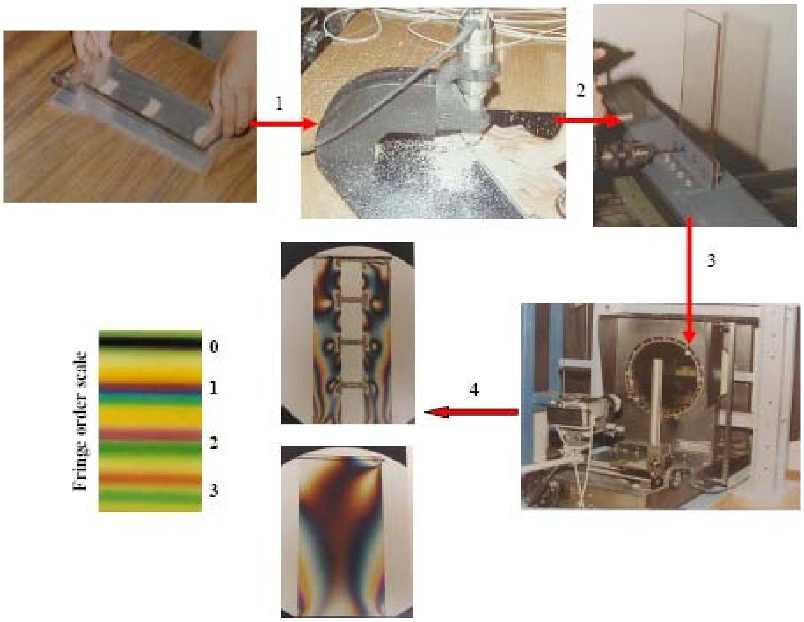
Depending on the goals of the study, two types of analysis are presented, one is the numerical analysis using SAP2000 software and the other is the experimental photoelastic technique. The numerical analysis using SAP2000 shows the modeling of a 2D section across a gothic building using 2D finite elements as shown in Figure 5, while the experimental photoelastic technique shows the graphical outputs of the stress contours for two different wall systems which may be used for visualizing the behavior of a structural form as shown in Figure 6.

The internal stress distribution can be visualized using photoelastic experimental method. Photoelasticity, from an experimental perspective, is the study of stress and strain field distributions within a loaded photoelastic specimen, as viewed under a polariscope. Such a system could be used in conjunction with the finite element method to analyze, optimize, and redesign structural components. This technique is explained in details by G.S.Holister. [8] and J. Dally [10]. The intensity of stress at any point can be determined using lengthy mathematical calculations and should be scaled to indicate the behavior of the actual structure.



a. FEA method.
b. Photoelstic experimental method.

Figure 7. The stress contour map in a wall system subjected to concentrated lateral load.



1. Cutting the model from photoelastic material.
2. Drilling the hole to prepare the support conditions.
3. Use of the polariscope to show the stress distribution contours in the model.
4. The Stress Pattern which can be analyzed according to the fringe order scale.

Figure 8. Model preparation and testing.

Figure 7-a. Shows the FEA stress contours on a deformed wall system affected by lateral concentrated point load, while Figure 7-b shows the same model photographed in the polariscope.

EXPERIMENTAL STRESS VISUALIZATION

The experimental technique used in this study is photoelasticity. It is one of the oldest methods used for experimental stress analysis involves applying a given stress state to a model and utilizing the induced birefringence of the material to examine the stress distribution within the model. The magnitude and direction of stresses at any point can be determined by examination of the fringe pattern, and related to the studied structure. It is a feasible technique for qualitative stress analysis specially for documentation. Finite element modeling has become the dominant technique, over many traditional techniques for stress analysis including photoelasticity. But many times there are many factors that affect the analytical analysis including the difficulty in fully understanding the complexity of an ancient building or monument, uncertainties regarding material characteristics, so photoelasticity may assist in understanding the structure. A model has a similar geometry to that of the structure on which stress analysis is to be performed should be prepared. This ensures that the state of the stress in the model is similar to the state of the stress in the structure. The model should be produced using a special material that permits the visualization of the stress distribution within the component. The material is typically a transparent plastic with certain optical properties that is illuminated while being loaded. Showing isochromatic fringes which appear as a series of successive and continuous different-colored bands each is representing a different degree of birefringence corresponding to the underlying strain. The patterns can be read like a topographic map to visualize the stress distribution over the surface of the tested part. Different colors mean different stress levels. As a matter of fact it provides a visual mean for observing overall stress characteristics of an object by means of light patterns projected on a screen or photographic film. Photoelasticity is generally used to study objects stressed in 2D. but with refinements it can be used for objects stressed in three spatial directions [9].

Figure 8 shows the steps for preparing and testing the models using photoelasticity to get the projected stress patterns on photographic films or a digital picture using digital camera.

SUMMARY

As the main goal of architectural preservation is to protect and preserve materials and features that transmits the significant history of a place . Careful structural and architectural investigation-together with archeological and historical studies provides a firm foundation for this goal. Studies on the structural behavior of historical structures present appropriate solutions in the assessment of structural performance. Therefore the methods and techniques chosen for archeological documentation should be the most effective, least destructive, most efficient and economical means of obtaining the needed information. Methods and techniques should be selected so that the results may be verified if necessary. Non-destructive techniques should be used whenever appropriate.

The Finite Element Method or the Photoelasticity technique may work as suitable tools for obtaining the stress distribution graphical output to be studied even for non-engineer colleagues, which provides a suitable structural documentation including stress contours for main structural parts which serves as a tool to make structural information accessible to the archeologists or engineers during conservation, reinforcement and restoration of architectural heritage to visualize the critical supporting structures that maintain stability for the building.

The Evaluation of a structure should be based on two dependable related methods. The qualitative study depending on visual observation and documentation and the quantitative study which includes mathematical modeling and testing for both material and structural system.

Checking the documented stress contours for the structure will help reinforcing the structure where needed so as not to intrude upon the aesthetic and historical or archeological quality of the property.

The visual study of the stress graphical contours can indicate the flow of the stresses and possible critical areas to worry about in stabilization or restoration. For example the material characteristics with time may be badly affected due to decay caused by chemical, physical or biological action. This will produce stresses and strains in the structure. If this decay appears to be in one of the structural critical areas indicated by the stress diagrams, then this will clearly identify the area to start with in repairing.

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Chapter 7

TRACING MINIMAL CULTURAL SIGNATURES: COMBINING NON-LINEAR AND LINEAR MICRO-ARTEFACT PATTERNING FOR INVESTIGATING CULTURAL SITE FORMATION PROCESSES

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ABSTRACT

The information potential of micro-artefacts can assist in archaeological interpretation. This paper presents a combination of a non-linear method (i.e., the spherical self-organizing feature map) and a linear one (i.e., Spearman's rho) that may improve the interpretation of micro-artefacts when investigating cultural site formation processes. An example is given on micro-artefact data from the Neolithic tell/extended site at Paliambela (Northern Greece).

Keywords: *Micro-artefacts, non-linear, spherical self-organizing maps, linear, pattern recognition, cultural formation processes*

1. INTRODUCTION

An archaeological deposit may contain particles (artefacts and non-artefacts) of numerous materials and size classes derived from various sources. The particles and their arrangement typically reflect a complex depositional history of natural and cultural processes (Stein 1987). However, complete analysis of an archaeological deposit is not an easy task. Micro-artefacts (i.e., cultural particles smaller than 2mm in diameter), due to their abundance and incorporation into the sedimentary matrix of an archaeological deposit, constitute a significant part of the cultural particles present (Sherwood 2001).

Moreover, micro-artefact analysis is extensively complex due to the different micro-artefact categories that may appear in an archaeological context and also because of the numerous cultural (and non-cultural) formation processes that may have been involved in the creation of characteristics specific to an archaeological context. Linear methods such as the Spearman's rank correlation and Pearson's correlation have been extensively used in the study of micro-artefacts in order to better interpret hidden structures/properties (e.g., Vance, 1987; Madsen, 1992; Rainville, 2001). These linear methods provide a means to sort relatively stronger covariants, either positive (values approaching 1) or negative (values closer to -1) from weaker ones (values closer to 0).

However, they are not able to deal with nonlinear characteristics of a distribution that are often inherent in multidimensional data. Instead, they depict the overall variance, shared by the two distributions, with respect to two or more variables. Nonlinear characteristics, inherent in the data, are therefore not revealed in the linear correlations. Thus, although the linear correlation methods provide a very accurate comparison of two isolated variables, they do not provide adequate information regarding the complete data set, which may be much more extensive than the sum of information contained in its parts.

Recently, the implementation of a non-linear method (i.e., spherical-SOFM) on micro-artefact data has shown that the method is able to recognize and to provide a visual representation of micro-artefact patterns prior to performing any statistical analysis on the data, providing a quick view into possible relationships or differences that may occur between temporally, spatially, and culturally different archaeological contexts (Kontogiorgos *et al*, 2007). In order to understand the reason for such variability the researcher should investigate the proportional relationships between different micro-artefact types.

This study proposes the combination of a non-linear (S-SFOM) and a linear technique (Spearman's rho) in micro-artefact analysis suggesting that it may help unravel the cultural information of these complex multidimensional data. The structure of this study is as follows: Section 2 describes the applied methodology. Section 3 presents the non-linear and linear quantitative relations on micro-artefact data and finally, section 4 presents the conclusions of this research.

2. METHODOLOGY

The micro-artefact data presented below represent only a part of a larger geoarchaeological project that aims to identify the processes that resulted in the formation of the Neolithic site at Paliambela Kolindros, in the Northern Pieria region, Central Greek Macedonia, Northern Greece which unusually comprises both a tell and an extended settlement (Halstead and Kotsakis 2001, Halstead and Kotsakis 2002; Kotsakis and Halstead 2004). The samples used in the present study come from sampling eleven (11) contexts (five ditches and six pits) of the Neolithic period. Three (3) pits of the Byzantine/Ottoman period were also examined for comparative purposes in order to explore micro-artefact pattern recognition on a broad temporal and spatial scale.

2a. Laboratory Procedures

A total of two hundred forty six (246) sediment samples were collected in columns at 5cm vertical intervals on the profiles of the contexts; ranging from 50 samples for the deepest contexts (i.e., ditches) to 10 samples for the relatively shallow pits and weighting ca 1500g each. The laboratory procedure used two divisions of the phi (ϕ) scale that is, -2.00ϕ and 0ϕ. Contents of the bulk samples were passed through a stack of 4mm (-2.00ϕ) and 1mm (0ϕ) sieves. The material retained in the 1mm sieve created the sub-sample that was processed for micro-artefacts and an optical microscope was used for identifications. To avoid damaging the artefactual contents (e.g., shell, bone) there was no pretreatment for removal of organic matter or carbonate. The sub-sample was saturated with 1% sodium hexametaphoshate and washed through the 1mm sieve to separate the sand fraction from the silt/clay fraction. For each sub-sample, 1000 particles were point-counted.

The identified micro-artefact types were: Microfragments of Unburnt Clay, Microfragments of Burnt Clay, Microbone, Microshell, Microfragments of Charcoal. To deal efficiently with the large numbers of samples derived from the contexts, and reduce the processing time, the point-counting procedure had to be applied. The procedure for determining the proportions of compositional types follows the one described by Stein and Telster (1989: 10-11). A small fraction of the sub-sample was poured gradually, into a glass petri-dish, below which was attached a piece of graph paper of no greater than 1cm graph intervals. The particles are spread evenly across the grid. While looking through the microscope, the particles located in one grid unit were counted according to compositional types. To improve the identifications and to observe more accurately the measurement error, 250 particles were counted and recorded each time, until a total of 1000 particles were examined (Kontogiorgos and Leontitsis, 2005).

2b. Non-Linear Method of Analysis (S-SFOM)

The Self-Organizing Feature Map (SOFM), introduced by Kohonen (1981), maps n-dimensional data into a low-dimensional space. In the spherical-SOFM (Sangole, 2003) the low-dimensional space is a tessellated sphere that is formed by subdividing an icosahedron. Every vertex on this sphere is a strategic location of an n-dimensional vector that represents an ensemble of similar data vectors which get assigned to the vector during the mapping operation. It is therefore necessary to visually enhance variations in the data using the physical attributes of the mapping lattice. The benefit of a spherical lattice in the implementation of the SOFM is that the enclosed space can be used to generate a 3D visual representation of some physical aspect of the n-dimensional data. Examples illustrating the various implementations of the spherical SOFM on different data and the use of possible measures to create spherical SOFM graphical representations are discussed in Sangole (2003) and Sangole and Knopf (2003).

The implication of using S-SOFM on micro-artefact data is that it enhances attempts for developing interpretations on micro-artefact patterning by providing strong pattern recognition (Kontogiorgos *et al*, 2007). The construction of the S-SOFM graphical representation was based on a database of 246 five-dimensional records each dimension representing a micro-artefact category (i.e., Microfragments of Unburnt Clay, Microfragments of Burnt Clay, Microbone, Microshell, Microfragments of Charcoal). Every row represented the point-counting results. A spherical-SOFM graphical representation was created as described in Sangole (2003), Sangole and Knopf (2003), and Leontitsis and Sangole (2005).

2c. Linear Method of Analysis (Spearman's rho)

Spearman's test of association was used to assess the quantitative relations between the various micro-artefact classes. A non-parametric statistic was chosen because these types of distributions often violate assumptions of normality.

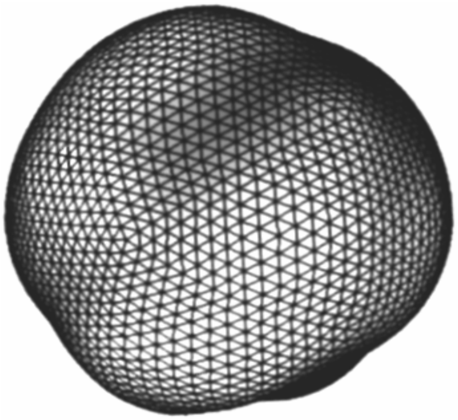

Figure 1. One view of the S-SOFM graphical representation showing the formation of two distinct white regions – the larger (bottom-right) corresponds to the Neolithic micro-artefact data, and the smaller (top- left) corresponds to the Byzantine-Ottoman micro-artefact data.

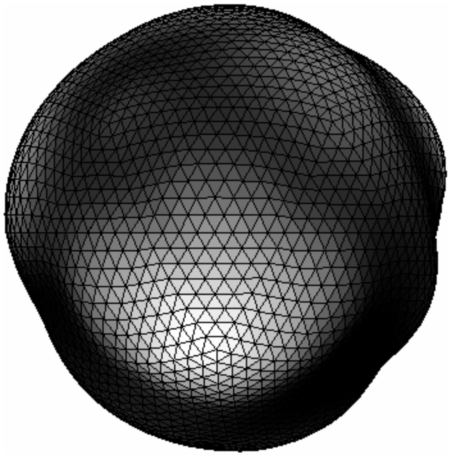

Figure 2. Second view of the S-SOFM graphical representation showing the formation of one distinct white region corresponding to the Neolithic micro-artefact data from the extended part of the site.

In statistical tests of association, correlation coefficients have a value range from –1 (perfect negative association between a pair of variables) to +1 (perfect positive association between a pair of variables). For the purposes of this study, a significance level of 0.05 or less was demanded, that is to say, that there are 5 (or less) chances out of 100 that the observed correlation coefficient value for a pair of variables could have occurred by chance.

