

Increasing Scales of Social Interaction and the Role of Lake Cahuilla in the Systemic

Fragility of the Hohokam System (A.D. 700-1100)

by

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## ABSTRACT

Exchange is fundamental to human society, and anthropologists have long documented the large size and complexity of exchange systems in a range of societies. Recent work on the banking system of today's world suggests that complex exchange systems may become systemically fragile and in some types of complex exchange systems that involve feedbacks there exists a fundamental trade-off between robustness (stability) and systemic fragility. These properties may be observable in the archaeological record as well. In southern Arizona, the Hohokam system involved market-based exchange of large quantities of goods (including corn, pottery, stone, and shell) across southern Arizona and beyond, but after a few generations of expansion it collapsed rapidly around A.D. 1070. In this case, increasing the scale of a pre-existing system (i.e., expanding beyond the Hohokam region) may have reduced the efficacy of established robustness-fragility trade-offs, which, in turn, amplified the fragility of the system, increasing its risk of collapse. My research examines (1) the structural and organizational properties of a transregional system of shell exchange between the Hohokam region and California, and (2) the effect of the presence and loss of a very large freshwater lake (Lake Cahuilla) in southeastern California on the stability of the Hohokam system. I address these issues with analysis of ethnographic, ethnohistoric, and archaeological data, and with mathematical modeling. My study (1) produced a simple network model of a transregional system of interaction that links the Hohokam region and California during the centuries from A.D. 700 to 1100; (2) uses network and statistical analysis of the network model and archaeological data to strongly suggest that the transregional exchange system existed and was directional and structured; (3) uses

network and other analysis to identify robustness-fragility properties of the transregional system and to show that trade between Lake Cahuilla fishers and the Hohokam system should be included in a mathematical model of this system; and (4) develops and analyzes a mathematical model of renewable resource use and trade that provides important insights into the robustness and systemic fragility of the Hohokam system (A.D. 900-1100).

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## CHAPTER 1: INTRODUCTION

Exchange is fundamental to human society, and anthropologists have long documented the large size and complexity of exchange systems in a range of societies (e.g., King 1976; Malinowski 1922; Strathern 1971; Wiessner 2002). Recent work on the banking system of today's world suggests that complex exchange systems may become systemically fragile (Beale et al. 2011; Haldane and May 2011; May and Arinaminpathy 2010; May et al. 2008) and in some types of complex exchange systems that involve feedbacks, there exists a fundamental trade-off between robustness (stability) and systemic fragility (Anderies and Janssen 2011; Bode 1945; Csete and Doyle 2002; May 1972). These properties may be observable in the archaeological record as well.

In southern Arizona, the Hohokam system involved market-based exchange of large quantities of goods (including corn, pottery, stone, and shell) across southern Arizona and beyond, but after a few generations of expansion it collapsed rapidly around AD 1070 (Abbott et al. 2007). In this case, increasing the scale of a pre-existing system (i.e., expanding beyond the Hohokam region) may have caused the system to move along a one such robustness-fragility trade-off frontier, amplifying the fragility of the system, increasing its risk of collapse. In this dissertation I investigate these issues by examining the properties of a transregional system of exchange between the Hohokam region and California (Figure 1.1).

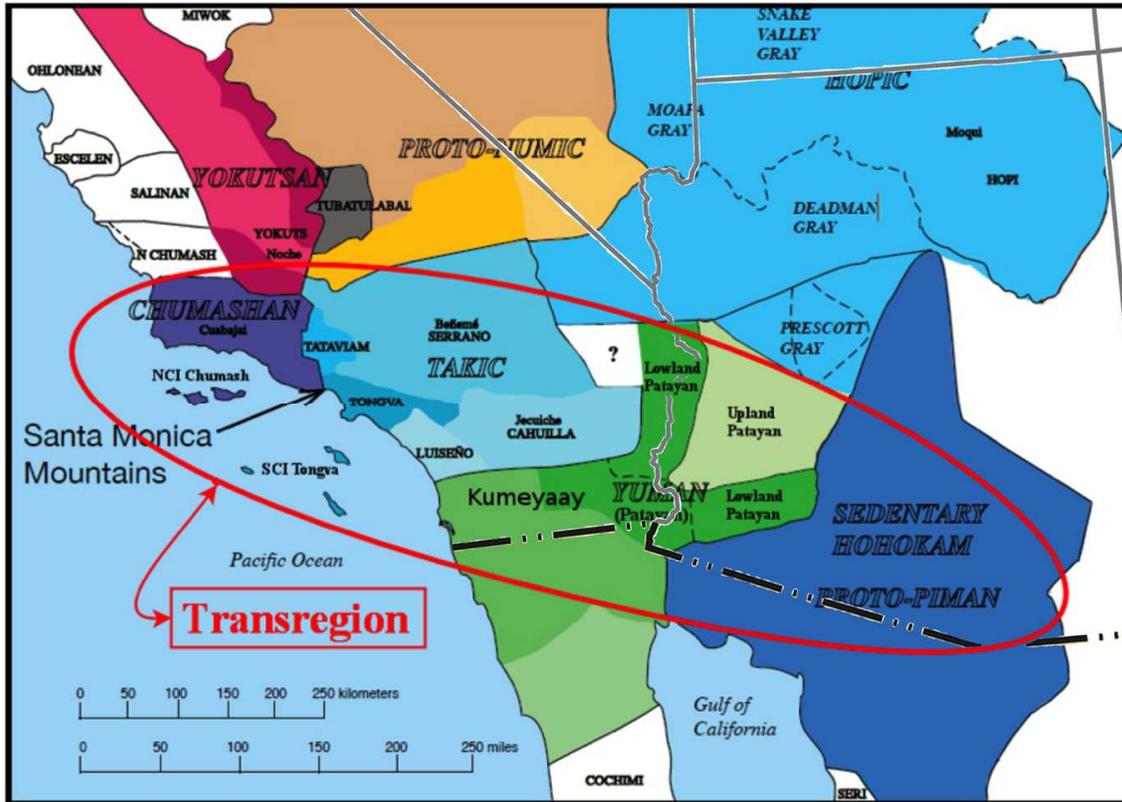


Figure 1.1. Hohokam/California Transregion (A.D. 700-1100). The north, east, and west boundaries of Sedentary Hohokam are from Gumerman and Haury 1979:75. Areas south of those mapped by Gumerman and Haury are areas where Piman speakers lived historically and/or areas mapped as O’odham by Di Peso (1979:91). The northern distribution of River Yuman (Lowland Patayan) groups is based on Patayan I (AD 700-1000) pottery type distributions from Waters (1982:281-296). Note that the terms in large type (with the exception of Sedentary Hohokam) are language families associated with a specific geographic region (identified by color), and terms in small type are the names of the native American society (ies) in a designated (with color) geographic region associated with a given language family. For example, the Tatavium, Tongva, Cahuilla, Serrano, and Luiseno people spoke Takic languages, and the presumed ancestors of Hopi people spoke a Hopic language. Both Takic and Hopic are sub-families in the Uto-Aztecan language family (see Sutton 2009; Hill 2001, 2007).

## **Expansion, Systemic Fragility, and the Rapid Collapse of the Hohokam System**

The Pre-Classic Hohokam system of southern Arizona is of great interest because it provides a valuable case study of an agrarian middle-range social ecological system (Bayman 2001; Doyel 1991; Fish 1993) that greatly expanded in scale and complexity over a few generations, followed by a rapid collapse around A.D. 1070. Previous work on the Pre-Classic Hohokam system has focused on intra-regional exchange (Abbott et al. 2001; Seymour 1988; McGuire and Howard 1987) and on internal and localized shocks (see Ensor et al. 2003 and Waters and Ravesloot 2001) as the most likely causes for the collapse of the system. However, there have been no published discussions of the broader question of how economic expansion of the Pre-Classic Hohokam system beyond the Hohokam region could have affected its long-term stability. This is the focus of my research: Could increasing the scale of a pre-existing system (i.e., expanding beyond the Hohokam region) have induced robustness-fragility trade-offs, exposing new fragilities of the system and increasing its risk of collapse?

My research investigates these issues by examining the properties of a transregional system of exchange between people in the prehistoric Hohokam region of Arizona and people in regions of native southern California. Much of my research focuses on the interaction of people in the Hohokam system with people living around Lake Cahuilla, an enormous (i.e. 5184 square kilometer) body of water that existed in prehistoric times in southeastern California (see Figure 1.2). This study examines two components of Hohokam/Lake Cahuilla interaction: (1) The impact of the increasing scale of interaction, and (2) the effect of the filling/drying cycles (ca. A.D. 850-1100) of Lake Cahuilla on the stability of the Hohokam system.



Figure 1.2. Ancient Lake Cahuilla in relation to the present day Salton Sea (left portion of figure, slightly modified from Gobalet et al. 2005, Figure 1).

The project has four interrelated goals implemented in four iterative stages: (1) Document the transregional system of interaction that linked the Hohokam region and California during the centuries from A.D. 700 to 1100; (2) determine whether the transregional exchange system was directional and structured or was largely stochastic using simulation, network, and statistical analysis; (3) identify regions in the network model that are probably strongly tied to the Hohokam system and each other through regular interaction; and (4) use mathematical modeling to evaluate the effects of additional labor allocations for specialized production and trade, population size, and the filling/drying cycles of Lake Cahuilla on the stability of the Hohokam social ecological system. These goals will be addressed with analysis of existing ethnographic, ethnohistoric, and archaeological data, and with mathematical modeling.

### **My Research Strategy to Address the Four Goals**

To address the first goal requires ethnographic, ethnohistoric and archaeological data to map exchange relationships between each of the regions I relate to specific cultures or

ensembles of cultures in the Hohokam/California transregion (Figure 1.1). The regional boundaries that I use are supported by ethnographic, linguistic, archaeological, and ethnohistoric studies. When ethnohistoric data agrees with archaeological data (e.g., correspondence of the locations of historic villages to a prehistoric settlement system) it is reasonable to suggest that the historic pattern existed prehistorically. Ethnohistoric data is often useful for mapping regional or finer scale exchange relationships. For example, California mission register data have been used to reconstruct inter-village marriage patterns and social networks at or near the time of first European contact (e.g., Horne 1981; Johnson 1988; King 1984). Mission documents have also been used to map linguistic groups in California during the colonial period (e.g., Callaghan 1996; Fountain 2013; Johnson and Earle 1990), which often correspond to exchange relationships. I use written accounts by Spanish missionaries and early American travelers in southern California and Arizona, along with ethnographic and archaeological data to identify interregional exchange relationships. The ethnohistoric and ethnographic data are post European contact, which requires that I also examine archaeological data. Ceramic data is used to a very limited extent to qualitatively suggest the presence of specific groups (e.g., Hopic) within a region or at specific locales (e.g., shoreline of Lake Cahuilla). Local and non-local shell artifacts from residential sites in each of the regions and from two contexts (burials and house areas) are used to identify interregional connections and directionality in the movement of different types of shell artifacts. Detection of directionality in the movement of artifacts also relates to establishing the existence of a transregional system (part of Goal 2). To address Goal 1, I also compare the shape of one type (small barrel beads) of shell artifact from burials in a California site to samples of

this type from contemporaneous Hohokam sites and to shell samples from the Gulf of California and the Pacific Coast, to assess the likelihood that the California sample originated in the Hohokam system. I also analyze changes in the variability of the shape of the California sample over time, to see if reduced shape variability (which I suggest is correlated with increased production) corresponds to filling cycles of Lake Cahuilla. If so, and if the shell artifacts were manufactured in the Hohokam system, then this supports the idea that this kind of shell artifact was often exchanged for dried Lake Cahuilla fish, and that fluctuations of Lake Cahuilla had a significant effect on the dynamics of the transregional system (which relates to Goal 4). Also, as a necessary prior to analyzing the shape variability over time, I chronologically seriate the burials from which this sample was taken. The specific analytical methods (some of which have not been previously used in archaeology), data, and the goal(s) they address, and where they are used is summarized in Table 1.1. Each of these methods is described in more detail where they are used and/or in appendices.

Table 1.1. Purpose of analysis, data, and analyses used in this study. Methods new to archaeology are also identified.

Purpose	Data	Analyses	Goal(s)	Method(s)	Chapter(s)
Identify presence/absence of historic interregional interaction	Written accounts of exchange, ethnographic data, qualitative archaeological data	Ethnohistoric, ethnographic, archaeological	1	New to archaeology No	3
Species identification Sourcing	Shell attributes Landmarks on shell	Morphological	1	No	5
		Geometric morphometric	1	Yes	5
Order by time	Counts of typed shell artifacts in burials or residential areas	Chronological seriation (several procedures which are discussed prior to their use)	1	Yes	6
Determine if data is homogeneous, and if not, partition data into homogeneous subsets	Measurements of shell	Identification of modes	1	No	6
Measure production intensification	Measurements of shell	Bootstrapped and jackknifed coefficient of variation	1, 4	No	6
Detect significant changes in exchange activity in the transregional system	Proportions of typed Gulf of California and Pacific Coast shell artifacts from burials or residential areas	Boschloo' s and Barnard' s exact tests	1,4	Yes	6
Evaluate if shell artifacts from sites in two different regions are contemporaneous	Diameter of shell Artifacts	Analysis of means	1	No	6
Evaluate age of shell artifacts	Length of shell artifact Diameter of shell artifact	Dot plot	1	No	6
		Simulation based 2-sample Smirnov test	1	Yes	6
Detection of “communities” Evaluate if the reconstructed network was likely the result of random processes	Adjacency matrix of reconstructed network Adjacency matrix of reconstructed network and a large number of Erdős-Rényi random graphs with the same number of nodes and edges as the reconstructed network	Walktrap community detection algorithm	2,3	Yes	7
		Observed values of transitivity and average path length and estimated p-values of transitivity and average path length	2	Yes	7
Evaluate directionality of exchange in transregion	Site location and proportion of Gulf of California and Pacific Coast shell artifacts	Kriging	2	No	7

A reconstructed graphical model of the California/Hohokam transregional system is the end result of the ethnohistoric and archaeological analyses. Specifically, this model is a network graph, in which only the presence or absence of exchange relations between regions are shown. I first use what are called Erdős-Rényi random graphs, which I discuss in detail in Chapter 7, with the same number of nodes (regions) and edges (ties between regions) as the network and several graph-theoretic measures (transitivity, average path length, betweenness centrality, and motifs) to construct empirical (or approximate) sampling distributions. These distributions are used to show that the observed values for each of the graph-theoretic measures in the network model are not expected to occur by chance, which addresses Goal 2. The graph-theoretic measures are also interpreted in relation to the robustness-fragility properties of the Hohokam/California transregional system, which addresses Goal 3.

Although simple, the network model contains subtle and pertinent information for my study that can be revealed using sophisticated mathematical methods designed to detect community structure in network graphs (e.g., Fortunato and Castellano 2007; Fortunato 2009). To address Goals 2 and 3, I analyze this model using a method that is capable of identifying multi-scalar patterning in the network that relates to highly cohesive subunits or modules, called communities. The purpose in doing this is to: (1) identify what regions the Hohokam system may have been most dependent on, and (2) compare the structure revealed by this analysis with that of ethnohistoric and archaeological data on exchange relations from the transregion, and to make predictions about such relations, when data is not available. The idea is that if the structure revealed by the analysis is similar to that of the ethnohistoric and archaeological data, then it is likely that the topology of the network

model is a reasonably good approximation to the topology of the actual prehistoric system. Showing this supports the existence of the Hohokam/California transregional system. I also address Goal 2 by examining the directionality of shell artifact exchange in the transregion (Table 1.1). Directionality of exchange is an essential component of an organized system of interaction (e.g., Plog 1977), and I propose that if directionality cannot be detected than it is questionable that the Hohokam/California transregional system existed.

To address Goal 4, I construct and analyze a dynamical bioeconomic model, whose dynamics are the growth and consumption of renewable resources and the filling and emptying cycles of Lake Cahuilla. Briefly, a bioeconomic model is a mathematical model of a dynamical system (a system that changes with time) that is composed of biological system(s) coupled to an economic system(s), such as fishery. The dynamics of both the biological and economic systems (because they are linked) produce complex feedbacks that often result in surprising outcomes related to the effects of perturbations on the stability of the system. In this study, the bioeconomic model is constructed so that changes in labor allocated to obtaining wild resources, agriculture, and trade for Lake Cahuilla fish are determined by the model dynamics. Understanding under what conditions values of model parameters and/or the emptying and filling cycles of Lake Cahuilla could destabilize the system will help identify systemic fragilities.

### **Organization of the Remaining Chapters**

Chapter 2 begins with a discussion of the Pre-Classic Hohokam regional system, followed by a discussion of the Hohokam/California transregional system. Next I discuss robustness-fragility trade-offs in exchange systems. This is followed by a discussion of

globalization (since the development of the Hohokam/California transregional exchange system is a globalization process), and then by a discussion of the combined effects of complexity and diversity of export goods on systemic fragility.

Chapter 3 provides a synthesis of ethnohistoric, ethnographic, and qualitative archaeological evidence that are used conjecturally and with some rigor in the case of the archaeological evidence to construct a preliminary network model of the Hohokam/California transregional system of exchange, which addresses Goal 1. The sections of Chapter 3 focus on a specific region and the cultural groups historically and probably prehistorically associated with that region. For each region, the focus is on the kinds of items (with an emphasis on shell) and with what other regional groups within the transregion exchange was significant, which addresses Goal 3.

Chapter 4 gives a detailed discussion of the Lake Cahuilla fishery and provides substantial evidence for the efficacy of the Gila River as a major route of exchange between the Phoenix Basin and Lake Cahuilla, which addresses Goals 1 and 3, and relates to Goal 4. Information is also provided that shows the significance of fish as a protein rich food with a high energetic return rate. Two examples of historic and prehistoric fisheries from the Great Basin are provided that support the existence of a Lake Cahuilla fishery, which addresses Goal 1. Ethnohistoric evidence is also provided that shows the importance of fish in the diet of people who are probable descendants of Lake Cahuilla fishers, which relates to Goal 4. Finally, archaeological evidence is provided that supports the idea that long distance transport of fish occurred in other parts of the U.S. Southwest, which relates to Goal 4.

In Chapter 5 new methodology is used for a morphometric analysis and comparison of *Olivella* sp. small barrel beads from a cemetery in the Chumash village of Humaliwo (Malibu) at the west end of the transregion and from (1) Las Colinas, a large Phoenix Hohokam residential site, tied to the Salt River, and (2) Snaketown, a large Gila River Hohokam settlement. The purpose of this comparison is to evaluate my hypothesis that the Malibu beads originated in the Hohokam system, which addresses Goal 1. An attribute-based morphological comparison is made between the Malibu *Olivella* sp. small barrel beads, *Olivella biplicata* (a Pacific Coast endemic) and several species of *Olivella* from the Gulf of California. I conclude from this comparison that the Malibu small *Olivella* sp. beads are most likely made from a single Gulf of California species (*dama*). This supports the idea that the likely origin of these beads is the Hohokam system, where beads of this type and from this type of shell were most often made, which addresses Goal 1.

In Chapter 6, studies of archaeological sites from specific regions in the transregion, and shell artifacts recovered from these sites provide strong evidence that most of the shell valuables exported from the Hohokam system into the California component of the transregion ended up in the vicinity of Lake Cahuilla, which addresses Goals 2 and 3. The results of these studies are also used to identify strong connections between regions to compare with the preliminary transregional model resulting from the analyses in Chapter 3, which addresses Goals 1 and 3. The results from this chapter are rigorous and are consistent with the results from Chapter 3. Combined the results from this chapter and Chapter 3 provide a simple network model that is analyzed in Chapter 7, which addresses Goal 1. Also, studies in this chapter also provide information on the directionality of

exchange, which addresses Goal 2, and which are consistent with the results of the kriging analysis in Chapter 7.

Chapter 7 involves the application of two novel network analysis methods (Table 1.1), which are used to study the structure and organization of the Hohokam/California transregional system, which addresses Goal 2. I discuss these methods in detail in Chapter 7. Kriging (or “optimal prediction”) is used to establish directionality in the exchange of shell artifacts, which addresses Goal 2. Briefly, kriging is an interpolation method used to predict values (including directionality) using estimates of the spatial distribution of predicted values from data observed at known locations (Oliver and Webster 1990). This method also uses variograms to visually represent spatial variation. I discuss my analytical strategy for kriging in detail in Chapter 7. Together these analyses address the key questions of Goals 2 and 3.

In Chapter 8 a simple bioeconomic model of renewable resource use and trade is developed and analyzed, which addresses Goal 4. The goal of the analysis is to identify what conditions (social and environmental) could result in the collapse of the Hohokam system. This model is an extension of the model developed and analyzed by Anderies (2006). Compared to Anderies’ model, my model has a much larger spatial scale (interregional trade) and resource base, greater complexity in labor allocation and institutional arrangements, as well as the dynamical effects of expansion and contraction cycles of Lake Cahuilla on the output of fish protein.

## CHAPTER 2: THE STUDY AREA AND ROBUSTNESS AND SYSTEMIC FRAGILITY IN THE HOHOKAM SYSTEM

This chapter provides a detailed discussion of my study area and the key theoretical concepts that are needed to achieve the goals discussed in Chapter 1. First, I describe the principal regional focus of this study, which is the Pre-Classic Hohokam regional system between A.D. 700 and 1100. Then, I describe the Hohokam/California transregional system. Next, I discuss the key theoretical concepts that I will use in my study of how involvement of the Hohokam regional system in a transregional system of exchange may have contributed to its rapid collapse around A.D. 1100. My theoretical focus relates to four paradigms, which are: (1) robustness and fragility in networks, (2) systemic fragility, (3) complexity, and (4) globalization. I also explain how I will use each of these theoretical frameworks in this study.

### **The Pre-Classic Hohokam Regional System**

Crown (1991a:154) defines a regional system as "a number of interacting but geographically separate communities that were dependent on each other through the exchange of goods and services (Judge 1984:8 Wilcox and Sternberg 1983:222, 231)". Crown estimates the boundaries of the Pre-Classic Hohokam regional system (Figure 2.1) with the overlapping distributions of locally made ceramics (mostly red-on-buff), shell artifacts (made of exotic marine shell obtained mostly from the Gulf of California), and ballcourts. Crown argues that the very similar general distributions of red-on-buff ceramics, ballcourts, and shell suggest they were part of the same economic and social systems and that the boundary estimates are strongly supported by multiple lines of

evidence (Crown 1991a: 156). In sum, these data suggest the existence of formalized exchange networks between the Phoenix Basin inhabitants and populations outside this area during the Pre-Classic period.

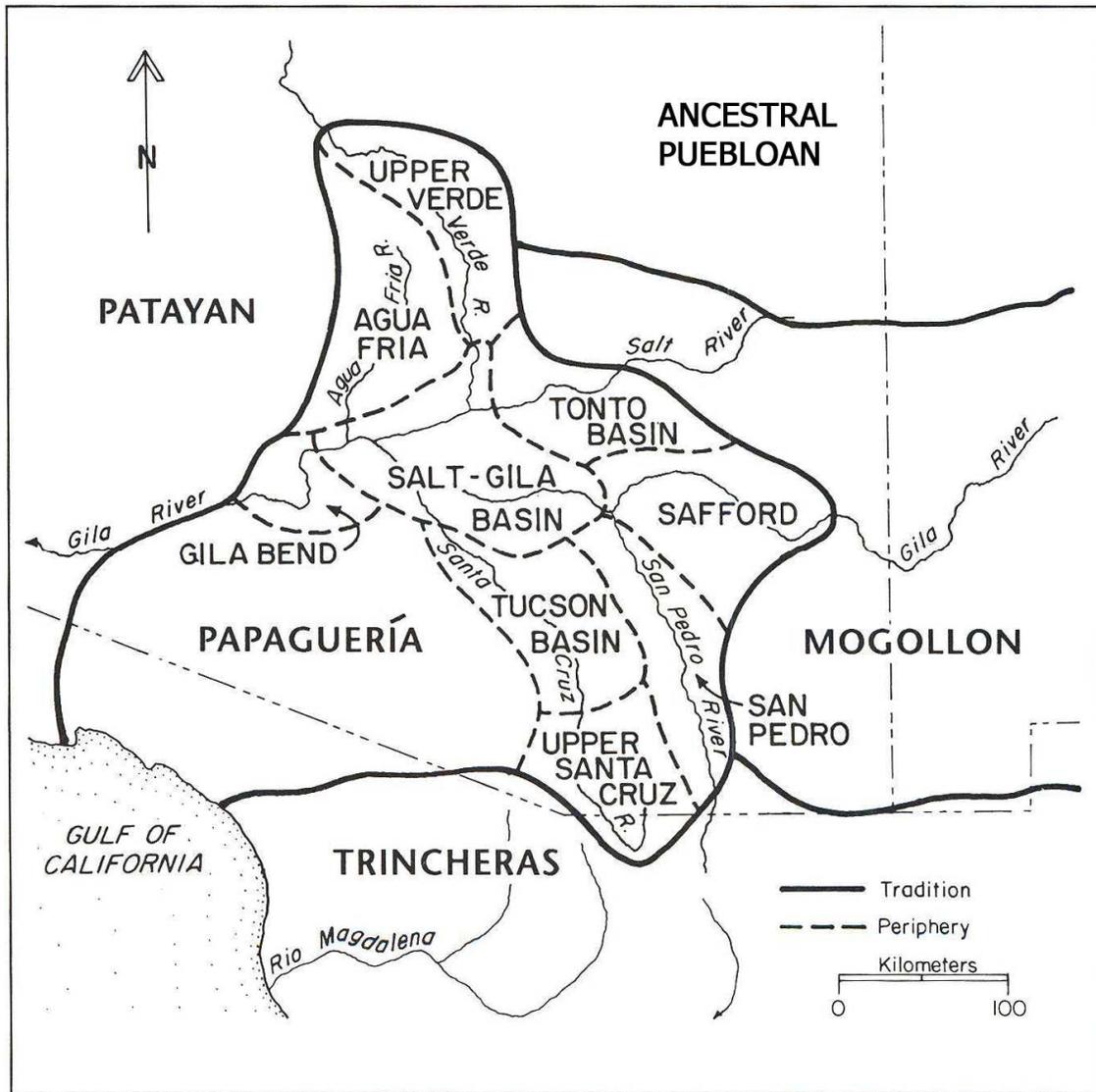


Figure 2.1. Pre-Classic Hohokam regional system and adjacent regions. The core area of the Hohokam regional system is the Salt-Gila (or Phoenix) Basin. Modified from Crown 1991a, Figure 7.1.

Masse (1991) also shares Crown perspective on the existence of a Pre-Classic Hohokam regional system, but adds that the system was probably more extensive and complex than Crown suggests, along with a caveat about the stability of the system.

I firmly believe that the Hohokam had sustained economic (see Doyel 1991) and social (see Wilcox 1991) networks beyond those of simple irrigation community networks (see also Masse 1980, 1982), and that several such regional networks variously existed and competed in Arizona's Sonoran desert. These regional networks most likely were dynamically fluid and unstable—a response to periodic large-scale environmental change, and in part a reflection of the population structure. [p. 204].

Although my research encompasses the period A.D. 700-1100, the main focus of this study begins during the Santa Cruz Phase (A.D. 850-950) of the Colonial Period of the Pre-Classic Hohokam regional system. Throughout this period the Hohokam regional system was expanding in the Salt-Gila or Phoenix Basin (Crown 1991a: 147). During this time shell and other imported materials increased in abundance, along with intensification of agriculture and greater use of wild foods (Crown 1991a: 148-149). By the Sedentary period (A.D. 950-1070) settlements had become larger and were distributed in more ecological zones and irrigation and trade networks continued to grow (Doyel 1991a: 248). In fact, the large-scale canal systems and other irrigation infrastructure that characterizes the Hohokam system may have been largely in place by this period (Howard and Huckleberry 1991). During the early and part of the middle Sedentary period (A.D. 950-1020) the Hohokam regional system continued to expand geographically, economically and agriculturally (Abbott et al. 2007; Crown 1991a: 149-150). This was followed by a rapid collapse of the regional ballcourt network and a major restructuring of the Hohokam system during the latter part of the middle Sedentary period (A.D. 1020-1070, see Abbott et al. 2007).

But the questions not considered by Crown, Doyel and more recent researchers in Hohokam archaeology is to what extent did the Pre-Classic Hohokam system become involved in interregional interaction, what were the processes that may have resulted in this, and could such globalization processes (possibly as a response to local food shortages and other problems) have contributed to the collapse of the system?

As Crown (1991a) admits, she only provides information that supports the existence of a regional system and which can estimate its boundaries, and not the processes related to the formation, robustness and fragility of the system.

By these means we can outline the boundaries of what we would designate the Hohokam regional system: however, we cannot indicate the processes responsible for the growth and decline of the system, or the mechanisms by which the boundaries were maintained [p.156-157].

### **The Hohokam/California Transregional System**

The Hohokam/California transregion encompasses a large ecologically and culturally diverse area that includes parts of coastal and interior southern California and a large region in central and southern Arizona, with the core area in the Phoenix basin (Figures 1.1 and 2.1). Much of the interior portion of the transregion is desert, which is transected by several major river systems (Colorado, Salt, Gila, and Mojave). During A.D. 850-1100 a large freshwater lake (Lake Cahuilla) filled much of the Salton Basin in southeastern California. During that time Lake Cahuilla emptied into the Colorado Delta, which was a vast estuary connected to the Gulf of California, and which provided a wide array of resources for people living in that portion of the transregion. Large mountain ranges also characterize the interior portion of the transregion that include San Francisco Peaks in Arizona and the San Bernardino Mountains in southern California. The coastal portion of

the transregion is characterized by a Mediterranean climate. Coastal rivers and streams and large estuaries provide an abundance of fresh water and wild resources. Coastal prairie, expansive grasslands, coastal sage scrub, chaparral, and oak woodland are examples of the many plant communities and associated ecosystems that typify much of the southern California landscape. Each of these ecosystems has a diverse assortment of terrestrial and riparian wild resources that were available to native people. For example, Chumash people whose territory included some of the east to west trending coastal mountain ranges, such as the Santa Monica Mountains, had access to a large variety of wild resources from all of the preceding plant communities and their associated ecosystems. Extensive coastline and sizeable offshore islands add to the ecological richness of this region and provided an ample and dependable supply of marine resources, including shellfish that were used for food by native people such as the Chumash and Tongva and to make many kinds of socially valued objects, including shell bead money (King 1990).

Several southern California societies (which I discuss in detail in Chapter 3) occupied the transregion and often traded shell and many other items for both social and economic reasons (Gamble 2011, 2008; King 1990). My interest in the transregion is very specific and relates to whether a transregional system of interaction between people in the Hohokam system and people in other parts of the transregion existed during A.D. 700-1100 and, if so: (1) why did people in the Hohokam system increase their scale of interaction beyond their regional system and (2) could and how might increasing the scale of interaction have affected the systemic fragility of the Hohokam system and (3)

how might involvement in a transregional system of exchange have contributed to the collapse of the Pre-Classic Hohokam system around A.D. 1100?

Exogenous factors resulting from environmental changes have long been considered to be likely contributors to the growth and eventual collapse of the Pre-Classic Hohokam system. In my view, environmental shocks may have been an important factor in increasing the scale of interaction of the Pre-Classic Hohokam system. Jones et al. (1999) discuss a major climatic “shock” (ca. A.D. 800-1350) that may have been compelled people of the Pre-Classic Hohokam system to search for sources of food at increasingly larger spatial scales.

The Medieval Climatic Anomaly (Stine 1994) was a time of increased aridity that coincided with a unique pattern of demographic stress and frequent economic crises across much of western North America. Large populations of agriculturalists and hunter-gatherers were confronted with serious and abrupt declines in productivity caused by repeated and prolonged droughts [p. 138].

Periodic mega floods may also have been important shocks that facilitated the expansion of the Hohokam system. Interestingly, the extreme flood of A.D. 899 identified by Gregory (1991) in the Phoenix Basin corresponds (as I will discuss in detail in Chapter 4) was the beginning of a major high stand of Lake Cahuilla in the Salton Basin of southeastern California. This is also coincident with the Medieval Climatic Anomaly.

What is particularly interesting about Lake Cahuilla is that its filling and emptying cycles are not the result of climatic events. Jones et al. (1999) discuss this in relation to the Medieval Climatic Anomaly.

Immediately southwest of the Mojave Desert in the Salton Sink, the timing of the episodic filling and desiccation of Lake Cahuilla stands out as sharply distinct from the chronologies of drought related above. Geomorphic analysis and the historical record demonstrate that these lake high stands were forced not by climate change but by the shifting of the Lower Colorado River channel (Fenneman 1931, Waters 1983). Although

expansive, the deltaic cone of the Colorado River provides an alluvial barrier only about 15 m high between the river and the Salton Sink, and because the latter is below sea level the river periodically breaches this barrier and fills the basin. This episodically created freshwater lake covered an area of approximately  $5,700 \text{ km}^2$ , with a maximum depth of about 96 m, in response to events that have no known relation to climatic change [p. 143].

This shows that local floods and large scale and long-term droughts were not correlated with high stands of Lake Cahuilla (which as I discuss in Chapter 4 are now known to be linked to seismic events in the Salton Basin). This means that Lake Cahuilla was a rich and enduring ecosystem during a period when local resources in the Hohokam system may have been seriously reduced. It is possible that the rich and substantial supply of Lake Cahuilla resources may have facilitated trade between people in the Hohokam system and people living in the vicinity of the lake as a means to avert shortages of local wild resources resulting from climatic problems. In turn, trade with Lake Cahuilla people would have connected the Hohokam system with a large and well-established network of southern California societies.

### **Robustness and Fragility in Social-Ecological Systems**

Robustness and fragility in social-ecological systems and complex adaptive systems (Miller and Page 2007) in general has been an area of important theoretical discussion and development in the recent literature (Anderies and Janssen 2007, 2011, 2013; Anderies et al. 2007; Janssen and Anderies 2007; Scheffer et al. 2012). All complex systems that can adapt and transform have complex regulatory feedback networks. Such regulatory feedback networks are involved with the generation of basins of attraction and provide the capacity of complex adaptive systems to adapt and transform, i.e., to generate and maintain complexity. A social-ecological system (or SES)

is a type of complex adaptive system that consists of multi-level human generated (or social) systems coupled with an ecological system. Interactions of the social systems with the ecological system involve intricate and nonlinear feedbacks that affect the dynamics and stability of both systems (Anderies et al. 2004; Janssen et al. 2007). Both social and ecological systems are typically self-organizing systems (a theoretical concept that originated with Ashby 1947), which include large-scale exchange systems, such as the Hohokam regional system and the Hohokam/California transregional system. Krugman (1996) provides a discussion on self-organization in today's market economy and Squartini and Garlaschelli (2012) provide a specific example of a modern exchange system (in fact the largest), which they recognize as a complex adaptive and self-organized system.

The global economy is a prototypic example of a complex self-organizing system, whose collective properties emerge spontaneously through many local interactions. In particular, international trade between countries defines a complex network, which arises as the combination of many independent choices of firms. It was shown that the topology of the World Trade Network (WTN) strongly depends on the Gross Domestic Product (GDP) of world countries (Garlaschelli and Loffredo 2004). On the other hand, the GDP depends on international trade by definition (Garlaschelli et al. 2007a), which implies that the WTN is a remarkably well-documented example of an adaptive network, where dynamics and topology coevolve in a continuous feedback. In general, understanding self-organizing networks is a major challenge for science, as only few models of such networks are analytically solvable (Garlaschelli et al. 2007b).

In social-ecological systems cooperation of individuals often creates infrastructure (physical or institutional) as a response to a variety of internal and external shocks to the system (Anderies et al. 2004). External shocks include environmental disturbances, such as floods, earthquakes, and drought, that negatively affect: (1) resources and infrastructure and/or (2) produce socioeconomic changes, such as population growth that also impacts resources and infrastructure. Internal disturbances produce rapid

reorganization of the social-ecological system that originates in specific subsystems (Anderies et al. 2004). People at all levels of society create infrastructure to make specific components of the system more robust to shocks. Robustness in this way relates to the maintenance of some desired system characteristics despite fluctuations within a complex adaptive system such as an SES or in its environment (Carlson and Doyle 2002). Also as Janssen and Anderies (2007) observe, robustness in SESs also occurs at many levels and scales and that robustness at a specific level or scale may increase fragility in other places in the system.

Since robustness to unpredictable perturbations occurs at particular levels or scales in the system, we need to accept the potential for increased chances of failure at other levels and scales [p. 44].

Anderies and Janssen (2013) illustrate this aspect of SESs with irrigation systems, which was a key technology to the sustainability of the Hohokam system.

Irrigation systems provide an important example: human societies can build large-scale physical infrastructure (canals, reservoirs) and social infrastructure (rules for water allocation, canal maintenance) to eliminate sensitivity of food supply to inter-annual variation in local water supplies. However, in so doing, societies become much more vulnerable to low frequency variation in rainfall (the 100 year flood that destroys the irrigation system) and social upheaval. That is, building robustness to certain classes of disturbances and increasing narrowly focused efficiency (e.g. agricultural yield) introduces fragilities in the system. Worse yet, such fragilities typically are hidden from the user by virtue of good design (Csete and Doyle, 2002), and are only exposed through failure. The irrigation systems works extremely well for a century, and no one is thinking about the 100-year flood and subsequent famine until it happens [p. 9].

Also, because shocks to an SES are detected through variability in signals and other inputs into the system, robustness in an SES can be interpreted as reduced sensitivity of outputs to environmental and social shocks. The study of robustness in SESs focuses on the inherent and hidden fragilities that are associated with the complex regulatory

feedback networks of these systems, which are often, only observed when the system fails. This also relates to the trade off of increasing robustness in one place and diminishing it in another.

Increasing robustness to one type of known disturbance necessarily increases vulnerability to other types of disturbances (Chandra et al., 2011; Csete and Doyle, 2002). Worse yet, these emergent vulnerabilities are largely hidden, revealed only by a system-level failure (Anderies and Janssen 2013:12).

Robustness in an SES is therefore relational with cost-benefit trade-offs associated with each of the components of these kinds of systems. This is a specific case of what Bode (1945) showed is a robustness trade-off property of all feedback systems, which is: by reducing the sensitivity to disturbances in one frequency band by feedback control increases sensitivity to disturbances at other frequencies.

Robustness develops in SESs as a way to deal with uncertainty. Anderies et al. (2007) identify the kinds of uncertainty that SESs must deal with and provide examples.

Both exogenous signals and endogenous dynamics can be sources of uncertainty. Examples include limited understanding about the dynamics of subsystems (e.g., ecological dynamics are not fully understood), measurement error (sensor dynamics and noise), and policy implementation errors (controller dynamics) [p. 15195].

Anderies and Janssen (2013) offer additional insight into the relationship between uncertainty, feedbacks, and adaptability in SESs (and all complex biological systems).

The reason is, we never have perfect information about the state of the system (e.g. we can never know the actual stock level in a fishery), and we never fully understand the causal relationships that generate dynamics in SESs, and there are always exogenous disturbances and stresses impinging upon the system of interest. It turns out that all complex biological systems (of which SESs are examples) must cope with uncertainty, stress, and disturbance. As such, complex biological systems with the capacity to adapt to these difficult circumstances have a common feature: they are composed of complex regulatory feedback networks. These distributed, multi-scale networks make the maintenance precise biological processes possible. They also enable the control of

uncertain systems, and are used extensively in engineered systems that must function in spite of disturbance and stress (e.g. modern passenger aircraft in the face of air turbulence). A moment's reflection reveals that SESs are feedback systems [p. 9].

Modularity, diversity, and redundancy are three core properties of SESs that relate to robustness. As Anderies and Janssen (2013) observe, there is a trade-off between local self-sufficiency (modularity) and adaptive capacity (local diversity), connections to the global system (redundancy and global diversity), and hidden fragilities in complex systems. They provide examples for each of these properties that illustrate their relationship to robustness in complex adaptive systems [p. 11].

*Modularity* provides a system with different functional parts or modules that can evolve somewhat independently. The modules might be loosely linked with each other, but a failure in one module does not severely affect the others, as would happen if they were tightly linked. Sufficient links between modules are required as modules might learn from the activities occurring within other modules. Within the social sciences this is referred to as *polycentricity*. Ostrom et al. (1961) identified a polycentric metropolitan area as having many centers of decision-making, which were formally independent of each other, but one could learn from experimentation in the other various centers (McGinnis, 1999).

Tinkering, mutations, and making errors are essential to generate new components and links in a system (Kirschner and Gerhart, 1998). Importantly, in a modular system, such novelty can be tested without severely disturbing other modules - i.e. experimentation can occur locally without impacting overall system function.

*Redundancy* is common in engineered infrastructure systems (both hard and soft) and, and biological systems. The engineered system of a Boeing 777, which has 150,000 different subsystem modules, can continue to fly when many modules have been knocked out (Csete and Doyle, 2002). This high level redundancy is necessary to achieve extreme robustness (at great financial expense): ability of the Boeing 777 to continue to function when modules fail is crucial because the cost of overall system failure is so high.

A population of organisms with the same ability to initiate an immune response will be hit hard when a harmful new disease enters the population. Genetic *diversity* provides the capacity to create novel antibodies, so at least a few individuals in the population might be able to resist the new disease.

The preceding examples show that polycentricity is an important component of SESs that facilitates robustness, which, in turn, promotes redundancy, modularity and diversity in these systems. In Chapters 7 and 9, redundancy, modularity and diversity are used to identify and discuss some of the robustness properties of a network model of the Hohokam/California transregional system.

To date very little has been published in the literature (with the notable examples of Anderies and Hegmon 2011; Anderies 2006; Schoon et al. 2011) that uses the robustness-fragility trade-off property of complex adaptive systems to study past social-ecological systems. In this work I examine robustness and fragility tradeoffs in the Hohokam/California transregional system with network analyses and mathematical modeling to evaluate how increased scale of interaction may have been instrumental to the collapse of the Pre-Classic Hohokam System. The role of the expansion of the Hohokam regional system during the Pre-Classic (A.D. 700-1100) beyond the Hohokam region as a major factor in its rapid collapse around A.D. 1070 has not been previously studied. I suggest that the greatly increased scale of interaction that included trade with southern California societies (Hohokam/California transregional system) may have induced or actualized a robustness-vulnerability trade-off, assuming that the total capacity (consisting of both natural and human made components) of the Hohokam regional system to buffer variation in key resources is limited. This, in turn, may have amplified the fragility of the Hohokam system, increasing its risk of collapse. Specifically, in the case of the Hohokam system, enlarging the scale of exchange provided increased robustness to high frequency variation (e.g., yearly fluctuations in rainfall and streamflow) and increased vulnerability to low (multidecadal) variation (e.g.,

recession of a large freshwater lake as the result of a change in the course of a river that was its primary water source). The research I am conducting examines the properties of the Hohokam/California transregional system (with an emphasis) on the role of shell and dried fish, and will focus on the impact of the transregion on the stability of the Pre-Classic Hohokam system.

### **Globalization**

The expansion of the Hohokam system beyond the regional level is an example of globalization. In general, the processes by which human societies become inter-connected over larger spatial scales are processes of globalization and may be socially and culturally transformative. Globalization facilitates the development and spread of technology, cultural information (which often results in new social identities and boundaries), and increased social complexity (Scholte 2005). For example, the Silk Roads contributed to great social change, and (probably) greatly increased social complexity in several human societies in ancient Asia, Africa, and Europe (Elisseff 2000). Since globalization processes build connections between people over great distances, they restructure and enlarge pre-existing exchange networks. Globalization processes can be unidirectional (expansion only, see Scholte 2000), but often are cyclical (Chase-Dunn and Hall 1997; Chase-Dunn et al. 2000; Wallerstein 2004:45-64).

Examples of both unidirectional and cyclical globalization processes have been studied in western North America. Chase-Dunn and Mann (1998) provide an example of a unidirectional globalization process among small-scale societies (e.g., Wintu, Pomo, and Patwin) from protohistoric Central and Northern California. This system is characterized by a politically controlled clam-disc “money” economy that grew very

quickly following A.D. 1500, in which local and large-scale exchange networks became increasingly interdependent (Chase-Dunn and Mann 1998:140-144). Bennyhoff and Hughes 1987 provide an example of a cyclical globalization process involving small-scale native societies in the Great Basin and central California. In this case, shell bead and ornament trade between the Great Basin and California expanded from 2000 to 200 B.C., then contracted from 200 B.C. to A.D. 700, and then expanded again from A.D. 700 to 1500.

Globalization involves numerous social and economic processes that result in long distance flows of ideas, people, and goods, which create networks of interregional interaction (Bentley 1993; Gills and Thompson 2006; Jennings 2011). Such interaction may result in significant webs of connectivity at very large spatial scales (Bentley 1993; Gills and Thompson 2006). These kinds of networks often have an abundance of hubs and other structural properties that are not expected to occur by chance and which can be tested with mathematical methods such as the Erdős-Rényi random graph model, which is used in Chapter 7 and 9 to identify the significance of such structures in the Hohokam/California transregional network model.

## **Complexity, Systemic Fragility, and Diversity of Export Goods**

As exchange systems become larger, they typically increase in complexity (as discussed in the preceding section), which may also facilitate major increases in complexity in the societies that comprise the system as well. As Haldane and May (2010) observe, there is a strong relationship between system complexity and instability, or as they say: “too much complexity implies instability” (p. 351). System stability is also linked to the diversity of exchange items, in that more diversity (or greater heterogeneity) of exchange items correlates with lower systemic risk (Haldane and May 2010:355).

In a transregional exchange system at one extreme each region can produce a wide range of export good classes that maximizes overlap in these classes between regions. This can be conceptualized as one end of a continuum in which the diversity of export good classes and the overlap in these classes between regions diminishes in the direction of the other end of the continuum. At the other pole of the continuum each region exports: (1) a minimum number of good classes and (2) good classes that to the greatest extent possible are not exported by other regions in the system. Modeling studies (e.g., Beale and colleagues 2011) suggest that if systemic cost is non-linear (which means that the cost function is convex), the probability of system failure in a transregional exchange system is minimized by having each region invest in increasingly fewer classes of export goods as the non-linearity of systemic cost increases, or moving in the direction of the second pole in the continuum described above. Also, at some threshold value of nonlinearity of systemic cost, in order to minimize the risk of system failure, the regions should invest their procurement and production efforts in an absolute minimum number of export good classes that minimizes overlap in these classes between regions across the

system. This corresponds to the second pole in the preceding continuum. Beale et al. (2011) call this the *diverse diversification* endpoint of the continuum (Figure 2.2), and is also what they call “full specialization”. Or, in terms of inter-regional connectivity, regions should be highly modular so that there are not too many connections across the regions. In so doing they maximize diversity in production for local consumption (minimize redundancy) and minimize diversity in the specialized production of goods for export.