3. NON-LINEAR AND LINEAR MICRO-ARTEFACT PATTERNING

3a. Non-Linear Micro-Artefact Patterning as a General Indicator of Differences in the Site's Contexts

Figures 1 and 2 present the S-SOFM graphical representation resulting from the micro-artefact database comprising the results obtained from point-counting. Figure 1 shows a formation of two distinct white regions that correspond to the data from the Neolithic and Byzantine/Ottoman contexts from the tell component of the site while in Figure 2 the white area corresponds to the data from the Neolithic contexts from the extended component of the site. This suggests that the Neolithic contexts from the tell and the extended part of the site as well as the Byzantine/Ottoman contexts are characterized by different multivariate distributions. A non-linear structure lies within this statistical space which can be distinguished into three separate sub-structures.

The spherical-SOFM pattern recognition procedure provides a comprehensive preliminary visual representation of inherent non-linear characteristics in data, serving as the initial step in the analysis of the multidimensional micro-artefact data. In this study three meaningful components were revealed – Neolithic contexts on the tell, Neolithic from the extended part of the site, and Byzantine/Ottoman contexts, which appeared to be the determinants for the constitution of the analysed data set. The next step is to understand the reasons for this variability by further investigating the proportional relationships between micro-artefact types.

3b. Linear Micro-Artefact Associations

The spherical-SOFM non-linear method revealed patterns among the data that linear methods are unable to classify. Furthermore, the method attempted to overcome the difficulties posed by the friable nature of the five classes of micro-artefacts- unburnt clay, burnt clay, bone, shell, and charcoal. Material characteristics and the process of micro-artefact generation, including the effects of post-depositional processes, were considered as important factors in the search for strong pattern recognition (Kontogiorgos *et al*, 2007). With these considerations in mind, the analysis has shown that similar classes of micro-artefacts in the three data sets are characterised by different non-linear associations. These observations further suggest that the three sets of contexts were possibly formed through different formation processes. The recognition that the complete data set of these complex multidimensional data exhibit strong non-linear characteristics, attributable possibly to different formation processes, warrants further statistical analysis of the data in order to explore the information contained in its parts - in other words, to investigate how comparisons among micro-artefact distributions can provide insights into the varied processes that form the site's contexts.

The statistical test (i.e., Spearman's test of associations) in the three ditches from the tell component of the site (Table 1) in each case indicates a significant positive relationship between shell and bone, suggesting a similar set of formation processes for these classes of materials. In contrast, unburnt clay and charcoal display indirect or insignificant correlations with the other materials in the three ditches. This suggests that a single distinctive formation process should be invoked to explain much of the patterning in shell and bone. On the other hand, burnt clay exhibits a significant positive correlation with shell in two of the three ditches (ditches 2 and 3), but with bone only in ditch 2. The different distribution patterns of burnt clay in the three ditches suggest thus that this material ended up in each ditch through different formation processes.

Significant variability was also observed in micro-artefact associations from the five pits on the tell (Table 4.2). In pit 1, only shell and bone display a significant positive association with each other. For pit 2, unburnt clay and shell exhibit a significant positive correlation with each other and with both the remaining microartifact classes (bone and charcoal), while bone and charcoal are positively but less strongly associated. In pit 3, by contrast, unburnt clay has a significant positive relationship with charcoal but a strong negative association with shell, while there is also a strong negative association between shell and charcoal. Finally, the analysis of pit 4 and pit 5 does not reveal any significant correlation, either positive or negative, between micro-artefact classes. These differences, therefore, suggest that each pit was subject to different sets of formation processes or was filled at a time when different sets of activity had been taking place in the vicinity.

Micro-artefact correlations for the Neolithic contexts on the extended part of the site reveal a different picture from those on the tell component of the site. In ditch 4, ditch 5 and pit 6 alike, burnt clay, shell and bone consistently exhibit a strong negative association suggesting a distinctive formation process for each of these materials (Table 3).

Finally, the statistical analysis of the three Byzantine/Ottoman pits consistently shows a significant positive correlation between burnt clay, shell and bone and a mostly negative association (of varying strength) between these materials and charcoal (Table 4). The results of this correlation suggest similar formation processes for burnt clay, shell and bone.

Therefore, the proportional relationships between micro-artefact classes in the three data sets indicate three basic patterns: a) more variable linear associations in the data from the Neolithic contexts on the tell suggesting different sets of formation processes occurring in the deposits; b) indirect relationships between micro-materials from the Neolithic contexts on the extended part of the site suggesting a single distinctive process for each material class; and c) direct associations (with the exception of charcoal) between different classes of micro-artefacts from the Byzantine contexts implying similar sets of formation processes.

Table 1. Micro-artefact correlations for the Neolithic ditches on the Tell (the values in bold demonstrate the significant associations, either positive (rho ≥ 0.5) or negative (rho ≤ -0.5))

Ditch 1				**Ditch 2**				**Ditch 3**			
		Burnt Clay			**Burnt clay**				**Burnt clay**		
Shell	Bone	Charcoal	Unburnt Clay	Shell	Bone	Charcoal	Unburnt Clay	Shell	Bone	Unburnt Clay	
-0.33	-0.19	0.11	0.32	**0.74**	**0.56**	-0.4	**-0.91**	**0.88**	0.25	**-0.76**	
		Shell			**Shell**				**Shell**		
Unburnt Clay	Bone	Charcoal	Burnt Clay	Burnt clay	Bone	Charcoal	Unburnt Clay	Burnt clay	Bone	Unburnt Clay	
-0.33	**0.59**	0.19	-0.36	**0.74**	**0.52**	**-0.47**	**-0.72**	**0.87**	**0.57**	**-0.77**	
		Bone			**Bone**				**Bone**		
Unburnt Clay	Shell	Charcoal	Burnt Clay	Burnt clay	Shell	Charcoal	Unburnt Clay	Burnt clay	Shell	Unburnt Clay	
- 0.19	**0.59**	0.06	- 0.18	**0.56**	**0.52**	0.1	**-0.54**	0.25	**0.57**	-0.12	
		Charcoal			**Charcoal**				**Unburnt Clay**		
Unburnt Clay	Shell	Bone	Burnt Clay	Burnt clay	Shell	Bone	Unburnt Clay	Burnt clay	Shell	Bone	
0.11	0.19	0.06	0.18	-0.4	**-0.47**	0.1	0.32	**-0.77**	**-0.77**	-0.12	
		Unburnt clay			**Unburnt Clay**						
Shell	Bone	Charcoal	Burnt Clay	Burnt clay	Shell	Bone	Charcoal				
- 0.33	- 0.19	0.11	0.32	**-0.91**	**-0.72**	**-0.54**	0.32				

Table 2. Micro-artefact correlations for the Neolithic pits on the Tell (the values in bold demonstrate the significant associations, either positive (rho ≥ 0.5) or negative (rho ≤ -0.5))

pit 1			**pit 2**			**pit 3**			**pit 4**			**pit 5**		
	Unburnt Clay			**Unburnt Clay**			**Unburnt Clay**			**Burnt Clay**			**Burnt Clay**	
Shell	Bone	Charcoal	Shell	Bone	Charcoal	Shell	Bone	Charcoal	Shell	Bone	Unburnt Clay	Shell	Bone	Unburnt Clay
-0.04	-0.3	0.34	**0.55**	**0.64**	**0.5**	**-0.73**	0.05	**0.84**	0.37	0.39	0.3	-0.3	0.03	0.41
	Shell			**Shell**			**Shell**			**Shell**			**Shell**	
Unburnt Clay	Bone	Charcoal	Unburnt Clay	Bone	Charcoal	Unburnt Clay	Bone	Charcoal	Burnt Clay	Bone	Unburnt Clay	Burnt Clay	Bone	Unburnt Clay
-0.04	**0.7**	-0.19	**0.55**	**0.72**	**0.62**	**-0.73**	0.19	-0.71	0.37	0.35	0.36	-0.3	0.44	0
	Bone			**Bone**			**Bone**			**Bone**			**Bone**	
Unburnt Clay	Shell	Charcoal	Unburnt Clay	Shell	Charcoal	Unburnt Clay	Shell	Charcoal	Burnt Clay	Shell	Unburnt Clay	Burnt Clay	Shell	Unburnt Clay
-0.3	**0.7**	-0.38	**0.64**	**0.72**	0.41	0.05	0.19	0.18	0.39	0.35	0	0.03	0.44	-0.36
	Charcoal			**Charcoal**			**Charcoal**			**Unburnt Clay**			**Unburnt Clay**	
Unburnt Clay	Shell	Bone	Unburnt Clay	Shell	Bone	Unburnt Clay	Shell	Bone	Burnt Clay	Shell	Bone	Burnt Clay	Shell	Bone
0.34	-0.19	-0.38	**0.5**	**0.62**	0.41	**0.84**	**-0.71**	0.18	0.3	0.36	0	0.41	0	-0.36

Table 3. Micro-artefact correlations for the Neolithic contexts on the extended part of the site (the values in bold demonstrate the significant associations, either positive (rho ≥ 0.5) or negative (rho ≤ -0.5))

PIT 6		**DITCH 4**			**DITCH 5**	
Burnt Clay		**Burnt Clay**			**Burnt Clay**	
Bone	Shell	Bone	Shell		Bone	Shell
-0.82	**-0.61**	**-0.59**	**-0.50**		**-0.54**	**-0.63**
Bone		**Bone**			**Bone**	
Burnt Clay	Shell	Burnt Clay	Shell		Burnt Clay	Shell
-0.82	**-0.54**	**-0.59**	**-0.57**		**-0.54**	**-0.51**
Shell		**Shell**			**Shell**	
Burnt Clay	Bone	Burnt Clay	Bone		Burnt Clay	Bone
-0.61	**-0.54**	**-0.50**	**-0.57**		**-0.63**	**-0.51**

Table 4. Micro-artefact correlations for the Byzantine-Ottoman contexts on the Tell (the values in bold demonstrate the significant associations, either positive (rho ≥0.5) or negative (rho ≤ -0.5))

	Burnt Clay				**Shell**				**Bone**				**Charcoal**		
	Shell	Bone	Charcoal		Burnt Clay	Bone	Charcoal		Burnt Clay	Shell	Charcoal		Burnt Clay	Shell	Bone
B/O pit 1	**0.57**	**0.53**	**-0.5**	**B/O pit 1**	**0.57**	**0.58**	0	**B/O pit 1**	**0.53**	**0.58**	0.28	**B/O pit 1**	**-0.5**	0	0.28
B/O pit 2	**0.58**	**0.59**	-0.34	**B/O pit 2**	**0.58**	**0.71**	**-0.47**	**B/O pit 2**	**0.59**	**0.71**	-0.26	**B/O pit 2**	-0.34	**-0.47**	-0.26
B/O pit 3	**0.54**	**0.57**	-0.19	**B/O pit 3**	**0.54**	**0.58**	**-0.51**	**B/O pit 3**	**0.57**	**0.58**	-0.17	**B/O pit 3**	-0.19	**-0.51**	-0.17

4. CONCLUSION: A CULTURAL EXPLANATION FOR NON-LINEAR AND LINEAR MICRO-ARTEFACT PATTERNING

Non-linear and linear micro-artefact patterning reveals that the archaeological contexts from the site exhibit strong spatial patterning. The observation of this dual pattern in cultural indicators such as micro-artefacts should be related at least in part (and arguably for the most part) with differences in the spatial organization of activities carried out in the site and ending up in the deposits. In other words, it should be related with spatial differences in cultural formation processes. That these differences in cultural processes had become so embedded in the sedimentary traces of the deposits arguably reflects long-term continuity of distinct patterns of spatial organisation of behaviour. The implementation of the two methods needs to be explored in other site contexts and further tested but seems to provide the researcher with a useful tool to unravel the cultural information often hidden within these complex multidimensional data.

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Chapter 8

A PECULIAR FUNERARY RITE IN THE PHOENICIAN-PUNIC NECROPOLIS OF MONTE SIRAI (CARBONIA-SARDINIA-ITALY) STUDIED BY XRD AND FT-IR TECHNIQUES

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ABSTRACT

The recent summer 2007 campaign of excavations of the Phoenician–Punic necropolis of Mount Sirai, located in the South-West part of Sardinia (Italy) has brought to light a number of tombs contextually attributed to a period from early VIth to the early Vth century B.C, which is simultaneous to the beginning of the Carthago influence in Sardinia.

In the interred burials recently brought to light the skeletal remains, sometimes of two superposed bodies, were discovered in a primary position and with fine anatomic connection. Some of the bones were visually stained, suggesting they were possibly subjected to a fire treatment.

In order to ascertain more objectively whether the bodies were subjected to burning, the bones from all the tombs were investigated by the X-ray powder diffraction (XRD) and Fourier Transform Infra-Red (FT-IR) spectroscopy techniques. After excluding the role of important diagenetic effects, from line broadening/sharpening analysis of hydroxylapatite in the bones according to the Rietveld method it was evaluated that the bodies were likely subjected to a regime of temperature from 300 to 700 °C. These data were supplemented and confirmed by an analysis of the splitting factor SF of apatite phosphate peaks in the Infrared spectrum of the bones. Our results point out to the existence of a rite intermediate between incineration and inhumation. This sort of "semi-combustion", perhaps limited to the period of early V^th century B.C, appears to be peculiar just of this site.

Keywords: *Phoenician-Punic necropolis, burned bones, X-ray powder diffraction (XRD), Infrared Spectroscopy (FT-IR), funerary rite*

INTRODUCTION

The village of Monte Sirai, located in the South-Western part of Sardinia near the city of Carbonia (see figure 1), appears of fundamental importance for a better knowledge of the phoenician and punic civilizations since in the site all the fundamentals historical components can be retrieved, while further superposition of other civilizations are absent.

The site of Monte Sirai is made by three large sectors that represent the scientific and tourist hub of the old town. The main sector is of course the city centre, located in the southern part of the hill. The so-called tofet is found in the northern second part, which is a sacred place where dead-born children or dead young bodies were fired according to rites typical of this civilization. The third sector is constituted by two necropolis located in the valley separating the town from the tofet. It consists of a Phoenician necropolis of incineration, where only holes excavated in the tufa are today visible and a punic, inhumation necropolis made by underground tombs, all open to visits.

The coastlines of Sardinia were known and frequented for trades by foreign populations since 1500 BC. The first visitors were Greeks from Mycene and the Aegean Archipelago that were used to rape slaves from the coasts and trading them. Following on, around 1200 BC, the sailors from Cyprus arrived together with people from the Syrian and Palestinian Near East coasts of the Mediterranean Sea.

The first tracks of a stable Phoenician presence (the successive population to reach Sardinia) can be dated around 750 BC. Clear signs of that are found at Monte Sirai, though they can be attributed even to a later period, because actually the most ancient items can be dated not earlier than 730/720 BC.

It is presumed that Monte Sirai was founded as a real village around 740 BC and soon assumed importance for its strategic position near the coastline, conducting to the Campidano plane of the island.

Its foundation is likely due to the Phoenicians that were allocated before the first half of the VIII century BC in the city of Sulcis from the nearby island of S. Antioco. The hypothesis of a consistent role in the foundation by the people living in the area of the village today named Portoscuso appears less probable.

In any case the Phoenicians established in Monte Sirai around ca 725 BC, by building up a sizeable area around the old nuragic stone tower, with an extension approximately coincident with the village as it is visible today.

It is documented that around the year 540 B.C Carthago decided to occupy military the island, but a coalition of Phoenician cities in Sardinia, certainly involving Sulcis and Monte Sirai, firmly resisted to this expansion. However, few years later Carthago organized a second army expedition that defeated the Phoenician alliance. The population of Monte Sirai was massacred and the city almost completely destroyed. It is estimated that after this event only a dozen of families were inhabiting the village. This is supported by the necropolis of that period consisting of thirteen underground burials of the Punic mode representing as many family tombs. Under the Punic control of the territory, Monte Sirai become marginal and economically depressed. The inhabitants were presumably involved in agricultural activities with scarce trade connections except for the nearby city of Sulcis, until ca 360 B.C when Carthago decided to strengthen various Sardinian sites, including also Monte Sirai.

After the year 238 B.C, in coincidence with the change of domination from Carthago to Rome, the so-called neo-punic period, the fortress of Monte Sirai was completely demolished. A new city plan was made with four large building arrays.

In the years around 110 B.C, the Romans deported the inhabitants of Monte Sirai, likely within a frame of repression of frequent insurrectional riots, because situated in a naturally well-defended hill. So, the site was abandoned and not inhabited anymore apart from sporadic occasions [1].

A first excavation stage was carried out between 1963 and 1966 [2; 3; 4; 5].

After a stop across the ‘70, the investigations were resumed in 1980 by the groups leaded by P. Bartoloni and M. Botto [1; 6]. These systematic excavation campaigns originally involving a large graveyard area were further continued between 2005 and 2007 [7].

Overall, it was established that Phoenicians adopted mostly incineration rites of dead human bodies, similar to the other Phoenician cities of Sardinia and of other territories of the western Mediterranean Sea.

In facts, in years between 1981 and 1987, 75 ground tombs of Phoenician attribution, were dated between the late VIIth century and ca 525 B.C, when the incineration rite was mainly practiced. Nevertheless, the case of inhumation was also coexisting. This may have been derived from the local population culture and enforced by the subsequent Carthago influence. As a matter of fact, it seemed likely that the inhumation rite continued to survive during and after the Carthaginiensis period because previously practiced by the inhabitants of Nuragic origin that contributed together with the Phoenicians to populate the first urban nuclei of Sardinia [8; 9; 10].

Figure 1. The location of Monte Sirai and its nearby context in the island of Sardinia.

In facts, it is not conceivable that the inhabitants of Phoenician culture in Monte Sirai and other cities of the Sardinia coastlines were all of Near East origin. It is presumable that the population was mixed, i.e., a minority of Phoenicians with a local majority of nuragic birth.

A strong presence of autochthonous families in the first years of the foundation is suggested by the design of some items of daily practice such as pants, that were fabricated using a Phoenician technique but with a typical nuragic shape.

After the conquest of Mount Sirai by the Punics from Carthago dated 525 B.C [11], and during later repopulation of the site by new colons, the funerary rite changed suddenly. Thus, the incineration was replaced by inhumation, according to what well established in Carthago as well as among the Northern African populations [12; 13]. In this respect, it is also worth reminding another punic custom, consisting in the storage of infant bodies inside transportation amphora (“enkythrismòs”).

General Considerations about the Recent Monte Sirai Tombs

The most recent excavations of the site has brought to light 18 tombs contextually attributed to a period from early VIth to the early Vth century B.C, which coincides with the beginning of the Carthago influence in Sardinia. The complete list of excavated tombs is reported in Table I.

Table I. List of the bones here studied and the chronology attributed according to the tombs context

Sample code	Part of the body examined	Chronology and period
Tomb 248	Femur	Beginning VIth (590-570 B.C) phoenician
Tomb 253	Femur	Beginning VIth, (560-540 B.C) phoenician
Tomb 245	Femur	Half VIth (550-530 B.C) phoenician
Tomb 256	Tibia	Half VIth, (560-540 B.C) phoenician
Tomb 257	Femur	Half VIth, (570-540 B.C) phoenician
Tomb 255	Infantil fragment	Second half VIth (550-520 B.C) phoenician
Tomb 7	Femur	Second Half VIth (540-510 B.C)
Tomb 3-1	Pediphalanx	End VIth
Tomb 236	Homerus	End VIth-start Vth (510-490 B.C) punic-phoenician
Tomb 3-2	Homerus	End VIth-start Vth (520-480 B.C) punic-phoenician
Tomb 5	Homerus	End VIth-start Vth (520-480 B.C) punic-phoenician
Tomb 6	Fibula	End VIth-start Vth (520-490 B.C) punic-phoenician
Tomb 14 D	Sacrum	End VIth-start Vth (520-490 B.C) punic-phoenician
Tomb 14 B	Cranium	End VIth-starti Vth (520-490 B.C) punic-phoenician
Tomb 15	Fibula	End VIth-Start Vth (520-490 B.C) punic-phoenician
Tomb 8-1	Femur	Start Vth (500-480 B.C) beginning punic
Tomb 8-2	Rib	Start Vth (500-480 B.C) beginning punic
Tomb 10	Fibula	Uncertain; probably start Vth (500-480 B.C) beginning punic
Tomb 12	Femur	Start Vth (500-480 B.C) beginning punic
Tomb 13	Femur	Uncertain; probably start Vth (500-480 B.C) beginning punic
Tomb 16	Femur	First half Vth (490-450) B.C punic

Figure 2. An example of two superposed bodies found in the tomb 8, during the 2007 excavation campaign.

In this type of interred burials the skeletal remains, sometimes of two superposed bodies (see figure 2), were discovered in a primary position and with very good anatomical connection (see figure 3). Note also that tomb 16 was actually an “enkytrismòs” with remains of a infant inside.

In some bodies a dark-brown colour was observed for the bones that may be attributed to a burning process. (see figure 4)

In order to ascertain with objective tools whether all the bodies were subjected to burning and to what an extent, the bones recovered from tombs were investigated both by the X-ray powder diffraction (XRD) and Fourier Transform Infrared (FT-IR) techniques which, under specific assumptions, have been demonstrated able to discriminate the degree of fire treatment to which the bones were possibly subjected [14; 15; 16].

MATERIALS AND METHODS

All the bone remains from the 18 tombs of Monte Sirai necropolis were investigated by XRD and FT-IR. The tombs were attributed according to the context to a period encompassing the end of VIth until the beginning of the Vth century B.C.

The line broadening analysis of XRD patterns may be applied just to the (002) reflection at half height of hexagonal hydroxylapatite (HA) [17; 18; 19; 20] for simple crystallinity evaluations, but more complex indices have also been developed, though in a limited angular range (e.g. 30-40° in 2θ using CuKα radiation) [21; 22; 23; 24]. The term “crystallinity” is instinctively intended as degree of organization of the HA phase on an atomic scale.

It is now well understood that the X-ray peak sharpening of HA bones is caused by an increase of the average size of domains diffracting coherently (otherwise referred to as crystallites) and a decrease of average imperfection density, also called lattice disorder or microstrain. These parameters supply a means to define numerically the organization of bones in an atomic scale.

Figure 3a. These two tombs supply an example of human bone remains in primary position and good anatomic connection.

Figure 3b. These two tombs supply an example of human bone remains in primary position and good anatomic connection.

In analogy with the work by Michel et al. [25], we have recently suggested to collect X-ray patterns in an extended angular range (10-130° in 2θ) employing long times of acquisition and using the Rietveld refinement method [26; 27]. These type of experiments and analyses are supposed to be more reliable for a precise description of the growth phenomena (i.e., degree of organization) which are induced in the HA micro-(or nano-) crystals as a function of fire temperature. As a matter of fact, the procedure is not limited to the analysis of a few selected peaks but evaluates the pattern with the maximum collectable evidence.

A concomitant investigation was carried out by the FT-IR spectroscopy, whose absorption bands are related to the bond strength of carbonate and phosphate groups of HA [28; 29; 30; 31; 32; 33; 34; 15].

Figure 4. A detail of a femur with a dark-brown colour suggesting that the bone was subjected to a firing process.

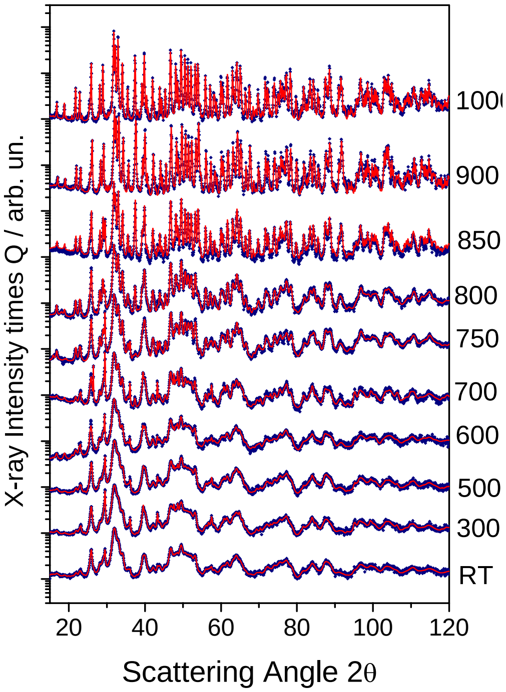

Figure 5. The XRD pattern evolution of a sample human bone treated in a muffle at the indicated temperatures. The heat treatment involves a concomitant sharpening of all peaks in the pattern.

The bands that we are considering are generally constituted by overlapped lines whose width decreases as a function of treatment temperature according to an empirical crystallization index also called splitting factor (SF).

In both XRD and FT-IR cases it is expected that a heating process of HA bones, such as that due to burning of bodies at high temperature, modifies irreversibly the energy state distribution, i.e., the average crystallite size of HA increases and the distribution of vibrating energy modes becomes sharper because of an increased order, respectively.

It is often argued that simple heating of a sample bone can not reproduce satisfactorily a real firing process of bodies, because the burning of meat also occurs simultaneously. However, while meat is subjected to the oxidation reactions commonly involved in a combustion process with evolution of vapour, carbon dioxide and other gaseous products, this is not so with HA. Chemically speaking, this phase is an inorganic hydroxide that remains solid and chemically inert at least up to temperatures around 1200 °C.

So it is clear that the calibration study in a furnace is the most adequate procedure to simulate a real firing process because it permits to assess, just from physical changes, the temperature reached in the course of a programmed thermal treatment (21; 22; 35).

In summary, though the basics of interaction between light radiation and matter in the two techniques here considered are completely different, in both cases we expect to observe a sharpening of diffraction peaks and IR bands, respectively as a function of heating processes.

To this regard, we have developed first for the XRD technique a calibration of a human bone as a function of the temperature by numerically analysing the growth of crystallites [27]. A similar approach was adopted also for the FT-IR technique in the case of the SF parameter.

The human sample bone coming from Sassari ossuary graveyard used for XRD and FT-IR calibration, were heat-treated with an heating rate of 20 °C/min at selected temperatures (200-1000 °C) in air using a NEY muffle furnace.

Powders of ca. 0.5 g were prepared for XRD by hand grinding with an agate mortar and pestle until reduced to a sufficiently fine powder.

The X-ray diffraction (XRD) patterns were recorded overnight using Bruker D8, Philips PW-1050, Siemens D-500, Rigaku D/MAX diffractometers in the Bragg–Brentano geometry with CuKα radiation (λ=1.54178 Å). The goniometer was equipped with a graphite monochromator in the diffracted beam and the patterns were collected with 0.05° of step size. The X-ray generator worked at a power of 40 kV and 30 mA and the resolution of the instruments (divergent and antiscatter slits of 0.5°) was determined using α-SiO_2 and α-Al_2O_3 standards free from the effect of reduced crystallite size and lattice defects. The powder patterns were collected in the angular range 15 - 130° in 2θ and were analyzed according to the Rietveld method [36], using the programme MAUD [37]. This is an efficient approach that evaluates quantitatively the amount, structure and microstructure parameters of mineralogical phases keeping also into account the instrumental parameters. This is a necessary pre-requisite in order to correctly distinguish from the peak broadening the average crystallite size from the lattice disorder.

The hand-grinded bone powders were mixed with KBr in the weight ratio 1:100 respectively, to make pellets suitable for FT-IR spectra that were collected with a JASCO FT 480 spectrometer in terms of absorbance vs wavenumber ν in the range 400-4500 cm^{-1}. In particular, the cluster of bands of HA in the range 500-700 cm^{-1} was analysed because generally recognized as the most reliable zone where to define the splitting factor SF as a function of temperature treatment. The peaks were processed using standard non-linear least squares fitting procedures incorporated in the Origin ® software assuming for the transmitted line shape a symmetric Pearson VII type function and a polynomial background of order 1 or 2.

RESULTS AND DISCUSSION

a) Calibration of XRD Patterns and FT-IR Spectra as a Function of Temperature

Figure 5 shows the XRD patterns of a sample bone subjected to heating in a furnace at the indicated temperatures. As it can be seen, the sequence of line profiles typical of the HA structure is maintained troughout the course of the thermal treatment. Note that data points are from experiment, while full-lines are best fit curves according to the Rietveld method. The broad peaks pertinent to the un-treated specimen or to specimens treated below 500 °C are becoming progressively sharp to the point that at high temperature (1000 °C) their broadening is due mainly to the instrument resolution. The sharpening of the XRD diagrams is a well known effect ascribed to an increase of the average, coherently diffracting, domain size (crystallite) and elimination of defects in the crystalline structure of HA [38].

In the Rietveld approach [25] the diffraction of bones is modelled and calculated starting from the monoclinic or hexagonal crystal structure of HA. [39] The algorithm of the program changes automatically structure parameters like the volume size of the unit cell and the location of atoms inside it, according to what permitted by the symmetry involved. By this way, the location of peaks in the 2θ scale and their relative intensity can be controlled and adjusted to conform to the experimental data. In addition to this, the line profile shape is determined by changing the average crystallite size and the average lattice disorder, which are referred to as microstructural parameters.

It turns out that the microstructure of HA crystals is very fine (average size values below 170 Å) and that sensible growth phenomena start to occur for temperatures higher than 550-600 °C. Also this process of growth occurs faster in correspondence of approximately 750 °C and seems to be accomplished after 900°C. In addition to this, at higher temperatures the average size dimension of crystallites seems to approach a steady value. This is a sigmoidal-type behaviour commonly observed in physical sciences on accounting for processes that cannot proceed indefinitely, as is a growth phenomenon. However, we can not disregard that this effect is partially due to the resolution of the instrument, i.e., the finite width of slits, monochromator, energy counting resolution etc. [40]. In facts, even for the modern diffractometers commercially available accompanied by the best software for deconvolution for the line broadening, the superior limit for reliable estimation of the crystallite size is set around 1600 Å. The logistic function used to fit the sigmoidal behaviour is reported in Figure 6 as a full line.

In a recent paper we have studied also the behaviour of the average crystallite size of HA as a function of temperature at the holding times of 0, 18, 36 and 60 min respectively (Piga et al., 2007b). Such a calibration permits to evaluate a range of modalities in temperature and times for the process to which the unknown bones were possibly subjected.