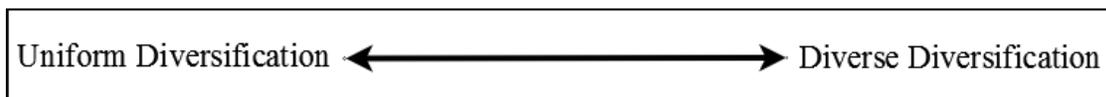


Figure 2.2. Continuum of export class good diversity related to the degree of specialization of transregional economic exchange.

In a broader sense the results of Beale et al. relate to the general “modularity”, redundancy, diversity discussion around general properties of robust systems. In the case of the Hohokam/California transregional system, regions should become highly modular so that there are not too many connections across regions. In so doing, they also reduce redundancy in the types of goods being traded between regions, resulting in specialized production of export goods and autonomy in the production of domestic consumer goods within each region in the system. This is an example of the robustness-fragility trade-off, in which the diverse diversification arrangement increases robustness to system failure at the global scale, but may increase vulnerability to other kinds of problems, such as population growth facilitated by the import of staple items. For example, in the Pre-Classic Hohokam system using the diverse diversification arrangement, the diversity of

goods produced to exchange for Lake Cahuilla fish would be minimized, making the Hohokam/California transregional system more robust, but with an increased vulnerability of the Hohokam system to shortfalls of wild protein if the trade connection with Lake Cahuilla fishers breaks down. This is the arrangement I implement in the bioeconomic model in Chapter 8.

### **Archaeological Examples of Diverse Diversification of Exchange from the Hohokam/California Transregion**

It has been suggested that the interaction between Lowland Patayan people in the western Papageria and the Salt-Gila Basin component of the Hohokam system, was (see Figure 2.1) characterized by the high volume exchange of staples (mostly agricultural products from the Phoenix Basin) that were traded for shell preciosities manufactured in the western Papageria (Crown 1991b: 389-390). This corresponds to the *diverse diversification* portion of the continuum (or high specialization in the production of export items, with a minimal overlap of export goods classes between the two regions). A similar arrangement or interaction sphere is observed at the opposite (western) end of the Hohokam/California transregion between the Northern Channel Island Chumash and the Mainland Santa Barbara Channel Chumash (which I discuss in Chapter 3). In this sphere, the Island Chumash (analogous to the peripheral Papageria shell jewelry artisans) specialized in manufacturing and exporting preciosities (especially shell “money” and jewelry) in exchange for staple items unavailable on the islands (e.g. deer and rabbit meat and a variety of plant foods) from mainland (analogous to Phoenix Basin) sources (Delaney-Rivera 2001; King 1978, 1990, 2000; Arnold 1992; Arnold and Munns 1994).

Another similar trade relation probably existed between the Santa Monica Mountains Chumash and Mainland Tongva, and the Island Tongva on Santa Catalina Island (King et al. 1982:112). During Middle Period Phase 4 (A.D. 700-900) there was a significant increase in the quarrying of talc schist (or steatite) on Catalina Island, which was exchanged in raw form, or as finished utilitarian items (e.g., cooking bowls, see Figure 2.3), to Mainland Tongva and Santa Monica Mountains Chumash, for mainland food items (e.g., acorns, cherry pits, and deer meat, see King 1976).

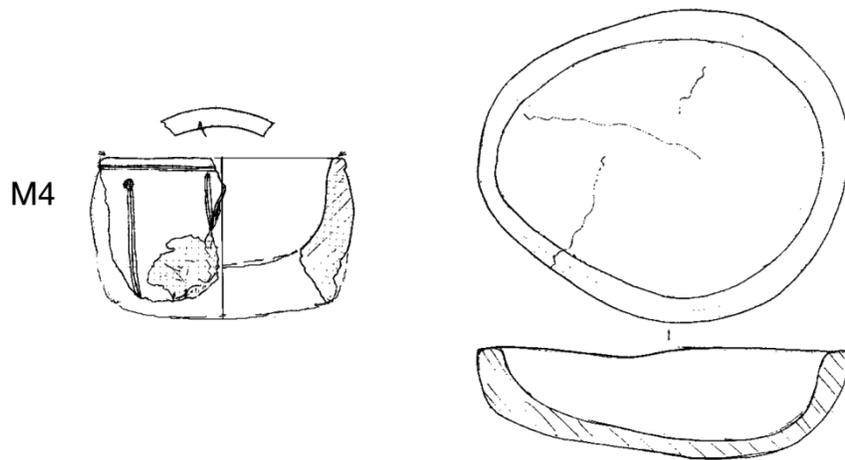


Figure 2.3. Line drawing of a small Middle Period Phase 4 (A.D. 700-900) steatite cooking pot (from Figure 7.85, King 2008:72).

In sum, these examples from the archaeological record support the possibility that at least a significant proportion of the Hohokam/California transregional system had developed institutional arrangements to minimize systemic risk that includes both endogenous risk and risk related to exogenous environmental variation.

### Summary

The expansion of the Hohokam system to a scale that includes interaction with people in different regions of southern California greatly increased the complexity of this

system which very likely changed some of the system's robustness-fragility properties, particularly those related to systemic fragility. Long-standing institutional arrangements and infrastructure that maximized robustness (stability) in relation to regional trade, agriculture, and the use of local wild resources may not have been capable of maximizing the stability of the expanded Hohokam system circa A.D. 900-1100. Identifying and understanding how the altered robustness-fragility properties of the expanded Hohokam system may have led to its collapse are a main focus of this dissertation. In this work, ideas and theory from complex adaptive systems, institutional economics and analysis, and the robustness-fragility framework applied to social-ecological systems are used to reveal new insights into why the Pre-Classic Hohokam system may have collapsed.

In this study my focus is on trade that aims to minimize systemic risk (i.e. maximize robustness of the system) and not to increase overall productivity through specialization. In particular, I focus on the possibility of interregional trade between people in the Hohokam system and people in the Lake Cahuilla region, who could have provided an abundant supply of dried fish that reduced variation in the supply of protein rich wild food in the Hohokam system. Also, even though specialized manufacture of goods for export may have increased the overall productivity of the system, I suggest that this was an unintended consequence and that surplus production was not the focus of trade in this system. In the next chapter I begin the first task to achieve the goals discussed in this chapter, which is to construct a network model of the Hohokam/California transregional system.

### CHAPTER 3: ETHNOHISTORIC, ETHNOGRAPHIC, AND ARCHAEOLOGICAL EVIDENCE FOR INTERACTION IN THE HOHOKAM/CALIFORNIA TRANSREGION

The goal of this chapter is to synthesize a diverse array of ethnohistoric, ethnographic, and archaeological data to: (1) provide a regional classification for the Hohokam/California transregion circa A.D. 700-1100 and (2) produce a map of interaction for regions in the Hohokam/California transregion to help construct a simple network model of this system, in which nodes represent specific regions (e.g., Hopic), and edges between node pairs indicate strong interaction. This provides an initial (and largely conjectured) model that requires additional evidence and more rigorous analysis using archaeological data and theory, as well as methods from archaeological and network analysis to substantiate. Chapters 6 and 7 provide analyses that strongly support the validity and accuracy of the conjectural network model of this chapter.

Reconstructing exchange among native people in the Hohokam/California transregion is facilitated with multiple lines of evidence including: (1) written accounts by early European visitors to Arizona and southern California of the kinds of exchange and between whom it occurred, (2) ethnographies produced by anthropologists in the 19<sup>th</sup> and early 20<sup>th</sup> century that provide first hand information on the context of exchange for specific types of items and to whom and for what purposes the exchange of these items occurred, and (3) archaeological evidence consisting of local and exotic artifacts (such as decorated pottery and shell) that can be dated, sourced and possibly connected to specific societies (e.g., Chumash) and contexts of exchange. To achieve the goal of this chapter will require bringing together these kinds of information. In Chapter 6 archaeological

evidence and analyses are used to strongly support the accuracy of the preliminary network model provided at the end of this chapter. In Chapters 7 and 9, five network analyses give objective support for this model by showing that random processes could not likely produce it. I also provide network analyses in Chapters 7 and 9 that identify structural properties of the system that can be linked to vulnerability/robustness tradeoffs that may have been important to the long-term stability of the Pre-Classic Hohokam system. Finally, each section of this chapter focuses on a specific region of the Hohokam/California transregion in which patterns of exchange between regions are identified. At the end of the chapter (as I mentioned earlier) all of this information culminates in a network graph that is placed on a map of the transregion to provide scale and geographic orientation.

### **Chumash**

The Chumash (at the western end of the transregion) and people in the Hohokam system (at the eastern end) obtained and manufactured the majority of the shell artifacts (such as different types of beads and bracelets) that circulated in the system prehistorically (Figure 1.1). The Chumash were complex hunter-gatherer-fishers (Arnold 1992) who occupied a large region in coastal southern California, characterized by a well-developed economic system, enduring stability, and a steady increase in social complexity over time (King 1990). Trade between Chumash and non-Chumash groups was likely limited to a small variety of goods (King 1971:38). Archaeological evidence provided by King (1976) suggests that interregional interaction among the Chumash mostly occurred between the Santa Monica Mountains Chumash (at the southernmost end of the Chumash region) and Tongva people (discussed later). Archaeological and

ethohistoric evidence (including linguistic, see Golla 2011 and Klar 1977) suggest that Chumash people in the Santa Barbara Channel, the northern Channel Islands, and the Santa Monica Mountains of southern California were culturally distinct. For example, historically, people in each of these areas spoke a different Chumashan language (Barbareño, Island Chumash, and Ventureño, respectively). King (1976, 1990, 2000) provides substantial archaeological and ethnohistoric evidence that suggests strong interaction between the Santa Barbara Channel Chumash and the Island Chumash, and between the Santa Barbara Channel Chumash and the Chumash in the Santa Monica Mountains.

### **Hohokam Regional System**

In contrast to the Chumash region, the Pre-Classic Hohokam system of southern and central Arizona is noteworthy for a high degree of sedentism, large-scale irrigation agriculture, red-on-buff pottery, and the manufacture of shell artifacts for local and long distance exchange (Bayman 2000). The Pre-Classic Hohokam system is characterized by a rapid increase in complexity and regional interaction during the Sedentary Period (ca. A.D. 900-1100; Abbott et al. 2007; Abbott et al. 2001), followed by a swift and not well-understood collapse of the regional system at the end of this period (Abbott et al. 2007; Doyel 2000). Neitzel (1984:232-246) proposed subdividing this regional system into drainage systems (e.g., Salt River, Gila River, middle Verde, Tucson Basin, and Gila Bend). More recent archaeological research (Abbot et al. 2007) supports an economic and probably a social distinction between residents of the Salt and middle Gila River areas. For example, Abbott et al. 2007:465-466 state: “pottery was not made in most villages of the lower Salt River valley during the middle part of the Sedentary period”. In

contrast, specialist producers in Snaketown and vicinity in the middle Gila River valley made red-on-buff bowls and small jars during the Middle Sedentary Period (Abbott et al. 2007:467). Much of this pottery was exported to residents of the Salt River Valley, probably in exchange for goods that probably include surplus Salt River valley agricultural products (Abbot et al. 2007; Doelle 1980; Doyel 1991a; Gasser and Kwiatkowski 1991; Teague 1998). This supports at least an economic distinction and interdependence between Gila and Salt River residents, which I recognize in my study as separate regions.

At least one historic photograph from the Phoenix area (Figure 3.1) shows a group of men with a large catch of roundtail chubs and razorback suckers. It is possible that these men are local native people (possibly Akimel O'odham). Today most O'odham people believe they are descended from people in the Hohokam system (Griffen-Pierce 2000:165). Exploring this possibility is an important topic for future research. If it could be shown that fish were historically important in the diet of native people in the Phoenix Basin, would support the idea that fish were an important source of protein in the core area of the Hohokam system, since recent archaeological evidence (Loendorf et al. 2013; Loendorf 2012) strongly supports the idea that Akimel O'odham are descended from people in the Hohokam system. This would also suggest that other O'odham groups such as the Tohono and Hia-Ced are also descended from people in the Hohokam system, as they believe. Confirmed ethnohistoric evidence of the importance of fish to another native group (the Hia-Ced O'odham) whose territory was within the currently accepted boundaries of the Hohokam system is provided by Martinez (2013). In particular

Martinez summarizes an observation by Egbert L. Viele on the use of fish by the Hia-Ced O'odham.

In 1882, Egbert L. Viele, a former Union Army general, conducted a geographical survey of the Gadsden Purchase region for the American Geographical society of New York, in which he notes: "The region of country is inhabited by the Papago [O'odham] Indians, who wander over the country from San Xavier as far west as the Tinajas Atlas." With respect to the Hia-Ced O'odham, he observes after briefly noting that Papago women are "better dressed than most women": "A sub-tribe of the Papagos inhabits the country near the Gulf of California. These are called Arenenos. Their principal food is salt fish, which they prepare themselves with considerable skill" (Viele 1882:269) [p. 145].

Martinez also mentions Thomas Childs Jr. as a source of information on the historic use of fish by the Hia-Ced O'odham. Thomas Childs Jr. was a pioneer in southern Arizona who married a Hia-Ced O'odham woman and learned many things about their culture and history through his wife, her family, and other Hia-Ced O'odham people.

[Martinez, p. 155, 161; also see Dobyns 1954:33].



Figure 3.1. Fishermen with stringers of roundtail chubs and razorback suckers near the Phoenix area (very likely either the Salt or Gila River) in 1899. ASU Hayden Arizona Collection.

### **Patayans**

The Patayans occupied a large area of the transregion along the Colorado and Gila Rivers, part of the eastern shoreline of Lake Cahuilla, and upland areas to the north of the Hohokam system (see Figure 1.1). Patayans practiced small-scale agriculture, hunting and gathering, and are notable as shell artisans and for their likely role as middlemen. The Patayans probably also had regular interaction with the Cahuilla and Kumeyaay (Carrico and Day 1981; Davis 1961; Eidsness et al. 1979; Gifford 1931; Loumala 1978; Shackley 1981; Shipek 1991:33, see Figure 1.1) who occupied different areas of the region around Lake Cahuilla (next chapter). There is also a distinction between Upland

and Lowland (or River and Delta) Patayans. Giffin-Pierce (2000) discusses the distinction between these two groups.

The Patayan ancestors of the River (Mojave, Quechan, Maricopa, Halchidhoma, and Kavelchadom), Delta-California (Cocopah, Hayikwamai, and Kahwan) and Upland (Yavapai and Hualapai) Yuman peoples lived in a lowland region bordering the lower Colorado River and the surrounding desert (home of the River and Delta Yumans) and in an upland region consisting of the canyons and plateaus of the upper Colorado River (home to the Upland Yumans). Of all the prehistoric peoples of the Southwest, they are the least known because flooding of the river destroyed their riverine sites [p. 235].

Griffin-Pierce (2010) provides additional information on the Patayan groups.

The Upland Patayan lived farther east in the plateau country of present day Arizona. The River and Upland Yumans traded cultivated foods and manufactured items for raw materials and gathered foodstuffs; archaeological evidence showed that the Patayan and Hohokam had a similar relationship [p. 16].

Archaeologists have found cultural remains of Havasupai ancestors in the plateau region of Arizona that date to 600 A.D.; sometime between 1050 and 1200 A.D. they moved down into Cataract Creek Canyon probably for defensive reasons. [p. 16]

Strong trade and social relations existed between Upland, River, and Delta Yumans historically (Braatz 2003:33-34; Griffin-Pierce 2000, 2010), which suggests that similar relations existed prehistorically between their probable ancestors (Upland and Lowland Patayans). A close relationship between Upland Patayans and the Hohokam system is suggested by an isolated Hohokam burial near Kingman, Arizona (True and Reinman 1970), which is well within the Upland Patayan region and well outside the Hohokam regional system (see Figure 1.1). The presence of a three-quarter grooved axe (likely made in the Hohokam system) in the Willow Beach site (ca. A.D. 900-1100), which is located on a terrace of the Colorado River fifteen miles south of Hoover Dam and from several nearby sites (Schroeder 1961:1, 73) suggests trade ties between Upland Patayan, Hopic (which I discuss in a later section of this chapter) and the Hohokam system. A

gorget, possibly made from *Glycymeris* sp. shell and found in a child burial in the Willow Beach site (Schroeder 1961:70) also suggests interaction with the Hohokam system.

Finally, considering that the boundary of the Upland Patayan region is closer to the Salt River component of the Hohokam system than the Gila River component of this system, I assume that regular contact and strong relations between Upland Patayans and Salt River Hohokam was more likely than with Gila River Hohokam. More archaeological information is needed to support this assumption, but I use this assumption in my network model of the Hohokam/California transregional system with the acknowledgement that it is mostly speculative.

The Willow Beach site (Schroeder 1961), in Black Canyon below Hoover Dam (Figure 3.2) on the Colorado River provides evidence of the importation of exotic materials from the Pacific Coast. Even though the Willow Beach site is on the banks of the Colorado River in southeastern Nevada (Figure 3.3), it is located in an area within the Hohokam/California transregion in Figure 1.1.



Figure 3.2. Looking west across the Colorado River at the Willow Beach site (center foreground) [Schroeder 1961, Fig. 1, p. 136].

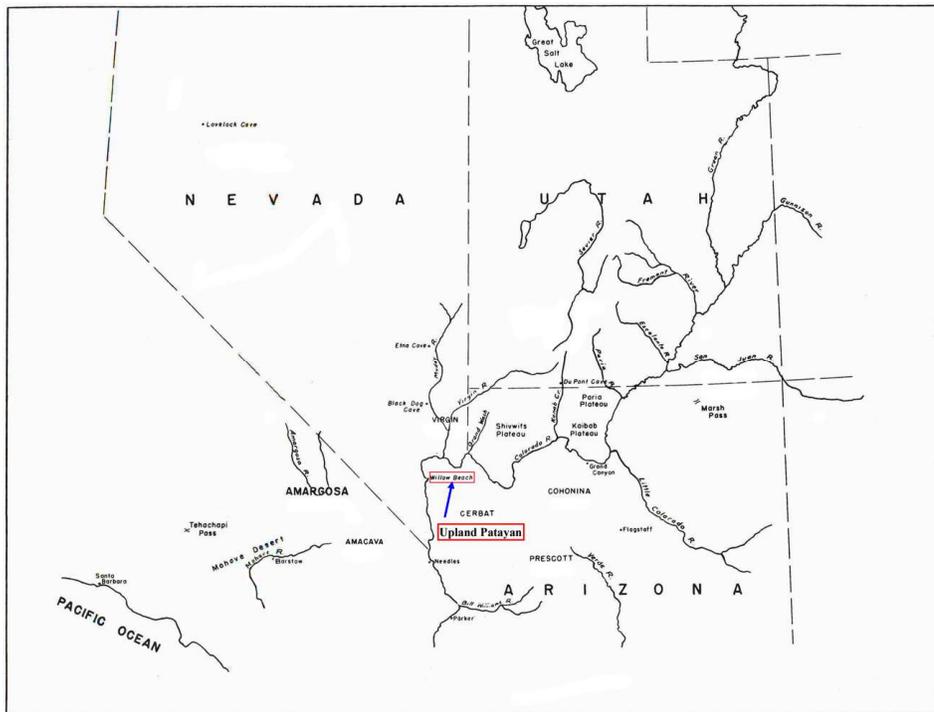


Figure 3.3. Location of Willow Beach site on Colorado River (Modified from Schroeder 1961, Fig. 37, p. 160).

Three common pottery types recovered from the 1936 excavations of the Willow Beach site are Pyramid Gray, Cerbat Brown, and Aquarius Brown (see Figures 3.4 and 3.5, and descriptions below). Pyramid Gray has a distribution from the vicinity of Barstow in the Mojave Desert, east to the Colorado River.

**Pyramid Gray.** A gray type of pottery, characterized in part by its color and large inclusions of quartz and biotite. Pyramid gray has been found in the Mojave Desert between Barstow and the Colorado River, and dated to ca. A.D. 900-1150. It has been classified within the Barstow series and Lower Colorado buff ware. Harold S. Colton and Albert H. Schroeder described the type. (Colton 1939; Schroeder 1958) [Online source: <http://scahome.org/about-ca-archaeology/glossary-of-terms/ceramic-types/>]

**Cerbat and Aquarius Brown Cultural Association:** Most often associated with the Yuman groups of Arizona, especially the Hualapai, Havasupai, and Yavapai. Euler and Dobyns (1985) suggest the Yavapai may have made Cerbat and/or Aquarius Brown. [Online source: <http://www2.nau.edu/~sw-ptry/Western%20Apache-Yavapai/TizonWarePage.htm>]

Schroeder provides observational, experimental and ethnohistoric evidence that Pyramid Gray pottery probably was manufactured at the Willow Beach site using techniques similar to those used historically by Upland Yumans and the Kumeyaay (formerly Diegueño).

The temper indicates that Pyramid Gray was manufactured in the near vicinity [p. 50].

Clay recovered from the preceramic levels was used in the tests, and slugs to which no temper was added were made. The following conclusions are based on the results of the experiments. The terra cotta clay from the preceramic levels at Willow Beach burns to the same orange color as do the sherds of Pyramid Gray when placed in an oxidizing atmosphere (slug 429). It is concluded that the clay recovered is probably identical to that used by the Indians to manufacture Pyramid Gray [p. 51].

The above experiments indicate that Pyramid Gray was manufactured with a terra cotta clay mixed with an organic substance. Vessels were fashioned by paddle-and-anvil. After a vessel was dried in the sun, a clay slip, with perhaps sufficient iron to produce a light cream to buff color when fired in an oxidizing atmosphere, was often added to the exterior surface of jars and both surfaces of bowls. The product was fired, probably in a small pit in a poorly controlled reducing atmosphere, at a relatively low or intermediate

temperature, to produce a gray color. Aside from the use of slip, the above method of manufacture is similar to that of the modern Walapais [Hualapais], Western Yavapais, and Diegueños (Kroeber 1935:89; Gifford 1936:281; Rogers 1936:7-8) [p. 53].

These results suggest that Pyramid Gray was mostly locally made and used by Upland Patayan residents of the Willow Beach site. It is likely that Lowland Patayan people west of the Colorado River within the geographic distribution of Pyramid Gray in the eastern Mojave also manufactured this pottery type.

The Cerbat and Aquarius Brown pottery types are associated with an Upland Patayan material culture called the Cerbat (Figure 3.3). The Cerbat are believed to be ancestors of the Havasupai, Hualapai, and Yavapai. Cerbat sites have been identified from the Grand Canyon (northern boundary) to the Bill Williams River and northern Phoenix Basin (southern boundary) and from as far east as the Verde River and as far west as the Colorado River. Euler (1963) divided Cerbat cultural history into three periods, of which his Desert period (A.D. 700–1150), when the Cerbat lived in lowland areas west of the Grand Wash Cliffs (on the northeastern edge of Arizona, near the Nevada border), is relevant to my study. The Cerbat probably had limited agriculture and depended mostly on foraging for wild resources.

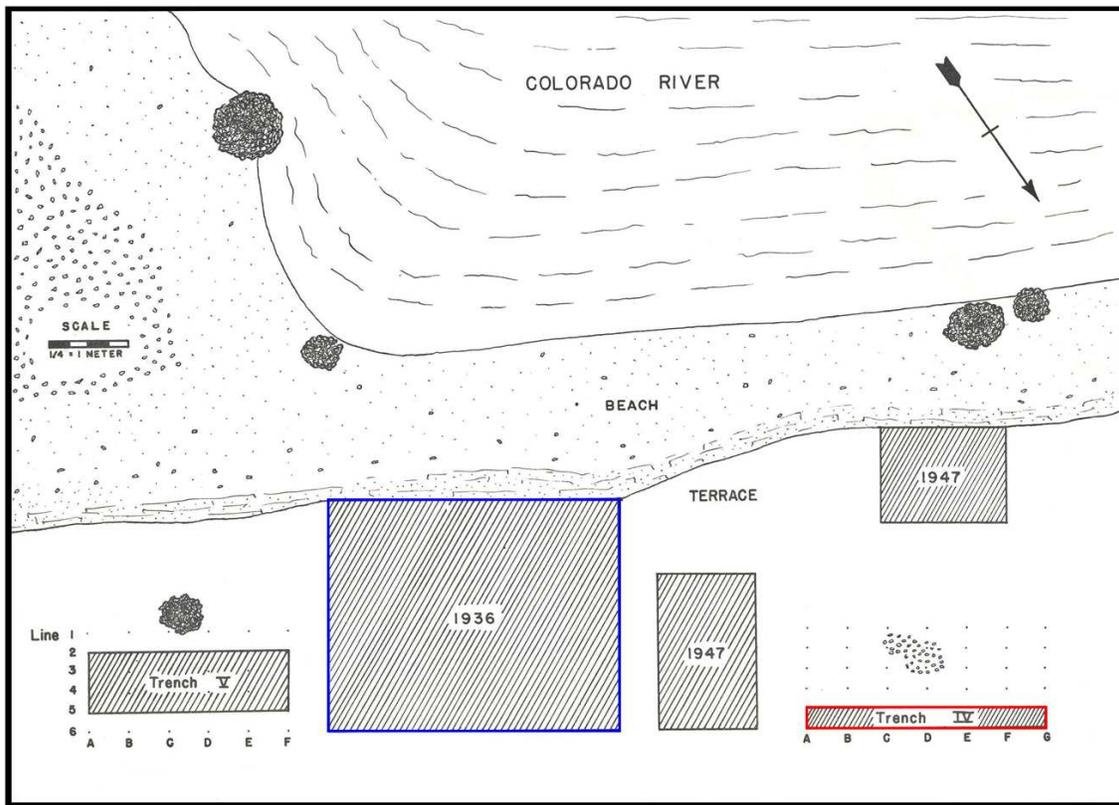


Figure 3.4. Willow Beach site excavation map (Schroeder 1961, Fig. 3, p. 137)

Schroeder (1961:59-62) provides probable radiocarbon dates and probable ages of the stratigraphic levels of Trench V from the 1947 Willow Beach excavation (Figure 3.4). He comments (p. 61): “the radiocarbon date for layer B is acceptable when either the range of experimental error or the post-1150 A.D. occupation by ancestral Paiutes is considered.” Figure 3.5 shows the changes in relative frequency over time of the four most abundant pottery types in the Trench V sample. Layer B, which is temporally relevant to my study, is dominated by Pyramid Gray, which suggests (based on the preceding discussion) that most of the use of the Willow Beach site during A.D. 900-1150 was by Upland Patayans.

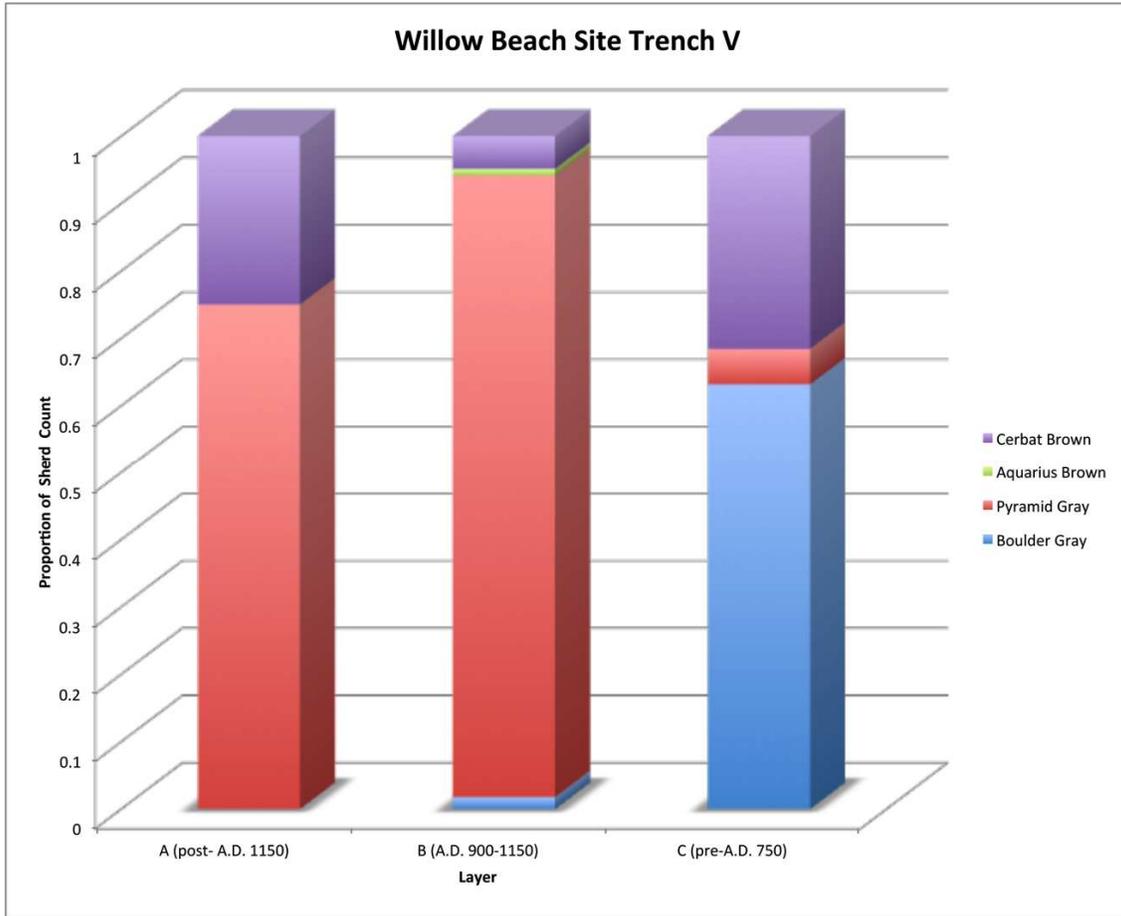


Figure 3.5. Relative frequencies by stratigraphic level of four pottery types from the 1947 Willow Beach site from Trench V (see Figure 3.4).

The 1936 excavations of the Willow Beach site (see Figure 3.4) recovered asphaltum, many *Olivella biplicata* saucer-disc beads and several *Haliotis* sp. artifacts (see Table 3.1). The shell and asphaltum most likely originated in the Chumash region. Also, based on evidence I provide in later sections of this chapter, it is very likely the people at Willow Beach obtained these items from Cahuilla or Hopic people, and not directly from the Chumash.

Table 3.1 Imported Pacific Coast shell artifacts from the 1936 Willow Beach site excavations.

Artifact(s)	Sample Size	Likely Regional Source	Context	Comments
<i>Olivella biplicata</i> Disc beads (small)	27	Chumash	Burial 2	
<i>Olivella biplicata</i> disc beads (large)	833	Chumash	Burial 2	
<i>Haliotis</i> sp. (Abalone) pieces	Not specified	Chumash	Burial 3	Abalone pieces probably from pendant.
<i>Olivella</i> sp. disc beads (probably species <i>biplicata</i> )	Not specified	Chumash	Burial 4	Inside the burned house.
<i>Haliotis</i> sp. (abalone) beads	3	Chumash	Burial 5	Directly below Burial 4
<i>Haliotis</i> sp. (Abalone) pendants	2	Chumash	Burial 5	Directly below Burial 4
<i>Olivella</i> sp. saucer-disc beads (probably species <i>biplicata</i> )	Not specified	Chumash	Burned house	A number of beads cemented with asphaltum (p. 66)

Trench IV of the 1947 Willow Beach site excavation (see Figure 3.4) produced several artifacts that probably were imported from the Chumash and Island Tongva regions of coastal southern California. Specifically, Trench IV produced two *Olivella biplicata* barrel beads (Schroeder 1961:12), a probable pipe fragment made from Catalina Island steatite (Schroeder 1961:13-14), and a piece of asphaltic siltstone (Schroeder 1961:14). The shell and asphaltic siltstone probably originated in the Chumash region (although the shell artifacts may have originated in the Tongva region, discussed later in this chapter) and the steatite pipe was probably made on Catalina Island by an Island Tongva artisan.

Archaeological evidence suggests that Lowland Patayan people in the interior region of southern California aggregated in fishing villages and camps, along the eastern shore of ancient Lake Cahuilla. For example, pottery distribution and temporal patterning of ceramics along the eastern shoreline of Lake Cahuilla provides strong evidence for increasing residence and association with the lake by Patayan (Yuman) people, after A.D. 700. Waters (1982:289) observes.

Salton Buff (a type of buffware pottery that was apparently made and, for the most part, used locally in sites within the 12 meter shoreline of Lake Cahuilla [Waters 1982:565]) and Salton Red-on-buff were manufactured along almost the entire shoreline of Lake Cahuilla. Based solely on geological association of Salton Buff and Lake Cahuilla, it could be inferred that Salton Buff was first manufactured around A.D. 700, the beginning of the earliest known lacustral interval of Lake Cahuilla to occur during the last 2000 years ... C-14 dates from shoreline ceramic sites suggest that this type was actually manufactured in great quantity from the second lacustral interval beginning perhaps at A.D. 950. The oldest ceramic C-14 date reported from an archaeological site with ceramics in the Salton Trough is 960 +/- 110 B.P. (A.D. 990: LJ-106- Hubbs, Bien, and Suess 1960:216). However, on a small segment of the eastern shoreline, a few Salton Buff sherds display ceramic traits typical of the Patayan I period and are associated with very small quantities of Black Mesa Buff. This may indicate that Salton Buff was also manufactured sometime during the Patayan I period, possibly during the first or at the beginning of the second lacustral interval of Lake Cahuilla.

The much greater presence of Patayan people with extended residence on the shoreline of Lake Cahuilla (suggested by pottery) beginning around A.D. 700, and also the large number of fish weirs associated with these lakeshore sites (discussed in detail in the next chapter), may relate to the emergence of a sizeable fishery with surplus harvests for export to other areas in the transregional system. In the Papagueria region of southwestern Arizona, Patayan people may have had a different role in the transregion. In this component of the transregion, Patayan people may have specialized in the procurement and manufacture of shell artifacts to exchange for agricultural products from

the Hohokam system (McGuire and Schiffer 1982:249-252;) and dried fish and (to a much lesser extent) Pacific Coast shell (see Vokes 1983:549-550, who suggests that Pacific Coast shell most likely entered the Hohokam system from interaction with people west and north of Gila Bend, Arizona) from Patayan and other groups associated with Lake Cahuilla. Connell (1977) provides an ethnographic example from Melanesia that supports this possibility that shell preciosities were made by specialist artisans for: (1) export and (2) to exchange for subsistence items and luxury goods (Guo 2006; McGuire and Howard 1987:128).

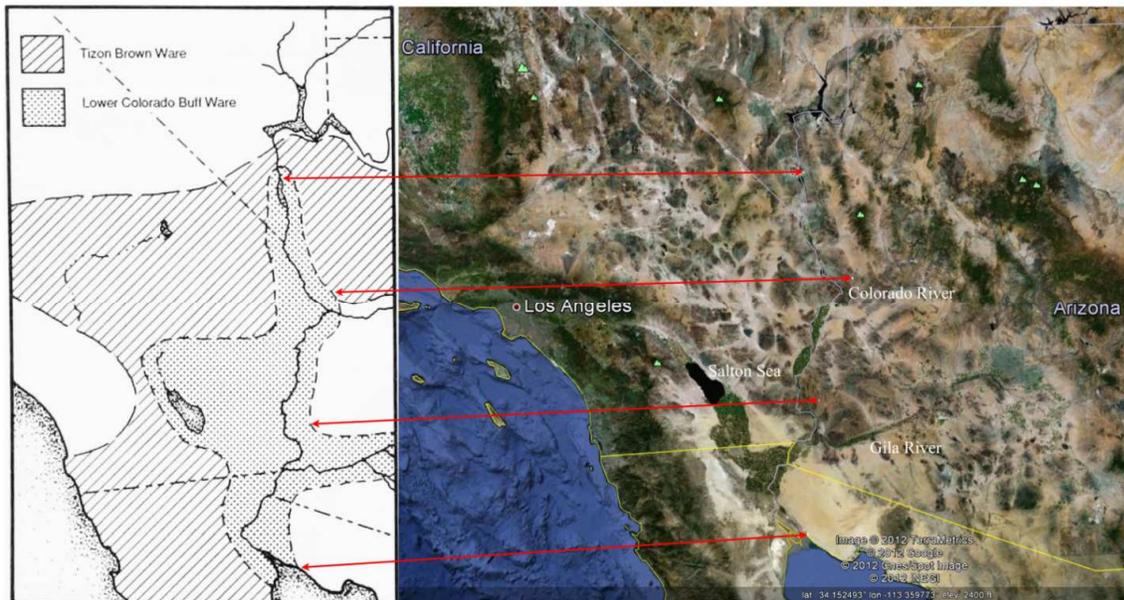


Figure 3.6. Approximate production zones of Lower Colorado Buff Ware and unified Tizon Brown Ware (Lyneis 1988, Figure 2). Note that the upper right distribution of Tizon Brown Ware is mostly in the Upland Patayan region of Arizona. The pre A.D. 1100 distribution of Tizon Brown Ware in southern California includes the northwestern shoreline of ancient Lake Cahuilla (Griset 1996). Colorado Buff Ware is associated mostly with the Lowland Patayan region of Arizona and southern California, including the eastern shoreline of Lake Cahuilla.

Another line of evidence (intrusive pottery, specifically Lower Colorado Buffware, see Figure 3.6 for its distribution) suggests a more geographically extensive and cohesive interaction between Lowland Patayans and the Hohokam system circa A.D. 900-1100. During this period, Lowland Patayans were exchanging pottery and co-residing with members of the far western Hohokam system (Abbott et al. 2012:984; Beck 2006, 2008, 2009; Beck and Neff 2007; see Figure 3.7 for the zone of overlap between Lowland Patayans and the Hohokam system ca. A.D. 900-1100). Evidence of this interaction is provided by the presence of Lower Colorado Buff Ware in (or in close proximity to) Hohokam sites in the vicinity of Gila Bend, the Lower Santa Cruz River Valley, and in the Las Colinas site, near Phoenix, Arizona.

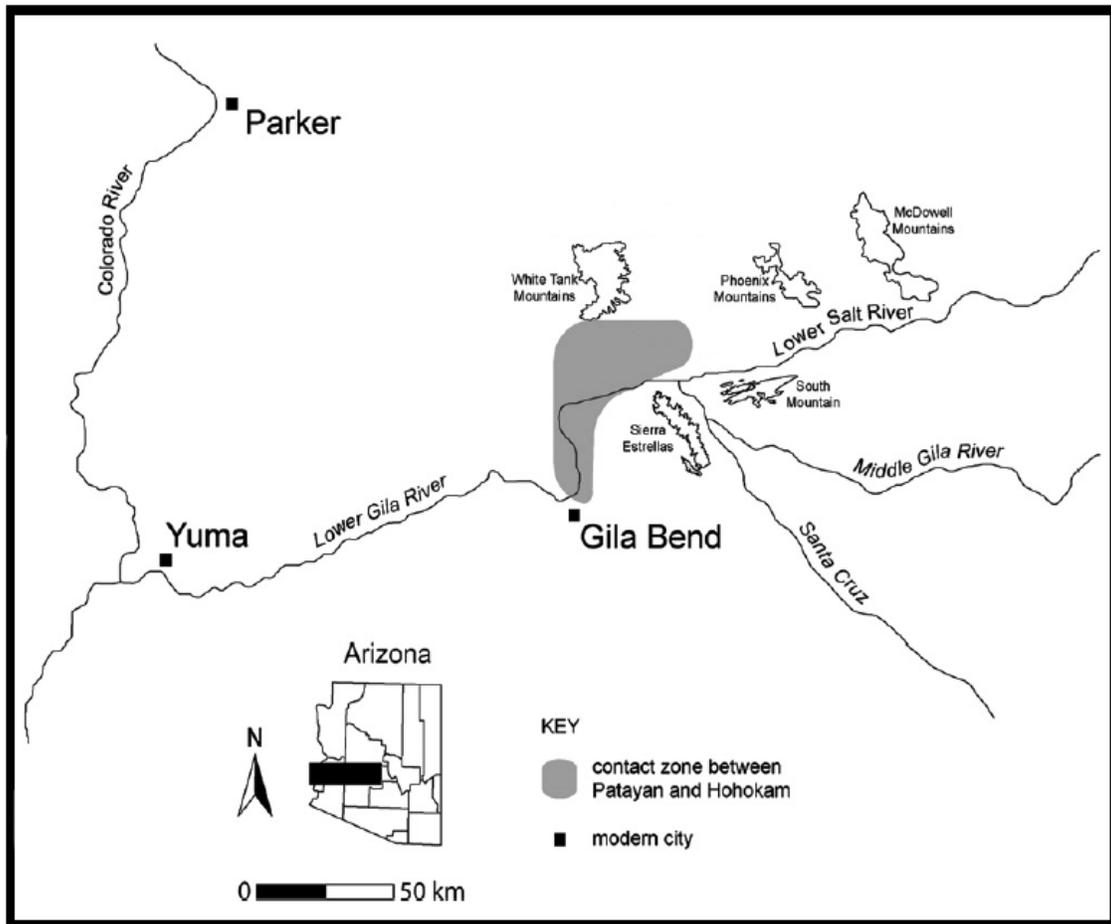


Figure 3.7. Lowland Patayan and Hohokam System in south-central Arizona (Modified Abbott et al. 2012, Figure 1).

Another example, the Gillespie Dam site (AZT:13:18 (ASM)],) on the Gila Bend portion of the lower Gila River provides additional archaeological evidence of a strong Lowland Patayan and a Pre-Classic Phoenix Basin Hohokam system connection. This example also supports my suggestion of the Gila River as a major travel corridor (discussed in detail in the next chapter) that linked the Hohokam system to Patayans and other people in southern California. In the Gillespie Dam site, two contemporary (with radiocarbon dates ranging from A.D. 950-1040) cemeteries about 30 meters apart on the

southern edge of the Gillespie Dam Site [AZT:13:18 (ASM)], one with Hohokam red-on-buff and plain ware ceramics and the other with Patayan I lower Colorado buffware vessels (Watkins and Rice 2009) provide additional evidence of a close relationship between Lowland Patayans and the Hohokam regional system. Also, shell artifacts from the Pacific Coast of California, recovered from the Gillespie Dam site support the idea of the Gila River as a major trade route between California and the Hohokam system (Malakoff 2010).

### **Cahuilla**

The Cahuilla resided in a large region in the interior of southern California, near Mount San Jacinto, extending to the shoreline of Lake Cahuilla, and were likely very much involved in the Lake Cahuilla fishery. Ethnohistoric evidence suggests that the Cahuilla had strong ties with the Tongva to the west that included the importation of shell beads (Kroeber 1908; Strong 1929).

Also, historically (and probably prehistorically), the Serrano (discussed later) probably had significant trade relations with both the Cahuilla and the Tongva, which included the exchange of dried seafood, and shell (Bean 1978). Ethnohistoric and ethnographic information provides strong evidence for the use of shell by the Cahuilla and for exchange relations with the mainland Tongva who obtained some of the shell from the Island Tongva (see the following quote from Strong 1929). In particular, the Pass Cahuilla provided the most detailed information to Strong (1929:94-96) concerning the use of shell bead money.

The modern exchange of shell money is fairly clear, although a certain amount of secrecy still surrounds it. Each of the four active ceremonial groups has several strings of shell

beads, which are kept by the clan chief, usually in association with the sacred bundle of the clan.

The kausiktum clan at Palm Springs calls these strings witecû, and the shell money itself hissavel or mûketem. The pisatañavitcem clan, who lived in the Banning Water canyon, called one string nuutska and many strings nuutskum.

The one called witecû by the Palm Springs Cahuilla is a piece four times the distance from a man's forehead to the ground in length, which is given to the leader of each invited clan at the close of the image-burning ceremony. The other called napanaa by the same people and this appears to have been the basic unit of shell money value. This was sent to any clan leader when a death occurred in his clan by all other clan leaders hearing of it.

The length of this piece is determined by wrapping it twice around the left wrist, carrying it under the thumb and twice around the fingers halfway to the tips, and back over the palm to a spot on the mid-wrist four inches from the posterior end of the palm. This spot, called tcic'hînut, was placed on the inner mid-wrist of the clan leader when he took office. It was done by the paha, who using a string of money as a measure, tattooed in the mark with a cactus thorn and inserted charcoal.

According to Potencio such a mark was once characteristic of each clan leader of the groups to the north and west but not to those of the Desert Cahuilla where the exchange of shell money did not occur. The long string of shell money, witecû, is given to the leaders of the three invited clans at the close of the image burning ceremony. A similar piece is returned by each when his clan gives a ceremony to which others are invited, thus keeping up a perpetual exchange.

According to Alejo Potenciano, the shell money was received for the Palm Spring clan by his grandfather who received it from the Serrano at Mission creek. They got it from the Tongva, who in turn received it from Santa Catalina Island [the occupants of which were Island Tongva]. Alejo's grandfather told him that the shell money was brought across from Santa Catalina Island on tule rafts to the San Fernando people, who distributed it among the inland groups.

There was another kind of money called somitnektcum "the small ones," composed of little shells which were much more valuable than the present large shell money. Alec Arguello, the last survivor of the Cahuilla who lived in San Timoteo pass, said that the mûketem, shell money, was brought to Juan Antonio, the Mountain Cahuilla capitan who brought the Cahuillas to San Bernardino by kânuk, a very old chief of the San Fernando people, who also brought new songs and ceremonies. This happened before Arguello was born, and he was told of it by his father.

In summary, the preceding ethnohistoric evidence for exchange practices of shell artifacts among the Cahuilla and trade of shell artifacts between the Cahuilla and people in other southern California regions in the interior of southern California identifies exchange relations between the Cahuilla and two other southern California groups. Specifically that in protohistoric time Pacific Coast shell artifacts were primarily exchanged between chiefs of Serrano and Cahuilla clans who obtained much of the shell from the Tongva. The religious importance of these exchanges is also suggested by the observation by Strong that shell was stored, transported, and exchanged in sacred bundles. The periodic contexts of the religious events in which shell was exchanged among Cahuilla and Serrano leaders suggests that the supply and frequency of exchange for this class of items was less compared to the Chumash, where most of the Pacific Coast shell artifacts were manufactured, and where exchange of these items occurred in many contexts (King 1976, 1990). It is possible Gulf of California shell artifacts obtained from the Hohokam system were used in similar ways as Pacific Coast shell by the Cahuilla (who at the time I am considering [A.D. 700-1100] were probably mostly living along the shoreline of Lake Cahuilla in fishing camps). Hohokam shell may have often have been exchanged for dried Lake Cahuilla fish by people in the Hohokam system, which may explain why Gulf of California shell often occurs in higher proportions in Cahuilla sites than Pacific Coast shell.