In analogy to the work of Surovell and Stiner [41] we have produced a calibration for the FT-IR splitting factor SF as a function of selected temperatures by making use of the same human bone from the Sassari ossuary.

For a quick and reliable measure of the FT-IR sharpening, [28; 32] after making reference to the $\nu_4(PO_4)^{3-}$ groups from 500 to 700 cm^{-1}, defined the quantity SF as the sum of intensities at 565 and 600 cm^{-1} divided by the intensity of the valley between them.

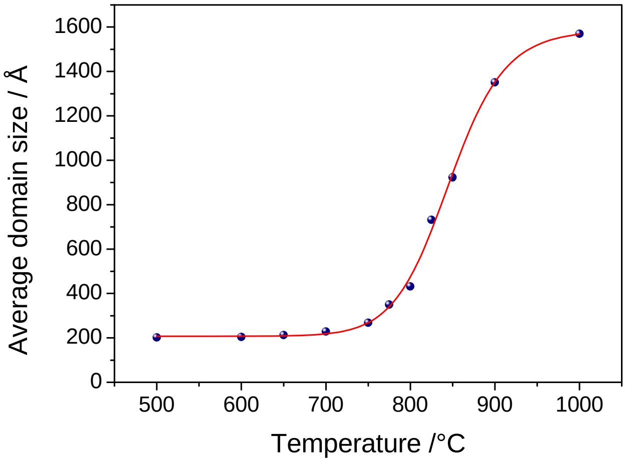

Figure 6. The process of apatite crystal growth as a function of temperature (data points) and the fit with a logistic function (full line).

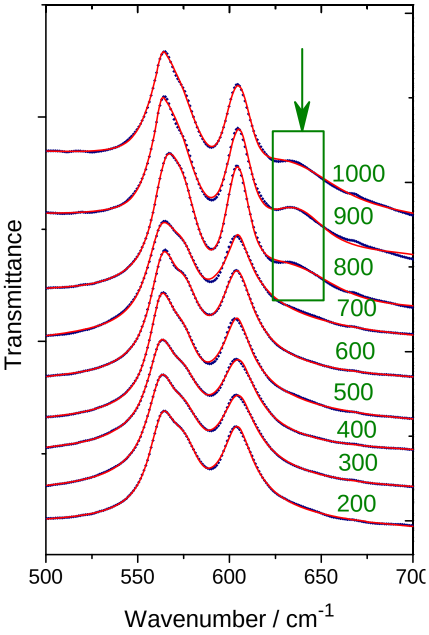

Figure 7. The FT-IR transmittance peaks of the phosphate group where the SF is evaluated. Experiment are data points, the full line is the result of a numerical fitting process employing four Pearson VII functions. Note the appearance of a shoulder at 634 cm^{-1} for temperatures above 700 °C, as indicated by arrow.

The data relevant to our calibration at the quoted temperatures are presented in Figure 7. We actually observe that the two main bands of the peak cluster at ca 565 cm^{-1} and 600 cm^{-1} respectively, become sharper as the temperature increases. Also, as this sharpening proceeds, for temperatures between ca 700 and 800 °C a further band emerges at ca 634 cm^{-1} and persists until 1000 °C.

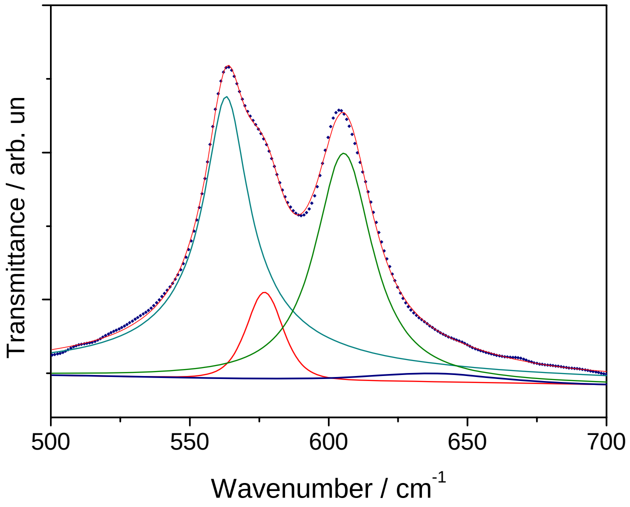

Figure 8. The numerical peak decomposition operated in the as-received bone used to carry out the calibration procedure for temperature.

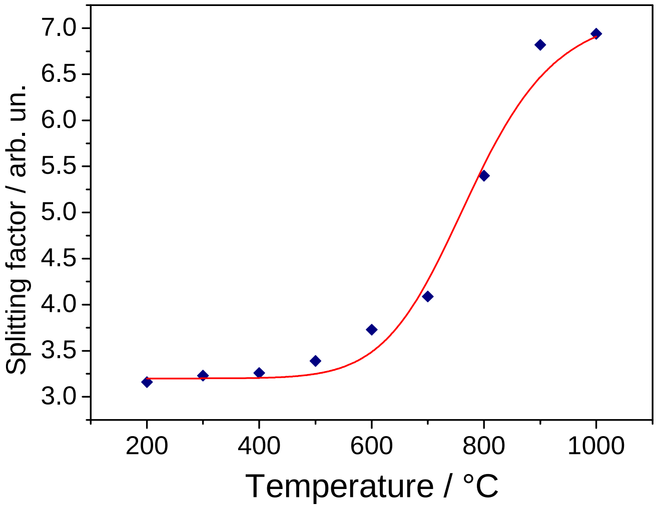

Figure 9. FT-IR SF behaviour as a function of temperature treatment (data points) and the best-fit logistic function (full line) used for calibration.

Defining the SF index requires a careful and objective determination of the background. In the absence of nearby bands one may reasonably trace a straight line connecting the two minima from the right to left hand side of the cluster. An alternative more elegant method can make use of a non-linear least-squares approach according to Michel et al. [25] that we have applied to our data of an untreated bone using symmetrical Pearson VII functions as shown on Figure 8.

One sees that the data points of the experimental spectrum can be satisfactory accounted for by a cluster of four bands (full lines) because of the presence of a shoulder at ca 573 cm^{-1} and one more weak and broadened at ca 635 cm-1 respectively.

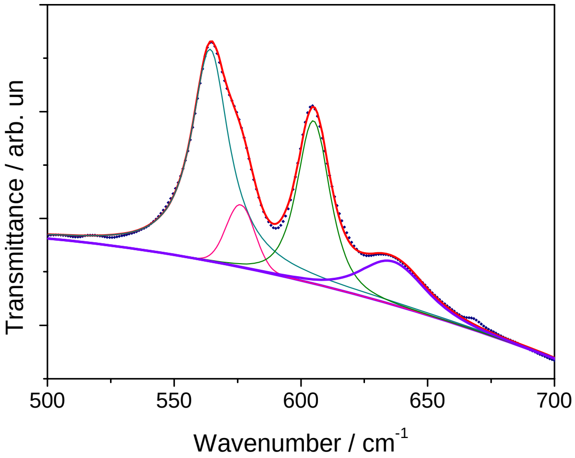

Figure 10a.

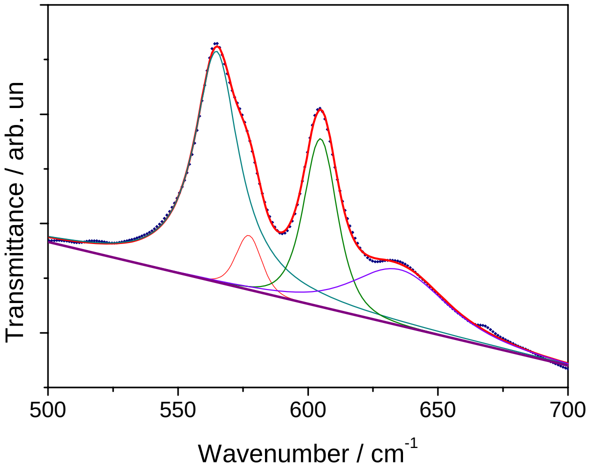

Figure 10b.

Figure 10a and 10b: The data of bone specimen heat-treated at 1000 °C (data points) may be fitted equally well whether considering a parabolic (LHS) rather than linear (RHS) background behaviour giving rise to some arbitrariness in the evaluation of SF.

The decomposition of the cluster in terms of individual best-fit peaks is in excellent agreement with results obtained by Michel et al. [25] and suggests that the background may lye below to what instinctively expected.

In particular, the parameters of the linear background are correlated to the shape character m of the Pearson VII functions that may vary from Gauss ($m = \infty$) to Cauchy ($m = 1$) and even to super-Lorentzian ($1>m>0$). In turn, a super-Lorentzian character, which seems to be the case of the line at ca 560 cm^{-1}, may be related to a wide or multimodal distribution of active IR states. Note that Michel et al. [25] have used Cauchy-type shape for all lines examined.

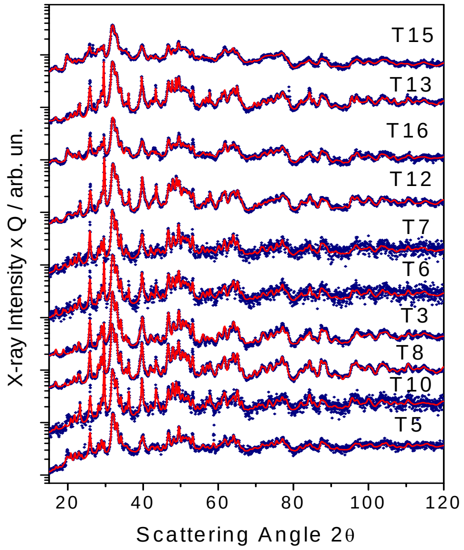

Figure 11. XRD patterns of some bones coming from the Monte Sirai necropolis. This entire collection of XRD patterns points out to the important approximations assumed in devising the microstructure properties of Hydroxylapatite (HA) just from one or few selected peak profiles. With the Rietveld method the goodness of the fit between calculated and experimental pattern is measured in terms of numerical agreement factors so this approach appears the most complete for evaluating simultaneously experimental data quality (i.e. signal-to-noise-ratio) and/or credibility of model assumptions.

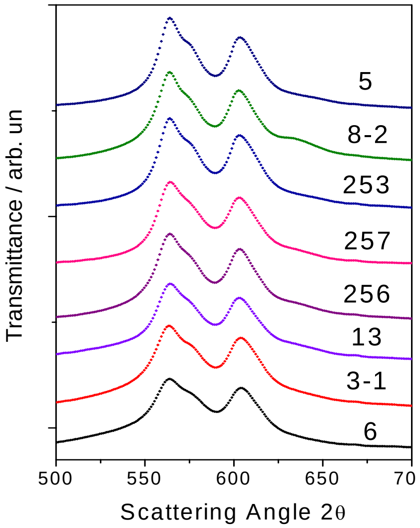

Figure 12. The IR bands of phosphate groups for some of the bone remains from tombs here indicated. The spectra are ordered on increasing SF factor. Note that for tomb 8-2 the shoulder at 634 cm-1 appears more defined with respect to other specimens.

Nevertheless, to be homogeneous with the FT-IR SF studies so far reported in the literature we have proceeded according to the simplified approach illustrated by Sillen and Stiner [41].

The plot of the SF as a function of applied temperature (data points) shows a logistic behaviour (see Figure 9), in analogy with the calibration of XRD data that, however, was involving the growth of the HA microcrystal and not the frequency of the active bands.

In any case, the logistic function was fit to the FT-IR SF data and referred to as a calibration curve.

It is possible to observe that the FT-IR information occurs in the same temperature range of XRD, i.e., the SF increases for temperatures higher than 600 °C and the process appears accomplished at ca. 1000 °C. For a further extension of the methods it appears logical to assess a correlation between the increase of SF and the lattice disorder decrease from XRD.

Sillen and Stiner (2001) reported SF data slightly different for similar heat treatments. In particular the SF values were similar to ours for temperatures below 600 °C but increased suddenly at ca 750 °C to decrease slightly to values around 6.5 at high temperatures.

Various reasons can be advanced to explain the discrepancies of FT-IR SF values from different laboratories. As already pointed out, among the various sources of subjectivity in evaluation of SF, the choice of the background appears very crucial. In facts, if we examine our cluster of bands at high temperatures we may suspect for the background behaviour that a parabola can by more suitable than a linear trend. In both cases the experimental data are very well reproduced even with sophisticated methods but it is clear from a comparison of the numerical analyses reported in Figure 10a and 10b, that the values of SF may oscillate sensibly. However, the subjectivity is sensibly reduced dealing with low temperature treatments because the intensity levels of the valley are quite insensible to the alternative choices of the background.

Keeping in mind these general limitations that to a certain extent are common to all experimental techniques, we have proceeded to estimate the temperatures from the FT-IR SF’s measured in the bones of Monte Sirai tombs.

b) XRD and FT-IR Analysis on Monte Sirai Remains

In figure 11 we show some experimental diffraction patterns (data points) and the relevant Rietveld fit (full lines) of some specimens that are of peculiar significance for the Monte Sirai necropolis situation brought to light in the recent excavation.

As expected, the XRD points to the presence of HA as the main mineralogical phase, which is accompanied by varying quantities of Calcite ($CaCO_3$) up to a maximum level of 31 wt.%. Sometimes, weak quantities of quartz and clay minerals were also observed at the limit of the technique detection.

At the moment we attribute calcite to an exogenous origin with respect to the osseous material, since the presence of carbonates units CO_3^{2-} that may substitute for phosphates groups PO_4^{3-} in the apatite structure and that can be likely separated during the deposition times of the bones, may amount to not more than 7-8 wt% [42].

The varying amount of calcite found in some Monte Sirai bones may be related to the tufa ground that was filling the excavated sepulchres capped on top by flat stones. It is likely that the ground penetrated into the burial through the interstices of the top due to weathering effects. The fact that small amphora and other ceramics with narrow necks were discovered empty inside, support further this hypothesis.

Table II. XRD average crystallite size, their estimated temperature, calcite wt.%, FT-IR SF and its estimated temperature for the bones considered

Sample code	Average cristallize size (Å)	Estimated Temperature/°C with XRD technique	% Calcite	Splitting Factor (SF) calculated	Estimated Temperature/°C with FT-IR technique
Tomb 248	224	600	0	3.53	590
Tomb 253	264	< 750	0	4.45	710
Tomb 245	241	650	0	3.83	639
Tomb 256	290	≅700	0	4.26	690
Tomb 257	240	650	0	4.2	670
Tomb 255	205	400	31	3.27	410
Tomb 7	233	≅650	<1	4.23	680
Tomb 3-1	252	650	4	3.67	620
Tomb 236	245	650	0	4.21	660
Tomb 3-2	187	300	29	3.25	390
Tomb 5	260	650	3	5	760
Tomb 6	250	650	14	3.61	605
Tomb 14 D	220	600<T< 700	0	3.59	610
Tomb 14 B	222	600<T< 700	0	3.71	625
Tomb 15	172	Not burned	3	2.99	Not burned
Tomb 8-1	251	650	5	4.2	670
Tomb 8-2	248	650	12	4.45	710
Tomb 10	258	650	15	3.96	650
Tomb 12	220	600<T< 700	20	3.59	610
Tomb 13	202	500	14	3.97	650
Tomb 16	218	≅650	5	3.55	600

Table II collects the average domain size of HA microcrystals (or crystallites) after separating from broadening the component due to lattice strain (column 2), the relevant temperatures to which the bones were likely subjected according to our calibration (column 3) and the percentage of calcite (column 4).