### **Kumeyaay**

Ethnographic and archaeological information indicates that the Kumeyaay (who occupied a large region that included Lake Cahuilla and the Anza Borrego Desert, had long standing relationships with the Yuman and Cocopa (descendants of Lowland

Patayan people), and the Cahuilla (Davis 1961; Eidsness et al. 1979; Carrico and Day 1981; Shackley 1981). Exchange among these groups consisted of many items, including baskets, carrying nets, tule roots, cattail sprouts, dried fish, and mesquite beans (Gamble and Zepeda 2002:73-74). The Kumeyaay probably also frequently used *Olivella* shell beads as exchange items (Carrico and Day 1981:75; Gamble and Zepeda 2002:7). Shell artifacts (both Gulf of California and Pacific Coast) are very common in prehistoric sites that were likely used by Kumeyaay people (Gamble and King 2008). Also, during the time of Lake Cahuilla the Kumeyaay may have been participants in a substantial fishery that produced large quantities of dried fish for local consumption and long distance exchange.

### **Hopic**

Sutton (2000:301) suggests that Hopic people may have occupied a specific part of the transregion, in a portion of the central and eastern Mojave Desert prior to and during A.D. 700-1100. This area includes a region in southeastern California, where gray ware pottery is concentrated (see Figure 3.8). In previous work (McGregor 1951; Rogers 1945), gray ware pottery from this region has been associated almost entirely with Patayan groups. Contrary to these studies, King (2008b: 279) argues that pottery recovered from numerous sites in the eastern Mojave and technologically and stylistically classified as San Francisco Mountain and Prescott Grayware were probably made by some of the ancestors of modern Hopi people, and to a large degree, (in support of his argument for associating a specific pottery technology with a specific ethnic group) locally produced and consumed.

He says.

The San Francisco Mountain and Prescott Gray Ware painted pottery have designs that parallel Tusayan White Ware during the Pueblo I-II period (Northern Arizona University 2001). The people south of the Grand Canyon and north of San Francisco Mountain who made San Francisco Gray Ware were probably also ancestors of the Hopi. The distribution of pottery indicates that the occupants of the Mojave Valley and the East Mojave Desert were also ancestors of the Hopi. Before AD 1100, Hopic peoples may have lived adjacent to their Takic linguistic relatives.

In one case, petrographic evidence also supports King's hypothesis, in which a Verde Black-on-Gray (Colton 1958, and synonymous with Prescott Gray ware) sherd from the Afton Canyon site (a year round settlement adjacent to the Mojave River in southeastern California) was determined be made from wash sand originating in the nearby Soda Mountains (Taylor and Brem 1993:127). Kojo 1996 provides further support for localized production and consumption of some White and Gray ware pottery types, with his study of Tusayan White and Gray wares (A.D. 850-1150) from northeastern Arizona. Also, considering that Pyramid Gray (which I have provided evidence may have been locally made by Lowland and Upland Patayans) is contemporaneous and has an overlapping distribution with San Francisco Mountain and Prescott Gray ware in the part of the eastern Mojave shown in Figure 3.8, suggests that this geographic area was occupied by both Hopic and Lowland Patayan people prior to A.D. 1100.

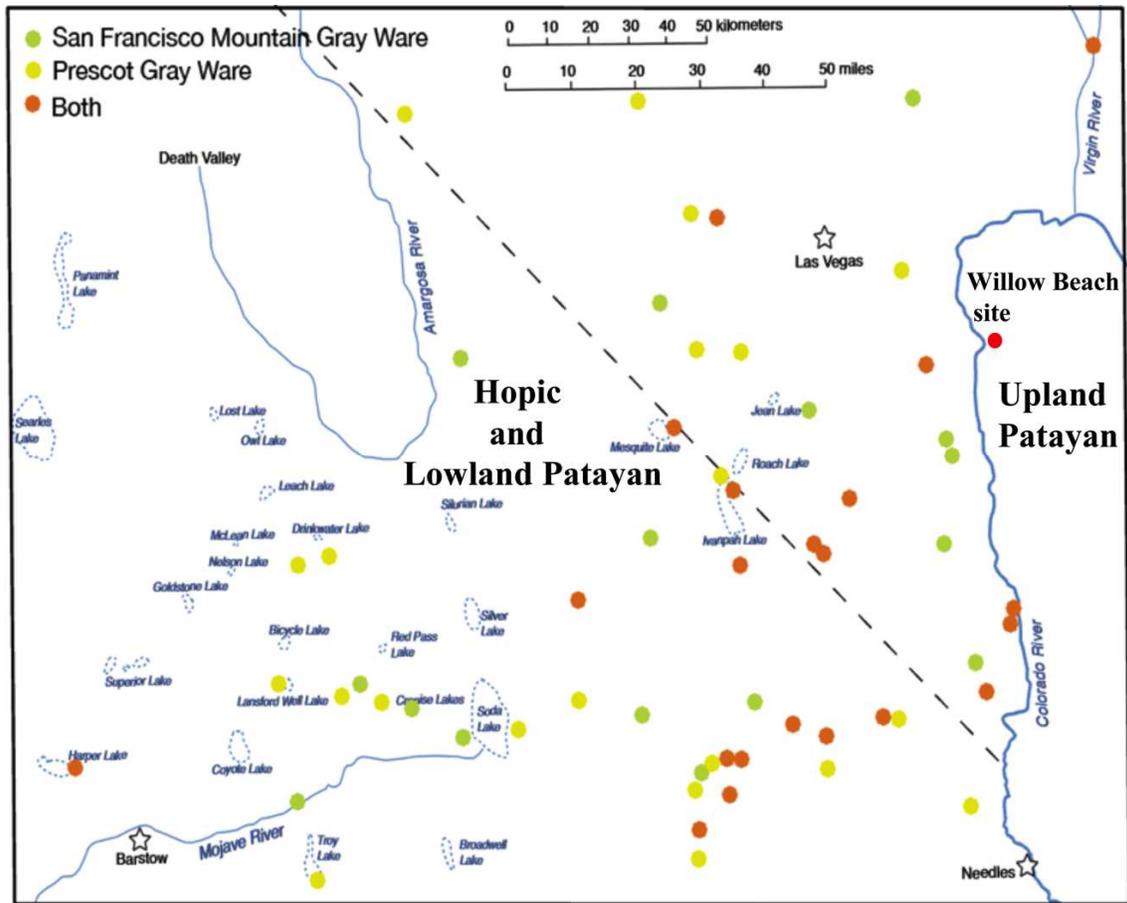


Figure 3.8. Distribution of San Francisco Mountain and Prescott Gray wares in the eastern Mojave Desert [King 2008b, Figure 8:3].

Kojo uses four additional independent lines of evidence in his study and concludes that these Tusayan wares were (for the most part) locally produced and consumed. Additional support is provided by Deutchman's (1979, 1980) neutron activation analyses of Tusayan White and Gray wares, in which she concludes that over fifty percent (probably an underestimate, see Kojo 1996:334-335) of the white ware pots were possibly made on site.

In the Afton Canyon site (which will be discussed in detail in Chapter 6), the recovery of both Pacific Coast and Gulf of California shell artifacts provides evidence that people in

the Hopic region interacted with other regions in the transregional system. Also, the identification by Sigleo (1975) of turquoise in a Gila Butte Phase (A.D. 500-700) house in Snaketown (a major settlement in the Pre-Classic Hohokam system), sourced to the Halloran Springs turquoise mine (in the Hopic region of southeastern California) provides further evidence of involvement of Hopic people in the transregional system. Also, Lower Colorado Buffware (radiocarbon dated to A.D. 920-1180) from the Afton Canyon site (Schneider 1989), and the predominance of these buffwares in the site suggests interaction with and/or co-residence with Lowland Patayans. All considered, the preceding archaeological evidence suggests that eastern Mojave sites such as Afton Canyon had Hopic occupants prior to A.D. 1100. This suggests that, prior to A.D. 1000 some of the Patayan groups (e.g. Yavapai) may have obtained many of their trade goods originating in the western end of the transregion (e.g., Pacific Coast shell artifacts) from Hopic peoples (whose range may have included a portion of eastern California). The Hopic people, in turn, may have directly acquired these items from coastal Tongva groups in Orange and Los Angeles Counties (King 2009, personal communication). For example, the Tongva may have manufactured some of the shell artifacts they traded to the Hopic groups, but they probably acquired the majority of these items from the Chumash (Chester King personal communication 2009). The Hopic and Patayan groups also probably had strong trade relations with the Cahuilla prior to A.D. 1100.

Additional ethnohistoric evidence also supports the proposed interregional linkage between Hopic and coastal southern California people, and the importance of shell in this interaction. Specifically, shell is one of the modern Hopi “hard substances” or “hard goods” (in Hopi, *hurúng*) and is associated with purity and durability (Hill et al. 1998;

Young and Morgan 1987). In Hopi mythology, a powerful female creator deity (*Hurúing Wuhti of the West* or Hard Substances Woman of the West) associated with shell and other hard substances leaves the ancestral homeland of modern Hopi people to live by the ocean on an island off the Pacific coast, discussed by Voth 1905.

The people [Hopi ancestors] at that time led a nomadic life, living mostly on game. Whenever they found rabbits or antelope or deer they would kill the game and eat it. This led to a good contention among the people. Finally, the Woman of the West said to her people: “You remain here; I am going to live, after this in the midst of the ocean in the west. When you want something from me, you pray to me there.” [p. 4]

In the story, Hard Substance Woman of the West creates clans from her body which return to the ancestral Hopi homeland to the east, to join their relatives, bringing shell and other substances with them (Matthews 1897:148-157; Voth 1905:1-9). This strongly suggests the longstanding importance of Pacific Coast shell in Hopi culture. The story of Hard Substance Woman of the West may relate to significant interaction between some of the ancestors of modern Hopi people and the Tongva people on one of the southern Channel Islands (most likely Santa Catalina Island, considering the close ties of people on this island with Chumash shell artifact manufacturers and suppliers on the mainland).

### **Serrano**

The Serrano occupied a large region in the interior southern California component of the transregion. Ethnohistoric evidence suggests that the Serrano had frequent and close ties with the Cahuilla and Tongva that extended far back in time (Bean 1978). Trade items among these groups included dried seafood, and shell (Bean 1978). Archaeological evidence (e.g., Rector et al. 1983; Schneider 1989) suggests the Serrano lived adjacent to,

and frequently interacted with Hopic people in the eastern Mojave Desert region prior to A.D. 1100. Pacific Coast and Gulf of California shell artifacts from the Oro Grande site (Rector et al. 1983, discussed in detail in Chapter 6) also provide strong evidence for participation of Serrano people in the Hohokam/California transregional system. Strong (1929:13,18,21,34) provides detailed ethnohistoric information on the use of shell by the Serrano, which suggests its use, was primarily in religious contexts that involved maintaining social cohesion between leaders and the redistribution of food.

These clans in turn invited the mārinna clan to their ceremonies, and an exchange of shell money was carried on between all the groups at the time of the ceremony itself, and on the occurrence of a death in any one of the clans, when all the others sent a certain amount of shell money to the clan leader of the deceased.

The paha, besides having charge of all ceremonial impedimenta, notified the people when ceremonies were due, carried the shell money between groups, and attended to the division of shell money and food at all ceremonies.

Both types of feather ornaments were wrapped in the muurte [sacred bundle], along with rattles, head plumes, ceremonial wands, and the strings of shell money.

The entire ceremony [annual mourning ceremony] ends with the distribution to the invited clan leaders of the strings of shell money.

### **Tongva**

The Tongva occupied much of the Los Angeles Basin south of Topanga Canyon, part of Orange County, and the southern Channel Islands. Shell artifacts that probably originated in the Hohokam system (e.g., *Olivella dama* barrel beads and *Glycymeris* sp. bracelets) have been found in several sites (Gibson and Koerper 2000; Koerper 1996) in the Tongva region. Recent evidence (e.g., high concentrations of *Olivella* bead manufacturing waste associated with sea urchin spines used to perforate shell) from San Nicolas Island (the outermost of the southern Channel Islands), suggest that there was

considerable *in situ* production of shell beads on the island (Dahdul 2011; Hintzman and Abdo-Hintzman 2006), possibly for exchange with Mainland Tongva and Santa Monica Mountains Chumash for staple items. The Tongva also exchanged Pacific Coast shell artifacts (as discussed earlier), with interior groups, such as the Hopic, Serrano, and Cahuilla.

### **Conclusion**

Shell artifacts are useful for helping to reconstruct the Hohokam California transregional system. Shell artifacts were a major exchange item in the Hohokam system and Hohokam shell may have been the principle exchange item for dried fish from Lake Cahuilla. Shell artifacts were also a major exchange item within and among southern California societies.

Shell artifacts that circulated in the transregion were used in a wide variety of social, political, and economic contexts that varied over time and space (Gamble 2011; King 1990). In particular, the role of shell within the system probably changed, depending on where and among whom and for what it was exchanged. For example, the Chumash made and used some kinds of shell items (e.g., *Olivella biplicata* saucer-disc beads, King 1990) as “money”. These same items probably had very different roles in exchange in other groups (Jackson and Ericson 1994:388; Kozuch 2002:698).

Figure 3.9 is the synthesis of the pattern of interregional interaction in the Hohokam/California transregion that was assembled from the information on interregional relations discussed in the sections of this chapter. Lines connecting pairs of regions in Figure 3.9 identify strong inter-regional relations, and more specifically, strong trade ties. Figure 3.9 from a structural standpoint is a network model (including spatial

relations and geographic boundaries of each of the regional groups in the network) that will be analyzed in Chapter 7. In Chapter 6, I analyze archaeological examples to provide additional support for this model.

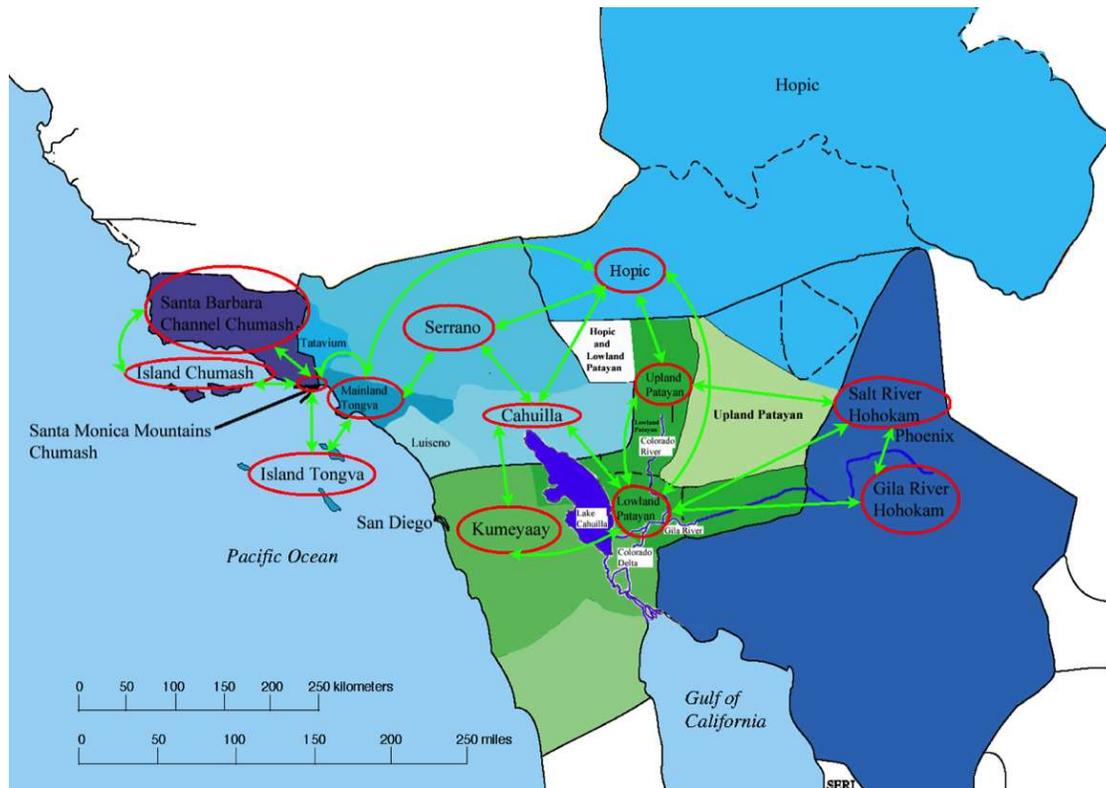


Figure 3.9. Network model of the Hohokam/California tranregional system that was constructed from information discussed in this chapter. The green lines (with arrows at both ends) identify significant interaction between regional pairs.

Finally, the possible importance of Hohokam shell as an exchange item for Lake Cahuilla fish is supported by large quantities of Panamic (Gulf of California) shell artifacts [that probably originated in the Hohokam system] that have been recovered from Lake Cahuilla shoreline sites. The idea that the export of large quantities of Hohokam shell artifacts to Lake Cahuilla residents in exchange for dried fish may have been a

major factor in the collapse of the Pre-Classic Hohokam system will be examined in Chapter 8 with a stylized bioeconomic model.

## CHAPTER 4: LAKE CAHUILLA, DRIED FISH, AND THE HOHOKAM SYSTEM

Lake Cahuilla was a giant freshwater lake in the Salton Basin of southeastern California. During its high stands corresponding to the Hohokam Late Colonial and Sedentary periods (ca. A.D. 850-1100) it had great potential as a highly productive source of protein rich fish, which could be preserved and transported great distances by drying. Beveridge et al. (2002:7) comment on the importance of fish in small scale societies.

Stewart (1994) and others believe the importance of fish in early hunter-gatherer societies to have been underestimated. Rudimentary proto-aquaculture techniques would probably have evolved among such societies, although evidence is scant. Native North American peoples living on the Pacific seaboard are believed to have transplanted the eggs of spawning salmon in an attempt to improve fish survival and returns.

The Lake Cahuilla fish weirs described later in this chapter could have been used for holding and protecting fish a form of proto-aquaculture, as discussed by Beveridge et al. (2002:5-8) or simply as fish traps. I treat them as fish traps, but future research should contrast and compare the robustness-fragility trade-offs of the two strategies (predation verses protection), and which strategy on average would have yielded greater protein output.

In this chapter I provide ethnohistoric and archaeological evidence that; (1) dried lake fishes were used as food by ancient people in the Great Basin; (2) a significant Lake Cahuilla fishery existed during the Hohokam Colonial and Sedentary periods; (3) freshwater fishes found in Lake Cahuilla were used as food in the Pre-Classic Hohokam system; (4) shell artifacts produced in the Hohokam system may have been exchanged for

dried Lake Cahuilla fish; and (5) there was an efficient route to transport dried fish into the Hohokam system from Lake Cahuilla.

### The Use of Dried Fish in the Prehistoric Western Great Basin

Raymond and Sobel (1990) provide a case study of the common use of a dried cyprinid fish (tui chub or *Gila bicolor*) by indigenous people in the prehistoric Western Great Basin. They consider the occurrence of large quantities of dried cyprinid fishes recovered from caves next to large Great Basin lakes (Figure 4.1) in relation to use as a valuable food source by local people. They do not consider that the large stores of dried fish may have resulted from surplus harvesting intended for trade.

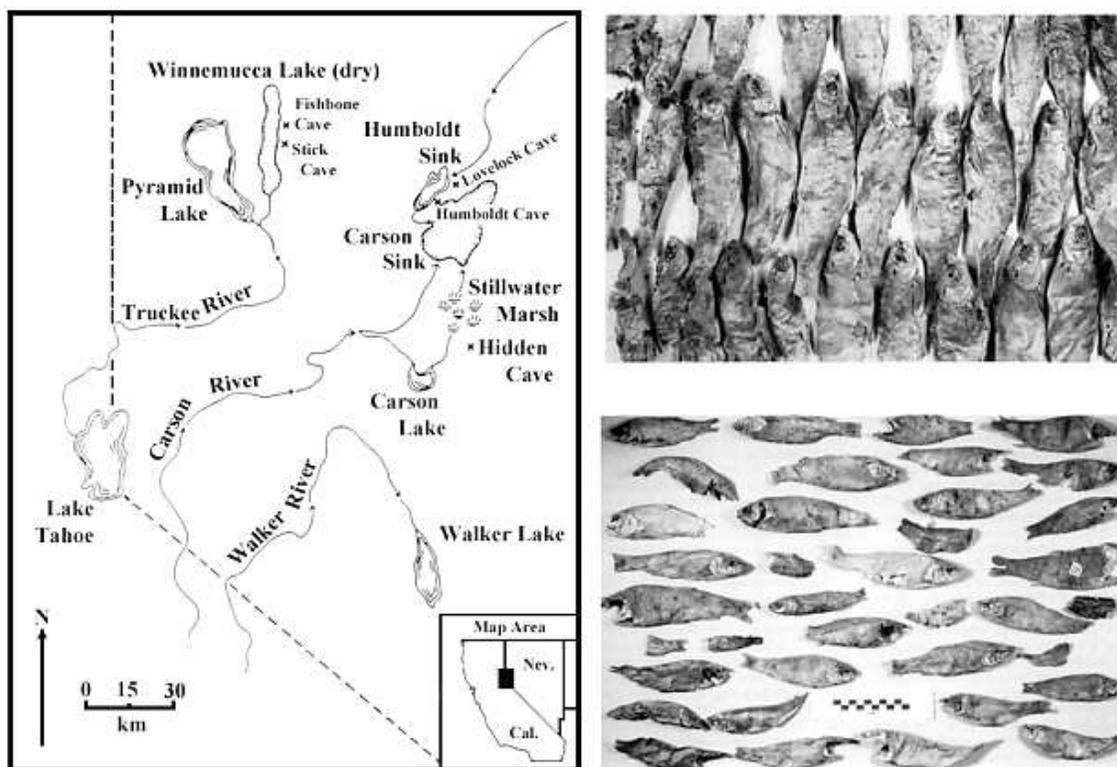


Figure 4.1. Dried fishes from prehistoric cave sites associated with lakes in the Great Basin.

Relevant to my study, Raymond and Sobel (1990:13) determine from empirical studies on tui chubs that caloric return rates of net fishing for the tui chub are much higher in some kinds of open water environments, compared to rivers and streams.

In large marsh, pond, or lake environments the caloric return rate is much higher. The experiments in Carson Sink returned a mean rate of 6,651 calories per hour for two gill nets of 14.5 cm chub that probably were schooling. Other researchers (e.g., Lindström 1990) report the take from schooling could be much higher.

Figure 4.2 provides a ranked comparison of the Raymond and Sobel result with the caloric returns (estimated by Simms 1984, 1985) for animal types commonly consumed in the past by native people in the Great Basin. Simms (1984) determines caloric return rates in relation to resource ranking and optimal diet curves for alternative scenarios (p. 156-166). He adjusted the total caloric return rates by subtracting the energetic costs of searching for (encounter rates) and processing the resources prior to consumption. Simms used Holling's disc equation (Holling 1959; Simms 1984:158), which was previously used by Charnov and Orians (1973) for this purpose. The animals in Figure 4.2 include types (e.g., jackrabbits) that are also commonly found in Hohokam deposits (Haury 1976:114; Szuter 1989, 1991). The tui chubs rank fourth, but as Lindström suggests, probably would rank much higher if more fishing studies were performed on lake populations of fishes where schooling is the norm. In the case of Lake Cahuilla (next section), the fishes most commonly recovered from archaeological sites in that region are schooling types, which form dense schools along gravelly shorelines during the spawning season (Gobalet and Wake 2000). This suggests the Lake Cahuilla fishery may have had energetic return rates that were considerably higher than the expected return rates for common Sonoran desert terrestrial animals, such as jackrabbits, gophers, and cottontails.

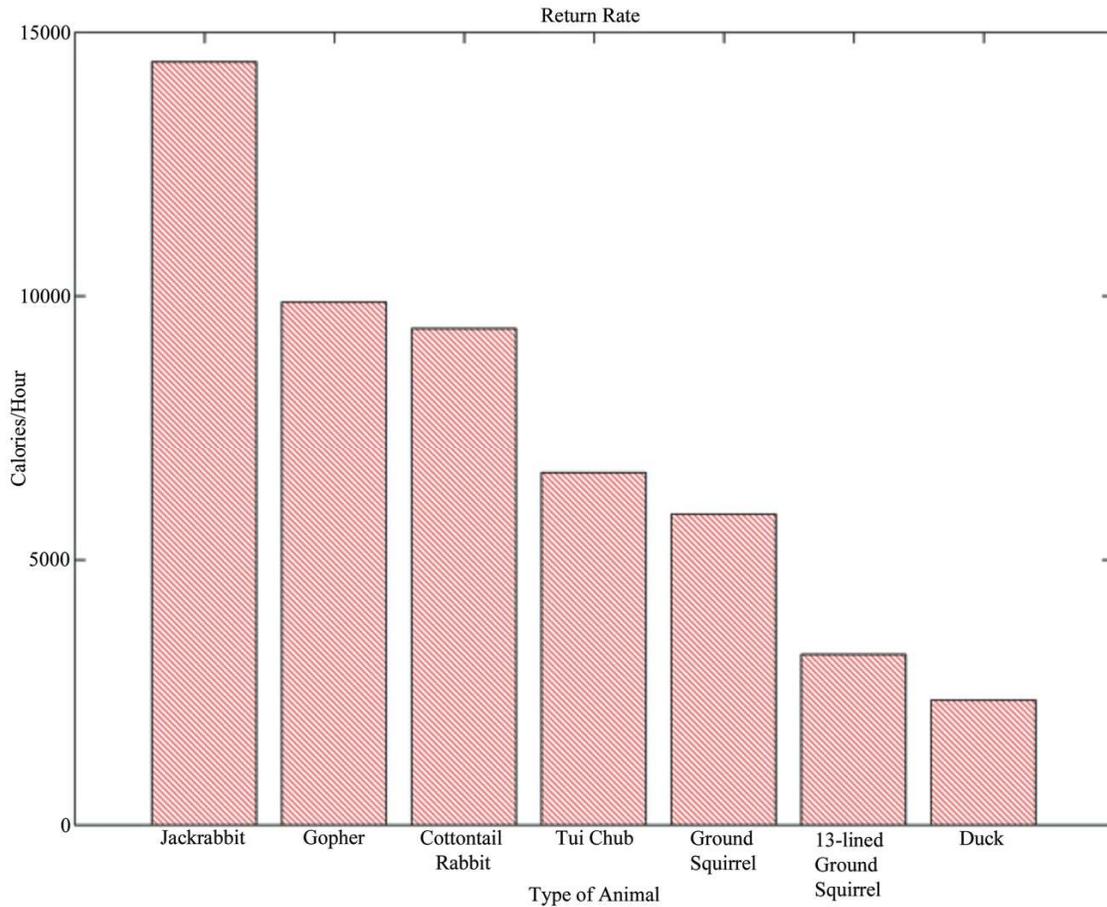


Figure 4.2. Averaged and ranked energetic return rates for animal types commonly used as food in the past by native people in the Western Great Basin (based on data from Simms (1984, 1985:122) and Raymond and Sobel (1990)).

### The Cui-ui Fishery in Nevada

A historic and probably prehistoric fishery in a large Great Basin lake (near some of the prehistoric cave sites with dried fish, see Figure 4.1) provides additional evidence for the possibility of a large-scale Lake Cahuilla fishery that produced large quantities of dried fish for later consumption and export to the Hohokam system. Located in the Great Basin of northwestern Nevada, Pyramid Lake is noteworthy for a major fishery of a large catostomid fish, the cui-ui (*Chasmistes cujus*), which is endemic to Pyramid Lake (see

Figure 4.1) and formerly to the now dry Winnemucca Lake (see Figure 4.1). The cui-ui harvest traditionally occurred during its annual and brief spawning runs (beginning in mid- April), when it ascends the Truckee River (which is the lake's water source) in great numbers. LaRivers (1962:371-372) comments that the cui-ui has a longstanding importance to Pyramid Lake Paiutes and other Paiute people as a staple food, and quotes Snyder 1917.

The flesh of this species is highly prized by Indians. In former times the coming of the 'cui-ui' was a great event, not only for the Pyramid Lake tribe but also for other Piutes from far to the south, who sometimes reached the fishing grounds in such a starved condition that many were unable to survive the first feast. At present numerous little camps may be seen along the river during the spawning season. The fishes are caught in large numbers and tons of them are dried for later use.

Tuohy 1990 provides additional information on the historic cui-ui fishery.

Ethnographic lake fishing [pertains to the Pyramid Lake fishery] was more of an individual enterprise accomplished with set lines, gill nets, single-barbed harpoons, and trident spears (Bath 1978:42-52; Fowler and Bath 1981:183; also see Follett 1982 for information on the former Winnemucca Lake fishery)[p. 124].

It is important to realize that the behavior and life history of the cui-ui differs considerably from that of Lake Cahuilla fishes (La Rivers 1962; Minckley and Marsh 2009). For example, it is likely that Lake Cahuilla fishes spawned near the shoreline of the lake (which I discuss later), whereas (as mentioned earlier) the cui-ui make spawning runs up the Truckee River into Pyramid Lake. When spawning both Lake Cahuilla fishes and the cui-ui mass in large numbers, which affords a great advantage to organized groups using fish weirs and large nets over individual fishers using smaller nets, hook and line, and spears (harpoons). Also, many of the items used in the Lake Cahuilla

fishery may not be preserved in the archaeological record as Tuoy (1990) observes in relation to any prehistoric fishery.

Some of the more fragile items, such as vegetable fiber fishing lines, nets and baskets disintegrate rapidly after having been submerged, and usually buried, and then, again, having been exposed to sunlight [p. 124].

Also the use of technologies such as animal and plant based fish poisons (Quigley 1956 provides an example of a plant derived poison from Sonora Mexico) are very difficult to detect archaeologically and may have been important to Lake Cahuilla fishers. The Akimel O'odham historically used at least one type of animal derived poison (rattlesnake venom) to catch fish in rivers (Rea 1998:80).

### **Evidence of the Long Distance Procurement of Fish in the Prehistoric U.S. Southwest**

Classic Mimbres pottery provides an iconographic line of archaeological evidence for prehistoric journeys to the Gulf of California for obtaining fish, and possibly the long distance transport of fish to the Mimbres area of New Mexico from the Gulf of California. Jett and Moyle (1986) were able to determine that some fishes depicted on Classic Mimbres pottery are Gulf of California species that (because of the accuracy of the depictions of the fishes by the artisans) probably had been seen firsthand by the artisans.

At very least, the depiction of many identifiable Gulf of California fishes by Mimbrenño potters seems to establish that Mimbrenños did indeed travel to the Gulf, there observing the fishes firsthand, presumably in the water. The fact that many of the species depicted do not presently normally occur in the upper third of the Gulf (north of Kino, Sonora), and the fact that extensive areas of the suitable rock habitats along the rest of the mainland shore are essentially confined to a stretch extending some 80 km northwestward from Guaymas (Thomson et al. 1979 [cited as 2000]: 3, 35), point to the Mimbrenños having been active in the Guaymas area [p. 714].

Snodgrass (1975) suggests that Mimbres people also transported fishes. As she observes, there are a few hints of the possible transporting of fish (presumably dried) for home consumption or trade. Snodgrass (1975) comments that (at least in the mid 1970's) there were three known examples. Mimbres pottery that depicted people carrying fish on their shoulders (see Figure 4.3 for one of them; also see Jett and Moyle 1986:713, Figure 19). The person carrying the fish on the bowl in Figure 4.3 has a feather and eye mask, which are associated with men (Munson 2000). There is also one Mimbres bowl showing a fish atop a trapeziform design (Snodgrass 1975:56) and other bowls showing men carrying possible burden baskets of similar form (Brody 1977a: 11, 168, 190, Plate 16, 1983:68-69; Fewkes 1923:27; LeBlanc 1983a: 136; Snodgrass 1975:iii, 137, 139; Tamarin and Glubok 1975:33). Snodgrass suggests the "men carrying burden basket" motif may symbolize the transporting of fish. These data suggest that future research should examine if there was a sexual division of labor in the transport of fish in Classic Mimbres culture that associated the transport of fish with men. The Mimbres example suggests that the long distance transport of dried fish may have been an effective strategy for obtaining wild protein used by people in the ancient U.S. Southwest.



Figure 4.3. Classic Mimbres bowl with a person carrying a fish. Downloaded from the Mimbres Pottery Images Digital Database (MimPIDD) using the Digital Archaeological Record (tDAR @ <http://core.tdar.org/project/377852>). (tDAR ID: 377852).

### **Historic Use of Dried Fish by Lowland Yumans**

In 1829 James O. Pattie one of the first American explorers who traveled along the Gila River, Lower Colorado River, Colorado Delta and into the Coachella Valley (including the Salton Basin) provides ethnohistoric evidence of the importance of fish in the diet of native people in this region. Native people in this region (Lowland or River Yumans) are likely descendants of some of the people who lived in the vicinity of the Gila River and on the southeastern shoreline of Lake Cahuilla. Thwaites (1966) provides an account from O. Pattie of an encounter his party had with Yuman people in the vicinity of the confluence of the Gila and Colorado Rivers near Yuma, Arizona.

At length they made up to one of our companions, who was of a singularly light complexion, fair soft skin, and blue eyes. They wanted him to strip himself naked that they might explore him thoroughly, for they seemed to be doubtful of his being alike white in every part of his body. This, but as mildly as possible, he refused to do. They went off and brought a quantity of dried fish of excellent quality, and presented him. We persuaded him to oblige these curious and good-natured women, by giving them a full view of his body. He was persuaded to strip to his skin. This delighted them, and they conversed and laughed among themselves, and they came one by one and stood beside him; so as to compare their bodies with his. After this, as long as we staid, they were constantly occupied in bringing us cooked fish and the vegetables and roots on which they are accustomed to feed [p. 209-210].

Rostlund (1952) comments that large quantities of fish were also dried, stored, and exchanged for other items by native Yuman people, which includes a comment pertaining to the preceding account by James O. Pattie.

In a small region of the lower Colorado and Gila rivers fish was dried and stored.

Fish was dried and stored even by the desert tribes west of the Colorado River; somewhere west of Yuma the party of James O. Pattie encountered some Indians who sold them a “quantity of dried fish of excellent quality” [p. 140].

In sum, this evidence suggests a longstanding importance of dried fish in the diet and economy of Lowland Yuman people. This supports the idea that Patayan ancestors of modern Lowland Yumans may have caught and dried Lake Cahuilla fish, some of which for trade with people from the Pre-Classic Hohokam system for shell preciosities.

### **Fish as a Protein Source in the Hohokam System**

The importance of fish as a protein source in the Hohokam system has not been adequately studied. Haury (1976:115) remarks on the importance of fish as food in Snaketown.

It appears that fish-eating was a custom of long standing in the Gila valley, for bones were recovered from refuse of all ages in Snaketown.

The practice of using coarse screen sizes (typically ¼ inch) by Hohokam archaeologists is possibly a main reason for the low frequencies of fish bone recovered from the great majority of excavated Hohokam sites (see Szuter 1989:182). Flotation, which uses finer mesh size has provided good preliminary evidence for the consumption of fish by people in the Hohokam system (e.g., James 1990), but is an inadequate method for processing the large volumes of soil needed to provide good statistical samples. Dean (2007) also acknowledges the coarse screen problem in Hohokam archaeological practice, and provides two examples of Hohokam sites, where finer screening led to significant recovery of fish bone.

Fish remains tend to be uncommon in Hohokam assemblages, with the notable exception of two large sites in the Phoenix Basin: Pueblo Salado (Stratton, 1995) and Pueblo Grande (James, 1994, 2003). The loss of fish remains through 1/4 in. screens is a contributing factor to the scarcity of fish bone [p. 113].

Wet screening using 1/16 inch or finer mesh produces very good recovery of fish bone, based on my own experience in southern California sites. Szuter (1989:183) also notes that insufficient training of Hohokam archaeologists in identifying fish bone may be another factor.

A second factor in the lack of fish remains lies in identification practices. It is perhaps noteworthy that the largest fish assemblage (Snaketown) was analyzed by an ichthyologist, W. L. Minckley. The small size and unusual nature of fish bones may have escaped the attention of zooarchaeologists working at other [Hohokam] sites.

The way fish were processed prior to consumption could also greatly reduce their recoverability, even with the use of fine screens and ichthyologists. For example, Raymond and Sobel (1990:10) provide the following caveat from their tui chub case study.

Drying and pounding of fish (reported ethnographically by Kelly [1932:97] would render handling of tui chub almost invisible to the archaeological record.

If dried fish was often pounded (crushing bone into a fine powder) for storage or cooking by people in the Hohokam system, chemical and/or spectrographic techniques would also be needed to detect and measure the occurrence of fish bone in Hohokam deposits.

The 1964 to 1965 excavation at Snaketown (Minckley 1976:379) provides the best published evidence to date on the importance of fish as a food source to people in the Hohokam system. The sample of fish bone from Snaketown studied by Minckley consisted of 277 bones, about 80 of which he was able to identify to species. Minckley (1976:179) concludes the following from his study.

The most common form was a sucker, Family Catostomidae--*Cataostomus insignis*, the second-most was the Gila mountain sucker, *Pantosteus clarki* (Baird and Girard). These were followed in decreasing order by Colorado chub, *Gila robusta* Baird and Girard, razorback sucker, *Xyrauchen texanus* (Abbott).

Interestingly, the razorback sucker is commonly recovered from Lake Cahuilla archeological sites, which will be discussed in the next section. Minkley (1976:379) also says in relation to the use of fish in the Hohokam system.

There is good evidence from localities on the Verde River that fish were dried for preservation (unpublished data).

More recent work in the Hohokam system at the Las Colinas site has provided evidence of fish used as food, and possibly dried for storage [and I suggest, maybe long distance transport as well]. James (1990:158) says in relation to the La Lomita site (a 10<sup>th</sup> Century Hohokam Occupation in South-Central Arizona).

The [fish] vertebra from pit Subfeature 71.2 is burned. Given the provenience this evidence indicates the use of fish as a food source and raises the possibility that dried fish may have been stored in the pits at one time.

Depletion of local fish stocks may have been another reason for importing dried fish from Lake Cahuilla. Minckley and Marsh (2009:26) cite archaeological evidence from central Arizona that suggests the possibility of local overharvesting of fish populations.

Evidence even exists of local fish harvests in central Arizona sufficiently intense to alter the size distribution of bones in archaeological sites, “larger ones [were seemingly] fished out, leaving only relatively small fish to be caught” (S.R. James, in Redman 1999).

I suggest that along with fish harvested from local rivers (e.g., Salt River) and irrigation canals, large quantities of dried Lake Cahuilla fish may have been brought into the Hohokam system via trails next to the Gila River. The importation of dried Lake Cahuilla fish may relate to the abundance of fish remains recovered from Snaketown, which was a major Pre-Classic Hohokam settlement on the middle Gila River. Note that the Gila River downstream from Gila Bend is outside what is considered to be the Hohokam system. The distance between Gila Bend (which is downstream from Snaketown) and its confluence with the Colorado River near the southeastern edge of Lake Cahuilla is about two hundred kilometers. This means that the majority of the length of the Gila River that could have been used as a trade route between the Phoenix Basin and Lake Cahuilla is outside the Hohokam system.

### **Lake Cahuilla Fish Traps and the Principle Catch of the Lake Cahuilla Fishery**

Hundreds of stone fish traps line the shorelines of Lake Cahuilla (Figures 4.4 and 4.5). As Minckley and Marsh (2009:25) comment.

Stone fishing weirs along old shorelines of pluvial Lake Cahuilla (present-day Salton Sea) stand along with nearby middens of disarticulated bones (Wilke 1978, 1980; Gobalet 1992, 1994; Gobalet and Wake 2000; Gobalet et al. 2005) in mute testimony of fish harvests a thousand years ago.

Bean (1974:62) provides ethnohistoric evidence that supports the use of nets and specialized bow and arrow technology for fishing in Lake Cahuilla.

Traditional oral literature describes fishing techniques and the use of fish nets for taking fish from the now desiccated Lake Cahuilla. This information is backed by archaeological finds of fish bones in association with arrowpoints, which I have seen in private collections, suggesting that the bow and arrow were used to capture the fish.

Gobalet and Wake 2000 provide evidence that these were used to catch gregarious fishes, such as the bonytail chub and razorback sucker (Figures 4.6 and 4.7). Stone fish weirs are well documented ethnographically and archaeologically (Bowen 1998; Dortch 1997; Goodwin 1988; Hunter-Anderson 1981; Jenkins 1974; Moss 2013; Moss and Erlandson 1998). They are used in a variety of marine and freshwater environments, including lakes. In the Lake Cahuilla fishery, fish probably entered the weirs near the shoreline, and were then captured in a net or basket trap placed at the narrow (v-shaped) end (Figure 4.4). Fish that entered the weirs may also have been captured with hand nets (or basketry scoops, see Wilke and Weide 1976) and fish arrows (Bean et al. 1989). Also, the height of the rock walls of the fish weirs was presumably slightly above the lake surface. White (2007) provides additional insight from replicative experiments on the productivity and use of the Lake Cahuilla fish traps.

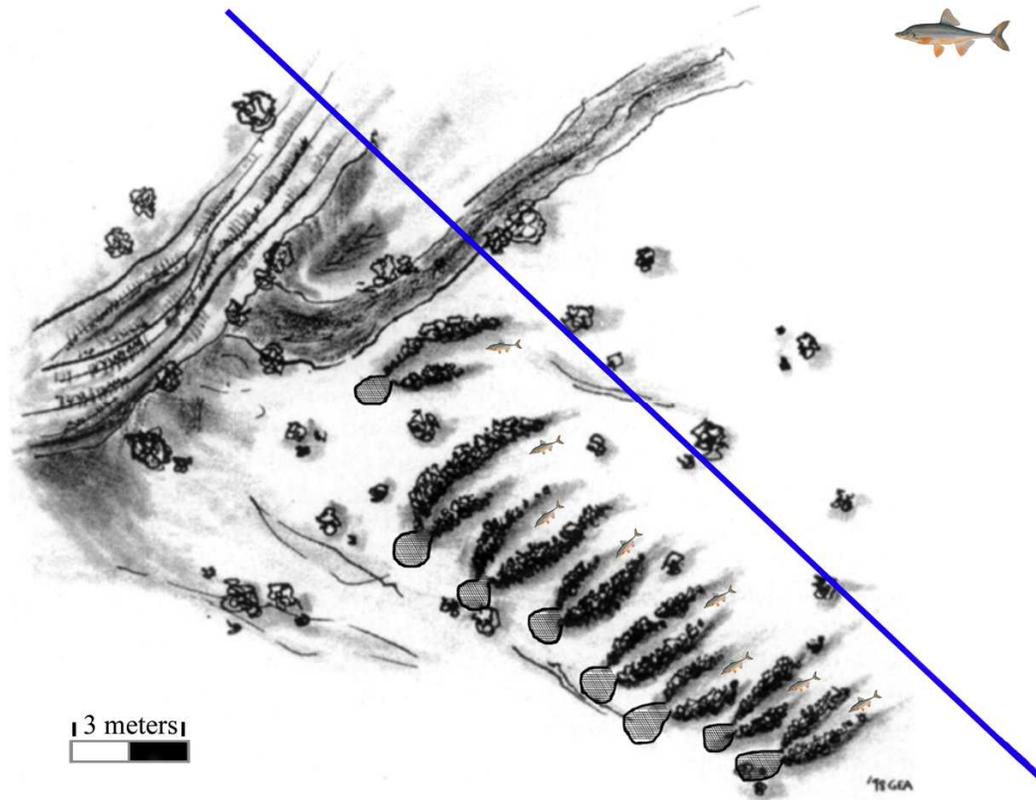
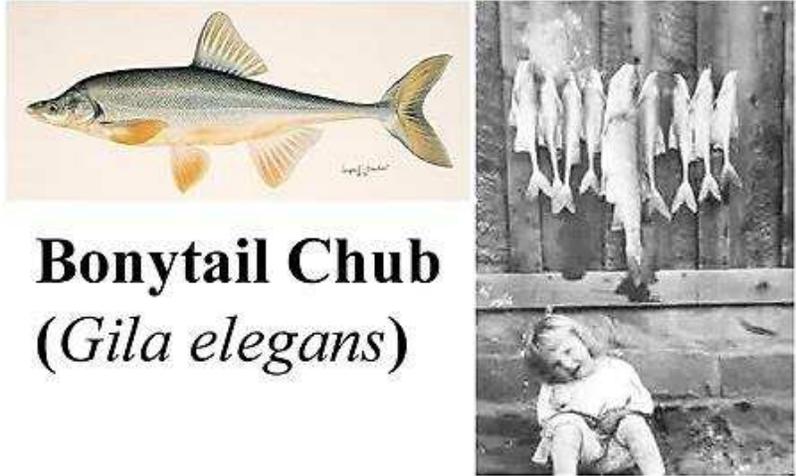


Figure 4.4. V- or U-shaped rock alignments (of which there are hundreds) along the shoreline of Lake Cahuilla (Gobalet and Wake 2000, Figure 2). Note the nets at the inner end of the fish traps. The water level of the lake would be slightly lower than the height of the rock walls of the fish traps. The blue line is an estimate of the Lake Cahuilla waterline.



Figure 4.5. Rows of Lake Cahuilla stone fish traps. The water line of Lake Cahuilla would have been to the right of the fish traps and the level of the lake would have been slightly lower than the height of the walls of the fish traps (see Figure 4.4).

Two fishes (bonytail chub and razorback sucker, see Figures 4.6 and 4.7) were very likely the principal catch of Lake Cahuilla shore dwellers (see Figure 4.8) based on archaeological samples from many Lake Cahuilla sites (Gobalet and Wake 2000).



**Bonytail Chub**  
*(Gila elegans)*

Figure 4.6. Bonytail chub.



**Razorback Sucker**  
*(Xyrauchen texanus)*

Figure 4.7. Razorback sucker.

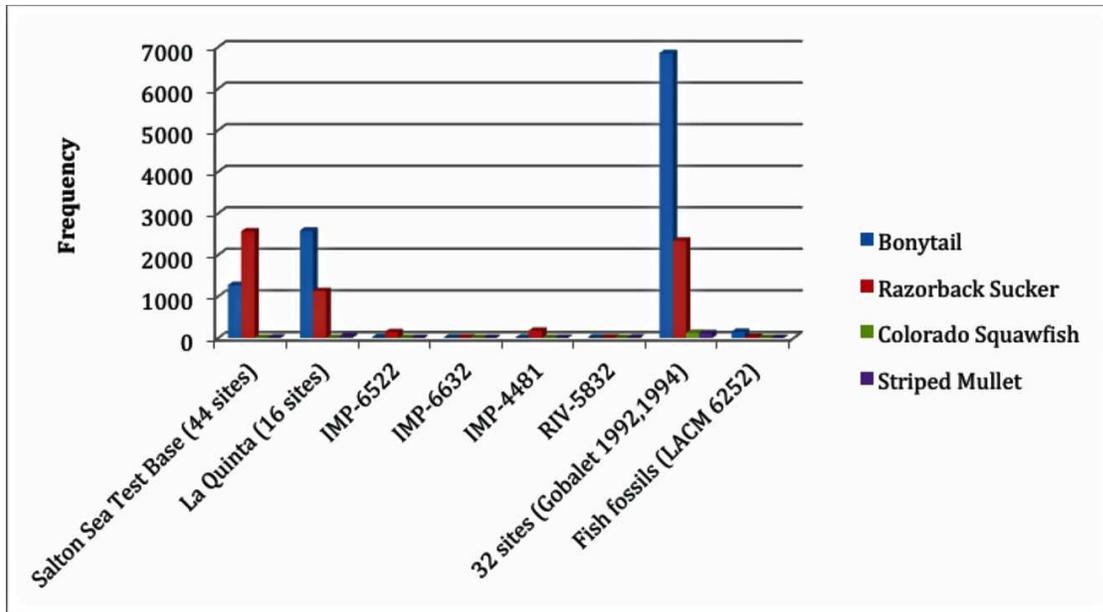


Figure 4.8. Number of native fish remains recovered from Lake Cahuilla shoreline archaeological sites and a fossil bearing sediment at least 2,000 years before present. The data used to construct this figure are from Gobalet and Wake 2000.

Both the bonytail chub and razorback sucker are large fishes and provide a substantial package of energy and protein (Minckley 1973). As discussed in the previous section, stone fish traps were the primary method (for which there is evidence) of fish harvesting in Lake Cahuilla. Also, the large number of these traps along the former shorelines of Lake Cahuilla, and the effectiveness of fish traps in catching large quantities of schooling fishes (such as bonytail chub and razorback suckers) in lake environments, suggests a major and highly productive fishery existed at Lake Cahuilla.

Additional details of the life history of razorback suckers and bonytail chubs provide even more insight into how a large-scale fishery was possible at Lake Cahuilla based on stone fish weir technology. Of the two fishes, the razorback sucker is the earliest to spawn and has the longest spawning season. Spawning usually begins in early January and continues into April. In contemporary desert lakes (such as Lake Mohave in

southeastern California), razorback suckers congregate in large schools next to the shoreline (Gobalet and Wake 2000; Mueller and Marsh 2002; also see Figure 4.9). The spawning season for bony tail chubs (in contrast) is only from April to May (Mueller and Marsh 2002). In Lake Mohave, spawning adults prefer deeper water during the day and after dark congregate in schools along the shore where they probably spawn over a substrate of large cobbles (Mueller and Marsh 2002, p.43). Seasonal and large assemblages of fish next to the shoreline of Lake Cahuilla would explain the use of fish weirs. In sum, this evidence suggests when (January-May) and why stone fish weirs on the shoreline of Lake Cahuilla may have been used to produce large yields of razorback suckers and bonytail chubs, and further supports my suggestion that a large Lake Cahuilla fishery was possible using stone fish weirs.



Figure 4.9. Large numbers of razorback suckers congregate along the shoreline of Lake Mohave in late winter to spawn (Fig. 44 Mueller and Marsh 2002).

## **The Lake Cahuilla Fishery and the Transregional Exchange of Dried Fish for Shell**

Lake Cahuilla, located at an intermediate point in the transregion, is an extremely productive island ecosystem that received much of its water from the Colorado River. Although not usually discussed with regards to Hohokam archaeology, changes in the lake correlate well with changes in the Hohokam sequence. I suggest that Lake Cahuilla was critical to the emergence of the Hohokam/California transregional system, and may have had a significant role in the collapse of the Pre-Classic Hohokam system.

During the mostly wet phase there were periodic earthquakes in the Salton Basin that may have changed the course of the Colorado River (the primary water source of the lake), resulting in multi-decadal filling and emptying cycles (see Table 4.1 and Figure 4.10) of the lake (Philibosian et al. 2011; Li et al. 2008; Waters et al. 1983). These filling and emptying cycles may have disrupted the Hohokam/California transregional system by interfering with the interregional exchange of Gulf of California shell artifacts (made by Hohokam specialists) for dried fish from Lake Cahuilla.

Philibosian et al. (2011) suggest there are six distinct high stands of Lake Cahuilla (horizontal blue bars in Figure 4.10), but these are grouped into two “mostly wet” periods. According to Philibosian et al. the intervals of subaerial deposition within the mostly wet periods were probably not long enough for the lake to desiccate completely [emphasis added], which is an important consideration for the bioeconomic model in Chapter 8. Lake Cahuilla durations from Waters (1983) and ages of deposits immediately preceding lake high stands from Rockwell and Sieh (1994) are also shown above the Philibosian et al. Lake Cahuilla chronology (Figure 4.10).

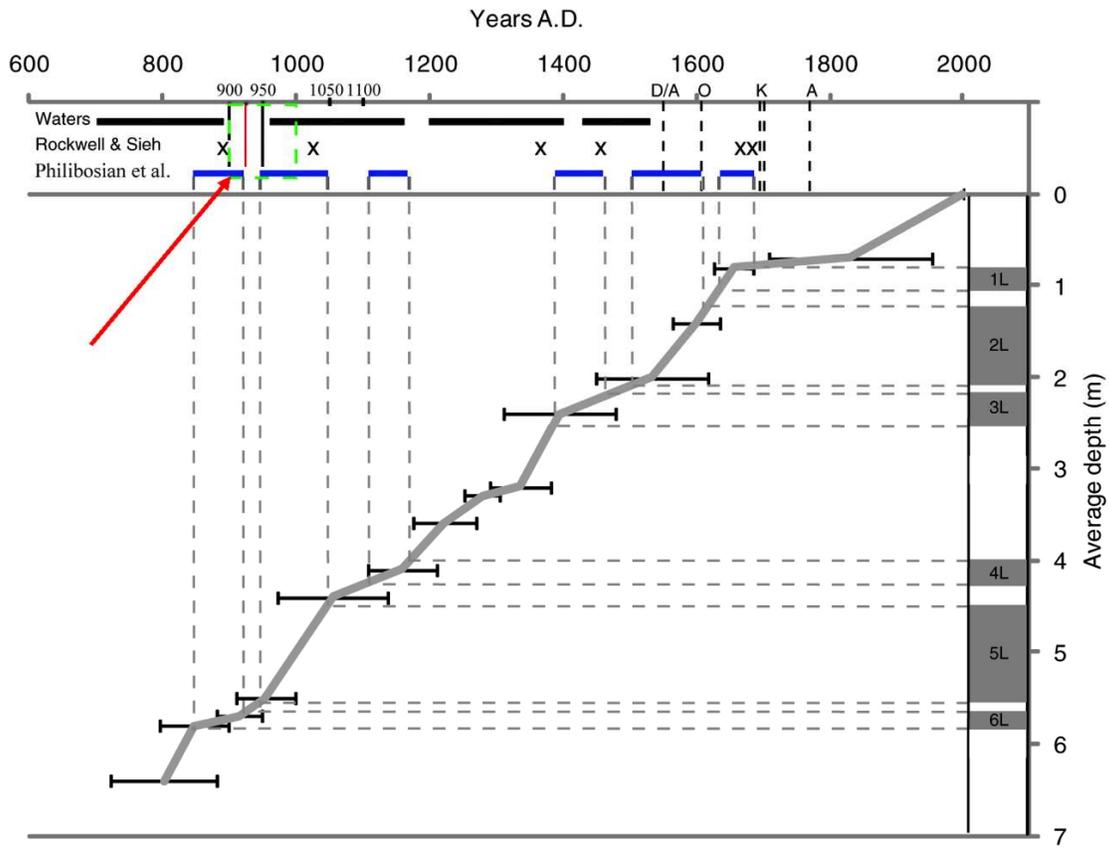


Figure 4.10. Approximate lake high stand chronology at the Coachella site and comparison to other Lake Cahuilla chronologies. The full 95 percent confidence range of the modeled ages of samples from each layer is plotted against average depth of the source layer. Lacustrine periods are projected from the depth axis to the time axis using the best-fit instantaneous sedimentation rate (heavy gray line).

Table 4.1. Lake Cahuilla Filling and Drying Cycles (A.D. 850-1150) [Source: Philibosian et al. 2011].

Interval	State	Maximum Extent of Lake ca. A.D.
A.D. 850-900	High Stand	895
A.D. 900-950	Drying/Filling	940
A.D. 950-1050	High Stand	985, 1030
A.D. 1050-1100	Drying/Filling	1075
A.D. 1100-1150	High Stand	1120

### **The Gila River: A Trade Route Between the Phoenix Basin and Lake Cahuilla**

It is essential to realize that the Sonoran Desert environment of the Pre-Classic Hohokam system was very different from the austere and dessicated landscape of today, which is the consequence of recent human modifications (e.g., intensive groundwater pumping, and the creation of “heat islands” in paved urban areas). Haury (1976:5) reminds us of this, and also comments on the importance of the Gila River as a trade route in ancient times.

It must be pointed out, however, that what we witness today is vastly different from the landscape the Hohokam first saw when they penetrated this land. It comes as a surprise to

learn that before the white man tampered with the Gila River, its valley was the “best practical route from the Rocky Mountains to California across the southern desert region” (Bryan 1925:119).

Even as recently as the mid-19<sup>th</sup> century, the Gila River was amenable to constructing a wagon road between California and Arizona. During the Mexican-American War in November 1846, General Stephen Watts Kearny led one hundred cavalymen from the 1st U.S. Dragoons along the Gila River. Kit Carson was the guide. The Mormon Battalion accompanied Kearny's troops for about a month, and during that time built a wagon road along the river (Calvin 1946; Cowan 1997; Hufford 1967; Jonas 2009; Roberts 1919; Tyler 1881).

In prehistoric time the middle and lower Gila River probably flowed for most of the year and was like a “linear oasis” across the long stretch of parched desert that separated the Phoenix Basin from Lake Cahuilla (see Figures 4.11 and 4.12 for a Google satellite map and recent pictures of the Gila River flowing near Yuma, Arizona).

Considering the ease and timely manor in which the Mormon Battalion built a road for horse drawn wagons along the Gila, it seems very plausible that large quantities of dried Lake Cahuilla fish could have been efficiently transported up the Gila River on the backs of residents of the Phoenix Basin and/or Patayan specialist traders. And to avoid confusion, I mean transport along a long stretch of the Gila River that includes the Gila River downstream from Gila Bend and extending to its confluence with the Colorado River. This segment of the river is outside the currently recognized boundaries of the Hohokam system and is continuous with the portion of the middle Gila in the core area of the Hohokam system.

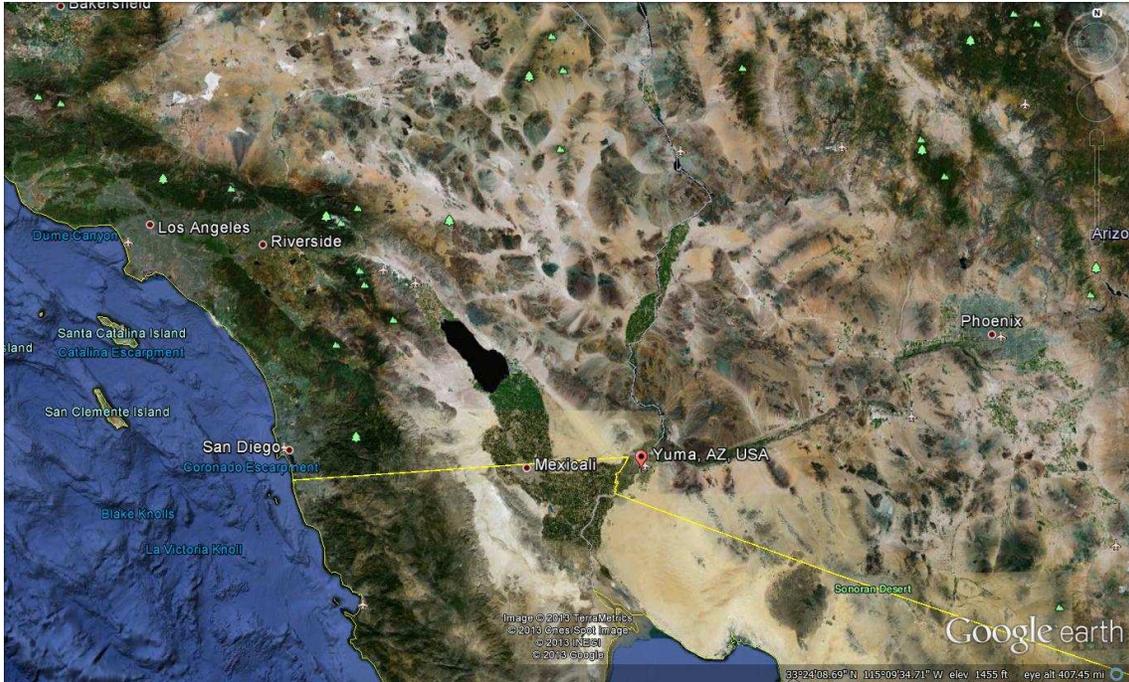


Figure 4.11. Google map showing the Gila River between the Phoenix Basin and its confluence with the Colorado River. Note the green line of the Gila River between Phoenix and the Salton Basin, in stark contrast to the brown of the surrounding desert. This suggests the role of the middle and lower Gila River as a “linear oasis” and major thoroughfare between the Phoenix Basin and Lake Cahuilla.



Figure 4.12. Gila River near Yuma, Arizona. Even today the lower Gila River has flowing water in some places.

## Summary

The evidence I presented in this chapter supports the existence of a Lake Cahuilla fishery that could have been an important supplementary protein source for the Hohokam system. The presence of large quantities of shell artifacts (most likely made in the Hohokam system, which I discuss in detail in Chapters 6 and 7) recovered from Lake Cahuilla shoreline sites suggests that during the Late Colonial and Sedentary Periods, Hohokam shell preciosities may have often been traded for dried Lake Cahuilla fish. I also provided evidence that the Gila River was a probable and efficacious route for economic exchange between Lake Cahuilla people and people in the Hohokam system.

## CHAPTER 5: MORPHOMETRIC ANALYSIS AND COMPARISON OF OLIVELLA SHELL SMALL BARREL BEADS FROM MALIBU (LAN-264) AND THREE HOHOKAM SITES

Two distinct species (*biplicata*, endemic to the Pacific Coast and *dama* found only in the Gulf of California) of *Olivella* shell often were made into beads in the Chumash region and the Hohokam system, respectively, and less often in other parts of the Hohokam/California transregion (Dahduhl 2011; Gibson 2000; King 1990). When both the spire and base of these shells are ground or chipped, they are often called “barrel” beads. The extent to which the spire or base is ground which affects both size and shape varies over time and space, and in part is the result of stylistic choice. Selection of unworked shell based on size and shape is also influenced by individual and group preferences. For example, *Olivella biplicata* barrel beads from the Chumash region made after A.D. 1000 are usually made from smaller shells and have more of the base removed than beads of this type from earlier periods in Chumash prehistory (King 1990:135).

Small barrel beads made from two Panamic species of *Olivella* shell are abundant in some Pre-Classic collections (e.g., Snaketown) from the Hohokam system. The two species are: *dama* (Haury) and *fletcheriae* (observation by Arthur Vokes, Arizona State Museum, 2013). For example, many barrel beads from the Snaketown site originally thought to have been made from juvenile *Olivella dama*, have attributes that identify them as *Olivella fletcheriae* (a more diminutive species).

The goal of this chapter is to address the following questions: (1) is a large sample of small *Olivella* sp. barrel beads from burials in the M5a-b (ca. A.D. 900-1150) Malibu cemetery in the Chumash region of southern California made from a Gulf of California

*Olivella* species, and (if so) which one, and (2) if the artifacts are made from a Panamic *Olivella* species are they stylistically similar to contemporary *Olivella* barrels made in the Hohokam system? If the *Olivella* sp. barrel beads from the Malibu cemetery were very similar stylistically to those from the Hohokam system this would support the existence of a Hohokam/California transregional system during that time, and one that extends to the southern California coast.

### **Attribute-Based Morphological Comparison**

It is easy to show that the Malibu and Snaketown small “barrel” beads are not made from *Olivella biplicata* shell, using simple non-metric attributes. To determine that the Malibu and Snaketown beads are not made from *Olivella biplicata* (a Pacific Coast species), all that is needed is to visually compare two morphological attributes (the vertical extent of callus relative to the position of the last suture, see McDonald 1992:272). Such a comparison shows that the *Olivella* sp. small barrel beads from Malibu and Snaketown are not made from *Olivella biplicata* (See Figures 5.1 and 5.2).

Of three common Gulf of California *Olivella* species (*dama*, *tergina*, and *zoenata*), the LAn-264 small *Olivella* barrel beads are much more similar to *O. dama*, based on:

- (1) The width of the callus (which is significantly wider in *dama*, see Figure 5.2) and
- (2) The greater convexity of the curvature of the inner margin of the callus (see Figure 5.2).

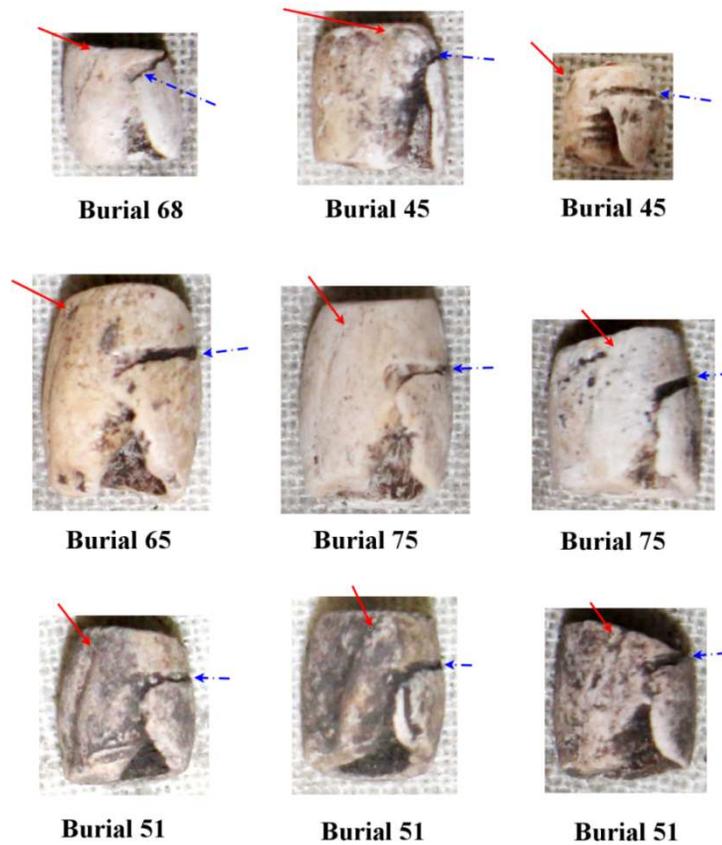


Figure 5.1. Attribute-based species identification of LAN-264 *Olivella* small barrel beads. Note that in each of the above LAN-264 Middle period cemetery *Olivella* sp. barrel beads, the callus (left edge visible as an inwardly curved vertical groove) continues above (solid arrow, left side) the last suture (dashed/dotted arrow, right side), which is a distinguishing character of *Olivella dama* compared to *Olivella biplicata* (in which the callus ends at or before the last suture).

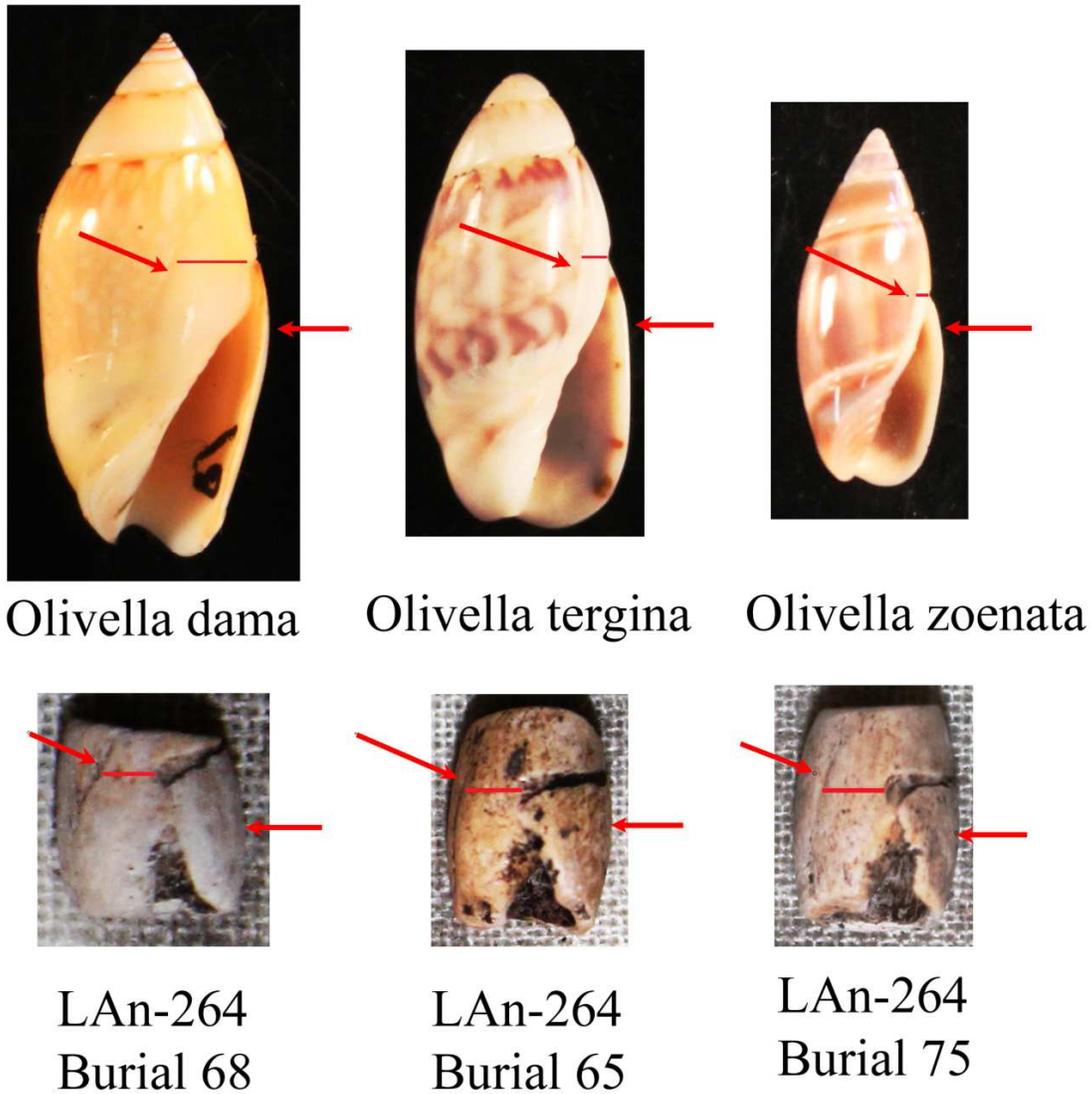


Figure 5.2. Example of attribute-based comparison of three species of Gulf of California *Olivella* with small *Olivella* sp. barrel beads from the LAn-264 cemetery. The horizontal line shows the width of the callus at the last suture. This is proportionately much wider in species *dama* than in species *tergina* and *zoenata*.

*Olivella gracilis* is another Gulf of California species that may have been used to make barrel beads in the Hohokam system. However, I do not expect it was commonly used, based on a large sample (n=245) of *Olivella* shell artifacts from southeastern California (see Dahdul 2011), many of which may have been manufactured in the Hohokam system.

Specifically, *O. gracilis* shell comprised 7.7 percent of the sample, whereas 91.7 percent of the sample was identified as *O. dama*. Another candidate species for the LAn-264 small barrel beads is *Olivella fletcheriae*, whose range includes the northern Gulf of California (Berry 1958, Keen 1972). Over one hundred-barrel beads made from this small species have recently been identified by Arthur Vokes from the Snaketown site. Barrel beads made from *O. dama* can easily be distinguished from those made from *O. fletcheriae* using a simple morphological attribute. Specifically, the parietal callus is wider and more curved (has greater concavity) on the inner edge in *O. dama* compared to *O. fletcheriae*, in which the inner edge of the callus is nearly linear (see Figures 5.2 and 5.3). Based on these attributes, the LAn-264 sample is consistent with *O. dama* and not with *O. fletcheriae*. In sum, I conclude that the LAn-264 small Olivella barrel beads are very likely *O. dama*.



Figure 5.3. Example of *Olivella fletcheri*, from the Gulf of California.

## Materials and Methods

### *Samples*

Size data on *Olivella* sp. barrel bead samples was obtained from the Arizona State Museum for the Snaketown and Las Colinas sites (Hohokam system), and from King 1996 for the LAn-264 (Malibu) site. To obtain the raw data for measuring shape, shells were photographed with an SLR digital camera equipped with a macro lens that was mounted on a photo stand with supplementary lighting. The LAn-264 shells were photographed at the UCLA Fowler Museum, and the Las Colinas shells were photographed at the Arizona State Museum (ASM), at the University of Arizona. The

shells were photographed from the ventral side in an orientation that showed both the inner and outer margins of the shell apertural lip. Seven landmarks (see Figure 5.4) were digitized using the Point Picker plugin to ImageJ (see Appendix D). The landmark data (x and y coordinates of the seven landmarks) was converted into .tps files in Excel. David Polly (in one of the handout pdfs on his G562 Geometric Morphometrics webpage) provides a detailed description on how to collect landmark coordinates with Point Picker in ImageJ, and then save them in a TPS file (see <http://www.indiana.edu/~g562/Handouts/Collecting%20Landmarks.pdf>). The .tps files were then transformed into the format required by the R statistical Shapes package, using the R function `read.tps`, written by David Polly (available at: <http://mypage.iu.edu/~pdpolly/Software/RFunctions/read.tps.txt>)

The R function `read.tps` was used to convert the .tps data file into a format needed by the R Shapes package, which must be loaded using the R command `library(shapes)` for the R functions required for the Geodesic Principle Components Analysis (discussed in a later section of this chapter) to run.

## **Morphometric Analyses**

### *Size Analysis*

In this section I consider size in relation to the diameter of *Olivella* sp. barrel beads. These data are from pithouses and trash deposits in the Las Colinas site and from burials in the Snaketown (AZ U:13:1) and Malibu (CA-LAn-264) sites. In mortuary samples, diameter distributions of a given type of shell bead may vary considerably between burials, due to chronological, production, and social factors (see, for example,

Vanderwal 1973:48; Weisler 2000:126). Similar factors may also result in size biases in bead diameter in non-mortuary contexts from different areas within a region. However, I expect that the diameter distributions of *Olivella* sp. barrel beads for a given species (e.g., *dama*) will (in at least some cases) be similar in contemporary and spatially local and distant samples, if the beads were (for the most part) produced in one region (e.g., the Hohokam system). Considering that *Olivella dama* is a Gulf of California endemic it seems most likely that the *O. dama* barrels from the Middle period Malibu cemetery were not manufactured locally by Chumash artisans, but were made by artisans much closer to their source.

A dot plot (Figure 5.4) is used to visually compare the diameter distributions of *Olivella* sp. barrel beads from seven Hohokam and four Malibu burial samples (all contemporaneous). The dot plot shows how much the size distributions of the samples overlap, where I assume that the greater the overlap in size distribution, the more likely the shell artifacts were made in the same general area. The diameter distributions of the Malibu *Olivella dama* barrel beads substantially overlap with those samples of *O. dama* barrels from Snaketown and Las Colinas (see Table 5.1, Figure 5.4, and Appendices A and B). The diameter distributions of the Malibu barrels do not overlap much with those of the *O. fletcheriae* barrels from Snaketown (Figure 5.4), and indicate that the Malibu beads (for the most part) are larger.

A boxplot (Figure 5.5) provides another (and more objective) way to compare the degree of overlap between the diameter distributions in the preceding samples. When the notch heights in a pair of boxes do not overlap, this is strong evidence that the medians of the two samples are significantly different (Chambers et al. 1983:62), which, in this

analysis, is sufficient to reject the null hypothesis that the two samples of *Olivella* sp. barrel beads are from the same population. A boxplot of the Malibu and Arizona samples shows that the diameter distribution of Burials 51 and 73a are closest to the *O. dama* barrels from Snaketown Cremation 52 (ST9) and Las Colinas (Figure 5.5). However only the vertical notch of the box of the Burial 51 sample overlaps with the vertical notch of the ST9 box (Figure 5.5), which suggests that only in this case is the null hypothesis that the two samples came from the same population not rejected.

To more precisely evaluate the similarities between the four samples, I formally compare the diameter distributions of the samples of *Olivella dama* barrel beads from Las Colinas and Snaketown Cremation 52 with those of the *Olivella* sp. barrel bead samples Burials 51 and 73a with a simulation based two sample Smirnov test (Baglivo 2005), which is appropriate for discrete data and very small sample sizes (see Appendix C). A two sample Smirnov (or often Kolmogorov-Smirnov) test compares the equality of the empirical distribution functions of two samples. The plots in Figures 5.6 and 5.7 are the empirical cumulative distribution functions of the diameter of *Olivella* sp. barrel beads from two samples of the four samples being compared (above). The null hypothesis being tested is that the diameter distribution of the *Olivella* sp. barrel beads from which samples 1 and 2 are drawn is the same (i.e., they both likely originated in the same area in the Hohokam system). The null hypothesis is rejected ( $\alpha = 0.05$ ) in the comparisons of the Las Colinas sample with Burials 51 and 73a (Table 5.2), in agreement with the result from the boxplot analysis. A major difference between the distribution of the Las Colinas and the two Malibu samples is that the distribution of the Las Colinas beads is biased towards larger beads (see Figure 5.6). In contrast, the null hypothesis is not rejected ( $\alpha =$

0.05) for the comparison of the Snaketown Cremation 52 sample with the Burial 51 sample, but is for the Burial 73a sample (Table 5.3)—again in agreement with the boxplot analysis. More than half of the barrel beads from the Burial 73a sample have larger diameters than any of the barrel beads from the Snaketown Cremation 52 sample (Figure 5.7). This suggests (based on size) that at least some of the Malibu barrels may have originated in the Hohokam system, possibly from different sources in the Hohokam system (since different groups may have had different selection preferences for diameter), and (in particular) that the Burial 51 beads may have originated in the Gila River area of the Hohokam system.

Table 5.1. Data on samples in dot plot (Figure 5.4).

	Site	Feature	Period/Phase	Type	Shell
TVWS (Tanque Verde Wash Site)	AZ BB:13:68	2275	Sedentary/Rincon	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	4014, Trash Pit	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	4208, Trash Pit	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	4014, Trash deposit	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	4050	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	4025	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	5061, Trash Pit	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	7023, Pit	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	5045, Area 5	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	5078, Trash Pit	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	5018, Area 5	Sedentary	Barrel bead	<i>Olivella dama</i>
Las Colinas	AZT:12:10	7501	Sedentary	Barrel bead	<i>Olivella dama</i>

Snaketown 1	AZ:U:13:1	9E, Pit 11	Pioneer	Barrel bead	<i>Olivella dama</i>
Snaketown 1	AZ:U:13:1	9E, Pit 9	Pioneer/Sweetwater	Barrel bead	<i>Olivella dama</i>
Snaketown 2	AZ:U:13:1	9-H, Cremation 52	Sedentary	Barrel bead	<i>Olivella fletcheriae</i>
Snaketown 3	AZ:U:13:1	12-G, Cremation 1	Sedentary/Sacaton	Barrel bead	<i>Olivella fletcheriae</i>
Snaketown 4	AZ:U:13:1	6-F, Cremation 1	Sedentary	Barrel bead	<i>Olivella fletcheriae</i>
Snaketown 5	AZ:U:13:1	9-I, Cremation 1	Sedentary	Barrel bead	<i>Olivella fletcheriae</i>
B68	CA-LAn- 264	Burial 68	Middle /5 a-b	Barrel bead	<i>Olivella dama</i>
B45	CA-LAn- 264	Burial 45	Middle /5 a-b	Barrel bead	<i>Olivella dama</i>
B51	CA-LAn- 264	Burial 51	Middle /5 a-b	Barrel bead	<i>Olivella dama</i>
B73a	CA-LAn- 264	Burial 73a	Middle /5 a-b	Barrel bead	<i>Olivella dama</i>

### Olivella sp. Barrel Beads

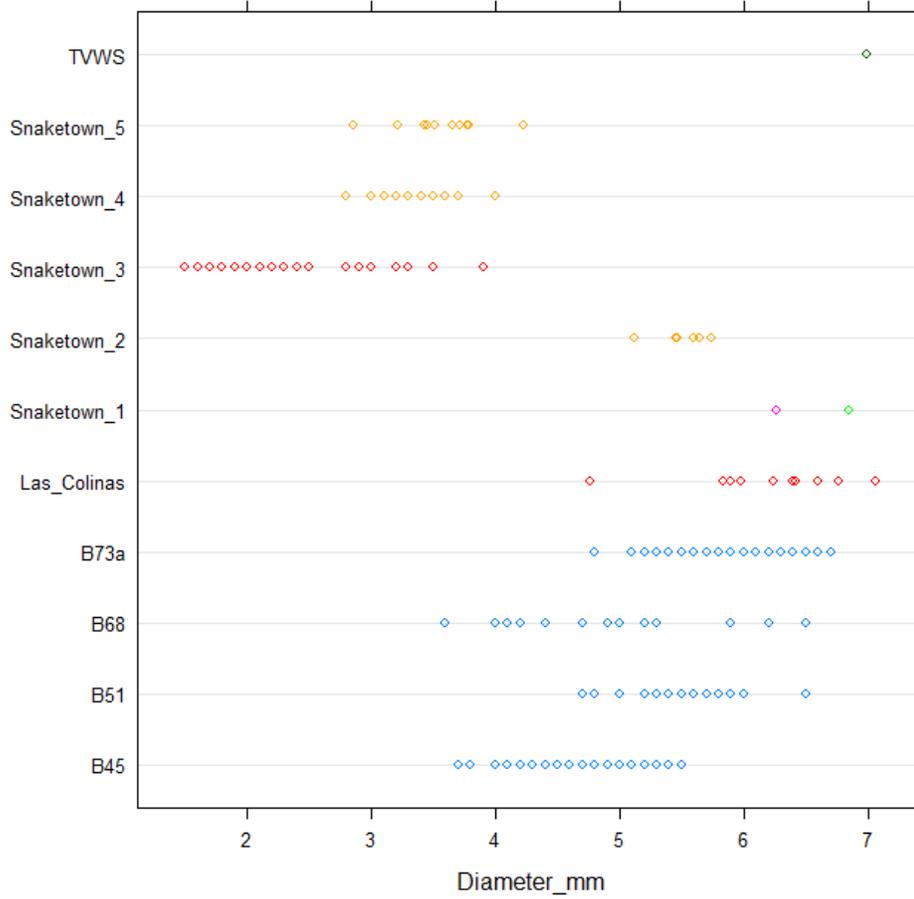


Figure 5.4. Dot plot of the diameter distributions of small *Olivella* sp. barrel beads from three Hohokam sites and Malibu. See Table 5.1 for more information on each of the samples in the dot plot.

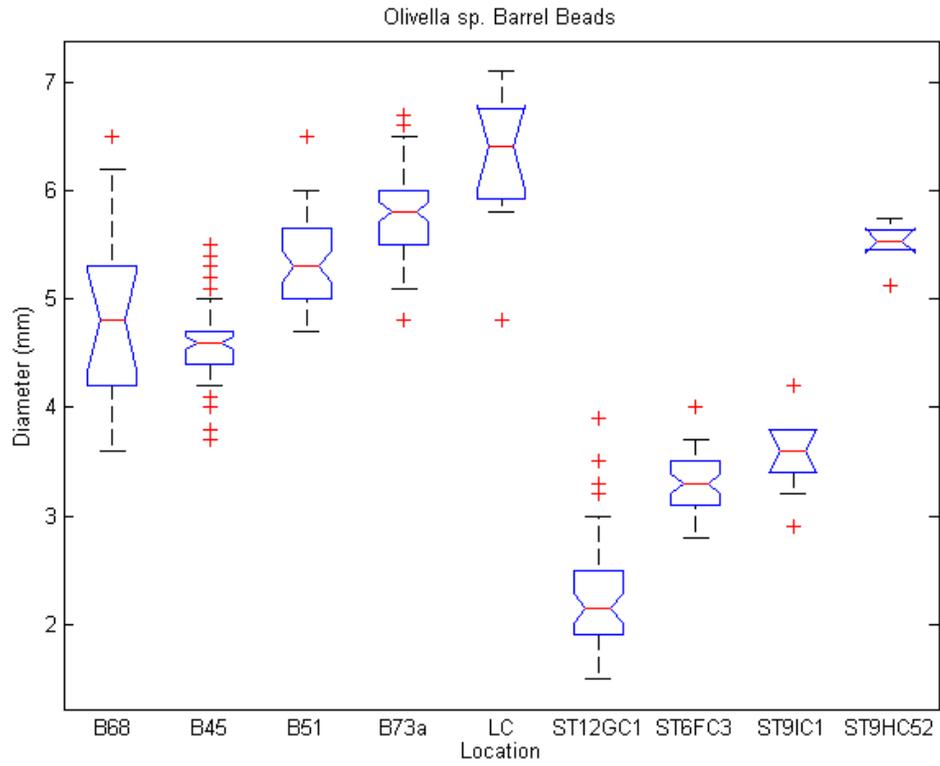


Figure 5.5. Box plot of diameter distributions of small *Olivella* sp. barrel beads from Las Colinas, Snaketown, and Malibu.

Table 5.2. Summary of results from the 2-sample Smirnov test on *Olivella dama* barrel bead diameter. Las Colinas sample compared with samples from LAn-264 Burials 51 and 73a.

Las Colinas (n=10) verses	Smirnov Statistic (Observed Maximum Difference between ECDF plots)	Maximum Difference Between ECDF plots (Random Partition)	P-value (Number $\geq$ Observed)/2000
Burial 51 (n=52)	0.736014 at 5.7 mm	0.15035 at 5.5 mm	1/2000 = 0.0005
Burial 73a (n=83)	0.479737 at 6.1 mm	0.15035 at 6.0 mm	13/2000 = 0.0065

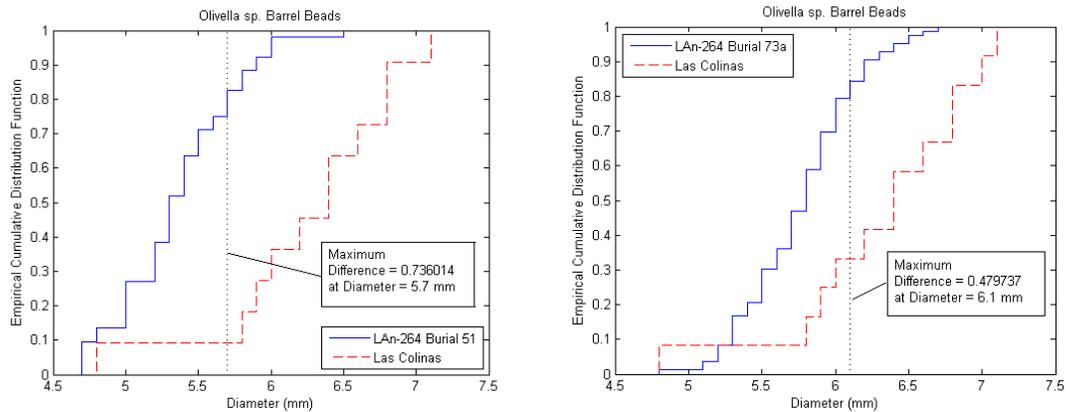


Figure 5.6. Empirical cumulative distribution plots *Olivella dama* barrel bead diameter for the Las Colinas sample compared to the samples from Burials 51 and 73a from the Malibu site.

Table 5.3. Summary of results from the 2-sample Smirnov test on *Olivella dama* barrel bead diameter. Snaketown sample compared with samples from LAn-264 Burials 51 and 73a.

Snaketown Cremation 52 (n=6) verses	Smirnov Statistic (Observed Maximum Difference between ECDF plots)	Maximum Difference Between ECDF plots (Random Partition)	P-value (Number $\geq$ Observed)/2000
Burial 51(n=52)	0.736014 at 5.7 mm	0.15035 at 5.5 mm	300/2000 = 0.1
Burial 73a (n=83)	0.479737 at 6.1 mm	0.15035 at 6.0 mm	13/2000 = 0.0065

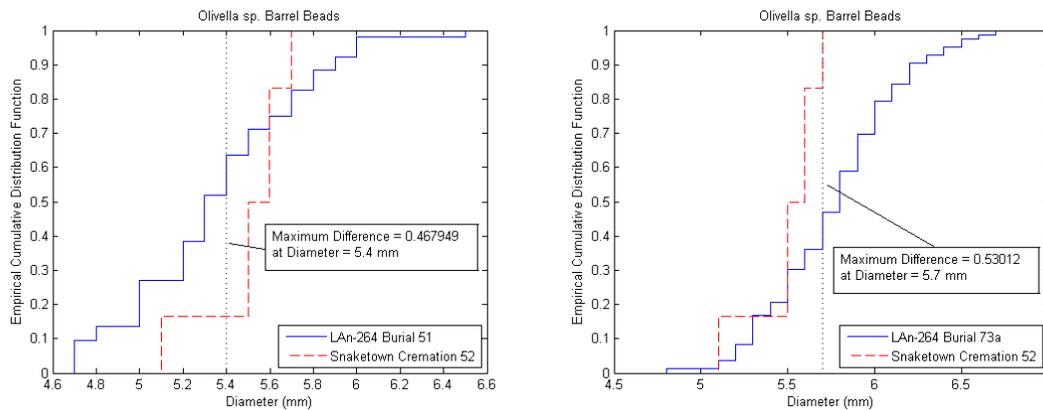


Figure 5.7. Empirical cumulative distribution plots *Olivella dama* barrel bead diameter for the Snaketown Cremation 52 sample compared to the samples from Burials 51 and 73a from the Malibu site.

## Shape Analysis

Shape analysis is often used to study complex biological shapes and to relate morphological similarities to genetic closeness. This type of analysis is contained within the broad field of morphometrics. In this study I use a landmark-based morphometrics approach that is typical of *geometric morphometrics*. Slice et al.

(<http://life.bio.sunysb.edu/morph/glossary/gloss1.html>) provide the following definition of geometric morphometrics.

**Geometric morphometrics** is a collection of approaches for the multivariate statistical analysis of Cartesian coordinate data, usually (but not always) limited to landmark point locations. The "geometry" referred to by the word "geometric" is the geometry of Kendall's shape space: the estimation of mean shapes and the description of sample variation of shape using the geometry of Procrustes distance. The multivariate part of geometric morphometrics is usually carried out in a linear tangent space to the non-Euclidean shape space in the vicinity of the mean shape.

I use a land-mark-based geometric morphometric analysis to evaluate the likelihood that small *Olivella dama* barrel beads from burials in the Malibu (LAn-264) Middle period cemetery originated in the Pre-Classic Hohokam system and (if so) from where in the geographic region associated with this system.

### *Landmarks*

A landmark is a point on an organism that can be identified in all organisms in a sample and can be considered the same anatomical locus. In this study two-dimensional landmarks are used. Landmark 1 (junction between end of suture and apertural lip, see Figure 5.8) is a preferred Type I landmark since it occurs at the intersection of well-defined morphological structures (Dryden and Mardia 1998:4). The remaining landmarks are Type II landmarks (see Dryden and Mardia 1998:4) since they are defined by a local

property (maximal curvature). The shape of the shell's aperture and last major whorl are measured with Landmarks 2 and 5 (Figure 5.8), which are locations on the shell that have been shown to be excellent discriminators of closely related gastropods (Cruz et al. 2012). Geometric morphometric techniques have also been successful in distinguishing between intraspecific groups of gastropods. For example, Carvajal-Rodriguez et al. 2005 using landmark based geometric morphometrics successfully identified separate ecotypes of the gastropod *Littorina saxatilis*. Landmarks 3, 4, 6, and 7 (Figure 5.8) are determined by the manufacture of the shell bead, and may be useful for detecting stylistic variation. The landmark data were analyzed using: (1) R script provided by Dr. Stephen Huckemann [ishapes package, see Appendix E] and (2) the R package Shapes. Graphs and additional analyses were done in Matlab.



Figure 5.8. Landmarks 1 through 7 on the outline of an *Olivella dama* barrel bead from Las Colinas.

### *Geodesic Principal Components Analysis*

Given a sample of *Olivella* sp. barrel beads from a well-dated context, it should then be possible to evaluate the likelihood of where they were made, based on statistical properties of the shape of the artifact. Landmark based methods from geometric morphometrics (that use a partial geometric description of an object) will be used to analyze the shape of shell artifacts. In the present study, a small number of well-defined points (or landmarks, see Figure 5.8) on two-dimensional photographs of shell artifacts are the raw data for the shape analysis.

Kendall (1984) introduced a commonly used procrustes-based method for the analysis of shape using landmark points (see Le and Small 1999:1601-1604 and Small 1996:6-14; 38-66; 77-94) for a detailed discussion of the mathematics of Kendall's approach, with an archaeological application. Huckemann et al. 2010a provide a summary of the steps and mathematical consequences of Kendall's approach.