In figure 12 we report the IR bands of phosphate groups for the specimens there indicated, ordered according to increasing values of SF. Note that, for the bone of tomb 8-2, the band at 630 cm^{-1}, normally assigned to the OH$^-$ group, appears to emerge clearer than in the other samples. The temperature values retrieved from the SF of FT-IR bands are reported in column 5 of Table II and appear in overall agreement with the XRD determinations, except for tomb 3-1, 5 e 13, respectively. The temperatures estimated by FT-IR (column 7) appear to be slightly higher than the correspondent values obtained by XRD, but within the uncertainty level of experimental error, so it is possible that such discrepancies may depend also from small systematic errors in the calibration procedure.

Overall, all bodies seems to have been fired to temperatures not higher than 700 °C.

In the case of Tomb 13 we determined a fire temperature of 300 °C but this value has a relatively high variance associated because below 500 °C the both XRD line broadening and IR spectroscopy may not be very precise. Because of the sigmoidal behaviour of experimental data located at ca. 750 °C, both techniques are not reliable to assess cremations carried out at temperature lower than 500 °C. In any case, the FT-IR and XRD data confirm unambiguously that all the bodies brought to light in the recent Monte Sirai excavation (except for Tomb 15) were burnt.

The specimen coming from tomb 15 shows an average domain size of 172 Å in close agreement with values determined in inhumated bones [27]. This observation permits to exclude an important role of diagenetic effects in the sharpening of XRD lines that was advanced in the case ancient bodies buried in acid grounds [43]. Actually limestone (calcite)-based ground of our burials is supposed to maintain a chemically alkaline character to the local environment (pH ≈ 8.2), that should preserve in times the microstructure of bones rather than deteriorating it in terms of apparent growth of crystallites with consequent false attribution to a temperature effect.

In any case, the precise modalities according to which the bodies were fired are not totally clear because nor traces of combustion neither charcoal or wood were recognized at the bottom and walls of burials as well as in the funerary ceramic miscellanea. Because of this absence it is admissible that the bodies were first fired and only later the items were buried into the tomb.

An alternative possibility is that the bodies were first fired in the “ustrinum” place (discovered nearby the grave area during the recent excavations) and later transferred and deposed into the burials together with the funerary items. However, preservation of the anatomic connection during transportation appears difficult to justify entirely, unless the combustion process occurred with limited time of residence at the maximum fire intensity.

As a matter of facts, the “pugilistic attitude” [44] observed also by Bonhert [45] is absent in the bodies of Monte Sirai, where arms and phalanxes are in a perfect supine position.

It should also be mentioned that Bohnert observes the pugilistic attitude after ca 10 min for after flame spray firing the body at a constant temperature of 720°C. However this situation appears to be quite different from what occurs in a real process of cremation. Nevertheless, it is still possible that an intense fire carried out in the “ustrinum” for a short time did not destroy completely the bodies allowing their subsequent transportation to the tomb.

The other literature of the Phoenician and Punic customs [46; 47] does not report observations similar to the case of Mount Sirai here discussed.

In any case, it is possible that the typical rite here documented was simply aiming at eliminating the fleshy parts of the bodies. If this is the case, we could identify the rite as a hygienic/cleaning process, may be adopted for deaths due to contagious diseases and/or infection pathologies.

However, even the simple hygienic motivation cannot be entirely convincing. The care given to the bodies, the valuable items found in the tombs and the persistent adoption of this practice across the times suggest that the “semi-combustion” process had also a symbolic motivation, probably related to faiths well-established in the community of the necropolis.

We may hypothesize that between VIth and Vth century B.C at the start of the Punic domination, part of the population of Monte Sirai, for sure in strong relation with the original Phoenician community from near-east Mediterranean, maintained also a strong observation for the funerary practice of cremation. This seems demonstrated by the whole temporal evolution in the necropolis of the Vth century that evidenced the coexistence of a row of tombs with hypogeal rooms and of another row with ground burials.

CONCLUSION

The recent excavations still going on Monte Sirai have brought to light 18 tombs, contextually attributed to a period from early VI-th to the early V-th century B.C, showing the skeletons in a primary position and fine anatomic connection.

A comparative analysis using X-ray diffraction and Fourier Transform-Infrared spectroscopy established that all the bodies examined, except for the Tomb 15, were fired before burial in a temperature range from 400 to 700 °C.

The issues stimulated by this result have been essentially developed for understanding the technical practice of the firing process and the anthropological meaning of the rite.

This investigation has permitted to assign the sepulchres with time continuity from the VIth to the Vth century B.C and to ascertain with a very fine detail the conversion from incineration rite to inhumation, pointing out the practice of an intermediate process of “semi-combustion”.

It will be a challenge for future work extended to other Sardinian necropolis to assess whether the data collected in Monte Sirai corresponds to a situation common to the other Sardinian cities or rather represents the result of a local and peculiar culture maybe typical of the Sulcis territory so highly dense of Phoenician-Punic locations.

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Chapter 9

USING MULTIVARIATE STATISTICS FOR PATTERN RECOGNITION IN ARCHAEOLOGY

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ABSTRACT

Pattern recognition is of primary importance to the field of archaeology, given that recognizing patterns is the key to both understanding problems with our current beliefs about the past and the generation of new and better ideas to resolve them. This chapter discusses the use of multivariate statistics for data reduction and pattern recognition in large archaeological datasets. Most archaeological research is at least partially quantitative, but most of this research has traditionally focused on hypothesis testing and the calculation of probability statistics. While statistical hypothesis testing is an important aspect of scientific approaches to archaeological research, the field has largely overlooked the use of non-probability based statistical approaches to pattern recognition. The chapter begins with a brief discussion of the philosophy of science and the role of archaeological pattern recognition in the construction of accurate generalizations about the archaeological record based on material remains, the construction of hypotheses based on these generalizations, and the critical testing of hypotheses based on new and better understandings of archaeological patterning. This chapter then outlines the use of multivariate statistical approaches including factor analysis, principal components analysis, and multiple regression, which are powerful and under-utilized approaches to large archaeological datasets. The chapter illustrates the use of these techniques by discussing several important case study analyses of some major categories of materials and situations commonly encountered by archaeologists.

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INTRODUCTION

There are many good discussions of the use of multivariate statistical techniques in archaeology (Baxter 1994, 2003; Shennan 1997). Based on these, it would be easy to for an archaeological researcher with a cursory knowledge of statistics to learn how to use widely available statistical software packages to calculate useful multivariate statistics. What is lacking from these discussions is a clear explanation of why any sane archaeologist would want to bother going through this imposing process. Let us begin by facing this fact: Most practicing archaeologists are not keen to spend their scarce free time reading statistics texts in order to learn more about approaches that are mathematically difficult and not obviously necessary to ongoing research. Furthermore, the ability to easily add new statistical techniques to our *repertoire* left most of us many years and brain cells ago. From a rhetorical perspective, this places the onus on me to explain how and why multivariate statistical techniques could be important tools for archaeologists in a readable way. This is not a reference piece, as there are many excellent specimens already available (e.g. Baxter 1994, 2003; Shennan 1997; and many others). Rather, this is intended to be a gateway for archaeologists interested in applying multivariate statistical techniques to their own research problems. This chapter assumes a certain level of statistical knowledge, but uses plain language and humor as ways of appealing to readers for whom statistics is not their favorite topic of light reading. The point of my discussion is that multivariate statistical techniques are powerful and under-exploited tools for archaeological pattern recognition, and that these approaches are more accessible than is generally thought.

In both the past and the present, dynamic human behavior results in *patterns* of material remains distributed in three-dimensional space. Archaeology is fundamentally based on the premise that patterns of archaeological remains were structured by activities of living people, and therefore that archaeological patterns may be used to make inferences about patterns of human behavior in the past. Because of the relationship between human behavior and the patterns of archaeological remains it produces, the importance of pattern recognition for archaeology should be self-evident. The key to making inferences about the past rests directly on accurate pattern recognition. Archaeological patterns are the direct sources of the ideas we hold concerning prehistory. Likewise, we discover problems with our views on the past through the discovery of contradictory patterning, and this stimulates the formation of new ideas. In short, to paraphrase Binford (1981), pattern recognition is the key to noticing our areas of ignorance about the past, and for resolving them.

It is also the case that most modern archaeological research is at least partially quantitative on some level. The process of fieldwork involves recording the location of important archaeological objects and features in three-dimensional space. Laboratory work involves counting various categories of objects, and counting or measuring certain features of objects. For this reason, archaeological patterns are usually recognized and described through quantitative methods. Statistical approaches for pattern recognition should be of utmost importance to archaeological studies. Surprisingly, the use of pattern recognition statistics in archaeology is relatively uncommon, and most statistical techniques that archaeologists use are aimed at the assessment of probability and hypothesis testing. This strong focus on probability, or what I might tongue-in-cheek call “p-value envy,” has an important place in deductive archaeological science, but it is not the only productive use of statistics.

It is important to point out that archaeological patterns are inherently multivariate phenomena. Clearly, the explanation of human behavior itself, which is one of the main goals of scientific archaeology, relies on the ability to understand the simultaneous operation of many environmental and social variables. Archaeologically, many forces affect the formation of sites and the characteristics of recovered assemblages. For this reason, multivariate statistical techniques are important ways of getting at this complexity in terms of both human behavior and natural forces of site formation. This chapter proposes that multivariate statistical techniques for pattern recognition are powerful tools for quantitatively studying the archaeological record.

The chapter begins by exploring pattern recognition in archaeology from the perspective of philosophy of science, and reviews the place of pattern recognition in terms of both the construction and testing of models. Next, the chapter reviews several important multivariate statistical techniques, including factor analysis (FA), principal components analysis (PCA), correspondence analysis (CA) and multiple regression / partial correlation. The chapter illustrates the potential uses of these statistical techniques through a number of cases studies concerning types of materials commonly encountered by archaeologists. These include (1) Binford's (1981) study of animal bones from Olduvai, Tanzania, (2) Bernardini's (2005) study of ceramic decoration and rock art in the American Southwest, (3) Wilson's (1998) study of rock art elements in Oceania, (4) my own work (McCall 2006) on the stone tool industries of Klasies River Mouth, South Africa, and (5) O'Connell's (1987) ethnoarchaeological study of the Australian Alyawara. Hopefully, these case studies will provide useful guides for researchers dealing with similar kinds of problems in their own research.

BEYOND "P-VALUE ENVY": ARCHAEOLOGY, PATTERN RECOGNITION, AND THE PHILOSOPHY OF SCIENCE

The potential for a discussion of multivariate statistical techniques to be incredibly boring is already high, but when combined with talk of philosophy of science, it becomes immeasurable. For this reason, I will try to keep a sense of humor in this section, and remain as brief as possible. It is also important to point out that I would never begin this discussion if it were not absolutely necessary to the main points of the chapter in terms of using statistics to make inferences about the past, and to build theory concerning the organization of human behavior over time.

The formation of the New Archaeology during 1960s led to a heightened awareness of the philosophy of science and a focus on archaeology as deductive science. As Flannery (1986: 511) quips, this involved a focus on Popper (mainly 1959) and Hempel (mainly 1965), and other philosophers of science "many of them named Karl." It is easy to be critical of this movement today, given changes in both the field of archaeology and the emergence of philosophical positions based in post-modernism. But it is impossible to deny the importance of these fundamental critiques in terms of rebuking a then largely discovery-driven field, and in showing the clear dangers of strict generalizing empiricism. Binford (1968) especially saw the problems with empirical generalizations about the past. He saw that such research resulted in the cumulative generation of archaeological descriptions of patterns and scenarios to account for them, but no clear way to recognize bad ideas or develop new ones. The significant contribution of deductive approaches based on falsification have been well-described elsewhere (e.g. Trigger 1989), so I will spare further discussion here.

Pattern recognition is important to any scientific enterprise, and this is definitely true for archaeology. Deductive scientific archaeology, of the kind advocated during the rise of the New Archaeology, depends on the recognition of patterns for two purposes: (1) The generation of models of past human behavior based on generalizations stemming from patterned characteristics of the archaeological record, and (2) the deductive testing of these models using patterned archaeological evidence. In short, archaeologists use patterns of archaeological evidence to both build models and to critically test them. No discussion of the philosophy of science would be complete without a flowchart, and mine is present in Figure 1. This flowchart shows the importance of pattern recognition to both the inductive and deductive aspects of scientific archaeological research.

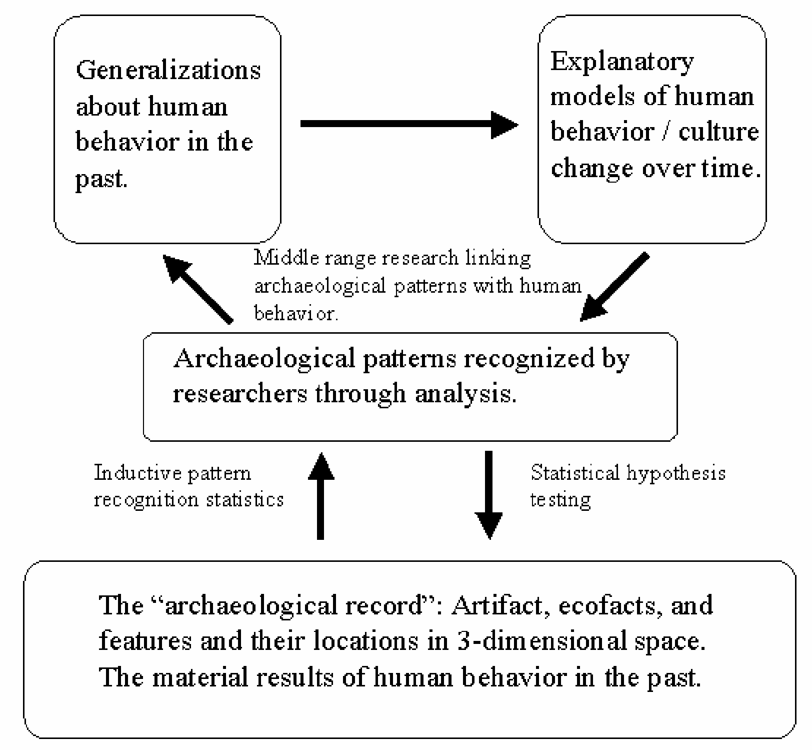

Figure 1. Flowchart representing the processes of scientific archaeological research.

The archaeology of the 1970s and 1980s focused on the deductive hypothesis-testing aspects of scientific archaeological research. In terms of statistical methods, this led to the dominance of probability assessment approaches to quantitative data. This emphasis on statistical hypothesis testing and probability assessment still dominates modern quantitative archaeological research. While most archaeological studies do not go to the fullest lengths in terms of framing null and alternative hypotheses, test implications, and other deductive scientific trappings, a high frequency do report some kind of statistical test resulting in a statement of probability, or a p-value. Such statistical tests can be both parametric and non-parametric (although frequently ignorant of the assumptions behind these terms), and include chi-square tests, t tests, F tests, ANOVA tests, correlation, regression, and many other derivatives of these that are too numerous to usefully list. What is frequently missed in the use of these statistical techniques is that their actual utility is in assessing the relationship between a sample and the population which it represents. These tests essentially answer the question, what is the probability that some observed characteristic of a sample could have resulted from chance alone, rather than actually representing some real characteristic of the population from which it was selected?