Different concepts of “size” lead to different landmark based shape spaces, cf. Small (1996). Taking “size” as the Euclidean norm of a matrix, the resulting quotient spaces are commonly called Kendall’s shape spaces. They are obtained as follows. Given a sample of original geometrical objects, from each object a landmark configuration matrix is extracted. In a first step, normalizing for location and size, this matrix is mapped to a point on the so called pre-shape sphere.

In a second step, filtering out rotation, the pre-shape sphere is projected to the shape space, containing only the “shape information” of the original object. Shape spaces can be rather complicated.

When planar objects are considered, the projection from the pre-shape sphere filtering out rotation is the well known Hopf fibration mapping to a complex projective space. This is a non-Euclidean positive curvature manifold.

One of the major problems of shape analyses that utilize Kendall's method involve the use of linear Euclidean approximation methods such as standard principal components

(or PCA) and principle coordinates analysis to compare the shapes of objects, represented by landmark point data that has been mapped into the non-Euclidean and positively curved geometry of a Kendall shape space. Huckemann et al. (2009, 2010b) develop a new approach building on the work of Bhattacharya and Patrangenaru (2003), which they call “Geodesic Principal Components Analysis for Riemannian Manifolds Modulo Isometric Lie Group Actions”. The Huckemann et al. method is far more suitable for use on Kendall shape spaces than any pre-existing PCA based method. They apply their method to the well-studied Münsingen swiss brooch data set (Doran and Hodson 1975:218-236), which reveals that the major source of shape variation in the brooches is increasing diversity of shape over time, which is not detected by standard linear Euclidean approximation methods, such as standard principle components analysis. Standard PCA and other similar methods are not able to detect this because they are based on the assumption that the data is flat (has zero curvature, see Figure 5.9), and as Huckemann et al. (2010b: 17) show, using a curvature measure they develop, that data sets often used for shape analysis are not flat. See also Huckemann and Ziezold 2006 who show that the brooch data set has considerable curvature. For these reasons I use the Huckemann et al. method for the shell artifact shape analyses. See Appendix E for a detailed description of the implementation of the method in R for my analysis.

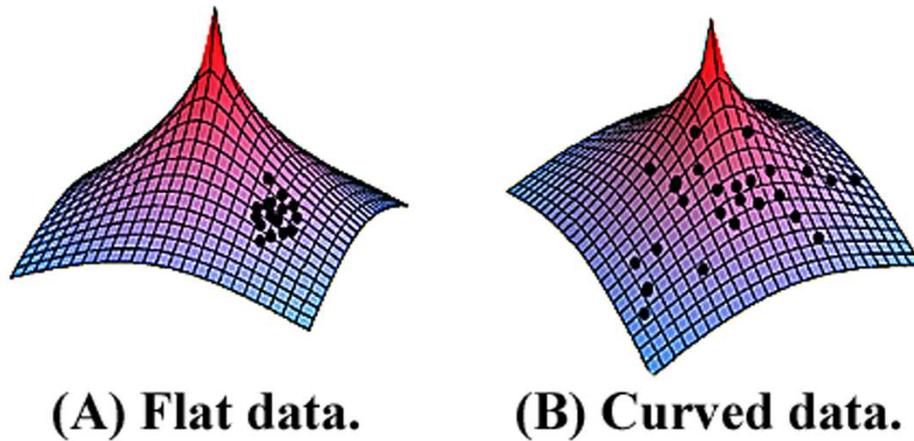


Figure 5.9. Graphical example of flat data compared to curved data (from Huckemann et al. 2010).

Due to the nonlinearity of the underlying manifold of Kendall's shape space of planar objects, a decomposition of effects acting separately can neither be modeled nor expected. This is expected for the archaeological samples in this study, and will be evaluated with the curvature estimate ( $CX$ ), discussed earlier in this section. If  $CX > 0$ , this supports using the GPCA method (Huckemann et al. 2010b).

### *Results*

Figure 5.10 provides a visual summary of the geodesic principal components (GPC) analysis for the first three GPC scores (see Appendix F for the GPC scores and Appendix G for the Matlab code used to produce Figure 5.10). A cursory inspection of Figure 5.10 reveals that the Las Colinas, Tanque Verde Wash Site, and Snaketown barrel beads are interspersed with the Malibu beads, which suggests the Arizona and Malibu beads have similar shape patterning. To formally evaluate the statistical significance of this qualitative result, robust one-way MANOVA tests, and pivotal bootstrap tests are used in the next two sections.

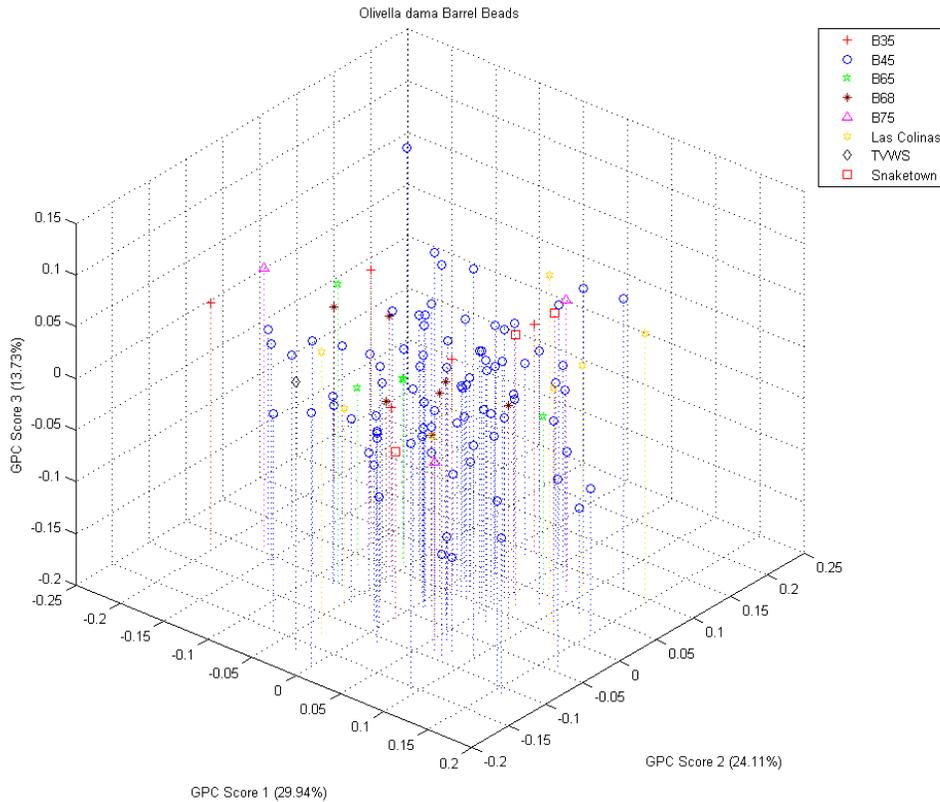


Figure 5.10. Plot of the first three geodesic principal component scores for the 2D shape analysis of *Olivella dama* barrel beads from Malibu (Burials 35, 45, 65, 68, and 75), Las Colinas, the Tanque Verde Wash site (TVWS), and Snaketown. Note that the estimated curvature for these data (estimated CX) is  $0.009710198 > 0$ , which supports using the GPCA method.

### *Robust One-way MANOVA (Bartlett Chi2)*

A robust one-way MANOVA method (Todorov and Filzmoser 2010) implemented in the Wilks.test function in the R rrcov package (see Appendix H) is used for the pairwise comparison of GPC Score 1, 2, and 3 centroids. The one-way MANOVA is used to test the null hypothesis that a pair of *Olivella dama* barrel bead samples is from the same population as measured by the mean shape of each bead sample. If the null

hypothesis is not rejected, I suggest that the beads were manufactured in the same region (in this case the Hohokam system). The null hypothesis is not rejected ( $\alpha=0.05$ ) for the shape comparison of the sample of Las Colinas *O. dama* barrels with each of the four Malibu burial samples (see Tables 5.4 to 5.7). However, the p-value of 0.064 for Malibu Burial 45 (Table 5.6) is close to the 0.05 cut-off for rejecting the null hypothesis. I will consider this further in my interpretation of the shape analysis in the next section.

Table 5.4. Results of robust one-way MANOVA for the mean shape comparison of the *Olivella dama* barrel bead samples from Las Colinas and LAn-264, Burial 35.

Data: x		
Wilks' Lambda	0.2389	
Chi2-Value	2.639	
DF	1.156	
p-value	0.1267	
Sample estimates:		
	GPC1	GPC2
LAn-264, B35	-0.07112507	0.01485968
Las Colinas	0.06596907	-0.01528582

Table 5.5. Results of robust one-way MANOVA for the mean shape comparison of the *Olivella dama* barrel bead samples from Las Colinas and LAn-264, Burial 68.

Wilks' Lambda	0.6772	
Chi2-Value	0.934	
DF	1.118	
p-value	0.3728	
Sample estimates:		
	GPC1	GPC2
LAn-264, B68	-0.03326896	0.007239924
Las Colinas	0.06596907	-0.015285821

Table 5.6. Results of robust one-way MANOVA for the mean shape comparison of the *Olivella dama* barrel bead samples from Las Colinas and LAn-264, Burial 45.

Data: x		
Wilks' Lambda	0.9187	
Chi2-Value	5.271	
DF	1.876	
p-value	0.0638	
Sample estimates:		
	GPC1	GPC2
LAn-264, B45	0.003916868	0.001733406
Las Colinas	0.06596907	-0.015285821

Table 5.7. Results of robust one-way MANOVA for the mean shape comparison of the *Olivella dama* barrel bead samples from Las Colinas and LAn-264, Burial 65.

Data: x		
Wilks' Lambda	0.292	
Chi2-Value	2.424	
DF	1.200	
p-value	0.1519	
Sample estimates:		
	GPC1	GPC2
LAn-264, B65	-0.04345417	0.005264723
Las Colinas	0.06596907	-0.015285821

Since Las Colinas is located in Phoenix, Arizona, and since the null hypothesis is not rejected in any of the pairwise comparisons I suggest that the Malibu *O. dama* barrel beads from Burials 35, 68, 65 may have been manufactured in the Phoenix area.

Considering the low, but not statistically significant p-value for Burial 45, I tentatively suggest that at least some of the beads from the much larger Burial 45 sample may have been produced in the Phoenix area as well.

#### *Pivotal Bootstrap Test*

I use a pivotal bootstrap test (Amaral et al. 2007) to examine differences in two-dimensional mean shape between two separate populations. This test uses complex arithmetic, has the inherent advantage of using the geometry of the shape space, and is appropriate for small samples, since it uses resampling with replacement to estimate the

p-value of the test statistic (see Amaral et al. 2007). As with the one-way MANOVA test, this test is used to evaluate the similarity of the common mean shape of the *O. dama* barrel bead sample from Las Colinas with the samples from four LAn-264 burials. This test is operationalized as the function `resampletest` in the R `shapes` package (see Appendix H). Since this test uses a different mathematical approach than the one-way MANOVA test, the agreement of both methods results in a stronger inference.

The results of this (see Table 5.8) and the preceding analysis, suggest that a good proportion of the Malibu barrels from Burials 35, 68, and 65 may have originated in the Phoenix area of the Hohokam system, due to their shape similarity with the *O. dama* barrels from Las Colinas. In contrast to the MANOVA result, in this analysis the null hypothesis is rejected for the very large Burial 45 sample (see Tables 5.6 and 5.8), which suggests my previous interpretation needs to be re-evaluated. I now suggest that the *O. dama* barrel beads from the Burial 45 sample were probably not made in the Phoenix area.

Table 5.8. Results of pivotal bootstrap test, number of resamples = 1000.

Las Colinas (n=7) verses	lambda (asymptotically pivotal test statistic)	lamda bootstrap p-value
B35 (n=5)	89.32224	0.2827173
B68 (n=8)	25.30161	0.4325674
B45 (n=85)	127.4633	0.03596404
B65 (n=4)	51.36648	0.5844156

## Summary

The morphometric analyses of this chapter suggest that the Malibu *Olivella* sp. small barrel beads are made from an endemic Gulf of California species (*dama*). The geometric morphometric study of this chapter suggests that the Malibu *Olivella* small barrel beads are stylistically very similar to contemporary samples of *O. dama* small barrel beads from sites in the Hohokam system. This suggests that the Hohokam system may have been the source of many of the Malibu *O. dama* barrels and supports the existence of a Hohokam/California transregional system that extended to the Pacific Coast of southern California. Interestingly, the analyses in this chapter also provide evidence that there may have been significant (though somewhat subtle, and previously undetected) stylistic and size variation in *O. dama* barrel beads manufactured in the Pre-Classic Hohokam system. A goal for future work should be to increase the total sample size, the number of samples from Snaketown (in both mortuary and non-mortuary contexts), and include *O. dama* barrel bead samples from additional Pre-Classic sites in the Hohokam system for size and shape comparison with the Malibu *O. dama* barrel beads. Beads from additional Malibu M5a-b burials (e.g., Burial 66A) should also be added.

## CHAPTER 6: ARCHAEOLOGICAL EVIDENCE USED TO RE-CONSTRUCT INTERREGIONAL INTERACTION IN THE HOHOKAM/CALIFORNIA TRANSREGION

In this chapter I use archaeological evidence (specifically shell) from several residential sites in the Hohokam/California transregion to map interaction between regions and to evaluate changes in the production intensity of one type of shell artifact (*Olivella dama* barrel beads) in the Hohokam system that may have been an important exchange item for Lake Cahuilla fish. I also order some of the data by time as a necessary step for my study of temporal patterning in the production of *O. dama* barrel beads and temporal change in the interregional exchange of other shell artifact types. Shell is an excellent proxy for studying the organization and structure of exchange systems. Previous research (Kenoyer 1983, 1984; Genscheimer 1984) has demonstrated the utility of shell in elucidating organization and structure in ancient exchange systems (at both the regional and transregional level). To this end, Genscheimer (1984:64) states.

Tracing the movements of shell species from their source areas to their occurrence at sites can help to reconstruct intercultural connections and clarify the mechanisms by which exchange functioned and changed over time.

Shell artifacts have been well studied in California and Arizona, and have proven very useful for re-constructing exchange patterns at local and larger scales (Bennyhoff and Hughes 1987; Bradley 1996, 2000; Farmer et al. 2009; King 1990; McGuire and Howard 1987; Nelson 1991; Ruby 1970; Vokes and Gregory 2009).

My goals in this chapter are: (1) use shell to map out exchange relations between regions in the Hohokam/California transregion to compare with the model developed in Chapter 3, (2) to provide a deeper understanding of the movement of Hohokam shell

artifacts in southern California (circa A.D. 700-1100), and (3) to evaluate my hypothesis that there was an increase in specialization and the intensity of production of at least one type of shell artifact in the Hohokam system for export into southern California during this time. Each section of this chapter focuses on a residential site from one of the regions in the Hohokam/California transregion that produced both Pacific Coast and Gulf of California shell artifacts from the time period of my study. The shell samples are either from burials or residential areas, which I identify for each sample. I use a variety of statistical tests that vary between samples. Details on the data, where and why I used a particular test, and additional supporting comments are provided in Table 6.1.

Table 6.1. Types of analyses used by section.

Section	Region	Data	Analyses	Why used	Comment(s)
The Chronology of the Malibu Site M5a-b Burials	Santa Monica Mountains Chumash	Counts of typed shell artifacts from ten burials.	Porčić Method	To determine if data is mostly chronological.	Very recently published (2013).
			Detrended Correspondence Analysis	Approximate microseriation of burials. For comparison with TSP seriation.	Very limited previous use in archaeology.
			TSP Seriation	Microseriation of burials	New method to archaeology. Very robust.
The Intensity of Production Measured by the Coefficient of Variation Statistic	Santa Monica Mountains Chumash		Spectral Decomposition	Subdivide burials into temporal groups.	New method to archaeology
			Baxter and Cool method for detecting modes in low dimensional data.	Used to evaluate if O. dama barrel beads from burials used in coefficient of variance analysis need to be subdivided into additional types based on size.	Modes in this case are expected to correspond to emic types (see Read 2007)
The Intensity of Production Measured by the Coefficient of Variation Statistic	Santa Monica Mountains Chumash		Bootstrapped and Jackknifed Coefficient of Variation (CV). This analysis requires the chronological seriation of the burials.	Evaluate intensity of production of O. dama barrel beads in Hohokam system and relate to fluctuations in Lake Cahuilla	Some samples are small, which justifies using re-sampling. Previous use of CV for studying intensity of production in archaeology.
The Intensity of Production Measured by the Coefficient of Variation Statistic	Santa Monica Mountains Chumash		Boschloo's Exact Test	More powerful for analyzing 2-by-2 contingency tables than Fisher's exact or Chi-Square test.	Some samples too small for Chi-Square test. Some too large for practical computation of Barnard's exact test, which is equally preferable.

Table 6.1. Types of analyses used by section (continued).

Section	Region	Data	Analyses	Why used	Comment(s)
2: Oro Grande Site	Serrano	Counts of shell from residential areas of the site, transformed to presence/absence data.	Kendall's presence/absence seriation method	Chronologically seriate house areas in order to permit evaluation of changes in proportions of Pacific Coast and Gulf of California shell artifacts with time (next analysis)	Low sample size of most of the shell types precludes using a seriation method based on abundance (Kendall 1971).
2: Oro Grande Site	Serrano	Proportions of Gulf of California and Pacific Coast shell artifacts from house areas.	Barnard's exact test. More powerful for analyzing 2-by-2 contingency tables than Fisher's exact or Chi-Square test.	Evaluate changes in interaction between the Chumash region and with the Hohokam system over time.	Some samples too small for Chi-Square test.
3: Afton Canyon Site	Hopic		Baxter and Cool method for detecting modes in low dimensional data		Modes in this case are expected to correspond to emic types (see Read 2007)
3: Afton Canyon Site	Hopic	Diameter of <i>Olivella biplicata</i> disc beads from Afton Canyon and Locus 5 of the Oro Grande site.	Analysis of means (ANOM) test.	Compare average bead diameter between the two samples with chronological patterns from the Chumash area (the most likely source) to evaluate the chronological placement of the Afton Canyon sample.	Used SAS PROC ANOM. ANOM is a graphical and statistical method for simultaneously comparing the means of $k$ samples with their overall mean at a specified significance level $\alpha$ .

Table 6.1. Types of analyses used by section (continued).

Section	Region	Data	Analyses	Why used	Comment(s)
5: FW-9 Site	Cahuilla	Diameter of <i>Glycymeris</i> sp. bilobed beads from FW-9, Locus 5 of the Oro Grande site, and several sites in the Hohokam system.	Cleveland dot plot	To refine the age estimate of the FW-9 sample.	See R statistical lattice package.  A good method for visually comparing multiple data samples to discover patterns.
6: Escuela Site	Lowland Patayan/Hohokam	Total and hole diameters of <i>Olivella biplicata</i> disc beads from the Escuela site and several chronologically ordered burials from the Malibu site.	Simulation based 2-Sample Smirnov test	To refine the age estimate of the Escuela sample.  Small sample size.	Total and hole diameters of this shell artifact type from the Chumash area are very good chronological indicators (King 1990).  This test uses a randomization approach to estimate the p-values, which is more robust for small samples.

### 1: The Malibu Site [Humaliwo (LAn-264)]

Humaliwo or the village of Malibu (CA-LAn-264) was a major Chumash political center and coastal village near the southernmost end of the Chumash region in southern California. Ethnographic and ethnohistoric data suggest that the native inhabitants of the Santa Monica Mountains and the Tongva people immediately to the south considered Humaliwo an important political center (Gamble et al. 2001:188; King 1982:12; King 1994:65). The chief of Humaliwo was described as a “god” and “king” to all the inhabitants of the region by Juan Esteban Pico, a Chumash consultant of Stephen Bowers (late 1800’s) [Gamble et al. 2001:188; King 1994:65]. Other Chumash consultants referred to *Humaliwo* as “centro” or capital (Gamble et al. 2001; King 1994:77). Previous studies (e.g., King 1995) of shell from this site suggest that a small proportion of high-ranking people in Humaliwo (ca. A.D. 900-1050) obtained large numbers of a

single type of shell artifact (small *Olivella dama* barrel beads). These beads were recovered from burials in Area 5 of the Middle period LAn-264 (Humaliwo) cemetery (Figure 6.1). Haury (1976) observed that small *Olivella dama* barrel beads were only used during the Santa Cruz and Sacaton Phases of the Hohokam (Haury 1976: 309), which corresponds with the age of the LAn-264 sample. In addition, Haury notes that the use of *Olivella dama* barrel beads increased significantly during the Sedentary Period after A.D. 950 in the Gila River area. In the previous chapter I provided morphometric evidence that suggests that at least some of the Malibu *O. dama* barrels may have originated in the Gila River area and possibly more originated in the Phoenix area.

Interestingly, although *O. dama* barrel beads in the late Middle period Humaliwo cemetery occur in large numbers in elite ascribed burials, they are very rare everywhere else in the Chumash region during this time (King 1996). The *Olivella dama* barrel beads in this sample were quite likely obtained by elite inhabitants of Humaliwo through exchange with the Tongva, who, in turn, acquired them through trade with Cahuilla people. The Cahuilla probably acquired many of these beads from Patayans, some of who lived in settlements in the Hohokam system (see Chapter 3) during this time.

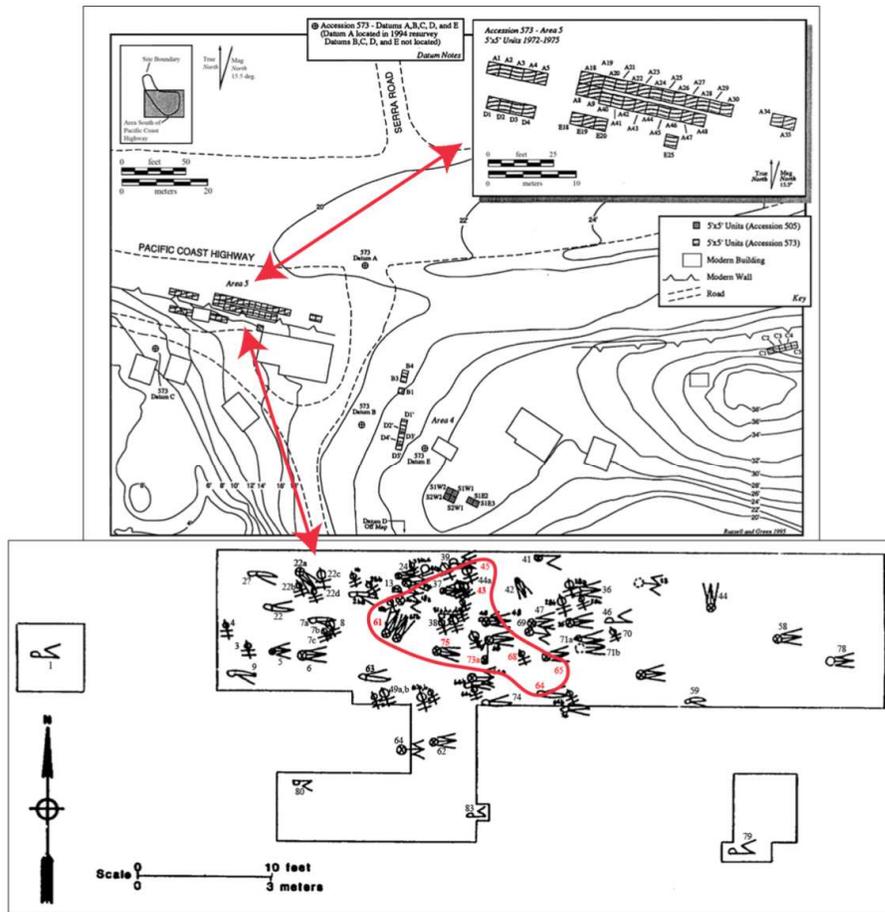


Figure 6.1. Map of M5a-b (A.D. 900-1050) Humaliwo cemetery (Area 5) and burials (Gamble et al. 1995; Martz 1984). The middle region of the cemetery where burials with *O. dama* barrels concentrate is outlined in the lower part of the figure.

### The Chronology of the Malibu Site M5a-b Burials

The purpose of the seriation analyses that follow this subsection is to answer the following questions: (1) Do frequencies of typed shell artifacts from burials in the M5a-b (ca. A.D. 900-1050) Malibu Chumash cemetery have a strong chronological signal, and if so (2) what is the chronological order of the burials, and (3) are there temporal burial groups in the Malibu burial sample and (if so) what calendar dates do these correspond

to? Answering these questions is sufficient to evaluate how the relative frequencies of the *Olivella dama* small barrel beads (which the results of Chapter 5 suggest probably originate in the Hohokam system) in this sample change over time and how such changes may relate to: (1) internal changes in the economy and organization of the Pre-Classic Hohokam system and (2) to the level of participation of the Pre-Classic Hohokam system in exchange with Lake Cahuilla residents through which the *O. dama* barrels were likely traded to people in other southern California areas.

### *Chronology in Archaeology*

Chronology in archaeology is often examined with a frequency or type seriation. The goal of an archaeological frequency or type seriation (see, for example, Smith and Neiman 2007 and Gifi 1990) for type frequency using correspondence analysis (which I discuss in the next subsection) and LeBlanc (1975) for type frequency seriation using multi-Dimensional scaling (or MDS) is to order a set of objects (e.g., burials) such that the distribution of relative frequencies of each type of artifact, in a corresponding set of artifact types associated with one or more of the objects (e.g., a set of shell artifact types recovered from a group of burials) is unimodal (Dunnell 1970). In the archaeological context, the ideal chronological pattern for each artifact type is a monotonic increase to a maximum relative frequency (proportion), followed by a monotonic decrease of that type, over time. When displayed graphically, this pattern results in what is often called a “battleship plot” or Ford diagram (after Ford 1952).

In a later subsection I introduce a new seriation method to archaeology that optimally permutes a standardized data matrix, and which is more likely to identify the correct ordering of objects than CA or MDS. But even if a seriation method identifies the correct ordering of objects, additional evidence (e.g., radiocarbon dates) is needed to determine the direction of the seriation sequence since the seriation alone does not identify which end point of the sequence is the oldest or youngest. In my analysis of the Malibu burials I use radiocarbon dates and information from Chester King's archaeological studies to identify the oldest burial and, in turn, establish the temporal direction of the seriation.

#### *Raw Data*

Table 6.2 provides the counts of ten shell artifact types from ten M5 a-b (A.D. 900-1050) burials in the LAn-264 prehistoric cemetery. The shell artifact typology used in Table 6.2 has been shown by King (1990) to correlate with time. However, the strength of the chronological signal in these data requires formal evaluation, which I do in the next subsection. Specifically, these data will be used in the following series of analyses to first formally demonstrate that changes in relative frequencies of the shell artifact types between burials is strongly time related, second to order the burials in Table 6.2 by time, and finally to divide these burials into coherent time based groups in order to better understand precisely when the residents of LAn-264 may have been participating in the Hohokam/California transregional system. Later I will use the chronologically sequenced burial data to study change over time in the production intensity of the only Gulf of California shell artifact type (*Olivella dama* barrel beads) in this data set, which as I showed in Chapter 5, probably were made in the Hohokam system.

Table 6.2. LAn-264 M5a-b burial verses shell artifact type abundance matrix.

Burial/Shell	<i>Olivella biplicata</i>	<i>Olivella biplicata</i>	<i>Olivella biplicata</i>	<i>Olivella biplicata</i>	<i>Mytilus californianus</i>	<i>Mytilus californianus</i>	<i>Mytilus californianus</i>	<i>Mytilus californianus</i>	<i>Olivella dama</i>	<i>Olivella biplicata</i>
Artifact Type	disc bead (2.3-3.3 mm)	disc bead (3.4-4.9 mm)	disc bead (5.0-7.1 mm)	disc bead (7.2-12.4 mm)	disc bead (2.4-3.4 mm)	disc bead (3.5-4.9 mm)	disc bead (5.0-7.1 mm)	disc bead (7.2-8.9 mm)	barrel bead	barrel bead
35	15	727	0	0	0	198	1	1	7	0
48	0	94	8	5	0	33	1	1	0	0
51	3	24	5	2	0	1	2	0	240	0
68	1	31	2	0	0	5		0	14	0
73a	1	3	8	2	0	0	2	1	200	0
10	0	0	234	4	0	0	1	40	0	0
64	0	28	119	112	0	3	7	9	1	0
61	0	0	36	130	0	0	0	0	2	0
45	2	12	4	355	2	15	0	120	301	3
43	7	69	294	1994	1	0	12	20	3	0

*Overview of Correspondence Analysis Seriation*

Correspondence analysis (CA) is a multivariate statistical technique that reduces the dimensionality of contingency tables. It is analogous to principal component analysis for data in the form of counts. CA has a long history of use among European archaeologists and has recently become more popular with American archaeologists (de Leeuw 2011; Smith and Neiman 2007:55) for seriation. Usually the results of CA are presented graphically as a scatter-plot with x and y-axes being the first two CA dimensions, since these dimensions often summarize much of the variability in the data. An additional criterion for a chronological interpretation of CA results is the presence of a “horseshoe”, which is an arch of points on a two-dimensional CA plot. If the points of the CA plot form this shape (usually on the first two CA dimensions) then the order of assemblages in the CA plot is interpreted as a relative chronological sequence, because

the arch effect appears to result from unimodality in type frequencies (Baxter 1994, 2003; Baxter and Cool 2010).

A horseshoe pattern in a two-dimensional CA display is a necessary but not a sufficient condition for a strong chronological signal. Evidence is also needed to relate the gradient in the data to chronological change (Baxter 1994, 2003; Baxter and Cool 2010; Porčić 2013), such as Porčić's method (next subsection) and absolute dates (e.g., radiocarbon).

#### *Evaluation of the Significance of the Chronological Signal in the Malibu Burials*

Porčić 2013 introduces a permutation-based statistical method for evaluating the significance of the chronological signal in a seriation of archaeological units (e.g., burials). The method is based on the idea that statistically robust unimodal patterns are consonant with a relative chronology (Dunnell, 1970). Unimodality in the most general sense correlates with a gradient in data, and may not result from temporal changes in archaeological materials. Additional evidence is also needed to relate unimodality in data to temporal change. For the Malibu burials, I use a well-established chronologically based typology of Chumash shell artifacts (King 1990) to support the chronological significance of my seriation of these burials.

#### Steps of the Analysis.

Step 1. Do a correspondence analysis (CA) on the raw Malibu data set (Table 6.2).

Step 2. Re-order the burials according to their order on the first CA axis.

Step 3. Transform the counts in the reordered table into relative frequencies of artifact types for each of the burials. This is because the seriation depends on gradation in the

relative proportions of each shell artifact type between the burials.

Step 4. Count the number of local maxima within each shell artifact type (column). A local maximum for a given type is a relative frequency value that is greater than both the preceding and the following relative frequency. The total number of modes in the ordered data is the sum of the number of modes for each shell artifact type, which is the test statistic.

Step 5. The test statistic is compared to a distribution of the total number of modes from randomized burials to evaluate its statistical significance. Randomization of assemblages is performed by interchanging (permuting) the observed frequencies of individual types (within columns) between different burials (rows) in the original data table. In this analysis 100,000 randomized data sets are used.

Step 6. A correspondence analysis is done for each randomized data table, followed by Step 4. In this analysis, Step 6 is repeated 100,000 times, which results in an empirical sampling distribution of the total number of modes of 100,000 (see Figure 6.3). This distribution provides the means to compute an estimate of the probability that the observed total number of modes of shell artifact types in the Malibu burials occurred by chance.

Step 7. The final step is to compare the test statistic (observed total number of modes) to the empirical sampling distribution.

Also see Figure 6.2, and Appendix I for the R code used in the analysis.

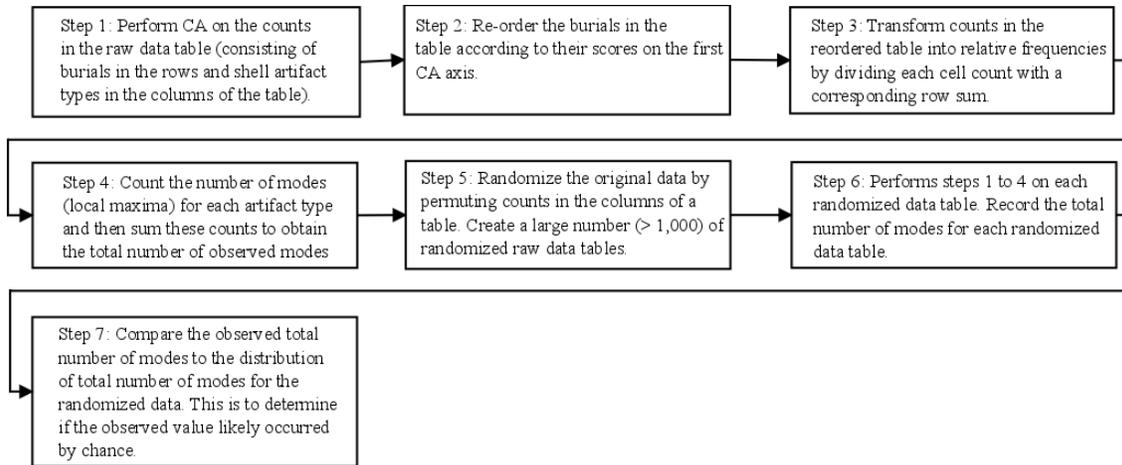


Figure 6.2. Steps of the significance testing procedure.

Applying Steps 1 to 4 to the Malibu raw data (see Appendix I) reveals there are 26 total modes in these data. Then, implementing Steps 5 to 6 (see Appendix I) results in the histogram in Figure 6.3. Finally, implementing Step 7 (see Appendix I) shows that observed result (26 modes) is statistically significant at  $\alpha = 0.05$ , which is depicted in Figure 6.3. This suggests that the Malibu data set has a strong chronological signal. This result is also supported by the Porčić *seriation coefficient*, defined as:

$$S = \frac{(Max - O)}{(Max - E)}$$

where *Max* is the maximum total number of modes (which for an even number of rows in the data matrix, which is the case with Table 6.1) is

$\frac{(Number\ of\ Artifact\ Types\ [columns]) \times (Number\ of\ Data\ Sources\ [rows])}{2}$ . *S* is the observed total

number of modes and *E* is the expected total number of modes, assuming that all of the artifact types in the data set have unimodal distributions (see Porčić 2013, p. 4555 for more information). Based on preliminary empirical and studies with archaeological data,

Porčić 2013 suggests that a value of the seriation coefficient greater than 0.5 indicates a strong chronological signal in the data. For the LAn-264 data, the seriation coefficient

$$S = \frac{\left(\frac{100}{2} - 26\right)}{\left(\frac{100}{2} - 10\right)} = \frac{(50 - 26)}{(50 - 10)} = \frac{24}{40} = 0.6, \text{ which is consonant with the preceding result. In}$$

sum, these results suggest that the Malibu burial data is mostly structured by time.

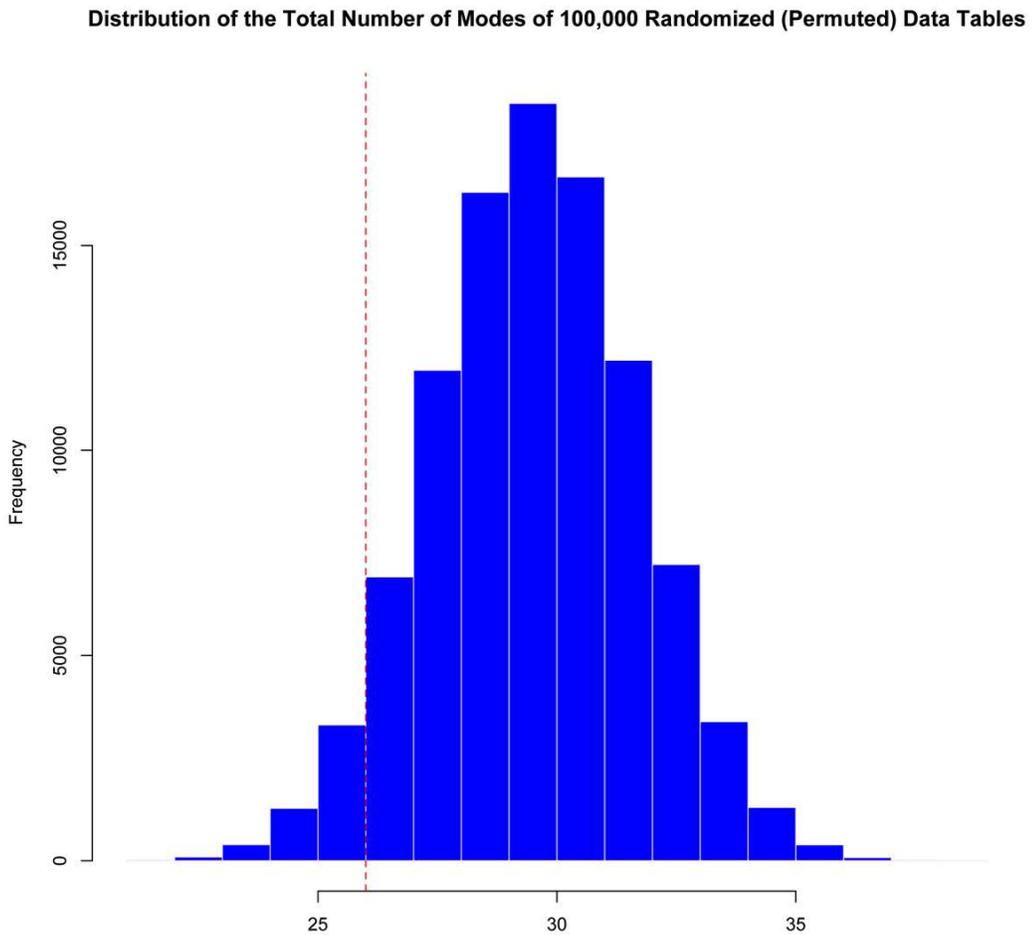


Figure 6.3. Histogram of the distribution of the total number of modes of 100,000 randomized data tables. The analysis shows that observed result (26 modes, dashed vertical red line in figure) is statistically significant at .

### *Simple and Detrended Correspondence Analysis*

A “horseshoe” in an ordinary CA plot and the bunching of points at the endpoints of this curve can obscure temporal patterning. The removal of the arch effect is called detrending (for applications of detrended CA in archaeology see Baxter and Cool, 2010; Lockyear, 2000). An experimental study of the application of detrended CA to archaeological data by Lockyear (1996) showed that this method sometimes reveals patterning in archaeological data that are not visible on ordinary CA plots. Surprisingly, archaeologists have rarely used detrended CA (Hill and Gauch 1980), although it is commonly used in other disciplines (e.g., ecology). One such example is from Beck and Sheenan (1991) who used detrended CA to analyze associational patterning of amber artifacts in sixty-four Bell Beaker/Early Bronze Age burials in England.

The Malibu raw data (Table 6.1) was analyzed using detrended CA (see Appendix J for details), which produced a seriation plot shown in Figure 6.4 (which is the plot of the first two detrended CA coordinates of the ten Malibu burials). A good seriation result for DCA is when objects are linearly ordered along the first DCA axis (DCA1). This is the case for six of the ten burials. If we assume that Burial 35 is the oldest (which is supported by evidence discussed later), then the DCA provides a partial seriation result of: 35->48->68->51->73a->45. The ordering of the remaining four burials is not clear, because of the significant displacement of burials 64 and 10 from DCA1. This validates the use of another seriation method that provides more robust and interpretable results. I apply such a method in the next section, and compare the results with this analysis.

## Steps of the Analysis

Step 1. Compute the detrended correspondence analysis coordinates for the first two dimensions (DCA1 and 2) using the *decorana* function in the R *vegan* package (see Appendix J).

Step 2. Plot DCA1 and 2 (Figure 6.4, see Appendix J for more details).

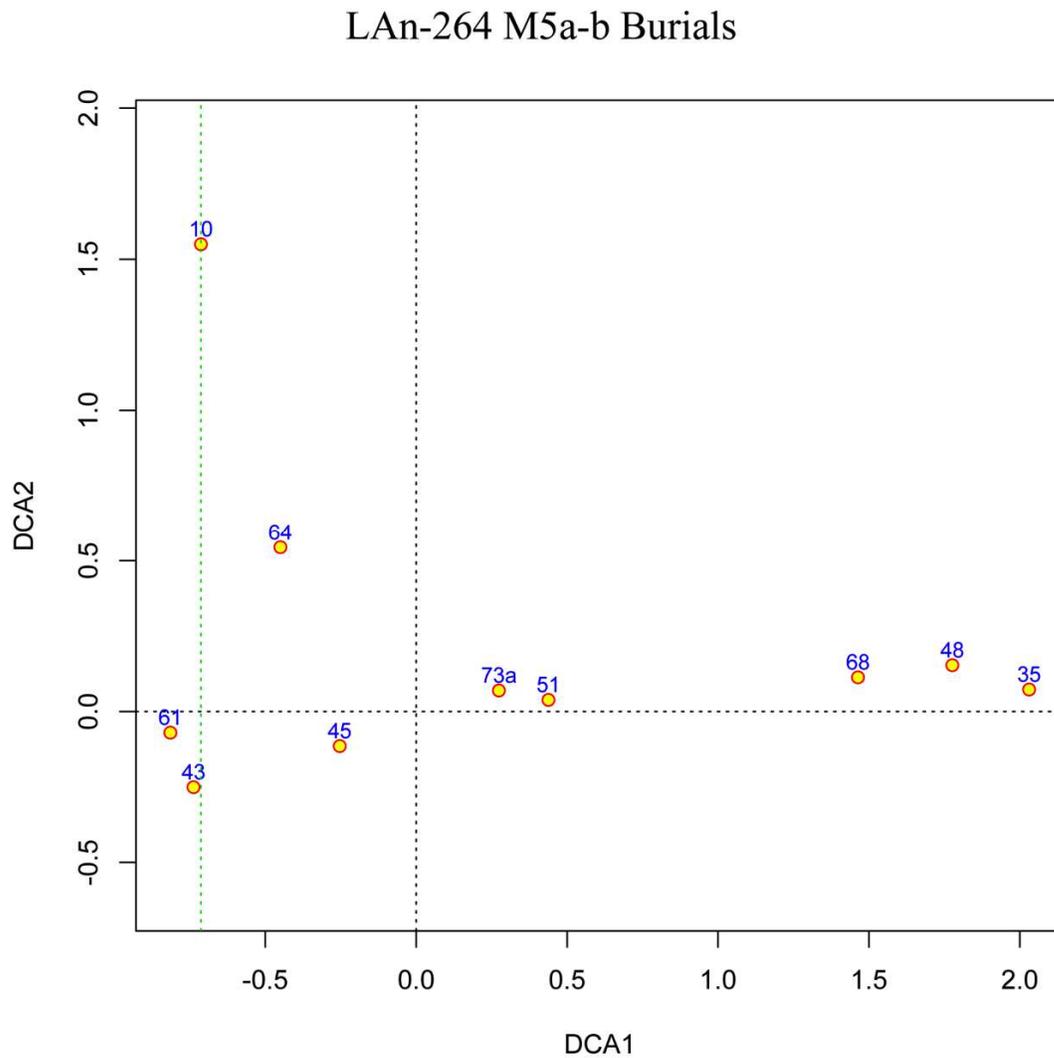


Figure 6.4. Plot of DCA 1 versus DCA 2.

### *TSP Seriation of the M5 a-b Malibu Burials*

The method I use in this analysis treats seriation as a combinatorial optimization problem (see Buchta et al. 2008) in which the goal is to place a finite set of  $n$  objects in a linear order that minimizes the sum of the pairwise dissimilarity measure values (e.g. Euclidean distance) for all of the objects which belong to the set. To search for an optimal solution in the multidimensional and potentially vast space (the number of possible paths for  $n$  objects is  $n!$ ) in which a dissimilarity matrix  $D$  (the  $n \times n$  symmetric matrix consisting of the pairwise dissimilarity measures for all objects in a set of objects) is embedded usually requires the implementation of a partial and computationally efficient enumeration method or heuristic, such as *dynamic programming* (Hubert et al. 1987) in a relatively small search space and a *branch-and-bound* algorithm (Brusco and Stahl 2008) or the like when the search space is large.

A symmetrical distance matrix  $D$  can be visually depicted as a weighted graph  $G$  where the set of objects are represented by the vertices of the graph and each edge  $E$  between a pair of objects  $i$  and  $j$  is given a weight  $w_{ij}$  equal to the corresponding dissimilarity measure  $d_{ij}$  in the dissimilarity matrix  $D$ . To search the graph for an optimal seriation of all of the objects a computer algorithm (often called a TSP solver) is used to search for the path (often called a Hamiltonian path) through the graph that visits each of the objects only once and at the same time minimizes the sum of dissimilarity measures  $d_{ij}$ . This process is equivalent to solving the familiar and well-studied combinatorial optimization problem often called the Traveling Salesperson problem or TSP (see Applegate et al. 2006). TSP applied to archaeological seriation has received some

discussion in the literature (see, for example, Wilkinson 1971; Laporte 1976; Laporte and Taillefer 1987; Schuchat 1984), but has not been used in recent archaeological studies.

In graph theory a TSP tour is called a *Hamiltonian Cycle*. Since a tour returned by a TSP solver is a closed path or cycle and a seriation is an acyclic path representing a linear order, we need to find the best cutting point. Garfinkle (1985) provides a clever way to "trick" a TSP tour algorithm into producing a Hamiltonian path, by adding a "dummy" row and column of 00s to the original  $n \times n$  dissimilarity matrix  $D$ . More recently, Climer and Zhang (2006) suggest adding a dummy city with equal distance to each other city before generating the tour. The placement of this dummy city results in an optimal tour with minimal length and is an unbiased cutting point (because it is equidistant to the other cities). In my analysis the Climer and Zhang strategy is used.

To perform a TSP seriation on the Malibu data I use the `seriate` function in the R *seriation* package, which in my application, "tries to find an linear order for objects using two-way one mode data in the form of a dissimilarity (or distance) matrix (see <http://cran.r-project.org/web/packages/seriation/seriation.pdf>, p. 21). I also use a traveling salesperson (or TSP) solver (specifically the `concorde exact` and the `Chained Lin-Kernighan` [Applegate et al. 2003] TSP solvers) to find the seriation solution. `Concorde` is an advanced TSP solver for only symmetric TSPs, and is based on the branch-and-cut algorithm (see Applegate et al. 2001). In the R *seriation* package the `concorde` TSP solver is passed to the `seriate` function by the control argument: `control = list (method = "concorde")`. `Linkern` is the `Chained Lin-Kernighan` TSP solver, which is included in the `Concorde` TSP solver (available at: <http://www.math.uwaterloo.ca/tsp/concorde.html>). The `linkern` TSP solver is passed to the `seriate` function in equivalent fashion to the

concorde solver, as `control = list (method = "linkern")`. The `seriate` function finds the Hamiltonian path (or a very close approximation to this path) for the objects in a symmetrical distance matrix, when a TSP solver is passed to this function. The order of objects in the Hamiltonian path is the seriation result.

Steps of the Analysis.

Step 1. *Compute* a proximity matrix from the raw data (Table 6.1). In the proximity matrix each entry is a distance (or dissimilarity measure) between a pair of objects (which in this analysis are burials—see Table 6.4). For my study I use Euclidean distance (see Appendix J) for the proximity measure pairs of burials. In this case distance relates to similarities in the proportions of the ten shell artifact types in Table 6.3

Step 2. Compute a seriation solution using the `seriate` function from the R seriation package. This function uses the proximity measure from Step 1 as the raw data. For my analysis I use a traveling salesperson solver (TSP) method [R `seriation` package, p. 22 and the `solve_TSP` function in the R `TSP` package, p. 8] and the `concorde` and `linkern` TSP solvers (discussed earlier).

Step 3. Extract the order of the seriation, using the `get_order` function in the R `seriation` package. The order conforms to (or very closely approximates) a Hamiltonian path (discussed earlier).

Step 4. Visually represent the seriated objects in relation to their proximities using a two-dimensional metric multidimensional scaling (MDS) plot, which uses the distance matrix from Step 1 as raw data. Then draw the Hamiltonian path from Steps 2 and 3 onto the MDS plot. See Figure 6.5 and Appendix J for more details.

Table 6.3. Proportions of ten shell artifact types in ten LAn-264 M5a-b burials.

Artifact Type Burial	O. b. 2.3-3.3	O. b. 3.4-4.9	O. B. 5.0-7.1	O. b. 7.2-12.4	Myt. 2.4-3.4	Myt. 3.5-4.9	Myt. 5.0-7.1	Myt. 7.2-8.9	<i>O. dama</i> Barrel	O. b. Barrel
35	0.0158	0.7661	0	0	0	0.2086	0.0011	0.0011	0.0074	0
48	0	0.662	0.0563	0.0352	0	0.2324	0.007	0.007	0	0
51	0.0108	0.0866	0.0181	0.0072	0	0.0036	0.0072	0	0.8664	0
68	0.0189	0.5849	0.0377	0	0	0.0943	0	0	0.2642	0
73a	0.0046	0.0138	0.0369	0.0092	0	0	0.0092	0.0046	0.9217	0
10	0	0	0.8387	0.0143	0	0	0.0036	0.1434	0	0
64	0	0.1004	0.4265	0.4014	0	0.0108	0.0251	0.0323	0.0036	0
61	0	0	0.2143	0.7738	0	0	0	0	0.0119	0
45	0.0025	0.0147	0.0049	0.4361	0.0025	0.0184	0	0.1474	0.3698	0.0037
43	0.0029	0.0288	0.1225	0.8308	4.00E-04	0	0.005	0.0083	0.0012	0

Table 6.4. Pairwise Euclidean distance matrix for burials based on shell artifact type proportions.

Burial	35	48	51	68	73a	10	64	61	45	43
35	0.0000	0.1272	1.1145	0.3365	1.2029	1.1639	0.9095	1.1293	0.9715	1.1370
48	0.1272	0.0000	1.0660	0.3112	1.1509	1.0599	0.7979	1.0310	0.8858	1.0452
51	1.1145	1.0660	0.0000	0.7873	0.0937	1.2052	1.0337	1.1679	0.6768	1.2005
68	0.3365	0.3112	0.7873	0.0000	0.8762	1.0409	0.7899	1.0222	0.7452	1.0417
73a	1.2029	1.1509	0.0937	0.8762	0.0000	1.2296	1.0757	1.2017	0.7132	1.2368
10	1.1639	1.0599	1.2052	1.0409	1.2296	0.0000	0.5854	0.9937	1.0052	1.0948
64	0.9095	0.7979	1.0337	0.7899	1.0757	0.5854	0.0000	0.4423	0.5782	0.5320
61	1.1293	1.0310	1.1679	1.0222	1.2017	0.9937	0.4423	0.0000	0.5552	0.1128
45	0.9715	0.8858	0.6768	0.7452	0.7132	1.0052	0.5782	0.5552	0.0000	0.5704
43	1.1370	1.0452	1.2005	1.0417	1.2368	1.0948	0.5320	0.1128	0.5704	0.0000

Figure 6.5 provides a visual depiction of the TSP seriation result for the Malibu burial sample. The arrows in the Figure 6.5 plot show the direction of time, with Burial 35 as the oldest burial and Burial 10 as the youngest burial in the sequence.

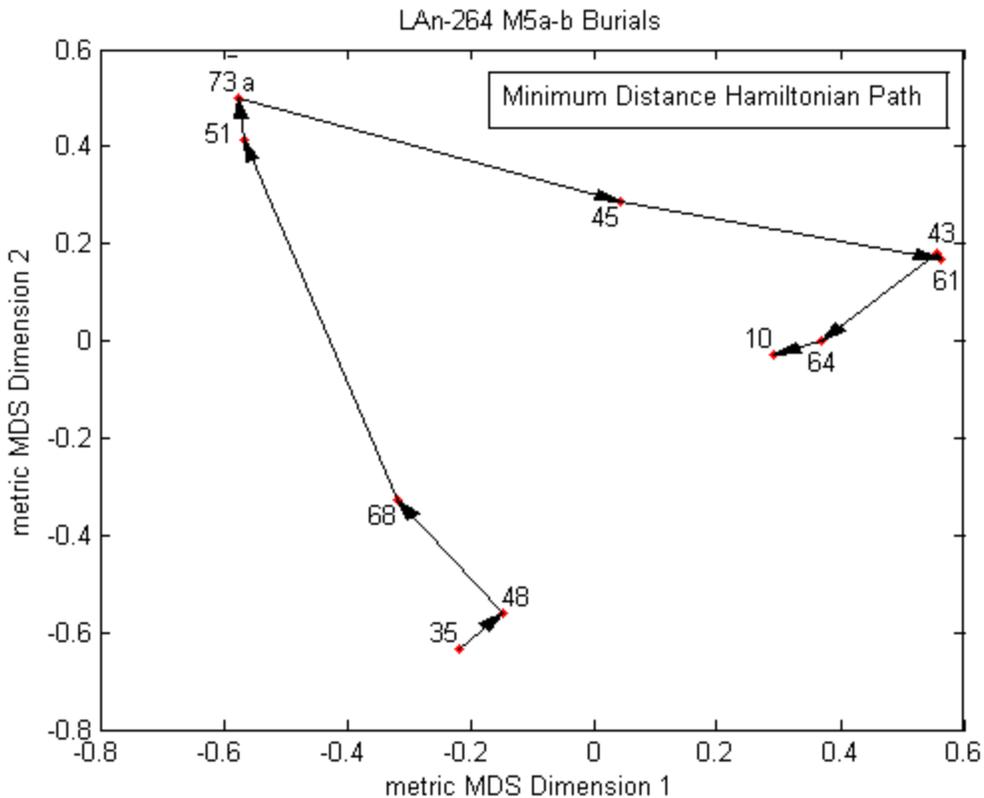


Figure 6.5. Placement of the ten LAn-264 burials in relation to their similarity using metric multi-dimensional scaling. Result of TSP seriation (minimum distance Hamiltonian path) drawn, where arrows show the direction of the sequence.

*Ford Diagram*

Visually, a good seriation solution should result in the “battle- ship” pattern of attribute/type frequencies. The particular sequence of units that produces this kind of result is interpreted as a relative chronological sequence. The underlying logic of the method is the popularity principle where each attribute/artifact type of a certain class of material culture (e.g. bowl shape type) first appears in small quantities, then rises in popularity, reaches a peak, followed by a progressive and monotonic decline. Figure 6.6 is the Ford diagram resulting from the TSP seriation (last section), which clearly has the expected battleship configuration for the five shell artifact types that predominate the

sample. Figure 6.6 will be used to facilitate the interpretation of the results in the remaining sections of this chapter. The main point to take away from the Ford diagram is that *O. dama* barrel beads appear shortly after A.D. 900 in substantial numbers in a few elite burials in the Malibu cemetery when the Pre-Classic Hohokam is quickly expanding and rapidly decline a few decades latter, probably during the period when the Pre-Classic Hohokam system is rapidly collapsing.

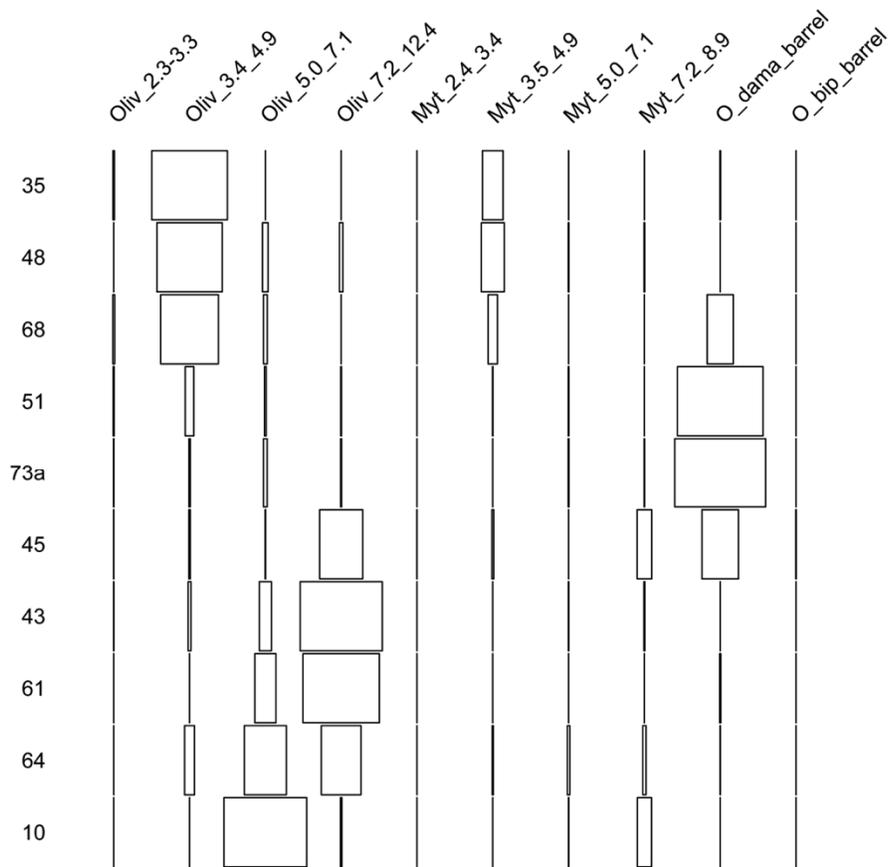


Figure 6.6. Ford diagram of TSP seriation result (see Appendix K for the R code used to make the diagram).

### *Direction of the Seriation*

Berger (1989:59) provides a radiocarbon date of A.D. 730-790 from bone collagen from LAn-364 Burial 35. Based on cross dating with the Southwest, King (1990:38) concludes that the radiocarbon date for Burial 35 is slightly earlier than expected. King (1990:148) states that: "Mussel (*Mytilus californianus*) disc beads were apparently rarely used prior to Phase 5." King (p. 148) also states that: "In Phase M5 contexts, mussel shell disc beads have always been in combination with *Olivella biplicata* wall disc beads." These criteria are fulfilled in Burial 35, which has an abundance of both mussel and *Olivella biplicata* disc beads. This suggests that the age of Burial 35 is not earlier than A.D. 900. Also, King 1990 (p. 38) places LAn-264 Burial 45 in M5a, which (based on the order of burials in the seriation) suggests that the four burials in the sequence between Burial 35 and 45 (see Figure 6.4) are also from M5a (A.D. 900-1000).

Additional evidence is needed to decide if any of the burials are from M5b. Well established temporal patterning in one of the shell artifact types provides the means to do this. Specifically, the increasing trend in the relative frequency of large diameter *Olivella biplicata* disc beads in the Malibu seriation (Figure 6.6) is consistent with King's (n.d.) observation that during M5b the diameters of large *Olivella biplicata* disc beads increase over time (see Figure 6.7, which is a temporal ordering of several M5b *Olivella biplicata* disc beads from LAn-264. Source: Figure 7.22 of King n.d.). This suggests that large diameter *Olivella biplicata* disc beads should concentrate in the M5b segment of the seriation. In Figure 6.6 large *O. biplicata* discs concentrate in the segment of the seriation after Burial 45, which suggests that the burials after 45 (Burials 43, 61, 64, and 10) are from M5b (A.D. 1000-1050), and that Burial 35 must be the oldest in the sample.

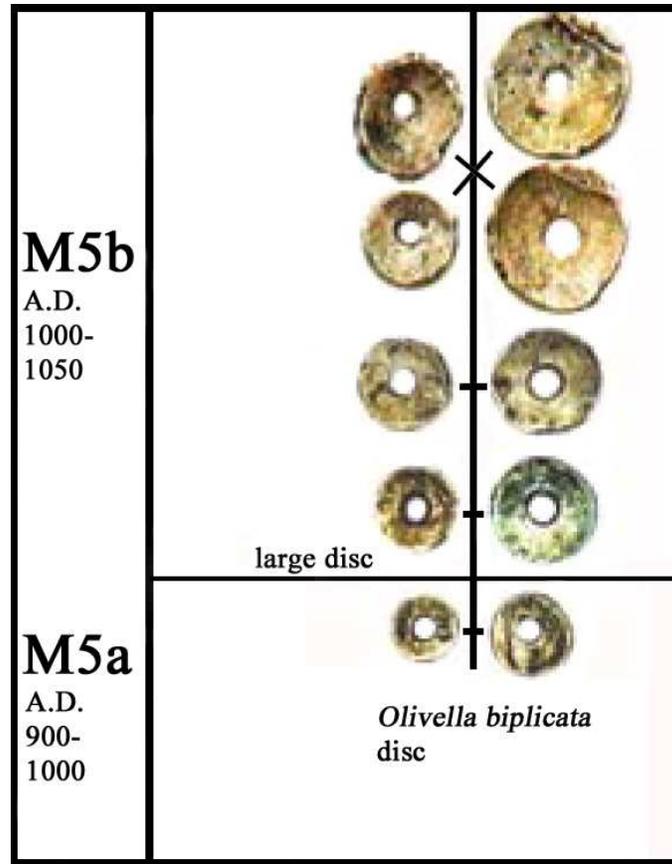


Figure 6.7. Temporal ordering of several M5b *Olivella biplicata* disc beads from LAn-264.

*Partitioning the Malibu Burials into Temporal Groups*

In this section I describe and use (for the first time in an archaeological analysis) a quantitative method that detects temporal clusters or groups in a time structured data set such as the burial sample from the LAn-264 cemetery. The purpose of this analysis is to identify what time period during A.D. 900-1050 small *Olivella dama* barrel beads were being obtained by LAn-264 residents (at the western end of the Hohokam/California transregional system). In Chapter 5, I provided morphometric evidence that these beads probably originated in the Hohokam system. It is my expectation that the time period

when these beads entered the Malibu site should correlate with the maximal size of the Hohokam/California transregional system and also with a high stand of Lake Cahuilla.

Steps of the Analysis.

Step 1. Compute Brainerd-Robinson Coefficient Probabilities.

The Brainerd-Robinson (BR) coefficient is a similarity measure that is useful for comparing proportions in archaeological data sets. I use a published R script for computing the BR coefficient (Peeples 2011), which implements the procedure in DeBoer, Kintigh, and Rostoker (1996). In my analysis, this is used to calculate the BR coefficient for each of the Malibu burials and then to determine which of the burials are similar and which are significantly different by computing the probability of obtaining the observed BR coefficient for each pair of burials in the Malibu data set, using Monte Carlo simulation consisting of 100,000 random samples (Table 6.5).

Step 2. Adjacency Matrix. In graph theory an adjacency matrix is used to identify (in the case of a simple [no self-loops] and undirected graph) where edges are present or absent between nodes (vertices) in a graph. In the matrix a 1 identifies a connection between two nodes in the graph, and a 0 the absence of a connection. For a simple and undirected graph the elements in the diagonal of the matrix are zero (because there are no self-loops and the matrix is symmetric (since the graph is undirected)).

In my analysis, I transform the BR coefficient probability matrix into an adjacency matrix using the following: If a BR coefficient probability is less than or equal to 0.05 replace with a 0 otherwise replace with a 1. The resulting adjacency matrix (Table 6.6) is then analyzed in the next step using spectral partitioning of the nodes (which in my analysis represent individual LAn-264 burials) of the graph.

### Step 3. Partitioning Burial Groups by Time.

This step uses what is often called *spectral partitioning* (see, for example, Spielman and Teng 1996). More than twenty years ago it was discovered that the second smallest eigenvalue ( $\lambda_2$ ) of the Laplacian (see Appendix L) of a graph  $G$  such as the one produced in Step 2 and its eigenvector or Fiedler vector (Fiedler 1973, 1975) have great influence on several properties of graphs (see Juvan and Mohar 1992 and Mohar 1991 for details). In particular,  $\lambda_2$  controls the separation properties of graphs. In this step the Fiedler vector and  $\lambda_2$  of the graph produced in Step 2 are computed (see Appendix L for more details on the mathematics of this step and the Matlab code used to compute  $\lambda_2$  and the Fiedler vector using the adjacency matrix from Step 2) to identify the partitions (or groups of nodes) of the graph, which minimize the numbers of edges (connections) between partitions. This is the pattern of connectivity between subdivisions of the graph that is most likely to correspond to actual divisions in the data. In my analysis these graph partitions correspond to burial clusters ordered by time.

In Figure 6.8, there are two major vertical increases in values of the Fiedler vector, the first between Burials 35 and 68, and the second between Burials 45 and 61. These increases suggest cuts of partitions in the data. This pattern becomes even more clear in the sorted adjacency matrix plot (see Appendix L), where there are three clusters that correspond to the partitions in the burials that result from the two cuts in the sorted Fiedler vector plot (Figure 6.8). The three partitions are also shown in the graph produced by the adjacency matrix (see Figure 6.9).

Table 6.5. Probability of BR distance  $\geq$  observed given sample size.

Burial	35	48	51	68	73a	10	64	61	45	43
35	0	0.84903	0.00000	0.77838	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
48	0.84903	0	0.00000	0.55415	<0.00001	<0.00001	0.00002	<0.00001	<0.00001	<0.00001
51	<0.00001	<0.00001	0	0.41550	0.82429	<0.00001	<0.00001	<0.00001	0.21306	<0.00001
68	0.77838	0.55415	0.41550	0	0.12480	<0.00001	<0.00001	<0.00001	0.14685	<0.00001
73a	<0.00001	<0.00001	0.82429	0.12480	0	<0.00001	<0.00001	<0.00001	0.29932	<0.00001
10	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0	0.32780	0.00012	<0.00001	<0.00001
64	<0.00001	0.00002	<0.00001	<0.00001	<0.00001	0.32780	0	0.45502	0.23230	0.23425
61	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.00012	0.45502	0	0.40675	0.90496
45	<0.00001	<0.00001	0.21306	0.14685	0.29932	<0.00001	0.23230	0.40675	0	0.01359
43	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.23425	0.90496	0.01359	0

Table 6.6. Adjacency matrix derived from Table 6.5.

Burial	35	48	51	68	73a	10	64	61	45	43
35	0	1	0	1	0	0	0	0	0	0
48	1	0	0	1	0	0	0	0	0	0
51	0	0	0	1	1	0	0	0	1	0
68	1	1	1	0	1	0	0	0	1	0
73a	0	0	1	1	0	0	0	0	1	0
10	0	0	0	0	0	0	1	0	0	0
64	0	0	0	0	0	1	0	1	1	1
61	0	0	0	0	0	0	1	0	1	1
45	0	0	1	1	1	0	1	1	0	0
43	0	0	0	0	0	0	1	1	0	0

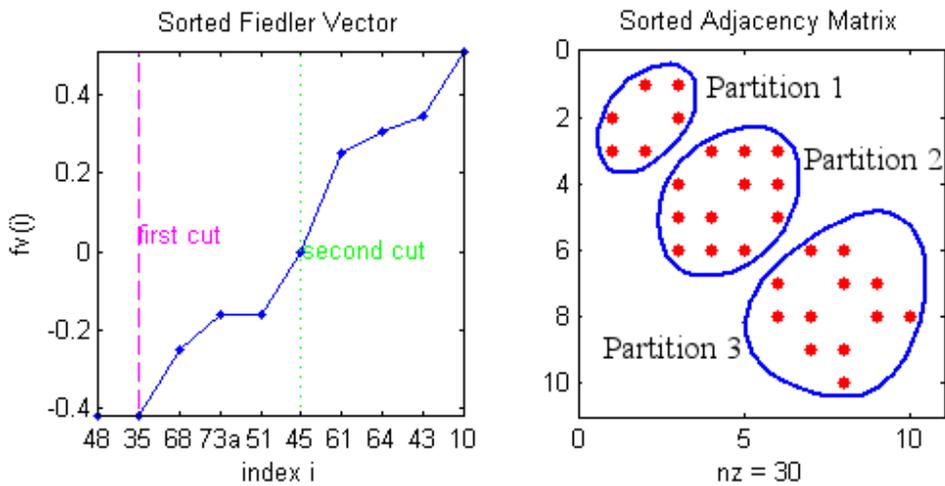


Figure 6.8. Sorted Fiedler vector and sorted adjacency matrix plots of the ten LAn-264 burials. Look at the amount of vertical increase to indicate cut points in graph. Also observe they vertical increase from -0.4 to  $> -0.3$ , and the vertical increase from  $\sim 0$  to  $> 0.2$ .

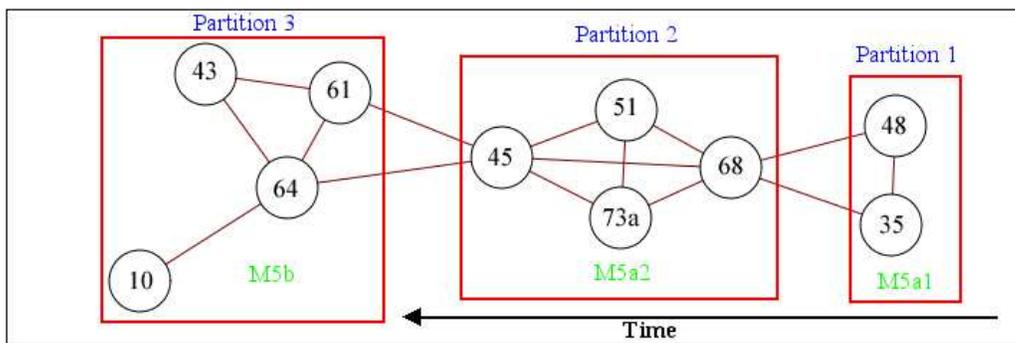


Figure 6.9. Temporally ordered graph of the ten LAn-264 burials showing the partitions identified by the Fiedler vector analysis. As a result of the Fiedler vector analysis, I subdivided M5a into two sub sub phases a1 and a2 and used the criteria provided by King (1990) to assign burials in partitions 1 and 2 to subphase M5a.

Note that Partition 2 (Figure 6.9) consists of Burials 51, 68, 73a, and 45, which are the burials that have the vast majority of *Olivella dama* barrel beads. Based on the radiocarbon result for Burial 35 (discussed earlier) and the placement of Burial 45 in M5a (A.D. 900-1000) by King (also discussed earlier), it is reasonable to suggest that the burials in Partition 2 date from post A.D. 900 to no later than A.D. 1000.

### *Conclusion*

The resulting seriation of burials and shell artifacts from the late Middle period (A.D. 900-1050) LAn-264 cemetery permits the study of changes over time of the proportion of *Olivella dama* barrel beads in burials. Based on the analysis of large diameter *Olivella biplicata* disc beads, and by inspection of the Ford diagram (Figure 6.6), it is clear that the great majority of *O. dama* barrel beads occur in M5a burials. This suggests that much of the interaction with the Hohokam system occurred between A.D. 900 and 1000. Changes in the relative frequencies of *O. dama* barrels in the Malibu burials during this period may relate to changes in the degree of interaction of the Hohokam system with the southern California societies that supplied *O. dama* barrels to the Malibu elite.

### **The Intensity of Production Measured by the Coefficient of Variation Statistic**

If the Hohokam system circa A.D. 900 became heavily involved in a transregional exchange system, and their involvement increased over some period after that, I expect that there was a corresponding increase in the intensity of production of export items. The coefficient of variation statistic provides a way to indirectly measure intensity of production. The coefficient of variation statistic is a summary statistic, which measures variation in a single variable (e.g., diameter of shell beads). The larger the coefficient of

variation statistic, the greater the sample variation. Eerkens and Bettinger (2001) provide strong evidence that the coefficient of variation (or simply CV) statistic is a robust measure of variation. Ethnographic studies focused on ceramic production have shown that the CV is also a reliable indicator of standardization (Roux 2003), which in turn, is also often strongly associated with intensity of production (Balfet 1965; Bowser 2000; Kvamme et al. 1996; London 1991; Longacre 1999; Longacre et al. 1988).

Archaeological evidence of this relationship has also been observed in some samples of ancient Southwest pottery (Schleher 2010).

In my study I use the CV statistic to evaluate the intensity of production of *Olivella dama* barrel beads) from the M5a-b (A.D. 900-1050) LAn-264 cemetery. Each of the samples is from a burial, and is ordered by time based on the results of the seriation subsection. Each sample is also subdivided into homogeneous subsets (which are required for this statistic) using a systematic technique for detecting modes in low dimensional archaeological data (Baxter and Cool 2010, see Appendix M). I attempt to reduce sampling bias by using resampling (Bootstrap and Jackknife). This is due to the non-random nature of the samples, and in some cases small sample size (see Appendix N for the R code used for the CV resampling procedure, and additional analytical results). I use the CV values as a proxy for intensity of shell manufacture and (presumably) exchange. *O. dama* barrel bead is used as an indicator of exchange activity in the transregion for three reasons:

- (1) My sample came from a cemetery in the Chumash area of the transregion, at the opposite end of the transregion from the Hohokam system.
- (2) These artifacts were probably made in the Hohokam system (based on results in

Chapter 5), and are a common type during the time period I am examining in Hohokam sites.

- (3) *O. dama* barrel beads are very common in Lake Cahuilla shoreline sites (Daduhl 2011), and may have frequently been exchanged for dried Lake Cahuilla fish.

### *Modes*

The purpose of this analysis is to determine if there is more than one size category in the *O. dama* barrel bead sample. Read (2007) has discussed modes in artifact dimensions in relation to emic types. Modes are statistical structures that can only be observed in the aggregate and often may have cultural salience (Read 2007). Specifically, metric variables such as the diameter of *Olivella dama* shells presumably continuously vary over some finite interval. In such an interval the diameter in a large sample of *O. dama* shells is expected to have a single mode. If there are preferences for specific diameter ranges of *O. dama* shells by the makers and users of *O. dama* barrel beads then this may result in diameter distributions with two or more modes. In this way the subdivision of the original distribution is the result of culturally salient conceptual frameworks of the people who made and used these artifacts. As Read (2007:47) says: “A mode is part of the ideational domain of the artisan shared among other culture bearers”. Baxter and Cool (2010) provide a systematic and robust method for discovering modes in low dimensional data (such as the diameter of shell artifacts). In my study I use their method to evaluate the modality of one small and three large *O. dama* barrel samples from four burials (see Appendix M). Detecting modes (in this case) is also necessary to maximize accuracy of the CV estimates, since the CV statistic requires that samples are homogeneous, which

would not be the case if there are two or more undetected types in the *O. dama* barrel bead sample.

The result of my analysis is that in all four burials the distribution of the diameter of *O. dama* beads is unimodal (Table 6.7, Figure 6.10). This suggests that the samples are homogeneous for this variable and do not need to be subdivided.

Table 6.7. Results from Baxter and Cool procedure (see Appendix K for more detail).

Burial	Number of Modes	Critical Bandwidth ( $h_0$ )	Corrected Critical Bandwidth ( $\lambda_\alpha * h_0$ )	Bootstrapped p-value
68	1	0.3886	0.4389	0.4137414
51	1	0.1704	0.1925	0.1424142
73a	1	0.1092	0.1233	0.5986599
45	1	0.1209	0.1365	0.5245525

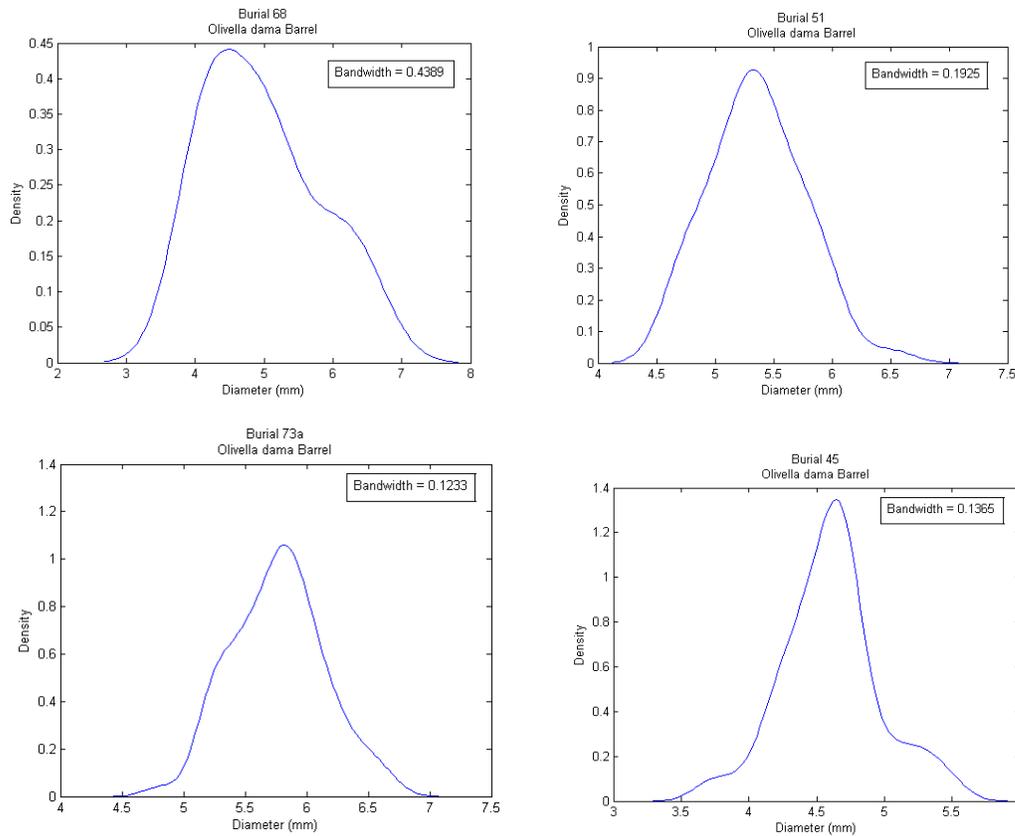


Figure 6.10. Kernel density estimates of the diameter distributions of *Olivella dama* bead diameter from the four LAn-264 burials used in the coefficient of variation analysis. This figure simply illustrates that the diameter distributions of *O. dama* barrel beads from four Malibu burials are unimodal (i.e. homogenous).

### *Coefficient of Variation Analysis*

Now that it is clear from the preceding analysis that the *O. dama* barrel bead diameter distributions are unimodal (homogeneous), I present the results of a CV analysis which uses the *O. dama* barrel bead diameter data in Appendix N (where each sample is considered to be homogenous). There is a clear decrease in the CV value for *Olivella dama* barrel bead diameter over time in the burials (Figure 6.4). Initially (in Burial 68, one of the earliest burials, see Figure 6.11) the CV value is close to 0.2 and drops to well

below 0.1 in the remaining three burials, which probably date to A.D. 900-1000. This suggests a significant increase in the intensity of production *O. dama* barrel beads in the Hohokam system shortly after A.D. 900 that continued during much of the next one hundred years. Also, Crown (1995:148-149) observes that specialist potters in the ethnographic record produce wares with CV values less than 0.1 and non-specialists produce wares with CV values greater than 0.1 (Schleher 2010:65). This may also hold for shell artifacts, which (if true) suggests specialist manufacture of the *O. dama* beads from the latter three burials (since the CV values for *O. dama* bead diameter are well below 0.1). This correlates with Haury's observation that *O. dama* barrel beads become much more common in Gila River area sites after A.D. 950. Also, *O. dama* barrel beads are very abundant in Lake Cahuilla shoreline sites from the same time period. These results support my hypothesis of increased production of *O. dama* barrel beads in the Gila River area after A.D. 900 to trade for dried fish from Lake Cahuilla.

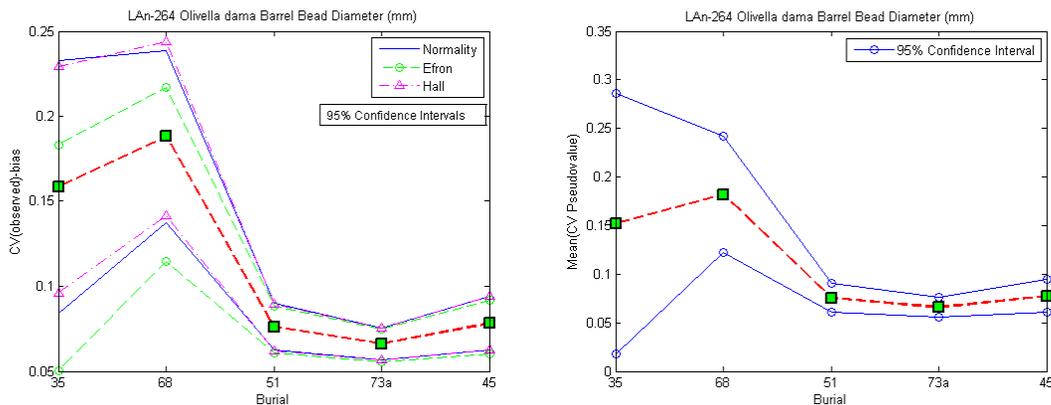


Figure 6.11. Bootstrapped and jackknifed CV values plotted against time (chronologically ordered LAN-264 burials).

### *Significance of Change in the Proportion of Olivella dama Barrel Beads with Time*

Another line of evidence compliments the results of the CV analysis. Specifically, a bar graph (Figure 6.12, also see Table 6.8) of time ordered burials in relation to the stacked proportion of *O. dama* barrels and Pacific Coast shell artifacts in each of the burials, shows a strict increasing trend in the proportion of *O. dama* barrels during much of M5a2 (after A.D. 900 and shortly before A.D. 1000). At the end of M5a2 (ca. A.D. 1000) there is a dramatic decline in the proportion of *O. dama* barrels to a value probably approaching zero (Figure 6.12, Table 6.8). The bar graph covers a longer time period than the four burials used in the CV analysis, but supports the conclusion of the CV analysis, of intensification of production of *Olivella dama* barrel beads in the Hohokam system during M5a2.

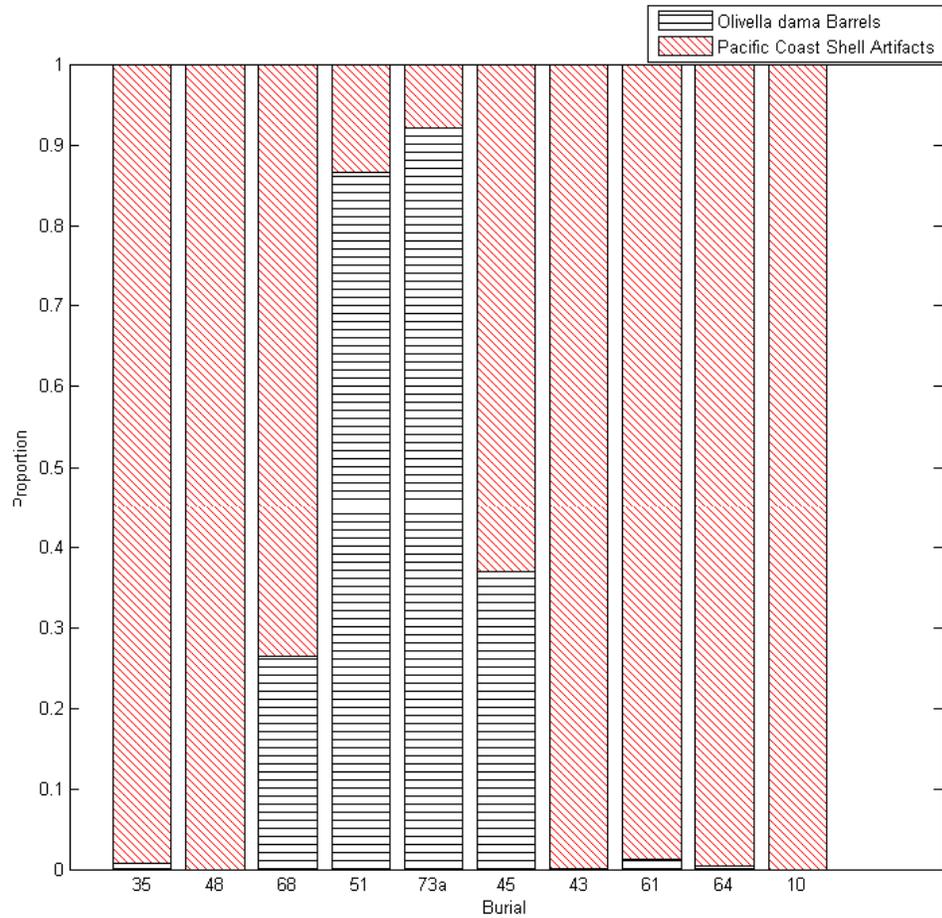


Figure 6.12. Bar plot of the proportions of *Olivella dama* barrel beads and Pacific Coast shell artifacts in chronologically ordered LAn-264 burials. This figure shows that the proportion of *Olivella dama* barrel beads in the M5a-b Malibu cemetery rapidly increase then decrease over several decades.

Table 6.8. Data used to construct Figure 6.12.

Burial	<i>Olivella dama</i> barrels	Pacific Coast Shell Artifacts
35	7	943
48	0	142
68	14	39
51	240	37
73a	200	17
45	301	513
43	3	2397
61	2	166
64	1	278
10	0	279

To determine the statistical significance of temporal changes in the proportion of *O. dama* barrels between the ten burials during A.D. 900-1050, an analysis of 2 x 2 contingency tables of the form in Figure 6.13 was performed. Boschloo's unconditional exact test (see Boschloo 1970; Berger 1994, 1996, also see Appendix O for a detailed description) was used to test the null hypothesis that the proportion of *O. dama* barrels did not change significantly between pairs of burials in chronological order. An exact test was used, since some of the frequencies in Table 6.8 are very small ( $\leq 5$ ). Also, Boschloo's test was used since it is more powerful than a conditional exact test, such as

Fisher's (Berger 1996). The R statistical Exact package was used to perform the tests (see Appendix O for more details).

	<b>O. dama Barrel Beads</b>	<b>PC Shell Artifacts</b>
<b>Burial A</b>	<b>A1</b>	<b>A2</b>
<b>Burial B</b>	<b>B1</b>	<b>B2</b>

Figure 6.13. Format of 2x2 contingency table used in the analysis of the Malibu burial data with Boschloo's test.

Table 6.9. Results of Boschloo's test, in which the p-value from Fisher's exact test is used as the test statistic in an exact unconditional test, is uniformly more powerful than Fisher's test (Mehrotra et al. 2003).

Burials	Model	Method	Alternative Hypothesis	P-value	Test Statistic (P-value from Fisher's Exact Test)	Nuisance Parameter that Maximizes the P-value	The Range of Nuisance Parameters Considered
35 vs. 48	Binomial	Boschloo	two-sided	0.5899413	0.6042973	0.4999996 0.5000004	0.00001 0.99999
<b>48 vs. 68</b>	Binomial	Boschloo	two-sided	2.189027e-09	2.940161e-09 **	0.4999912	0.00001 0.99999
<b>68 vs. 51</b>	Binomial	Boschloo	two-sided	1.086585e-18	3.073207e-18 **	0.2506629	0.00001 0.99999
<b>51 vs. 73a</b>	Binomial	Boschloo	two-sided	0.05648891	0.058917 *	0.5000003	0.00001 0.99999
73a vs. 45	Binomial	Boschloo	two-sided	3.04519e-53	5.890374e-53 **	0.4883237	0.00001 0.99999
45 vs. 43	Binomial	Boschloo	two-sided	1.326807e-195	2.69118e-195 **	0.4592144	0.00001 0.99999
43 vs. 61	Binomial	Boschloo	two-sided	0.03623044	0.03731482 *	0.4396234	0.00001 0.99999
61 vs. 64	Binomial	Boschloo	two-sided	0.5557041	0.5593669	0.4560934 0.5439066	0.00001 0.99999
64 vs. 10	Binomial	Boschloo	two-sided	1	1	0.9862474	0.00001 0.99999

The null hypothesis is rejected for burial pairs 48 and 68, 68 and 51, and 51 and 73a (see Table 6.9), where there is a substantial increase in the proportion of *O. dama* barrels (also see Figure 6.12) over time in this pairwise sequence. This suggests a significant and progressive increase in trade between the residents of the Malibu site and other southern California societies that were interacting with the Hohokam system between A.D. 900 and 1000. The null hypothesis is also rejected for burial pairs 73a and 45 and 43, where

there is a substantial decrease in the proportion of *O. dama* barrels (again see Figure 6.12) over time in this sequence.

Based on the earlier analyses, the time period of this sequence probably begins after A.D. 950 (near the beginning of the Hohokam Sacaton Phase) and ends shortly after A.D. 1000. As discussed in Chapter 4, Lake Cahuilla had been filled by the Colorado River by ca. A.D. 850 and remained full until about A.D. 925, when it began a 25-year drying cycle after the course of the Colorado River was diverted by an earthquake (Philibosian et al. 2011). This 75 year high stand may have provided the opportunity for a large Lake Cahuilla fishery to develop, and (interestingly) this period also overlaps with most of the Santa Cruz Phase (A.D. 850-950) of the Hohokam Colonial Period, during which the economy of the Hohokam was rapidly expanding and diversifying (Abbott 2009; Doyel 1991b). After A.D. 950, the Colorado River was again diverted by an earthquake, which initiated a filling cycle of Lake Cahuilla (Philibosian et al. 2011). This suggests that the increasing importation of *O. dama* barrel beads into the Malibu site after A.D. 900 may be due to a combination of social and environmental factors that include: (1) the Pre-Classic regional Hohokam system was rapidly expanding; (2) Lake Cahuilla was very large and stable for several decades; and (3) a Lake Cahuilla fishery of sufficient size and complexity developed to sustain surplus yields of dried fish for export to the Hohokam system, and possibly other foreign markets. Trade of dried Lake Cahuilla fish for (among other things) *O. dama* barrel beads manufactured in the Hohokam system is also supported by what may have been specialized production of these beads in the Hohokam system during this time (as suggested by the preceding CV analysis).

## 2: Oro Grande

The Oro Grande site (CA-SBr-616) is a village location on the west side of the Mojave River about 10 kilometers northwest of Victorville and directly across the river from the modern community of Oro Grande. The site is located in an area ethnohistorically occupied by the Vanyume or desert Serrano (Bean and Smith 1978:570, Fig. 1). The fact that no pottery was recovered by archaeologists in horizons corresponding to the time period of this study during the excavation of the Oro Grande site (Rector et al. 1983) is consistent with Serrano occupation since Serrano people during this time probably did not manufacture or typically use pottery (see Drucker 1937:47; Strong 1929:347). Hopic people living in southern California as I suggest in Chapter 3 probably made and used pottery during the time period of this study and likely would have left some material evidence (e.g., pottery sherds) if that had used the Oro Grande site for an extended period.

### *Chronological Study*

I next perform a seriation analysis of shell artifacts recovered from residential areas in the Oro Grande site to better understand time-based patterns of interaction of the residents of the Oro Grand site with coastal southern California societies and the Hohokam system. This will be used as an independent line of evidence to support the pattern of trade connections between the Serrano region and other regions in the network graph of the Hohokam/California transregional system constructed in Chapter 3, as well as to suggest how the intensity of exchange changed over time between Oro Grande and other regions. Figure 6.14 provides a plan view of the excavated areas (loci) of the site discussed by Rector et al. (1983).