There is no doubt that these issues of probability and sampling are very important to archaeology, which is entirely dependent upon sampling. However, there is frequently a sense in archaeological studies that statistical analyses resulting in a p-value greater than 0.05 (the traditional cutoff for rejecting a null hypothesis) have somehow come up with “bad results.” Likewise, studies with statistical tests resulting in very low p-values are frequently taken as powerful evidence for a strong statistical relationship, and therefore a high level of potency in terms of the original idea being tested. Ignoring the problematic conflation of probability and strength of association, which is almost never reported in archaeological studies, this situation creates an irrational lust after low p-values, or what I might call “p-value envy.” While we clearly need statistical methods for assessing probability and hypothesis testing, this is not the only effective quantitative learning strategy available for archaeological research. It is incumbent on the researcher to (1) know the actual assumptions behind the statistical tests being used, (2) know what question the hypothesis testing is actually addressing, and (3) to be smart about using statistical tests and their results to explore patterns in the archaeological record and to test models of their causes.

If most statistical approaches used in archaeology are not pattern recognition tools, then how are patterns actually recognized? The answer to this question usually involves general descriptive statistics and the eyeballing of relationships. For example, imagine two Neolithic villages are excavated, and one is found to have a higher mean number of ground stone axes per household than the other. The investigating researchers then perform a two-sample t test, resulting in a p-value of less than 0.05. The fact that one village has more ground stone axes per household than the other is then used to address some deeper theoretical issue concerning the organization of human behavior in the past. The pattern was recognized when the researchers found that one village had a higher mean number of axes per household-- a basic descriptive statistic. The t test did not help discover that pattern, but rather simply tested whether the pattern could be explained as the result of chance in the process of sampling. Recognizing the pattern through descriptive statistics and then testing it using probability statistics were separate tasks, but both necessary for establishing that the observed pattern was real and appropriate for examining important theoretical questions.

Often, situations occur where there are too many variables for descriptive statistics to be effective tools for pattern recognition. For instance, returning to the Neolithic village example, imagine that the researcher wants to compare not only the frequency of ground stone axes, but also forty other categories of object. Or imagine that the researchers want to compare a number of measurements (mass, length, width, thickness, raw material, color, etc.) on forty different categories of object. Also, imagine if it were twenty villages instead of only two. This could be done by eyeballing descriptive statistics, but it would be an incredibly time-consuming and painstaking process involving thousands of head-to-head comparisons. Furthermore, such comparisons have difficulty in examining how different variables relate to one another, at least without adding another hugely labor-intensive layer of descriptive statistical analysis. For example, the frequency of axes might covary with the frequency of sickle handles, and this might be an important archaeological pattern for addressing research questions. Finding this pattern would only be possible if the frequency of every category of object was compared with the frequency of every other category of object at every site. With forty categories of object and twenty sites, it would take literally thousands of head-to-head comparisons to explore every possibility. While archaeologists may follow hunches in exploring patterns using descriptive statistics, it is impossible to deal with such complex quantitative situations in a systematic way without more sophisticated multivariate statistical techniques.

Unfortunately, the last scenario described above is a fairly common situation faced by archaeologists. The result is that most archaeologists will do as many head-to-head comparisons of descriptive statistics as human ability, time, and budget will allow, and also pick a specific (but deliberately small) set of variables based largely on hunches to explore on an *ad hoc* basis. The complexity of this situation puts a premium on *data reduction* and the use of more sophisticated multivariate pattern recognition techniques in dealing with larger datasets.

Returning to issues of the philosophy of science, multivariate statistical techniques are important for identifying archaeological patterns that serve as the basis for the inference of human behavior in the past. As Binford (1981) proposes, the main strategy archaeologists have for learning about the past relies on establishing the relationship between dynamic, living human behavior and the static material arrangements it produces, or the archaeological record. Binford calls this process “middle range” research, emphasizing the importance of ethnoarchaeological observations of modern peoples as a way of learning the processes that produced the archaeological record in the past. Multivariate pattern recognition statistics are often used during the inductive phases of research, serving as the basis for generalizations about the archaeological record, and the source of scenarios of human behavior in the past. Hypothesis-testing statistics are usually used during deductive phases of research, and they are based on the premise of falsifying existing models (Popper 1959). They require both *a priori* knowledge of what important variables actually are, and specific existing hypotheses to be tested with know quantitative parameters.

It is important to point out that pattern recognition statistics, while less capable of calculating probability and testing statistical hypotheses, are equally able to call into question inferences of past human behavior, and therefore falsify models explaining behavior. When archaeological patterns are found that contradict fundamental understandings of human behavior in the past, this highlights important areas of scientific ignorance. This is integral to the process of deductive science; it leads to the abandonment of older, problematic models and the generation of newer, more elegant ones. In short, hypothesis-testing statistics are most useful during the deductive phases of research when specific variables have already been identified as crucial and there are defined models being tested through a process of falsification. In contrast, multivariate pattern recognition statistics are most useful in reducing data, identifying what variables are important, and systemically recognizing patterning between variables in terms of covariation.

The other reason for using multivariate statistics as opposed to bivariate (or univariate) approaches is that both human behavior and the formation of the archaeological record itself are inherently multivariate phenomena. Bivariate models are really only effective in dealing with phenomena where only one major independent variable explains only one other dependent variable. For example, when Newton examined acceleration due to gravity, this was possible using bivariate models, since gravity was the only major force affecting the velocity of a falling object. Human behavior and the formation of archaeological sites are not like this. As early social scientists realized, there are many causes for the complex behavior and ideas of living humans (Vogt 2007). Similarly, as Binford (1976) was quick to note, there are many variables affecting the characteristics of archaeological assemblages, including human behavior in the past with all of its complexity, and the *milieu* of natural taphonomic forces acting on archaeological sites during and after there formation. Put bluntly, multivariate statistics are important for archaeologists because they help model a complex multivariate reality.

This section should not be taken as a philosophical attack on either the deductive approach to science or the utility of statistical hypothesis testing. I am both a card-carrying logical positivist and processualist archaeologist, and I firmly believe that the wide-spread use of probability statistics has radically improved the practices of archaeology. I am only trying to point out that multivariate pattern recognition statistics are useful for archaeologists because they offer ways of reducing data, and they are powerful ways of dealing with complex data that go beyond simple descriptive statistics. I am also trying to make the case that not all quantitative research in archaeology must result in the calculation of a p-value less than 0.05. Science is a fundamentally creative endeavor, and archaeologists should strive to be creative in their use of pattern recognition statistics.

THE BORING MATH PART: MULTIVARIATE STATISTICAL MODELS AND ASSUMPTIONS

There are innumerable kinds of multivariate statistical approaches employed in the social sciences. This makes choosing a limited set to discuss in this chapter somewhat difficult. My choice is informed by two main research issues: (1) Conventional use of certain statistical techniques in archaeology and related fields and (2) the accessibility of statistical methods for researchers in terms of common computer software packages. Below, I discuss factor analysis (FA), principal components analysis (PCA), correspondence analysis (CA), and multiple regression / partial correlation, mainly because these techniques are available on every major statistical software package and because these have long histories of use in the field of archaeology. This discussion leaves out many potentially powerful approaches and other diverse members of the factor analysis and regression / correlations families of statistics. This section begins by discussing and comparing the statistical assumptions behind FA and PCA and closes with an examination of the statistical basis for multiple regression in archaeology.

Concepts and Statistical Assumptions Behind FA, PCA, and CA

FA and PCA are very closely related statistical techniques based on many common sets of mathematical foundations. As Baxter (2003) points out, often when the term FA is being used in archaeology, it is really referring to PCA. Likewise, Cowgill (1977) makes the case that there are no significant differences between the two. I am going to begin this discussion as if they were the same, using the term “factor analysis” to refer to both, and I will end by examining the more specific differences between the two.

When factor analysis came into common use in archaeology during the 1960s and 1970s, it was a controversial statistical approach, especially for statisticians with enough mathematical knowledge to understand the computation behind it. Factor analysis is a technique based in matrix algebra, which is used to analyze complex correlation matrices. Factor analysis is notorious for its computational intensity and it has only been widely available to researchers since the rise of powerful personal computers. No archaeologist can be reasonably expected to understand this matrix algebra well enough contribute to the math behind these statistical models. I would be lying if I said that I understood it completely myself. However, this is an example of a tool that may be utilized by archaeologists without total knowledge of its complex details. It is a bit like pointing out that archaeologists may use a laser theodolite without completely understanding the machinery involved in producing and measuring the properties of the laser. The effect of this situation places a burden on the archaeological researcher to understand the basic statistical assumptions underlying the approaches being used.

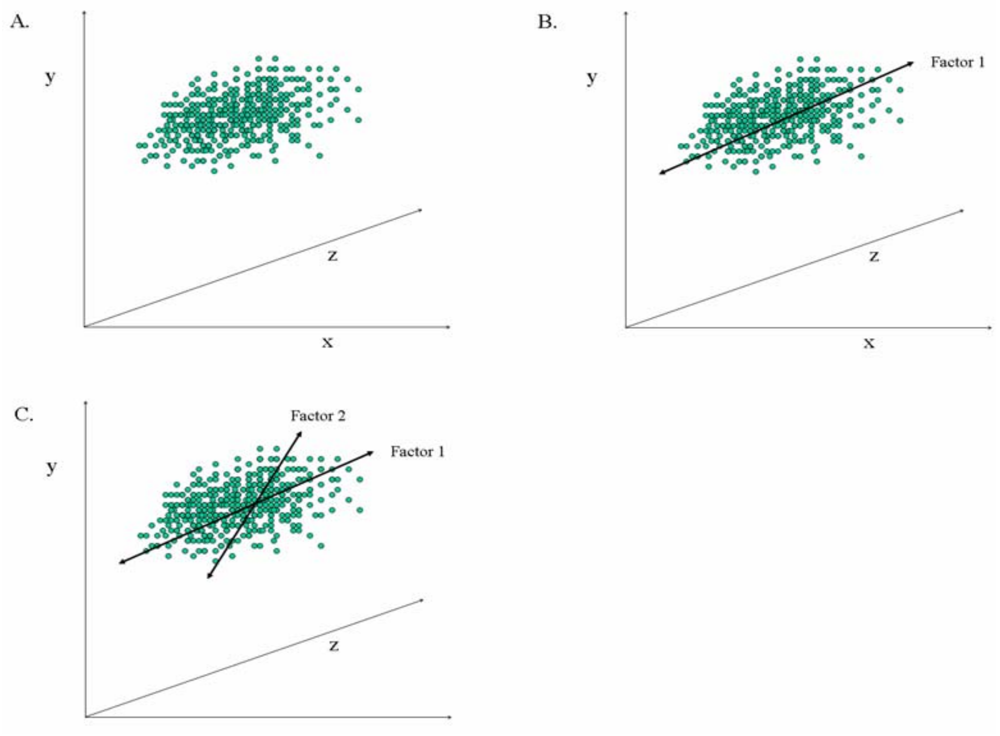

Figure 2. (A) shows the original swarm of data points in three-dimensional space. (B) shows the placement of the first factor regression line through the data, which best explains all of the data points. (C) shows the placement of the second factor regression line, which best explains the data not explained by the first factor. This processes continues with each successive factor addressing the data not explained well by previous factors.

In situations where many variables are operating, factor analysis presumes that, some of these variables will covary with one another. In other words, it works on the assumption that different variables will have relationships with one another, and that these relationships between variables are the result of some underlying dynamic of interest to the researcher. When different variables significantly covary, there must be some other variable or variables causing this relationship. The underlying dynamics that structure the covariation between variables are referred to as *latent variables*. They are latent in the sense that they are not visible in single observed variables, but are only seen through the covariation of several variables. Factor analysis hopes to discover latent variables by looking for patterns in the covariation of directly observed variables. This is the source of its power as a pattern recognition tool.

Factor analysis works by running a series of regression lines through data points in multidimensional space. These lines, referred to as factors, explain the data in best-fit fashion. The first line goes through all of the data points, and each subsequent line explains the data not explained very well by the previous line. Figure 2 shows this process with a fictional dataset. This example only shows three variable axes (x, y, and z), as it is hard to visualize more than three-dimensional multivariate space. Of course, factor analysis is not limited to three variables, but usually operates with many more than this. Each factor produces a series of regression scores for each variable that basically tells how strongly the variable covaries with the factor regression line. These scores are conventionally referred to as *eigenvalues*, and indicate how strongly a variable *loads* on a factor. Large positive eigenvalues indicate strong correlations of variables with a factor regression line, large negative values indicate strong correlations against a factor, and values near zero indicate weak relationships.

The examination of factor loadings is a way of recognizing the covariation between variables. When variables load strongly on the same factor, this indicates covariation, and points to a latent variable causing the relationship. This is especially the case when a set of variables all load strongly on a number of different factors. Frequently, these relationships are represented visually in two- or three-dimension scatterplots or hierarchical cluster analyses that show similarities in the loading of variables on major factors.

Factor analysis has two potential applications in analyzing data. Binford (1981) refers to these different applications of factor analysis as mode "R" and mode "Q." The "R" mode refers to the calculation of correlation coefficients for each of the variables. In other words, mode "R" is designed to look for latent variables through the covariation in observed independent variables. The "Q" mode refers to the use of factor analysis to understand how strongly the latent variables affect specific cases, and to use this information for the purposes of comparing and clustering cases. Mode "Q" involves the inversion of the correlation coefficient matrix to calculate scores for cases. This is frequently combined with other statistical approaches, such as hierarchical cluster analysis, in order to compare the characteristics of the cases. In dealing with the case studies presented later, both applications of factor analysis are used in each case, and I will use the "R" / "Q" distinction in talking about them.

Another common practice often performed in the course of a factor analysis is rotation. This is simply a process in which the factor solution rotated through the data points on which it was originally based in order to find the orientation that explains the data most parsimoniously. As with many things associated with factor analysis, this seems like an incredibly and confusing set of operations, and without the use of personal computers and statistical software, it certainly would be. Practically speaking, in most cases, performing a rotation is usually just a matter of clicking a box in the software program. The rotated solution is a more trustworthy reflection of the covariation between variables in the study, but usually the unrotated and rotated solutions do not differ very much. Many analyses, such as Binford's (1981), use the rotation as a way of generating regression scores for the cases in the study suitable for mode "Q" of the analysis.

As factor analysis is based on correlation matrices, it retains all of the regular assumptions underlying bivariate correlation and regression. These include continuous linear interval-scale data with more than two variables (and all of the other assumptions behind parametric statistics). This may sound like an imposing and confusing set of assumptions, but most large archaeological datasets meet them. For example, archaeological data representing both counts of objects in typological categories and standardized measurements of objects are both appropriate for factor analysis. The issue of whether data are linear and parametric is always complex, and should rightly be considered before any kind of statistical analysis. At the same time, with most archaeological datasets, it is probably safe to assume both of these unless there is some obvious *a priori* reason to think otherwise.