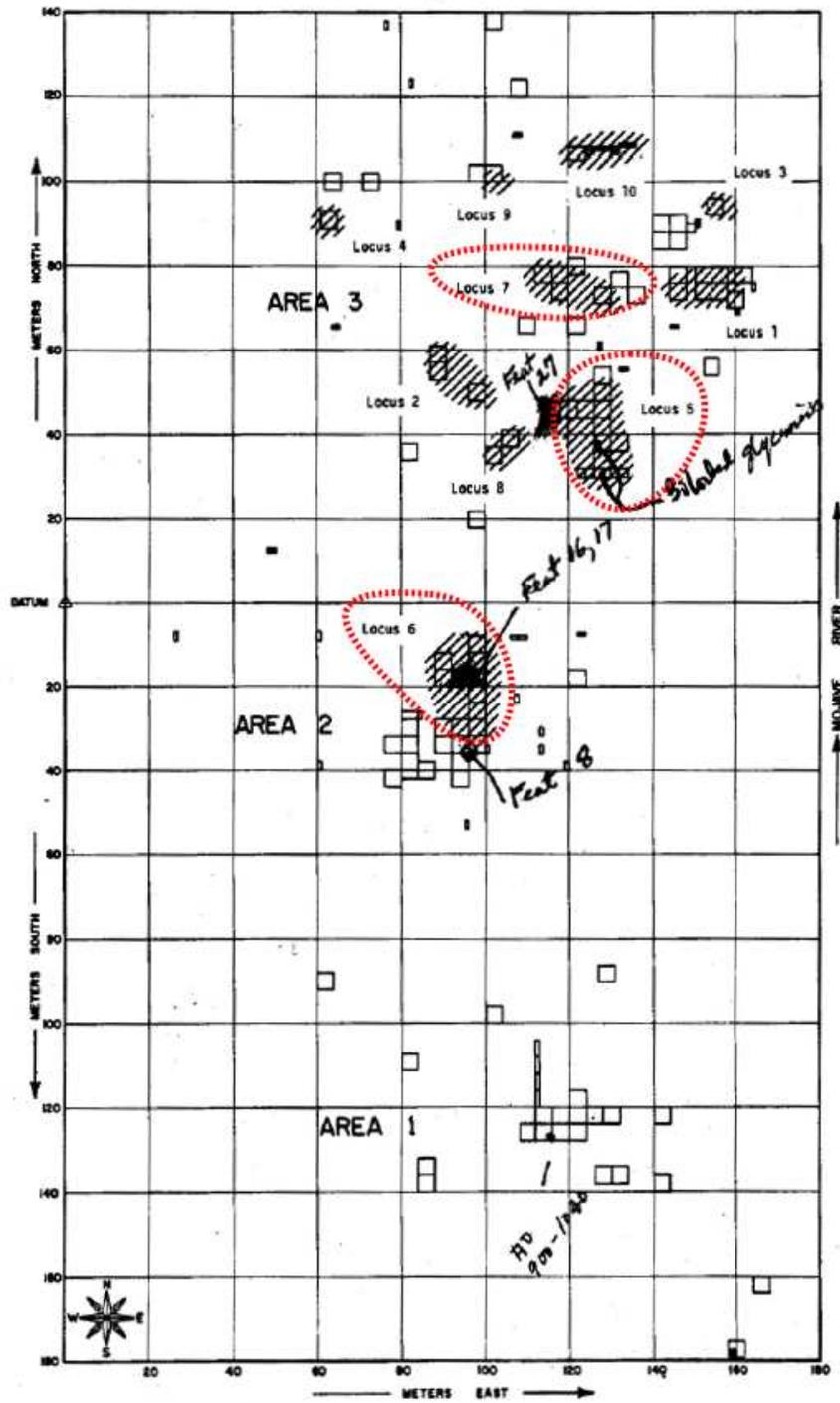


Figure 6.14. Plan view of the Oro Grande excavation areas and loci (Rector et al. 1983).

I examine the shell from five of the excavated loci (5, 6, 7, 8, and 10), which King 1983 interprets as probable residential areas. King also provides a chronological assessment of these areas, based on a judgmental interpretation of stone and shell beads (Table 6.10).

Table 6.10. King's 1983 chronological interpretation of five of the Oro Grande site area loci (Figure 6.14) excavated by Rector et al. 1983.

Locus	Cultural Phase	A.D.
8	Middle Period Phase 3	300-700
5	Middle Period Phase 4	700-900
7	Middle Period Phases 4 and 5	700-1150
6	Middle Period Phase 5a-b	900-1050
10	Late Middle Period or Late Period	1050 and later

I performed a seriation of the loci using shell (see Appendix J for more detail on the seriation method), which resulted in a different chronological ordering of loci 5, 6, and 7 from that in Table 6.5. Figure 6.15 is a chronological ordering and visual depiction of the Oro Grande shell artifact types.

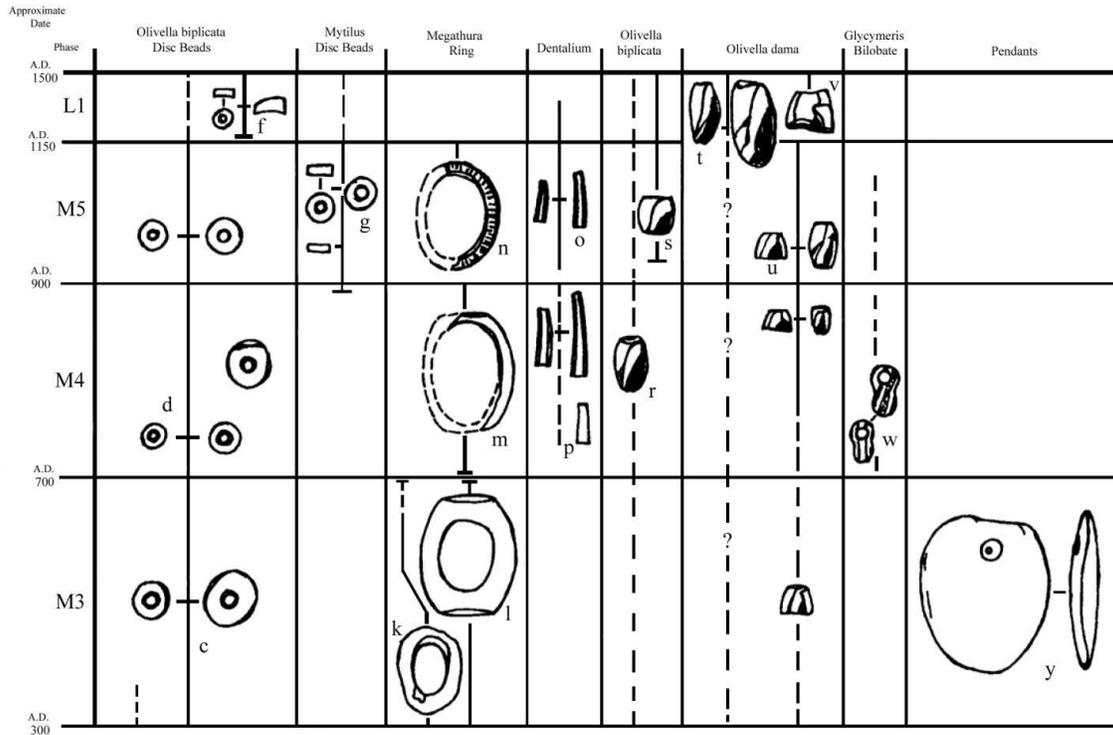


Figure 6.15. Chronological ordering of shell artifact types recovered from Oro Grande (Modified figure from King 1983). Shell artifacts: *Olivella biplicata* saucer/disc beads (c and d), cup beads (f), diagonal spire ground bead (r), barrel beads (s); *Olivella dama* spire ground beads (t), small barrel beads (u), large barrel beads (v); *Mytilus californianus* disc beads (g); *Megathura crenulata* ovoid ring with smooth surface (k), thick end-flattened ring (l), thin end-flattened ring (m), ground thin ring with crenulate surface (m); *Dentalium pretiosum* (p); *Dentalium neohexagonum* (o), *Glycymeris* sp. bilobate beads (w); *Haliotis* sp. pendant (y).

Table 6.11 is an abundance matrix for the five loci, and Table 6.12 is the incidence matrix that was used as raw data for the seriation. A bivariate kernel density estimate plot (see Botev et al. 2010) of the *Olivella biplicata* saucer/disc beads from Loci 5, 6, 7, 8, and 10 (Figure 6.16) identifies three modes, which are used in Tables 6.6 and 6.7.

Figures 6.17 and 6.18 provide a graphical representation of the seriation.

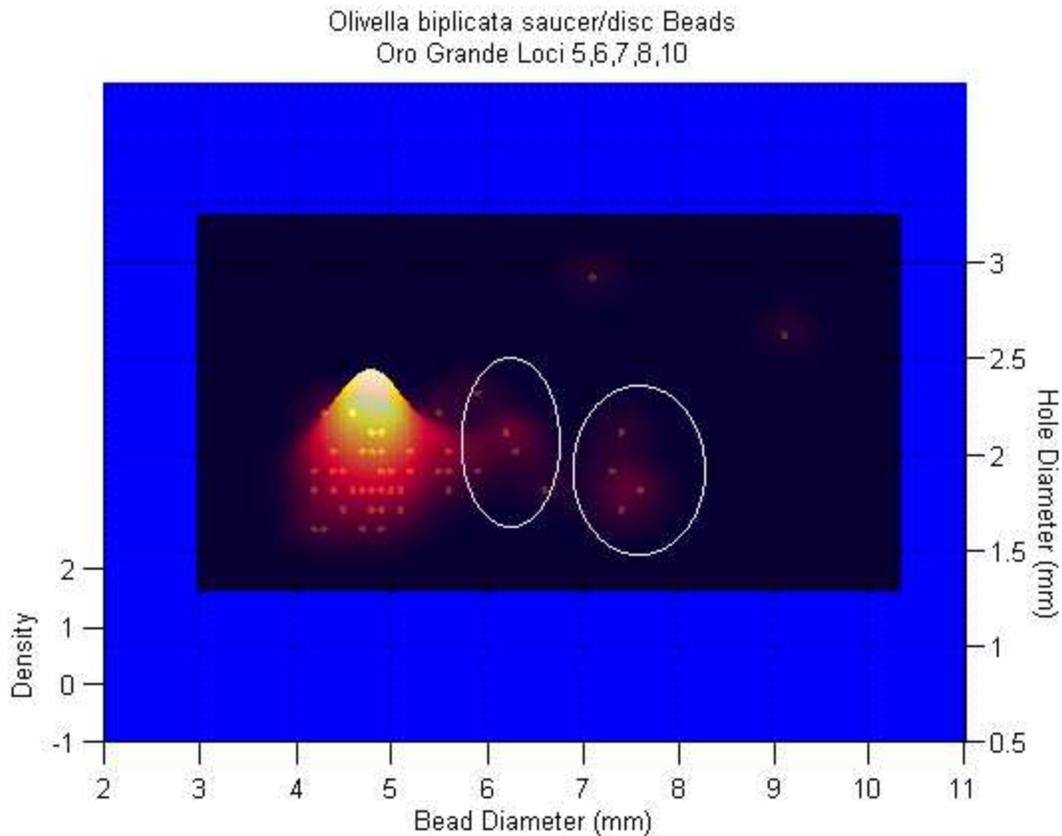


Figure 6.16. 2D kernel density estimate plot of hole diameter of *Olivella biplicata* saucer/disc beads from Oro Grande loci 5, 6, 7, 8, and 10. Three modes are indicated in this plot. The first mode (size class) corresponds to the 4.2-5.5 mm bead diameter interval, the second mode to the 5.6-7.1 mm interval, and the third to the 7.2-9.1 mm interval.

To chronologically order the loci I used Kendall's 1-mode multidimensional scaling method (or "horse-shoe method", see Kendall 1963, 1969a, b, 1971), in combination with a traveling salesman problem solver (see Appendix J). I chose this method, because of the very small sample size of the shell artifacts from residential loci 6, 7, 8, and 10, and because there (fortunately) are very good temporally diagnostic types of shell artifacts (that occur in very low frequencies  $n [1, 3]$ ) in the samples from these loci. The choice of a method (such as Kendall's) that uses an incidence (presence/absence) matrix seems preferable, because of the issue with sampling error which is less confounding when

magnitude is removed, and also because distinct and temporally diagnostic shell artifact types are present in each of the loci. This is the raw data for the seriation result (Figures 6.17 and 6.18). Note that in Tables 6.11 and 6.12 the *Megathura crenulata* ring type 1 has the crenulate surface removed and that the type 2 ring is thinner than type 1, and has both ends ground flat. Type 2 also retains the crenulate surface. The *Glycymeris* sp. bilobed beads and the *Olivella dama* barrel beads most likely were made in the Hohokam system. Note that the Oro Grande *Olivella biplicata* saucer/disc beads are divided into three size groups in Tables 6.11 and 6.12 (based on bead and hole diameter), using the results of the Botev 2009 matlab 2D kernel density estimate plot (see Botev et al. 2010; Figure 6.16).

Table 6.11. Counts of eleven shell artifact types from five residential loci (Figure 6.11) in the Oro Grande site.

L	<i>O. bip.</i> Disc 4.2- 5.5	<i>O. bip.</i> Disc 5.6- 7.1	<i>O. bip.</i> Disc 7.2- 9.1	<i>Mytilus</i> disc 3.5- 4.9	<i>O. dama</i> barrel	<i>O. bip.</i> Barrel	<i>Glycymeris</i> sp. Bilobed	<i>Dentalium</i> <i>neohexagonum</i>	<i>Dentalium</i> <i>pretiosum</i>	<i>Megathura</i> ring Typea 1a and 1b	<i>Megathura</i> ring Type 2	<i>Megathura</i> Ring Type 3	T
8	2	1	0	0	1	0	0	0	0	3	0	0	7
5	43	3	3	0	1	0	2	4	0	0	0	0	56
6	4	2	0	3	2	1	0	2	0	0	0	1	15
7	1	2	0	1	3	0	0	0	1	0	1	0	9
10	0	2	3	0	0	0	0	0	0	0	0	0	5

Table 6.12. Incidence matrix derived from the abundance matrix (Table 6.11). \* indicates a temporal diagnostic that occurs in only one locus.

L	<i>O. bip.</i> Disc 4.2-5.5	<i>O. bip.</i> Disc 5.6-7.1	<i>O. bip.</i> Disc 7.2- 9.1	<i>Mytilus</i> disc 3.5- 4.9	<i>O. dama</i> barrel	<i>O. bip.</i> Barre l	<i>Glycymeri</i> s sp. Bilobed*	<i>Dentalium</i> <i>neohexigonum</i> *	<i>Dentalium</i> <i>pretiosum</i> *	<i>Megathura</i> ring Types 1a and 1b*	<i>Megathura</i> ring Type 2*	<i>Megathura</i> Ring Type 3*	T
8	1	1	0	0	1	0	0	0	0	1	0	0	4
5	1	1	1	0	1	0	1	1	0	0	0	0	6
6	1	1	0	1	1	1	0	1	0	0	0	1	7
7	1	1	0	1	1	0	0	0	1	0	1	0	6
10	0	1	1	0	0	0	0	0	0	0	0	0	2

### Kendall's horse shoe with $th = 11.64$

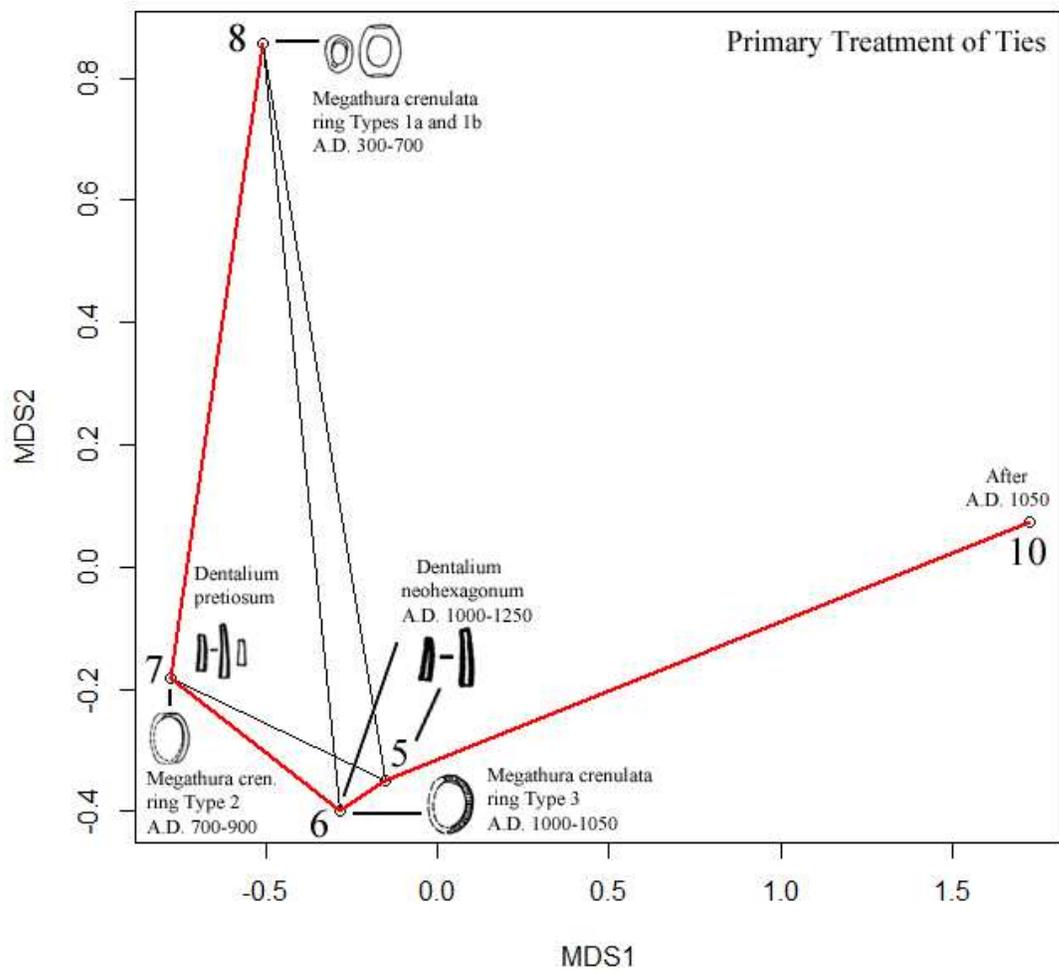


Figure 6.17. Chronological ordering of Oro Grande residential loci using primary treatment of ties (Kendall 1971:229-233).

### Kendall's horse shoe with th = 11.64

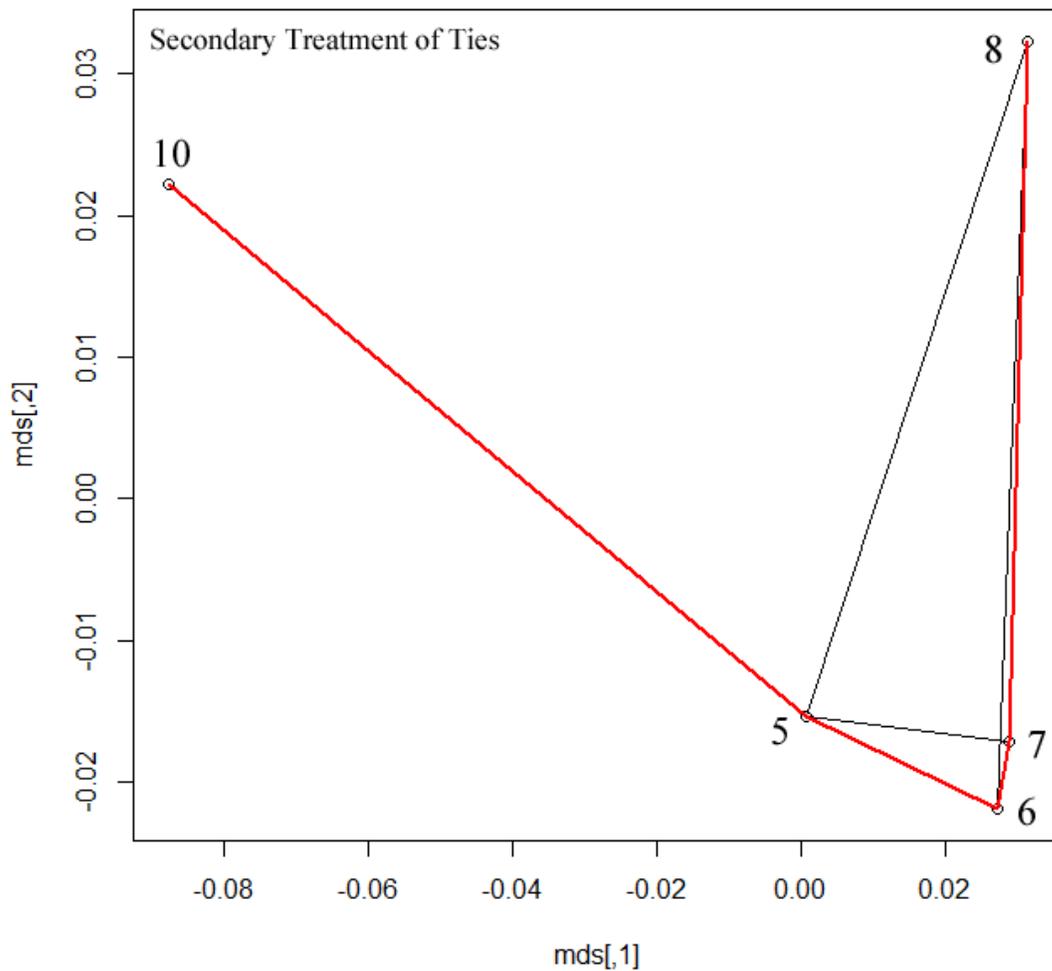


Figure 6.18. Chronological ordering of Oro Grande residential loci using secondary treatment of ties (Kendall 1971:229-233). Note that the loci order in this diagram is identical to the order in Figure 6.17.

### Results

Now that the loci are ordered by time it is possible to see how proportions of Pacific Coast and Gulf of California shell artifacts with time in the Oro Grande site. The proportion of Gulf of California shell artifacts in Loci 5, 6, and 7 is much smaller than the proportion of Pacific Coast shell artifacts (Figure 6.19), which suggests much more

interaction between the occupants of Oro Grande (ca. A.D. 700-1100) with native California societies to the west than with societies to the south and east that obtained shell from the Hohokam system. Figure 6.19 also shows a significant drop in the proportion of Gulf of California shell artifacts over time, which possibly suggests that the residents of Oro Grande had progressively less involvement with southern California groups (possibly those associated with Lake Cahuilla) that imported Gulf of California shell artifacts the Hohokam system.

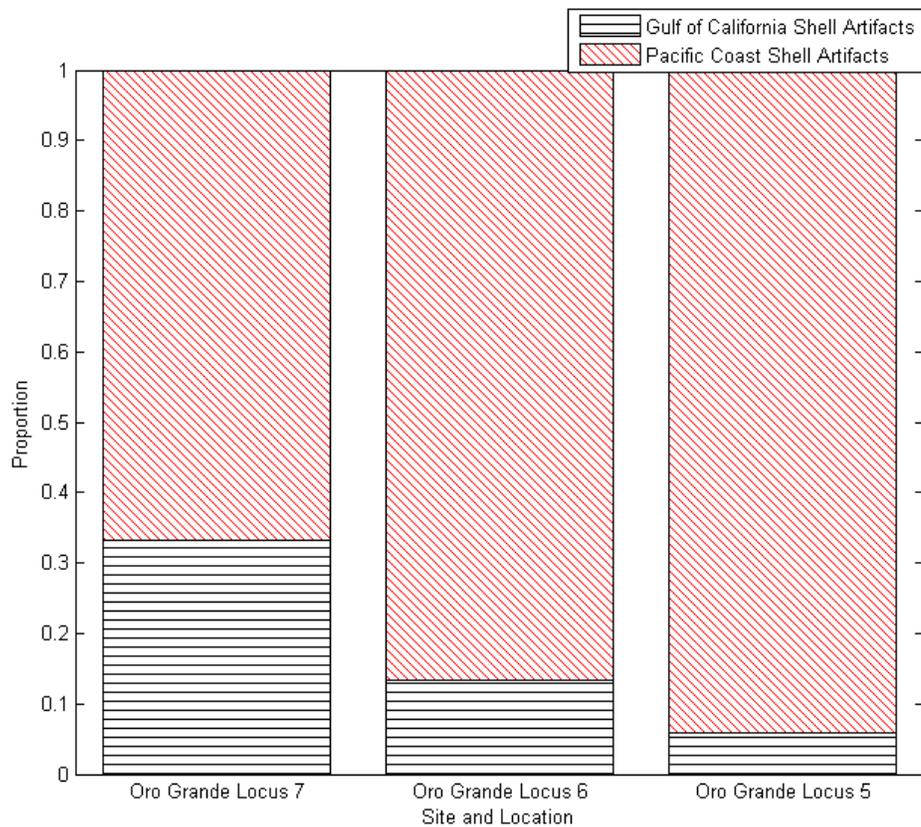


Figure 6.19. Chronologically ordered proportions of Gulf of California and Pacific Coast shell artifacts from three Oro Grande residential loci.

To evaluate if the changes in proportions of Gulf of California and Pacific Coast shell artifacts (Figure 6.19) are statistically significant I use Barnard’s exact test. Table 6.13 provides the results from Barnard’s exact test on the proportion of Gulf of California and Pacific Coast shell artifacts from residential Loci 5, 6, and 7. Visual inspection of Figure 6.19, suggests there is a significant drop in the proportion of Gulf of California shell artifacts over time. The results of the Barnard’s test support this conclusion, and show that although the decrease over time in the proportion of *O. dama* barrel beads between Loci 7 and 6 and Loci 6 and 5 is not statistically significant, the decrease over a longer time between Loci 7 and 5 is significant ( $\alpha = 0.05$ , see Table 6.13). I interpret this as: (1) the interaction of the Oro Grande residents (ca. A.D. 700-1050) with southern California groups, that imported Gulf of California shell valuables made in the Hohokam system, gradually declined over time, and (2) during A.D. 1000-1050 (the suggested use period of Loci 5 and 6) the production of shell valuables in the Hohokam system also declined, but at a faster rate.

Table 6.13. Results of Barnard’s exact test.

Locus Pair	Number of Tables Evaluated	Wald Statistic	Nuisance Parameter	P-value (1-tailed)
7 vs. 6	10000 20x6 tables	1.1680	0.7205	0.159670
6 vs. 5	10000 67x6 tables	1.0723	0.2341	0.211546
7 vs. 5	10000 60x7 tables	2.6913	0.9811	0.038033

### 3: Afton Canyon

The Afton Site (CA-SBr-85) is located next to the Mojave River, near Barstow California (see Figures 6.20 and 6.21). It is upstream and about one hundred kilometers northeast of the Oro Grande site (see Schneider 1989:13, Figure 9). As I suggested in Chapter 3, the occupants of the Afton Canyon site (circa A.D. 700-1100) were probably both Hopic and Patayan. King (1985:3) provides an assessment of the importance and context of shell exchange to the inhabitants of the Afton Canyon site.

The Afton Canyon site is adjacent to one of the most important trade routes between the Colorado River and the coast of Southern California. The people who lived at SBr-85 apparently participated in the trade of shell beads. During the Basketmaker III and Pueblo I and II periods when SBr-85 was occupied, many *Olivella* saucer and disc beads were traded from California to the Southwest. *Olivella* wall disc and saucer beads were traded to both the Hohokam and the Anasazi throughout the latter half of the Middle period and the Late period (Jernigan 1978:35 and 157). It appears that trade of Californian shell beads may have been most intense during the occupation at the Afton Canyon site.

Schneider (1989:114-115) provides radiocarbon dates from pottery found at the Afton Canyon site.

Two radiocarbon dates place lower Colorado Buffware (recovered from the site) at A.D. 920-1180 (Schneider 1989:91). The shell artifact sample from the Afton Canyon (according to King 1989:159) corresponds most strongly to A.D. 900-1050. Adding radiocarbon dates and projectile points suggests the site was mostly occupied circa A.D. 1000-1100.

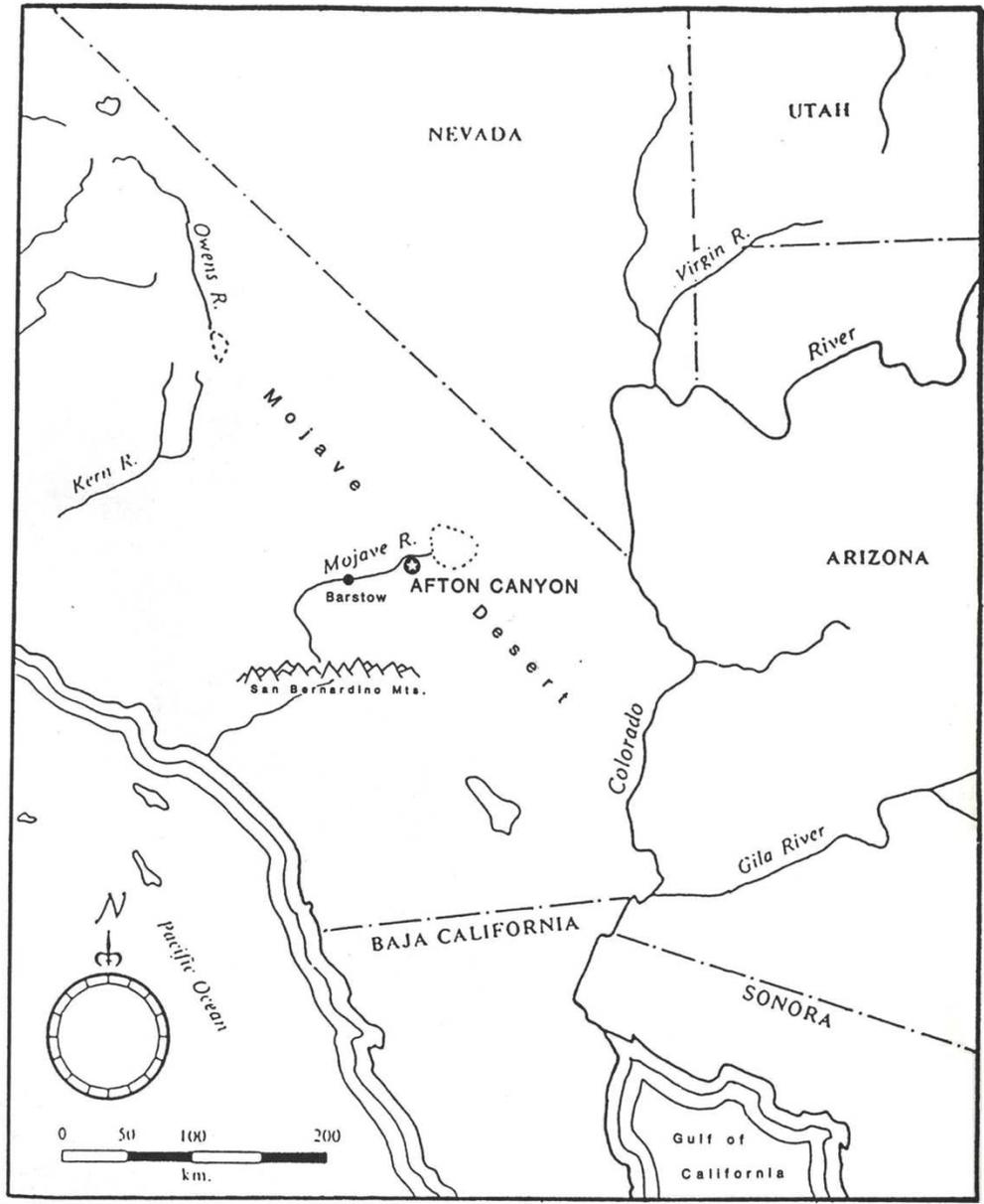


Figure 6.20. Location of the Afton Canyon site (Schneider 1989, Figure 2.)

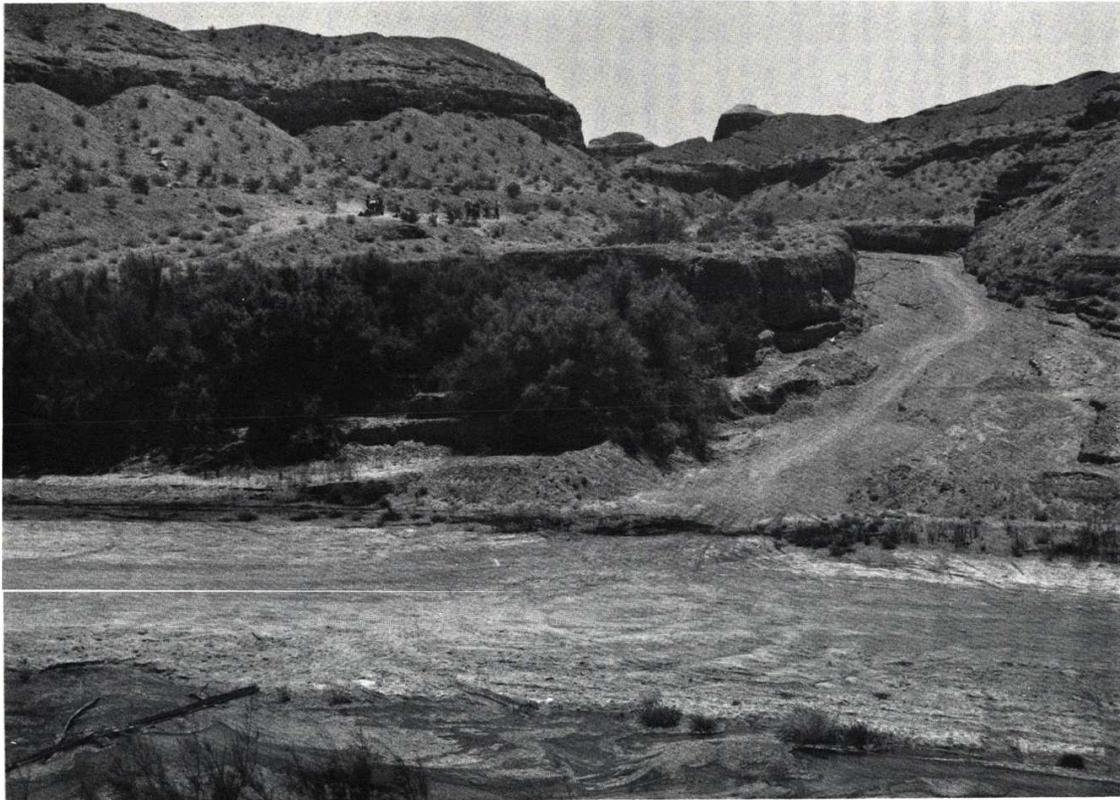


Figure 6.21. Looking south at the Afton Canyon site. Excavators identify the site location on a terrace above the Mojave River in the foreground (Schneider 1989, Figure 10).

Table 6.14 shows the provenience and depth of three types of *Olivella* shell artifacts recovered from Afton Canyon. Figure 6.22 is a plan view that shows the locations of the numbered Afton Canyon excavation units (also see Table 6.14).

Table 6.14. Shell artifacts from the Afton Canyon site used for analysis. Unfortunately, the excavators used 1/8-inch mesh screens, and smaller shell beads were not sampled, which both reduced and skewed the sample. This is a major problem not only in this sample, but also in the majority of excavated material from the Hohokam system and southern California sites. This is because most small wall disc beads used in Southern California circa A.D. 900-1100 pass through 1/8-inch mesh, and the majority of Hohokam and southern California archaeologists use 1/8 inch and larger (mostly ¼ inch) mesh screens.

Unit	Depth (cm.)	<i>Olivella biplicata</i> Wall Disc	<i>Olivella biplicata</i> Spire-Ground	<i>Olivella dama</i> Spire-Ground
1	20-30	1		
1	30-40	1		
1	40-50	1		
4	20-30	1		
5	10-20	1		
6	20-30	1		
9	10-20	2		
12	10-20	1		
15	10-20	1		
18	0-10	1		
19	10-20	1		
19	20-30	1		
19	30-40	1		
23	20-30			1
24	0-10		1	
Total		14	1	1

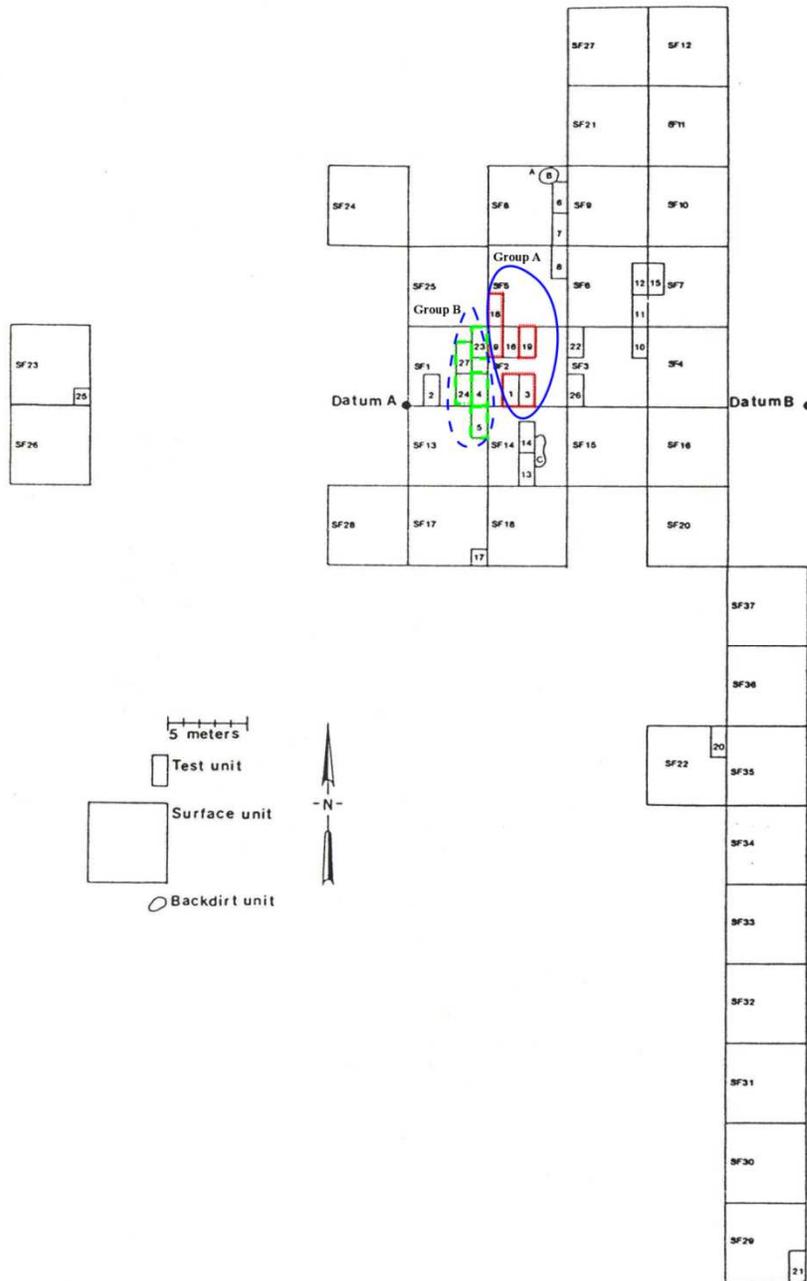


Figure 6.22. Plan view of the numbered Afton Canyon site excavation units (Schneider 1989, Figure 12).

The *Olivella biplicata* wall beads have a single mode for maximum bead diameter and hole diameter (using the Baxter and Cool 2010 method for detecting modes in low dimensional data, see Figure 6.23), which suggests Schneider’s subdivision of the Afton Canyon *Olivella biplicata* wall bead sample into Saucer, small and medium disc categories (using the criteria of maximum diameter and hole size, see Schneider 1989 Table 22, p. 99) is not statistically valid.

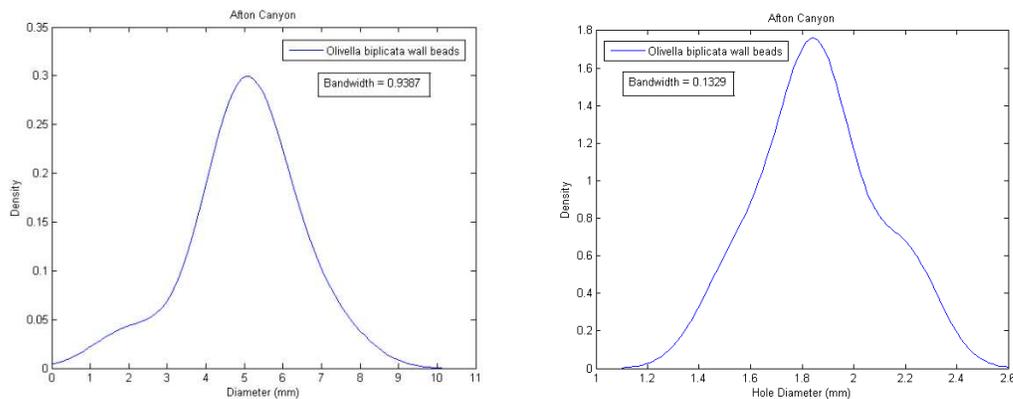


Figure 6.23. Kernel density estimates of the distributions of the outer and hole diameters for the Afton Canyon sample of *Olivella biplicata* wall disc beads.

Also, consider the estimated age range of the Afton occupation (A.D. 900-1100) and the estimate (A.D. 1000-1050) for Locus 5 of the Oro Grande site. Based on King’s (1990:135) observation that during M5b (A.D. 1000-1050), *Olivella biplicata* wall bead diameters again decreased in the Chumash area, it is expected that the *Olivella biplicata* wall beads from Afton Canyon will tend to be larger than the beads of this type from Oro Grande Locus 5 (because of the later average age of the Oro Grande sample). This is the observed pattern, where the mean diameter for Oro Grande Locus 5 is 5 mm and 5.7 mm for the Afton Canyon sample. The difference between the two samples in mean bead

diameter is statistically significant (at  $\alpha=0.1$ ), based on an unbalanced (different sample sizes) analysis of means (ANOM) test (Nelson et al. 2005, see Figure 6.24).

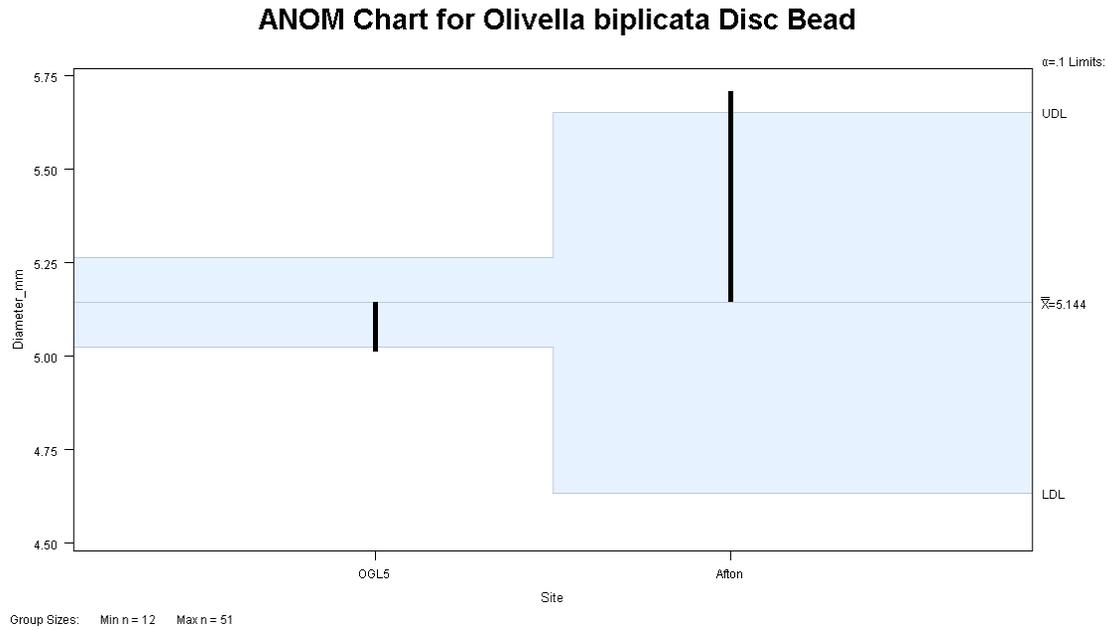


Figure 6.24. Comparison of mean diameter of *Olivella biplicata* disc beads from Oro Grande Locus 5 and the Afton Canyon site.

Finally, the Pacific Coast shell artifacts in Table 6.14 comprise much of the sample and are types common in the Chumash region circa A.D. 900-1100. This suggests much greater interaction between the inhabitants of the Afton Canyon site and southern California groups to the west, than with interior groups to the south and east that imported shell from the Hohokam system.

#### **4: Indian Hill Rockshelter**

The Indian Hill Rockshelter (CA-SDi-2537) is located in the Imperial Valley of southern California, and in the eastern foothills of the Jacumba Mountains. The site is also in close proximity to the southwestern shoreline of Lake Cahuilla. In fact, the Lake Cahuilla shoreline was within thirty kilometers (or a day's walk) of the site (McDonald 1992:65). Historic and ethnohistoric evidence suggests that in the absence of Lake Cahuilla, human occupation of the Imperial Valley was probably greatly reduced, because of extreme aridity (McDonald 1992:51). Also, ethnographic and ethnohistoric evidence suggests that a branch of the Kumeyaay were the main cultural group in the region, both historically and prehistorically, and that some of them relocated to the Colorado River after the loss of Lake Cahuilla (Hedges 1975; McDonald 1992:32).

McDonald (1992) concludes from radiocarbon (Table 6.15) and other evidence that depth is a good indicator of age in the 1986 Indian Hill Rockshelter excavation area (Figure 6.25) for the majority of excavation units (including the ones I use). Based on the radiocarbon results (Table 6.15) from excavation units D5 and D9 (see Figure 6.25 for the locations of the excavation units), depths of the Indian Hill Rockshelter (Figure 6.26) in the range of 15-21 inches closely correspond with calendar dates in the range A.D. 700-1100.

Table 6.15. Radiocarbon ages relevant for my study from the Indian Hill Rockshelter (Grisett 1986, 1996:253; McDonald 1992:102).