Let me briefly turn my attention to the unenviable task of distinguishing between FA and PCA in terms of their mathematical assumptions. For one thing, FA is the older of these two techniques, and to some extent, PCA represents an attempt to deal with some of the mathematical problems with FA. It is also the case that PCA is more widely used today, especially in fields like physical anthropology, where it has really become the industry standard. On the one hand, the two share most of their mathematical bases and generally produce highly similar results, especially with larger datasets. On the other hand, they do have one major distinction in terms of their mathematical assumptions that might sometimes have significant consequences in terms of the results of the analysis.

The major difference between FA and PCA is the orientation of the factor regression lines. One of the sources of controversy about FA has to do with possibility that the factor regression lines themselves might covary. This could be a major problem, because how can one use FA to recognize covariation between observed variables if the results of the FA also covary? The danger is that covariation in the factor regressions might make relatively minor relationships between variables seem much more significant than they really are, and *vice versa*. PCA addressed this problem by forcing its factor regression lines to be orthogonal to one another, thereby assuring that there is no mutual intercorrelation. In short, in PCA, the factor regression lines are assumed to be completely unrelated to one another, and therefore it is assumed that they must run at right angles, or be orthogonal. This is the nominal reason why PCA is generally the preferred variety of factor analysis today, especially in anthropology.

There is a sometimes-bitter debate over the importance or potential dangers of orthogonal factor regression lines within the statistical community (Vogt 2007). Advocates of FA point out that since factor regression lines are hopefully the result of interesting latent variables, there is no reason why they must be orthogonal, since there is no reason why latent variables themselves should be completely unrelated. As purely a consumer of this debate, I am compelled by aspects of both arguments. As Vogt (2007) points out, it is also usually the case that FA and PCA produce very similar results. For example, in a case study presented later in this chapter, I discuss a pattern recognition study of the Middle Stone Age lithic technology at Klasies River Mouth, South Africa, using PCA (McCall 2006). While I only reported the results of the PCA, I also did the same analysis using FA, and the two produced almost identical results. Vogt (2007) comments that this will usually be the case when large datasets are involved. Furthermore, using both statistical models to look at a dataset is a relatively easy option for most researchers, since it basically involves the clicking of a different box in statistical software program. Therefore, the debate over the superiority and advantages of FA and PCA usually has few major practical implications for anthropological research.

To summarize, FA and PCA will be most useful for archaeologists when: (1) Analyzing large datasets involving many variables and cases, and (2) these data are parametric and fulfill the assumptions of linear correlation and regression. These conditions are met by most archaeological datasets, which is why FA and PCA are powerful tools for pattern recognition in archaeology.

If there are clear reasons to think that a dataset does not meet the conditions of FA or PCA, there is another multivariate statistical method that is neither parametric nor linear called correspondence analysis (CA). The mathematics behind CA is similar to the other factor analysis techniques in relying on matrix algebra. The difference is that (1) CA was designed explicitly to deal with counts rather than including other kinds of interval data and (2) CA uses matrices of chi-square distances rather than correlation coefficients. The advantages of this include the potential to deal with non-linear non-parametric data, and in the past the calculations were dramatically simpler than the factor analysis techniques. The disadvantages of the technique are that it is much less powerful and lacks precision of the factor analysis techniques for the same reason that a non-parametric Spearman's *rho* measure of association is less precise than Pearson's *r* correlation. Though CA has been a very commonly used statistical technique in the past, there are relatively few situations today where it would be preferable to factor analysis techniques, given that most archaeological datasets are both linear and parametric, and given the ease of calculation using statistical software packages.

If there is uncertainty concerning the appropriate use of FA, PCA, or CA, one easy solution is to simply run all three using your statistical software. This is a quick way to determine if there are major differences in the results achieved using the different techniques. With most large datasets, there should be few major contradictions in the results of these three techniques. If there are large differences in the results, it may be a good idea to think harder about how the dataset under examination relates to the assumptions of these various statistical models. This is especially the case if the results of CA clearly contradict those of the FA or PCA. If this is the case, it may indicate that the dataset is either not appropriate for parametric statistics or the data are not linear.

Multiple Regression and Partial Correlation

Archaeological situations are frequently dominated by the dynamic interplay of multiple variables acting on one observed dependent variable. Multiple regression is a statistical technique for examining the overall effect of many different variables, and for recognizing which variables are having the strongest effect on one observed dependent variable. This stands in contrast with factor analysis, which is aimed at discovering latent variables causing covariation among the observed variables. Multiple regression does this by running a best-fit function through the scatter of observed data points in multivariate space. Simple linear regression does this with two variables, and the result is a line. Frequently, the linear regression equation is used to generate many useful statistics, including those related to correlation coefficients. Multiple regression works on the same principle, but includes many more dimensions. For example, the simplest multiple regression situation would involve three variables (two independent and one dependent) and the resulting regression equation would be a two-dimensional plane. Multiple regression obviously works with more than two independent variables; it can potentially have limitless number of independent variables. However, the results are impossible to display in graphical way.

By itself, the ability to put a regression equation through a scatter of data points in multivariate space is not that interesting, and this does not give much information of great use for archaeologists. The utility of this approach comes from the implications of the resulting regression equation for the relative effects of each independent variable on the observed dependent variable. For illustration, imagine the simplest multiple regression case with three variables. Each independent variable could easily be examined for its effect on one dependent variable using simple linear regression. The problem with this approach is that it lacks the potential to detect if one variable might be affecting the other, or which variable is having the strongest effect. Suppose that each individual regression shows a strong relationship between the independent and dependent variables. Multiple regression looks for the effect of both independent variables at the same time, and sees in multivariate space which variable has the strongest effect. Multiple regression equations can also be used to generate many of the same statistics as single linear regression, including multiple correlation coefficients and probability assessment.

A related technique is partial correlation, which involves examining the effect of specific variables while holding others constant. This is especially useful for finding the relative effects of two or more closely related variables on one independent variable. Mathematically, what partial correlation does is model two or more variables together using multiple regression and correlation, and then takes out the effect of certain variables on the others. This allows the researcher to statistically hold some variables constant while looking at the effects of others on the dependent variable. As Shennan (1997) points out, this is often practiced in reality in laboratory experiments, where certain variables can be controlled for through experimental design. Partial correlation offers a statistical way of doing this for archaeologists, who obviously cannot control variables operating in the past. Partial correlation offers another statistical technique for archaeologists dealing with variables that are often highly inter-correlated.

These statistical techniques are important tools for pattern recognition because they allow the researcher to look at many variables at the same time, and efficiently assess which variables are responsible for the most important observed effects. These techniques are most useful in situations where many closely related variables are involved. As with factor analysis, these techniques are parametric and assume that data are both linear and continuous. If data are not linear, it is still possible to do multiple regression, but the mathematics behind this become very complex, and this is often not allowed by most basic statistical software packages. A testament to this complexity is the work of Binford and Bertam (1977), who employed multiple curvilinear regression techniques working with animal bone density and anatomical part survivorship. The results were highly rewarding, but the mathematical complexity of even *reading* the paper is staggering.

Multiple regression and partial correlation are most frequently used in archaeology in the context of statistical hypothesis testing in basically the same way as simple bivariate regression. In fact, in collecting the case studies for this chapter, it was hard to find a good example of these statistical techniques used in a purely pattern recognition way. Indeed, the reader should be aware that if you must test a statistical hypothesis involving many variables, multiple regression and partial correlation are good ways of doing this. At the same time, they are generally under-utilized within archaeology in their roles as pattern recognition tools.

LEARNING BY EXAMPLE: ON TO THE CASE STUDIES!

At this point, the discussion of philosophy of science and mathematics is pushing the limits of most readers' attention. One of the best ways to learn how to use a new analytical tool is through the analogy of seeing someone else use it. For these reasons, I present a number of case studies using the statistical techniques discussed in this chapter on some types of material commonly dealt with by archaeologists. My hope is that these case studies will provide a framework for the reader in terms of (1) why the statistical approach was useful in a given situation and (2) how it was employed on a practical level by the researcher. These case studies should also illustrate some of my more opaque points in terms of the place of pattern recognition within archaeological science.

In this section, I present five important case studies covering the normal range of artifact types: (1) Binford's (1981) study of animal bones from the Early Stone Age (ESA) sites at Olduvai Gorge, (2) Bernardini's (2005) study of ceramic decoration in the later American Southwest, (3) Wilson's (1998) study of rock art motifs in Oceania, (4) my own use of PCA in studying the Middle Stone Age (MSA) lithics at Klasies River Mouth, South Africa, and (5) O'Connell's (1987) ethnoarchaeological study of the Alyawara using multiple regression.

I begin with Binford's (1981) case study, in part because of his pivotal role in bringing factor analysis techniques into the main stream of archaeological research. As Baxter (2003) points out, it was the success of Binford and Binford's (1966) paper that stimulated interest in factor analysis within archaeology. It is also the case that multivariate techniques for pattern recognition were a long-term interest of Spaulding (1977), and much of this work laid the foundation for Binford's early analyses. I choose to discuss Binford's (1981) faunal analysis because this is more like current applications of the factor analysis technique, and because it was among the first calculated using computers. It is important to credit Binford with his influence on the field both in terms of attitudes toward pattern recognition and the use of multivariate statistics.

Binford's Study of the Faunal Remains from Olduvai Gorge

This study comes at the close of Binford's (1981) highly influential book on the archaeology of animal bones. Most of the book is devoted to actualistic studies of modern animal bone assemblages produced by natural forces (e.g. modification by carnivores) and ethnoarchaeological studies of modern forager groups, such as the Nunamiut of Alaska. These are presented with the goal of illustrating the past dynamics responsible for the formation of archaeological bone assemblages, and constructing frames of reference for making inferences about past human behavior based on animal bone refuse. The book ends by using FA to look for patterns in the Olduvai ESA animal bone assemblages, and using the established analytical frameworks to make inferences concerning early hominid behavior.

Binford uses data from Leakey's (1971) summary monograph on the Olduvai excavations during the 1960s. Factor analysis was a useful analytical approach here because of Leakey's large dataset composed of many different variables and numerous cases. In performing his factor analysis, Binford treats the frequencies of various bone elements (presented in terms of animal part MNI, or a term later referred to as MAUs) as variables. Naturally, animals have many bone elements, creating a situation with many variables. Binford looked at 17 categories of anatomical parts for medium to large-size mammals. Olduvai is really a group of archaeological sites with many animal bone assemblages coming from different levels, which are treated as cases in this study. Binford examines the faunal data from 24 levels from 9 sites-- a relatively large number of cases. This is a situation commonly faced by archaeologists: Binford wanted to know about the covariation in the frequencies of various anatomical elements in order to look for the effects of latent variables, such as ravaging by carnivores or hominid bone-breaking for marrow, which are impossible to measure directly. In such a case, there are too many variables and cases to look for patterns effectively based on hunches or trying to eyeball every possibility with descriptive statistics.

Another interesting aspect of Binford's analysis is his integration of control samples into the factor analysis. In addition to the 24 archaeological cases, he also included 4 control samples-- 2 carnivore kill sites and 2 den sites. This is an important way of making sense of the results of the factor analysis, as it is known in these cases what the forces acting on the bone assemblages were, creating reference points for the other archaeological assemblages. Binford's analysis is composed to two basic phases: the "R" mode and the "Q" mode.

For mode "R" of the analysis, Binford recognizes 4 factors representing 4 latent variables affecting the frequencies of anatomical parts. The least dense anatomical elements that are most subject to destruction load strongly on the first factor. This leads Binford to recognize this factor as relating to bone destruction. The second factor groups animal parts most likely to be left behind at a kill site by carnivores, and the third factor groups parts most likely to be transported away from kill sites. The fourth factor groups parts which are most likely to covary as the result of large body size or old age of prey animals. Binford's interpretation of the meaning of these factor loadings is largely based on knowledge of the dynamic forces acting on animal bone assemblages outlined earlier in his book, and he also makes good use of his control samples in this part of the analysis.

For mode "Q" of the analysis, Binford uses these inferences of latent variables to examine the archaeological bone assemblages from Olduvai. In this phase of the analysis, Binford talks about a five-factor solution (though one wonders why the fifth factor was not discussed during mode "R" of the analysis). All of the cases score highly on the first factor, which represents destruction, indicating that all of the sites and the control samples show evidence for density-mediated attrition from numerous causes. Binford argues that the second factor represents transported assemblages, as the carnivore kill control samples do not score highly on this factor, but the den sites do. It is also interesting that relatively few of the archaeological assemblages score highly on this factor. None of the animal control samples score highly on the third factor, and Binford therefore takes this to represent activities of hominids. The Olduvai sites loading on the third factor have in common a pattern of high frequencies of scapulae, distal humeri, and distal tibiae, and low frequencies of distal metapodials. Binford sees this as the result of the removal of marrow-yielding elements from sites by hominids-- in other words, scavenging of animal resources left behind by the initial carnivores at kill or natural death sites. Binford sees factors four and five relating to the effects of carnivore kills (especially large kills in the case of the fourth factor), with the contribution of the elements missing from factor three sites, indicating the introduction of these parts by hominid scavengers. In summary, Binford uses FA in this study to examine the relative contribution of natural forces and hominid behavior to the characteristics of the faunal assemblages at Olduvai, and discovers an interesting archaeological pattern with important implications for early hominid behavior.

Binford's conclusions concerning early hominid scavenging have been quite controversial, though remarkably influential. In this study, whether or not one accepts Binford's explanation of the observed archaeological patterning, the utility of both his analytical approaches for quantifying animal bones and multivariate statistical methods for pattern recognition are clear. On a broader level, FA is a powerful tool for dealing with quantified faunal assemblage because of the obvious interesting in discovering pattern of covariation between categories of element. Most inferences about past behavior made from animal bone assemblages are at least partially based on element frequencies, especially when other variables (species of animal, age, sex, etc.) are included. As in Binford's study, by showing patterns of covariation in element frequency, FA is a method for identifying latent variables acting on animal bone assemblages that are impossible to examine directly, such as modification by non-human carnivores, density-mediated attrition, etc.

Binford's study also raises a few statistical questions that could easily be dealt with using modern statistical software packages, if it were done today. For example, Binford does not describe in great detail how much of the observed variation is explained by each factor. In FA, it is rare for factors beyond the second or third to explain enough of the variation to be very meaningful. In addition, as Baxter (2003) and Shennan (1997) both point out, aspects of Binford's statistical approach are more like PCA than FA, especially the rotation of the factor solution. These are minor issues, but there are currently better-defined conventions for dealing with them in terms of statistical nomenclature and what statistics are reported.

Bernardini's Work at Anderson Mesa and Homol'ovi

The next case study comes from Bernardini's (2005) study of the Hopi ceramic assemblages at Anderson Mesa and Homol'ovi-- groups of late prehistoric villages in northern Arizona. The research problem that Bernardini addresses concerns the dynamics of migration and aspects of social identity brought about by a period of drought-related population upheaval during the 14th century A.D. The specific archaeological question he examines is the movement of clans as indicated by the distribution of totemic clan signatures on the landscape and the transportation of ceramics as indicated by neutron activation analysis (NAA) of clay element compositions. Bernardini uses PCA to deal with the complex chemical signatures of ceramic vessels, composed of many different trace elements of interest in terms of sourcing.

Bernardini analyzed the amount of 14 different trace elements of 650 ceramic sherds from the Jeddito Yellow Ware (JYW) tradition from 15 sites at Anderson Mesa and Homol'ovi. This is clearly an appropriate case for the use of PCA, as it involves many different variables (amounts of the various trace elements) and many different cases (each individual sherd from the various sites). In this case, it is the covariation in trace element amounts that points to the latent variable of interest-- the source of the ceramics. Like Binford (1981), Bernardini also makes good use of reference samples by including chemical compositions of ceramics from 7 known locations, providing frames of reference for unknown samples. This approach allowed Bernardini to make inferences concerning the sources of ceramics at the Hopi villages in his study area.

Unlike Binford (1981), who was concerned with both modes "R" and "Q" in his FA, Bernardini is only really interested in mode "Q". The reason for this is obviously that mode "R" in this case would not provide information that was very interesting-- the patterns of covariation in element percentages for all sites considered together. In contrast, mode "Q" of the analysis tell how strongly the ceramics correlate with the various principal components, which provides a good basis for comparing and clustering ceramic assemblages on the basis of their source. Bernardini focuses on the first two principal components of the solution, which together explain 75% of the observed variation. Some of the reason for focusing on the first two principal components might be for ease of graphical display, as it is a lot easier to compose a two-dimensional rather than a three-dimensional graph. Even with only two principal components displayed, the graphs were quite striking in showing the association of ceramics of various villages in different locations. This information provided Bernardini with an important basis for making inferences about the flow of ceramics in his study area.

This case study also shows the value of multivariate statistics like PCA for dealing with complex trace element and sourcing analyses. Traditionally in archaeology, sourcing is done using other methods of pattern recognition. Often, the source of an object is inferred on the basis of the presence of one trace element found in a certain location but presumably not found at others. This method is sometime problematic because of the presumption that the signature element is not found at sources as of yet unknown to archaeological researchers. In other words, it is impossible to know what elements are present in the materials of unknown sources. It is also rare to find a case where there is one signature element that is unique to only one location. Another more complex approach is the comparison of amounts of many elements, which is the conceptual basis for Bernardini's study. This approach is problematic in that it is hard to recognize variation in the amounts of many different elements simultaneously that is linked to one specific location. Bernardini's study is innovative in using PCA to accomplish this task when trying to eyeball the covariation in element amounts with potential source locations in mind would be futile. Clearly, PCA provides a valuable statistical framework for handling the task of recognizing the complex patterns of covariation in element amounts present in different locations.

Bernardini's study is also partially based on a number of other statistical approaches for dealing with trace element amounts. For example, in establishing the initial reference groups, he uses a complex set of cluster analysis and probability assessment techniques. It also would have been better from a statistical standpoint if Bernardini had reported more information about the principal component solutions he arrived at, including a table of correlation coefficients and a list of eigenvalues. These were no doubt omitted in this paper for reasons of length and a larger focus on the social implications of ceramic sourcing information.

Wilson's Work on Petroglyphs from Oceania

I present the next case study not so much because it is a perfect model of how to use multivariate statistics to study rock art, but because it shows why this could be a very productive approach. As with many studies of Oceanian prehistory, Wilson's (1998) study is mainly concerned with examining questions of historical relationships between groups, migration, and interaction. In her study, Wilson uses CA to examine the relationship between rock art sites in various regions of the Pacific. The use of CA in this case may indicate Wilson's fears about whether her dataset meets the assumptions of parametric statistics and linearity-- the main reasons for using CA. This concern was probably not necessary in this case, as the frequencies of certain characteristics of rock art elements is an interval measure, and probably meets the other assumptions of FA and PCA models. Even given her conservative statistical approach, Wilson's use of multivariate statistics leads to many important insights about the prehistory of Oceania.

Wilson uses the frequencies of particular characteristics of rock art elements as the basis of her analysis. Her study focuses on the characteristics of anthropomorphs and geometric elements, and she treats the analysis of these two separately. In her study of anthropomorphs, Wilson examines 169 variables (characteristics of anthropomorphs, such as shape, presence of certain anatomical features, etc.) for 224 figures from 16 geographical regions. Obviously, 169 variables is a very large number, which is appropriate for using CA. However, these variables are not listed, and it presses the imagination a great deal to think of how there could be 169 easily identifiable features of each anthropomorphic figure. This study probably would have been better if it had reduced the number of variables to a more manageable set. For one thing, this sort of analysis does not have the ability to weight the importance of one variable versus another. I doubt that all 169 measured features of anthropomorphs are equally important or meaningful. Rather than coming up with a list of every conceivable minor aspect of variation in anthropomorph style, it might have been better to pick a smaller list of the most important stylistic difference. In general, one gets the impression that this number of variables was selected because of the *a priori* decision to use CA as a statistical approach.

Wilson uses two correspondence axes to examine the relationship between anthropomorphs in the various regions, and finds patterns of similarity and difference that generally confirm existing models of migration and settlement based on other ethnographic, linguistic, and archaeological data. Wilson's analysis of geometric shapes is based on the same design as with the anthropomorphs and came up with similar results. Wilson looked at 164 variables on 436 individual elements from the various regions of Oceania. Once again, a finer-grained focus on the most important aspects of variation in geometric shape style might have been preferable. I do not mean to take too critical of a tone with Wilson's work, despite some of the problems I pointed out, as her use of multivariate statistics to study rock art is quite unique and its seems to succeed in recognizing meaningful patterning concerning prehistory.

Let us stop for a moment and consider what the latent variables of interest are and how they relate to the covariation of observed variables. Wilson obviously hopes to identify latent variables concerning stylistic differences in rock art production based on differences of group identity stemming from patterns of migration and population history. In other words, she begins with an assumption that the many regional populations of the Pacific shared a common ancestor (probably in New Guinea) that had a relatively homogenous way of making rock art. Then, as the populations spread across the Pacific, diverse derived stylistic traditions of making rock art emerged, reflecting the cultural identity of group making it. In this scheme, the latent variable of interest is the cultural identity and historical context of the group making the rock art. This approach is squarely within the research paradigm of the anthropology of Oceania, and Wilson does a good job of generating innovative quantitative approaches of using rock art to address historical questions.

It is not hard to see how a similar multivariate approach to rock art might be used to study different social dynamics in the past. For example, the kinds of rock art elements at a given site might vary for other interesting reasons. For example, different social or ritual contexts of rock art sites might lead to variation in patterns of rock art. In this case, a latent variable might be some ritual context in which a certain set of rock art elements was produced. Mode “R” could be used show the covariation in element frequencies and might point to related sets of imagery produced in common contexts. Mode “Q” could be used to identify different types of rock art sites with different contextual features. Multivariate statistics for pattern recognition important for rock art research because they offer the potential to see the covariation in frequencies of various rock art elements, which is one of the primary issues facing rock art researchers. While her research is not perfect, Wilson was definitely quite innovative in seeing the utility of multivariate statistics for dealing with covariation in element frequencies, and her study is fairly unique in this respect.

McCall’s Study of the Lithics from Klasies River Mouth, South Africa

The next case study that I present is my own work on the lithics from Klasies River Mouth, South Africa (McCall 2006). This is an important archaeological site with remains including lithics, fauna, and early anatomically modern human skeletal material. Klasies River Mouth was initially important because it showed a very early presence of anatomically modern humans in South Africa. Later, debates developed concerning the nature of early human behavior on the basis of the lithic technology and faunal remains. One interesting aspect of the lithic assemblage is the emergence of the Upper Paleolithic-like Howiesons Poort industry, which is frequently related to the development of behavioral modernity in the Upper Pleistocene. The question I wanted to examine was whether there was continuity between the Howiesons Poort industry and later lithic technology present at Klasies River Mouth.

I performed a PCA using the categories of stone tools reported in the summary monograph of Singer and Wymer (1982) as variables and the culture-stratigraphic levels of the various caves at Klasies River Mouth as cases. In this study, there were 20 typological categories of stone tools and 8 culture-stratigraphic levels. The typological categories focused on strategies of core reduction and tool design, and mainly referred to differences between expedient, Levallois and blade core reduction strategies, and patterns of flake retouch. The culture-stratigraphic levels ranged included the Middle Stone Age (MSA) levels below to the Howiesons Poort, the Howiesons Poort, and the MSA levels above the Howiesons Poort.

Mode "R" of the analysis looked for relationships between the various categories of stone tools, and the results showed some clear patterns. The PCA found three main components: the first related to Levallois core reduction strategies commonly associated with the earlier MSA; the second related to blade core reduction strategies and microlith production typical of the Howiesons Poort; the third related to production of worked MSA points, and only this category of stone tools loaded strongly on the third principal component. This part of the analysis was useful in detecting latent variables affecting the covariation in stone tool frequencies related to basic approaches to lithic raw material and tool design.

In mode "Q" of the analysis, I used the varimax rotation to generate regression scores for the cases used in the study-- the culture-stratigraphic levels at Klasies River Mouth. These scores were useful for the purposes of clustering the cases and examining the question of continuity between the Howiesons Poort levels and those following them. The results of this part of the analysis showed that the MSA levels coming before and after the Howiesons Poort were much more similar to each other than any were to the Howiesons Poort. This is a provocative finding, suggesting that a radically novel strategy for stone tool production emerged at the end of the MSA, and then gave way to earlier strategies. This suggests that the emergence of the Howiesons Poort is not a clear signal of the origins of behavioral modernity, and it presents a case of the alternation of lithic industries similar to that seen in the Middle Paleolithic of Europe (e.g. Binford and Binford 1966).

PCA and FA are useful approaches for pattern recognition in lithic datasets because they have the potential to see covariation in both the frequencies of objects in various categories and between different kinds of measurement. The use of FA to study covariation in the frequencies of stone tool types has a very long history, extending back to early work of Binford and Binford (1966). Another interesting example of the use of PCA in studying stone tools is that of McPherron (2000), who uses the technique to examine the measurements of Lower Paleolithic hand axes. It is also the case that PCA and FA are flexible enough to deal with changes in the practices of lithic analysis and quantification and have remained useful for more than forty years.

O'Connell's Ethnoarchaeological Study of the Alyawara

The final case study I wish to present is O'Connell's (1987) ethnoarchaeological work with the Alyawara. This study used observations on living foragers in the Western Desert of Australia to understand the forces affecting site formation in the past. O'Connell was concerned with many characteristics of forager camp sites, including their location on the landscape, overall size, locations of various kinds of activity areas, and the locations of various kinds of refuse deposits—all things that are observable in the archaeological record. In order to understand to variables affecting these material characteristics, O'Connell made many observations on the human populations, demographic makeup of people living at a site, the kinds of activities that were done there, how long the site was occupied, and a number of other dynamics. This quantitative part of the study employs multiple regression because of interrelationship of many variables involved in shaping the various characteristics of camp sites, and the need to build models based on many variables.

I will briefly present one main example of the use of multiple regression in this study: modeling variables affecting the size of household activity areas. Here, the size of activity area refers to the size of the domestic space in which daily activities were carried out. These areas were cleared of vegetation and included important physical features, including domestic structures and hearths. This is the kind of information that archaeologists frequently deal with, and it is important to understand what human behavior is responsible for their various characteristics. In building a model to understand household activity area size, O'Connell needed to incorporate two variables to accurately understand the phenomenon: (1) the number of days for which the camp was occupied and (2) the total number of individuals occupying the household.

O'Connell's multivariate model of household activity area size has some interesting implications for archaeological research. First, he finds that activity area size relates directly with both household population size and duration of occupation. This is not an unexpected finding, simply showing that the more people that were present at a site and longer it was occupied, the larger the size of the resulting activity area. In this model, O'Connell makes the important connection between duration of occupation and household population size that could not be done effectively in separate, bivariate ways. It is also very important that this multiple regression model allowed O'Connell to hold each variable constant while examining the other. For example, this model shows that the effect of population size on activity area size decreases as population size increases. This basically means that amount of space per individual decreases as the total population increases. Similarly, holding population size constant, the effect of the length of occupation on activity area size decreases as the length of occupation increases. In other words, activity area size grows at a slower rate the longer a site is occupied. Both of these findings make a certain amount of intuitive sense, but it is important to be able to model them in a quantitative fashion, and knowing how these variables affect the physical layout of sites has very important implications for archaeological research.

O'Connell's (1987) use of multiple regression for ethnoarchaeological pattern recognition was innovative, and shows how the technique might be applied to other situations. For example, it is not hard to imagine the incorporation of other variables into a multivariate model of household activity area size or the expansion of the model to include other ethnoarchaeological cases. Indeed, O'Connell does make some interesting comparisons and contrasts at the close of his paper along these lines. More broadly, this ethnoarchaeological study is not unique in wanting to understand how many variables contribute to archaeological site formation. I stated at the outset of this chapter that many archaeological phenomena (especially the processes of site formation) are highly complex and multivariate in nature. O'Connell is also not alone in wanting the ability to hold the effects of certain variables constant while examining the effects of others. Controlling for the effects of specific variables is the key to sophisticated scientific archaeological model-building.

Summary Comments on Case Studies

It is my hope that these case studies have provided an *entrée* into the ways in which multivariate statistical techniques may be productively used for pattern recognition in archaeology. It is also my hope that seeing these statistical techniques in action might provide a more vivid demonstration of why (and perhaps how) these statistical procedure ccould be used. Along these lines, I highly recommend a more detailed reading of the original case studies on which this section has been based. Frequently, learning by example is easier than learning by abstract instruction, particularly for those of us whose analytical approaches are driven by the immediate needs of our research interests. I am also confident that a detailed reading of these case studies can provide a more compelling case for the use of certain statistical approaches than I have so far in this chapter.

CONCLUSION

In this chapter, I have tried to make the case for why certain multivariate statistical techniques could be extremely useful for pattern recognition in archaeological science. I wish to conclude with two main thoughts. The first is warning in terms of the relationship between scientific research problems and analytical methods. As Thomas (1978) warned almost thirty years ago, it is a mistake to put the “cart” of statistical methods and analytical procedures before the “horse” of specific research problems. In other words, the specifics involved in the investigation of the research problem should drive the selection of methods, not the other way around. This seems like a common sense statement, but is frequently violated as trendy theories, approaches, and methods come and go. This is no less true of statistical methods, which are often used for personality-driven reasons of convention rather than the requirements of research. More complicated statistical approaches do not equate with better science. My point in this chapter has been that there are often occasions where multivariate statistics might dramatically help the research process—not that they should be used in every situation all of the time. In this respect, Thomas points out the danger of “ritual” approaches to statistical analysis.

My second concluding thought is that too often statistical research is criticized, excluded, or ignored because of small mathematical problems. Statistical errors are inevitable, especially for archaeologists whose real job is understanding the past—not developing statistical models. As full-time consumers of statistical methods, mistakes are unavoidable, and we should acknowledge that these mistake range from very minor problems with no real implications for research conclusions to more serious and problematic errors. Most of the time, statistical mistakes in archaeology tend toward the former. Having made a great many mistakes in my own statistical analyses over the years, I know that these are not usually fatal flaws. The important point for this chapter is that researchers often fear the application of an unfamiliar approach because of the likelihood of mistakes. Statistical research in archaeology can be productive without being perfect, and fear of mistakes should not be an impediment to the development and application of innovative approaches.

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