Radiocarbon Number	Excavation Unit	Depth (inches)	Radiocarbon Age C14 Years B.P.	Calendar Date (A.D.)	1-sigma (A.D.)	2-Sigma (A.D.)
UCR-2100	D5	15	890 +/- 50	990-1280	1046-1222	1025-1276
UCR-2439	D9	18-21	1210 +/- 75	687-938	715-953	665-998

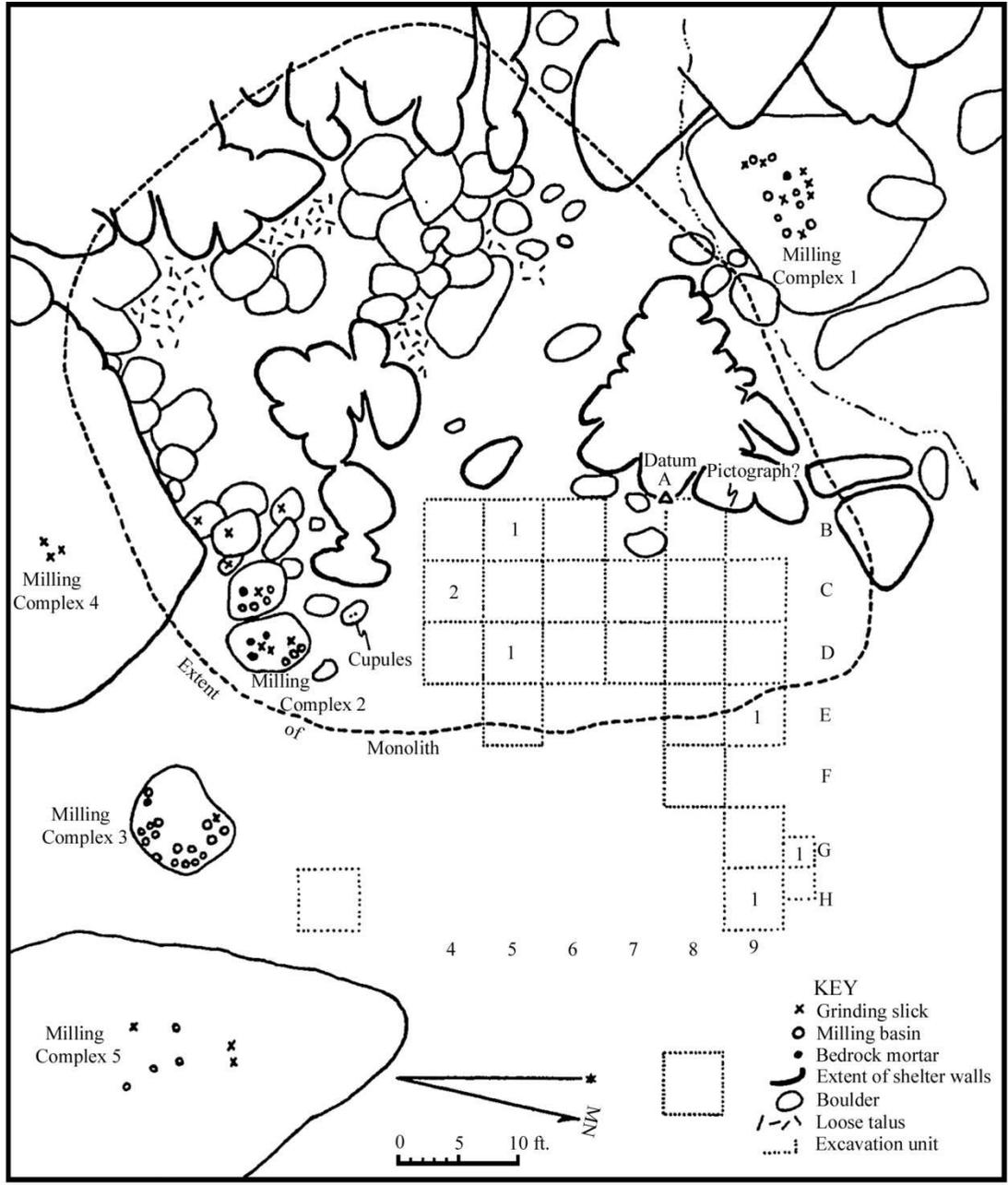


Figure 6.25. Indian Hill Rockshelter plan view with features, datum, and excavation units (modified Figure McDonald 1992:96). Numbers in excavation units are the number of shell artifacts from these levels in the 15-21 inch range, which are identified by species, type, and source in Table. Only units with numbers in them produced shell artifacts in the 15-21 inch range.

Gulf of California shell artifacts comprise most of the ca. A.D. 700-1100 Indian Hill Rockshelter sample (Table 6.16). These are types (e.g., *Olivella dama* barrel bead) commonly found in Pre-Classic Hohokam sites. For example, *Oliva* sp. beads, such as the type found in excavation unit E9 (depth 15-18 inches) are very common in Hohokam sites, and in some samples comprise as much as twelve percent of the shell (McDonald 1992:278). This suggests significantly more interaction (in relation to the importation of shell) with the Hohokam system than with groups on the Pacific Coast.



Figure 6.26. Indian Hill Rockshelter in the eastern foothills of the Jacumba Mountains in the Imperial Valley of southern California.

The single Pacific Coast shell artifact (*Olivella biplicata* barrel bead) in the Indian Hill sample in Table 6.16 is one of the most common types recovered from M5b (A.D. 1000-1050) Chumash sites (King 1990:136, 228). King (1981:174, 1990:135) also notes there is increasing base removal (or a trend of decreasing length) in *Olivella biplicata* barrel beads over time in the Santa Barbara Chumash region. This is the opposite pattern from the one observed in the Indian Hill Rockshelter sample, where length increases significantly with time (Figure 6.27).

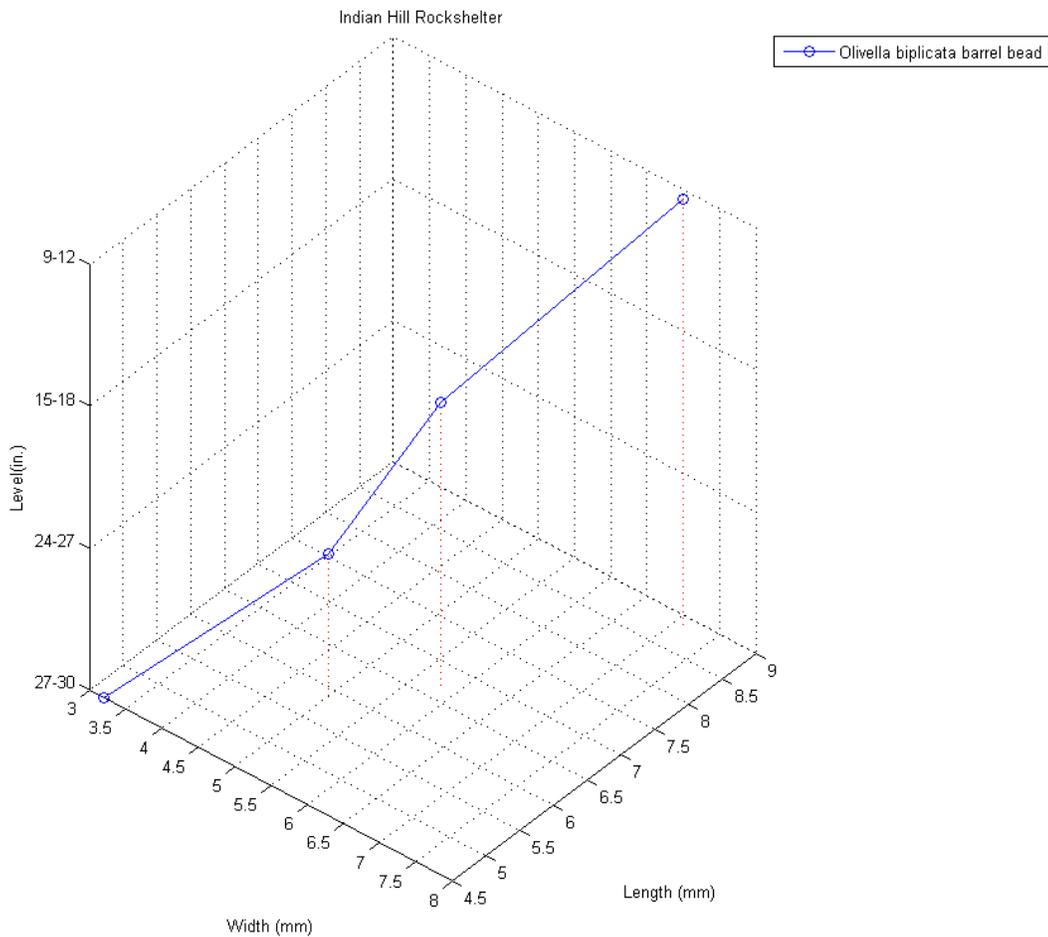


Figure 6.27. Plot of *Olivella biplicata* barrel bead width and diameter by level in the Indian Hill Rockshelter.

Table 6.16. Shell sample from the Indian Hill Rockshelter excavation that are from levels (based on the radiocarbon evidence, previous table), which likely correspond to A.D. 700-1100.

Excavation Unit	Depth (inches)	Shell	Source	Type
C4	15-18	<i>Olivella dama</i>	Gulf of California	Spire-chipped bead
G10	15-18	<i>Olivella dama</i>	Gulf of California	Spire- chipped bead
C4	18-21	<i>Olivella dama</i>	Gulf of California	Small barrel bead
E9	15-18	<i>Oliva undatella</i>	Gulf of California	Spire-chipped
B5	15-18	<i>Glycymeris</i> sp.	Gulf of California	Disc bead
D5	15-18	<i>Olivella biplicata</i>	Pacific Coast	Barrel bead (ground ends)

An *Olivella biplicata* barrel bead from Oro Grande Locus 7 (ca. A.D. 700-1000, see Figure 6.28) that is probably contemporaneous with Indian Hill *O. biplicata* barrel from the 15-18 inch level is very similar in length and width to one of Indian Hill *O. biplicata* barrels (Table 6.16, Figure 6.28). This suggests the temporal trend observed in the Indian Hill sample may be consistent, and that the Indian Hill *O. biplicata* barrels were not obtained from the Chumash. The Tongva region (another major southern California source of Pacific Coast shell artifacts) also appears to be an unlikely source for the Indian Hill *O. biplicata* barrels. Specifically, Gibson and Koerper (2000:349-350) find, using accelerator mass spectrometry dates of shell artifacts from controlled samples, that in the Newport Coast area of the Tongva region, *O. biplicata* barrels are strongly associated with deposits from a much earlier period (5350-1400 B.C.), than the time period of the Indian Hill *Olivella biplicata* barrel bead sample (which is from levels no deeper than 30 inches, with associated radiocarbon dates after 1400 B.C., see Table 6.17). It is possible that Kumeyaay artisans made the *O. biplicata* barrels in the Indian Hill sample, from shell harvested in the San Diego area. This is because the Kumeyaay historically (and probably prehistorically) regularly traveled between their territories on the San Diego Coast and the interior, including the area of the Anza Borrego Desert, where the Indian Hill Rockshelter is located (McDonald 1992; Shipek 1982:298, 301). Gamble and King (2008:9) make a similar conclusion that a comparable shell bead type (*Olivella biplicata* spire-removed bead) found at sites (e.g., Borrego Valley and Mason Valley) in the Anza Borrego Desert was probably manufactured in San Diego County (Kumeyaay territory).

In sum, during the major stands of Lake Cahuilla (which I discuss in Chapter 4) people who utilized the large and ecologically diverse region between the San Diego coast and the Imperial Valley, probably spent much more time in the area near the Indian Hill Rockshelter, which would have provided more opportunity to make shell beads there and at other locales in the Anza Borrego Desert. The results also suggest that at least some of the people living in the vicinity of Lake Cahuilla were mostly autonomous from coastal groups to the northwest, that include the Tongva and Chumash, and that much more of their interaction was with interior groups to the east (including members of the Hohokam system).

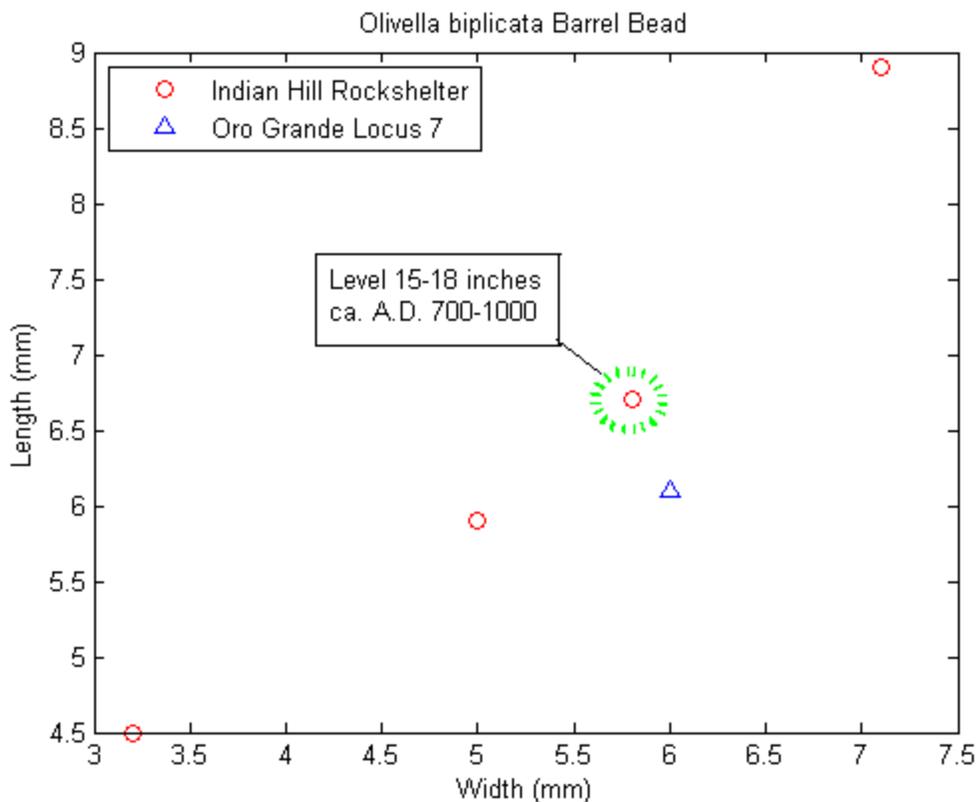


Figure 6.28. Comparison of width and length of *Olivella biplicata* barrel beads from the Indian Hill Rockshelter and Locus 7 of the Oro Grande site.

Table 6.17. Radiocarbon data for the Indian Hill Rockshelter (McDonald 1992) for depths between 27 and 42 inches.

Radiocarbon Number	Excavation Unit	Depth (inches)	Radiocarbon Age C14 Years B.P.	Calendar Date (B.C.)
UCR-2437	C9	27-28	2600 +/- 200	972-410
UCR-2441	D9	33-36	2320 +/- 70	410-364
LI-4216	D8	36-42	3840 +/- 80	2649-2144

### 5: A Lake Cahuilla Shoreline Site

The majority of recent shell data from Lake Cahuilla shoreline sites has resulted from CRM testing related to highway construction and residential development (Michael Morratto and Associates, Applied Earthworks, personal communication 2009). The bulk of the shell artifacts (which amounts to many large samples) produced by the CRM work is from cremation burials, and is protected by NAGPRA. Unfortunately, I was not able to get access to any of these samples or given their locations because the representative from Applied Earth Works that I talked to was not given authorization to provide me with that information. He told me that the shell and other grave goods were going to be repatriated.

The only data I currently have from Lake Cahuilla shoreline sites, which unambiguously corresponds to the time period of my study, is from a collection made by Douglas N. Fain (a local Coachella Valley artifact collector) in the mid 1970's.

Specifically, the collection he made from a deflating dune, east of Point Happy, and north of Highway 111 (which I call FW-9) contained several Gulf of California shell artifacts, including three *Glycymeris* sp. bilobed beads, which very likely were made in the Hohokam system (Figure 6.29). FW-9 is located on the northern tip of Lake Cahuilla (Figure 6.29), which today is part of a residential development.



Figure 6.29. Location of FW-9.

Haury (1937:140) provides a chronological assessment of bilobed beads from Snaketown.

A distinction in the bi-lobed class of beads can be drawn on the basis of size. In the Santa Cruz Phase, the type was usually small; averaging less than 5 mm in length, while in the Sacaton Phase the average length was approximately 1 cm.

A graphical comparison (with a dot plot) of the lengths of the FW-9 bilobed beads with dated samples from the Hohokam system (Vokes 1983), and the two bilobed beads from Locus 5 of the Oro Grande site (A.D. 1000-1100), suggests that the FW-9 bilobed beads have the strongest affinity to the Sacaton Period (A.D. 950-1100) bilobed beads from Snaketown (Figure 6.30). Also the FW-9 beads cluster at approximately 10 mm (Figure 6.30), which places them in the Sacaton, using Haury's classification scheme. This suggests that the occupants of FW-9 imported shell from the Hohokam system during the Sacaton Period.

The FW-9 case study provides preliminary evidence that suggests shell artifacts manufactured in the Pre-Classic Hohokam system may have been regularly imported by residents of the north shore of Lake Cahuilla. Future research on northern and other Lake Cahuilla sites should include the careful recordation and analysis of Gulf of California shell artifacts, to provide a better understanding of the intensity of interaction between Lake Cahuilla people and people in the Hohokam system (ca. A.D. 700-1100).

### Glycymeris sp. Bilobed Beads

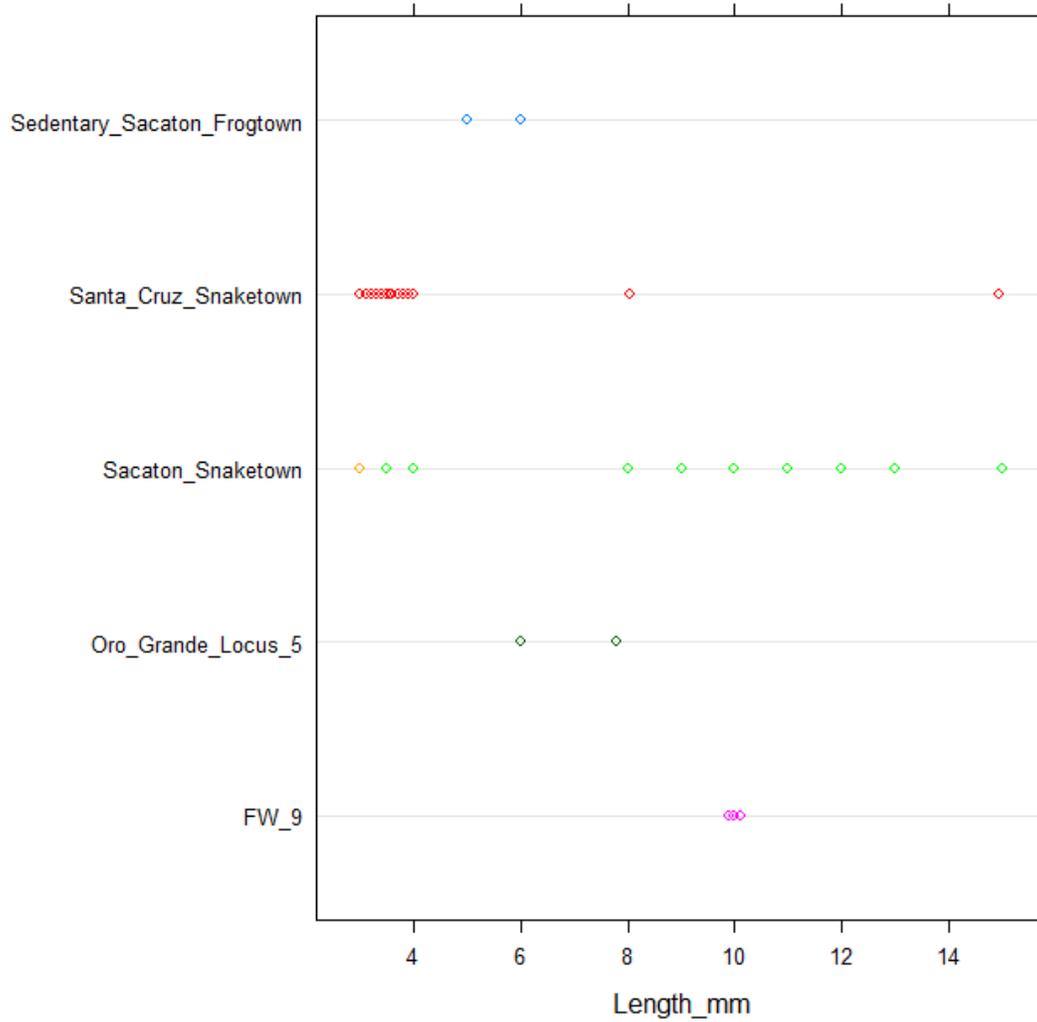


Figure 6.30. Comparison of the length of Santa Cruz and Sacaton Phase *Glycymeris* sp. bilobed beads with the bilobed beads from Oro Grande Locus 5 and the Fain-Wilke Lake Cahuilla shoreline sample (FW-9).

## 6: Escuela Site

The Escuela site is within the Hohokam system, and is located in the Gila Bend area, near the Gila River. The shell sample is from a cremation burial with Santa Cruz phase Hohokam pottery (ca. A.D. 700-900, see Figure 6.31). It is from the Norton Allen collection (ASM accession # 97-194). This sample is predominated by Pacific Coast shell (*Olivella biplicata* disc beads, possibly from a single necklace placed in the burial).

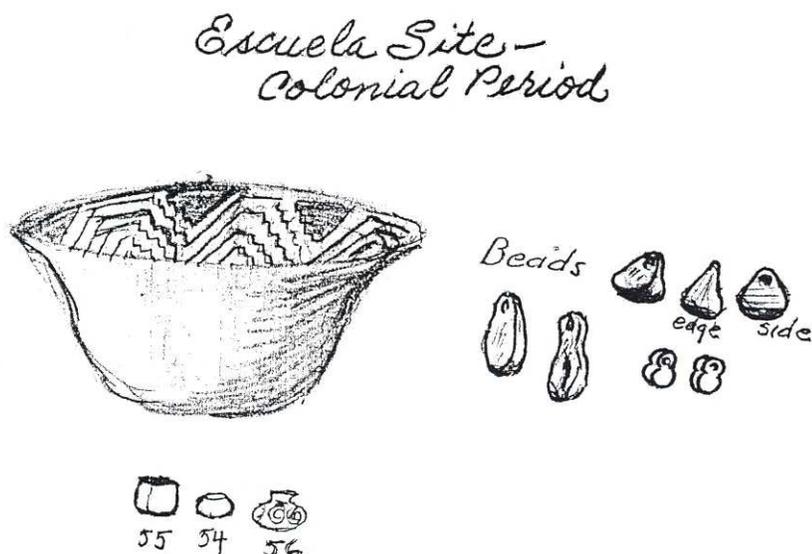


Figure 6.31. Norton Allen drawing of some of the pottery and shell beads recovered from the Escuela site.

The significantly greater diversity of Gulf of California shell artifacts in the burial (one *Glycymeris* sp. ring fragment, one *Laevicardium elatum* disc bead, eighteen *Glycymeris* sp. bilobed beads, seven *Spondylus* sp. pyramid beads, and five *Spondylus* sp. hinge beads) suggests locally made Gulf of California shell artifacts (at the time of the burial) were probably more socially and economically significant in this part of the Hohokam system than Pacific Coast shell artifacts.

The *Olivella biplicata* wall disc beads from the Escuela Site burial were very likely made in the Chumash area. King (1990:149) provides evidence that supports this.

During Phase M4, the general size of *Olivella biplicata* disc beads reduced so that few had diameters greater than 6.0 mm; perforation sizes also reduced to generally less than 1.6 mm in diameter. A number of other Phase M4 collections from the historic Chumash area also indicate that *Olivella biplicata* wall disc beads were virtually the only type of shell bead being manufactured during Phase M4.

Thirteen *Olivella biplicata* wall disc beads from the Escuela site burial were measured, and all have diameters less than 6 mm (the largest in the sample has a diameter of 4 mm), and all have a perforation size (hole diameter) less than 1.6 mm. Also, there are no other beads made from Pacific Coast shell (e.g. *Mytilus californianus*) in the Escuela sample, which matches King's criteria for M4 (A.D. 700-900) *Olivella biplicata* wall disc beads from the Chumash area. In addition, M4 has significant overlap with the Hohokam Santa Cruz Phase. Comparison of the Escuela wall disc bead sample (both outside and hole diameter) with M5a (A.D. 900-1000) burials from the Malibu (LAn-264) cemetery using a simulation based 2-sample Smirnov test (Appendix C) shows that the Escuela beads have significantly smaller outside diameters (Figure 6.32, Table 6.18), and perforation sizes (Figure 6.33, Table 6.19) than the Malibu beads. These results match the observation of King 1990:149, that M5a-b (A.D. 900-1050) *Olivella biplicata* wall beads made in the Chumash area usually have larger outside and perforation diameters than M4 *O. biplicata* wall disc beads. In sum, it is very likely the Escuela sample of *Olivella biplicata* wall disc beads were manufactured in the Chumash area during A.D. 700-900.

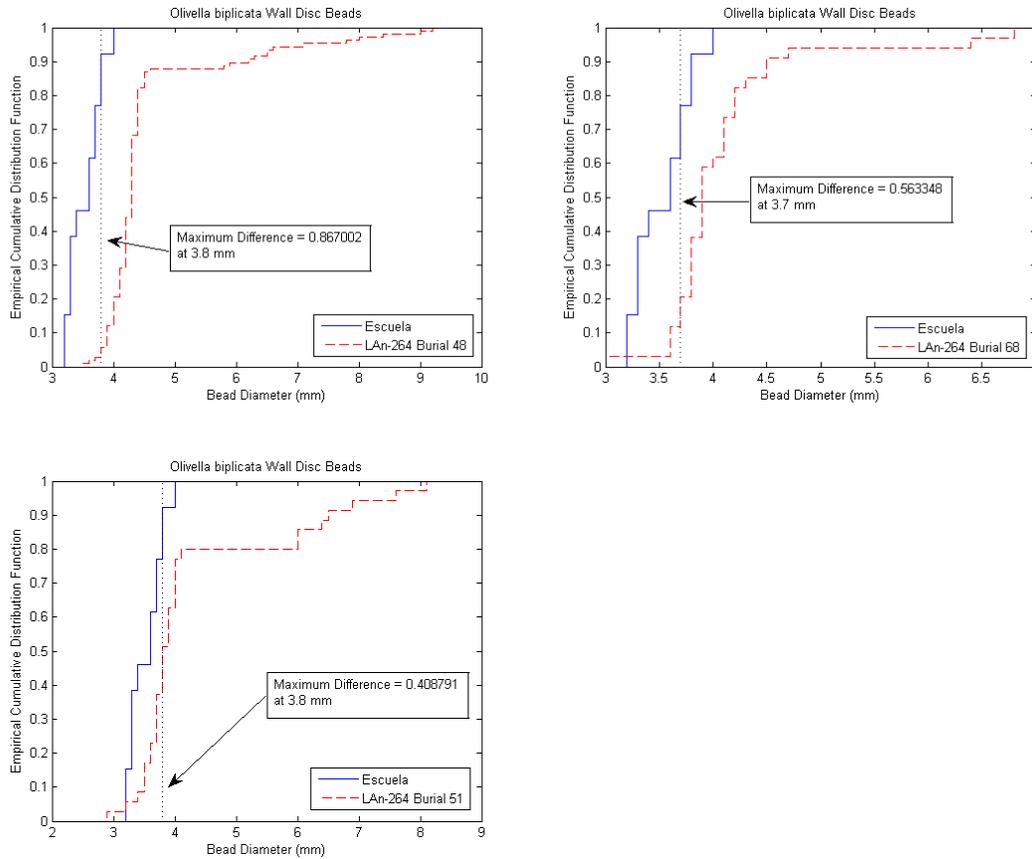


Figure 6.32. Comparison of *Olivella biplicata* disc bead diameter between the Escuela site and three chronologically ordered burials from the Malibu site (LAN-264).

Table 6.18. Summary of results from the 2-sample Smirnov test on *Olivella biplicata* disc bead diameter.

Escuela verses	Smirnov Statistic (Observed Maximum Difference between ECDF plots)	Maximum Difference Between ECDF plots (Random Partition)	P-value (Number $\geq$ Observed)/2000
Burial 48	0.867002 at 3.8 mm	0.154565 at 4.0 mm	1/2000 = 0.0005
Burial 68	0.563348 at 3.7 mm	0.248869 at 3.3 mm	1/2000 = 0.0005
Burial 51	0.408791 at 3.8 mm	0.151648 at 3.4 mm	64/2000 = 0.032

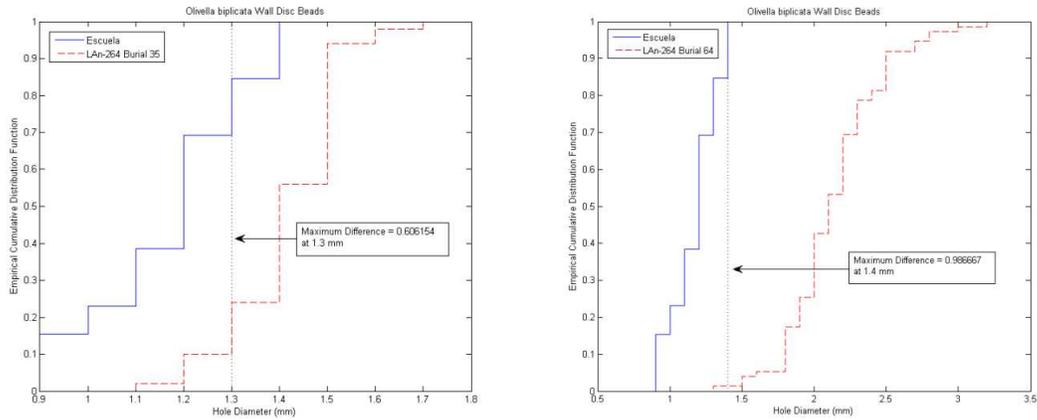


Figure 6.33. Comparison of *Olivella biplicata* disc bead hole diameter between the Escuela site and two chronologically ordered burials from the Malibu site (LAN-264).

Table 6.19. Summary of results from the 2-sample Smirnov test on *Olivella biplicata* disc bead hole diameter.

Escuela verses	Smirnov Statistic (Observed Maximum Difference between ECDF plots)	Maximum Difference Between ECDF plots (Random Partition)	P-value (Number $\geq$ Observed)/2000
Burial 35	0.606154 at 1.3 mm	0.238462 at 1.4 mm	1/2000 = 0.0005
Burial 64	0.986667 at 1.4 mm	0.306667 at 2.2 mm	1/2000 = 0.0005

### 7: Oatman Flat (Deepwell Ranch)

The Oatman Flat site is near Eloy, Arizona and is a few kilometers south of the city of Casa Grande. The sample is from a cremation burial excavated by Norton Allen in 1938 (ASM draft 2001). This sample is probably later than the Escuela Site sample, and as with the Escuela sample, the significantly greater proportion and greater diversity of

locally made Gulf of California shell artifacts (four *Glycymeris* sp. bracelet fragments, nineteen *Olivella dama* spire-ground beads, one *Theodoxus leutofasciatus* face ground bead) compared to Pacific Coast shell artifacts (five *Olivella biplicata* barrel beads) may relate to greater social and economic importance of Gulf of California shell artifacts in the Gila River component of the Hohokam system (ca. A.D. 900-1100). Interestingly, four of the *Olivella biplicata* barrel beads are much larger than typical beads of this type from the Chumash area during this time, as well as the barrel bead from the Indian Hill Rockshelter (Figure 6.34). As with the Indian Hill bead, it is possible Kumeyaay artisans made the Oatman Flat barrel beads, but future research should focus on sourcing these beads.

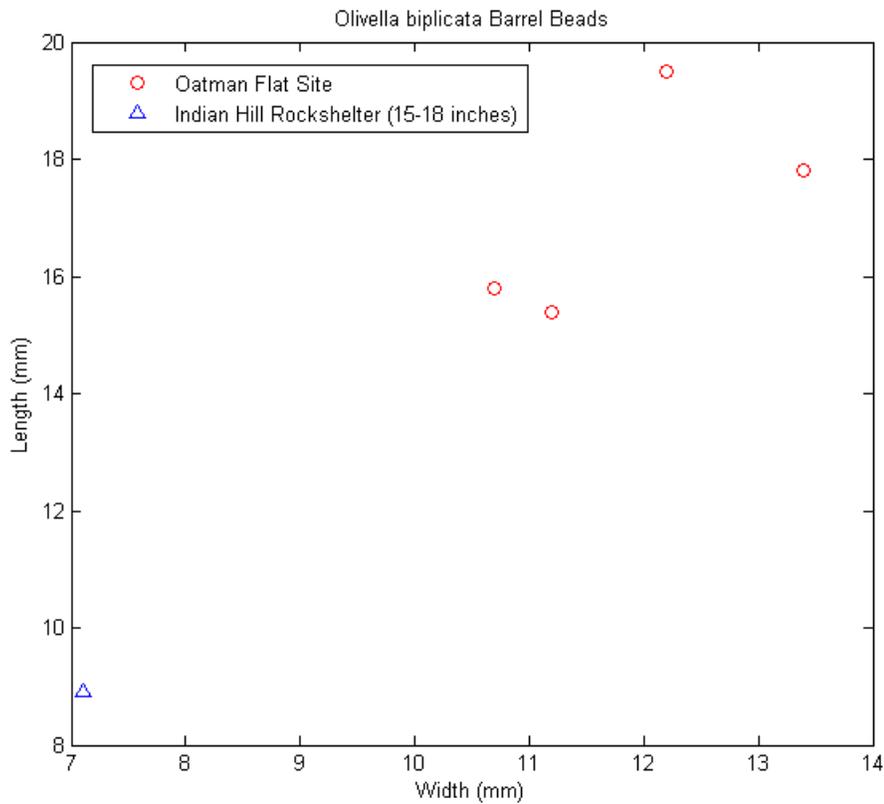


Figure 6.34. Comparison of *Olivella biplicata* barrel bead width and diameter in the Oatman Flat and Indian Hill Rockshelter samples.

## Summary

The purpose of each of the statistical analyses in this chapter is to identify patterns in shell artifact data from residential sites in the Hohokam/California transregion that provide insight into the organization and dynamics of interregional interaction in the transregion during A.D. 700-1100. Many of these analyses are probably unfamiliar to most archaeologists and are not available in “off the shelf” statistical software packages, which is why additional information, including computer code to implement them is provided in appendices. Also, the diversity and complexity of some of these methods may be a point of contention, but I argue that: (1) each method is relevant for the kind of data being analyzed, (2) the diversity of methods is a result of the diverse types of data and not ad hoc selection of methods to produce desired results, and (3) their complexity is simply a consequence of the complexity of the data and the problems being addressed.

The shell artifact samples from sites in the Hohokam/California archaeological cases analyzed in this chapter provide substantial support for the idea of the frequent export of Hohokam shell artifacts into the Lake Cahuilla region of southern California (ca. A.D. 900-1100) and by comparison very limited importation of Pacific Coast shell preciosities into the Hohokam system. The results of the Malibu study also suggest a rapid increase in the production of *Olivella dama* barrel beads in the Hohokam system during A.D. 900-1000 followed by a rapid decline in the production of these beads. These results also suggest an increase in the importation of *O. dama* barrels into southern California during A.D. 900-1000.

These studies also suggest that Hohokam shell was traded into several regions of southern California during A.D. 700-1100, but most of it was probably being brought into

the Lake Cahuilla region. Figure 6.35 provides a graphical summary of the movement of Gulf of California and Pacific Coast shell suggested by the studies and the locations of the sites in the Hohokam/California transregion. The thickness of the arrows in the graph provides an indication of the intensity of exchange. The pattern of interregional interaction in Figure 6.35 is consistent with the network model at the end of Chapter 3. Specifically, Figure 6.35 shows a major flow of shell artifacts from the Gila River Hohokam/Lowland Patayan region into the Lake Cahuilla region (Indian Hill Rockshelter site). This supports the idea that large quantities of Hohokam shell artifacts were exported to the Lake Cahuilla region between A.D. 900 and 1100. Figure 6.35 also shows the Chumash region (Malibu site) as the major source of Pacific Coast shell artifacts that entered the remainder of the Hohokam/California transregional system through the Tongva.

It is quite possible that Hohokam shell artifacts may have most often been exchanged for dried Lake Cahuilla fish. Future Hohokam studies should prioritize using finer screen sizes (ideally 1/16" mesh or finer), to recover much larger samples of small shell artifacts (such as *Olivella dama* small barrels), and to permit the recovery of small fish bone, in order to test my hypothesis that dried Lake Cahuilla fish was a major import item into the Hohokam system circa A.D. 900-1100.

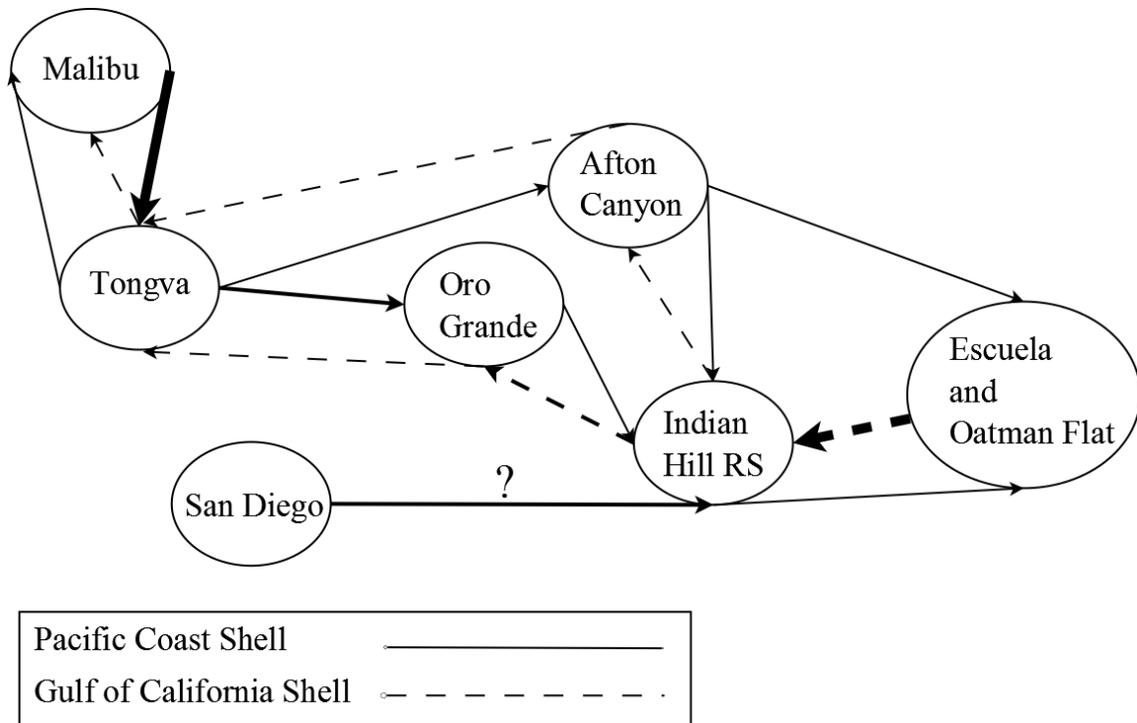


Figure 6.35. Graphical summary of the movement of shell in the Hohokam/California transregion, based on the results from all but one (FW-9) of the archaeological case studies, and other evidence (Chapter 3) for the movement of shell in and out of the Tongva region. The thickness of lines indicates exchange intensity. Case studies and their associated regions are: Malibu (Chumash region), Afton Canyon (Hopik region), Oro Grande (Serrano region), Indian Hill rockshelter (Kumeyaay and Lake Cahuilla region), Escuela (Hohokam/Patayan region), and Oatman Flat (Gila River Hohokam system).

## CHAPTER 7: EVALUATING THE EXISTENCE AND STRUCTURE OF THE HOHOKAM/CALIFORNIA TRANSREGIONAL SYSTEM

Network analysis using graph theory and other mathematical methods provides a rigorous means of predicting structural and operational properties of prehistoric exchange systems. The predictive power of network analytic methods has been suggested by numerous studies of ethnographic data (Grofman and Landa 1983; Hage 1977; Hage and Harary 1996:165-217; Kirch 1991:145). For example, ethnographic studies have suggested that middlemen are most often found in highly central positions within networks. Motivated by this observed pattern, Hage (1977) used the Kula Ring exchange system of the Trobriand Islands (Malinowski 1922) as a test case and a graph-theoretic measure of network centrality, to show that Tabetube island (a Kula Ring locale occupied mostly by specialist middlemen traders, Kirch 1991:145) had the greatest global centrality of all the islands within the Kula Ring network. Hunt 1988 provides an early example of the use of network analytic methods to the study of a prehistoric exchange system (Lapita culture). Very recently network analysis has rapidly gained interest and use among archaeologists (Brughmans 2010, 2013; Knappett 2013), particularly in the context of regional interaction. Two recent studies have used network analytical methods to study temporal patterning in reconstructed social networks in the prehistoric U.S. Southwest (Mills et al. 2013a, 2013b). Another study (Peeples and Haas 2013) uses a network analytical approach to study brokerage and social capital in the prehistoric western U.S. Southwest.

The first part of this chapter provides two network analyses of a reconstructed graphical model of the Hohokam/California tranregional system (the end of Chapters 3

and 6). The model was created using ethnographic, ethnohistoric, and archaeological information provided in Chapters 3 and 6. The model is organized at the regional scale, as an undirected graph, where the nodes of the graph represent distinct regions (e.g., Lower Patayan) in the system, and edges signify interaction between pairs of regions. My study uses network analytical methods (that although suitable) have not (to my knowledge) previously been applied to archaeological data. The goal of my network analytic study is to: (1) provide evidence for the existence of the Hohokam/California transregional system and (2) reveal and validate the hidden multidimensional structure of the network model that was constructed from ethnohistoric, ethnographic, and archaeological data in Chapters 3 and 6 in order to better understand how relationships between regions in the Hohokam/California transregional system may relate to the fragility and persistence of the system.

The second part of this chapter provides a kriging analysis, which uses the proportions of Gulf of California and Pacific Coast shell in archaeological sites, and the relative spatial locations of the sites as raw data. The kriging analysis is used to test the hypothesis that the movement of shell within the transregion was directional and not random.

### **Existence of the Hohokam/California Transregional System**

If the Hohokam/California transregional system were an organized system of exchange, the reconstructed network model (Chapter 3, Figure 7.1) would not likely have a topology consistent with network graphs with the same number of nodes and edges that result from random processes. Figure 7.1 is the simple graphical model of the Hohokam/California transregional system resulting from the studies in Chapters 3 and 6

(see Appendix Q for the R script used to make Figure 7.1). In this simple model, lines connecting nodes (regions) are not weighted by directional bias or volume of exchange. Lines only indicate that there is frequent interaction between pairs of regions. Table 7.2 is the adjacency matrix for the network graph in Figure 7.1, where a one in the matrix results in a line connecting a pair of nodes (regions) in the graph and a zero in the matrix results in the absence of a line between a pair of nodes (regions) in the graph.

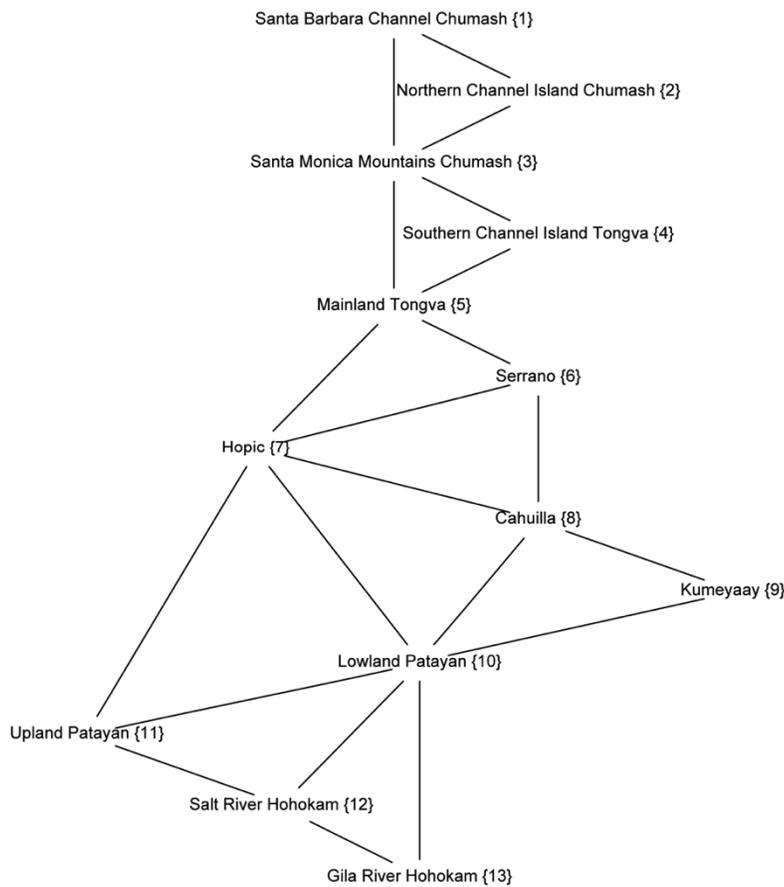


Figure 7.1. The Hohokam/California transregional system as a network graph. The numbers in curly brackets in this figure correspond to the regions they are next to. The numbers in Table 7.1 and Figures 7.4 and 7.7 also correspond to the same regions.

Table 7.1. Key to the numbers in Figures 7.4 and 7.7.

Number	Region
1	Santa Barbara Channel Chumash
2	Northern Channel Island Chumash
3	Santa Monica Mountains Chumash
4	Southern Channel Island Tongva
5	Mainland Tongva
6	Serrano
7	Hopic
8	Cahuilla
9	Kumeyaay
10	Lowland Patayan
11	Upland Patayan
12	Salt River Hohokam
13	Gila River Hohokam

Table 7.2. Adjacency matrix of Hohokam/California transregional network graph.

Region		1	2	3	4	5	6	7	8	9	10	11	12	13
		-	-	-	-	-	-	-	-	-	-	-	-	-
Santa Barbara Channel Chumash	1	0	1	1	0	0	0	0	0	0	0	0	0	0
Northern Channel Island Chumash	2	1	0	1	0	0	0	0	0	0	0	0	0	0
Santa Monica Mountains Chumash	3	1	1	0	1	1	0	0	0	0	0	0	0	0
Southern Channel Island Tongva	4	0	0	1	0	1	0	0	0	0	0	0	0	0
Mainland Tongva	5	0	0	1	1	0	1	1	0	0	0	0	0	0
Serrano	6	0	0	0	0	1	0	1	1	0	0	0	0	0
Hopic	7	0	0	0	0	1	1	0	1	0	1	1	0	0
Cahuilla	8	0	0	0	0	0	1	1	0	1	1	0	0	0
Kumeyaay	9	0	0	0	0	0	0	0	1	0	1	0	0	0
Lowland Patayan	10	0	0	0	0	0	0	1	1	1	0	1	1	1
Upland Patayan	11	0	0	0	0	0	0	1	0	0	1	0	1	0
Salt River Hohokam	12	0	0	0	0	0	0	0	0	0	1	1	0	1
Gila River Hohokam	13	0	0	0	0	0	0	0	0	0	1	0	1	0

To test the null hypothesis that the reconstructed network graph is the result of random processes (e.g., artifacts move between regions via random walks) I use the  $G(n, M)$  Erdős-Rényi random graph model (Erdős and Rényi 1959), where  $n$  is the

number of nodes and  $M$  the number of edges in the graph. The  $G(n, M)$  model is Poisson-distributed, where edges are chosen uniformly randomly from the set of all possible edges which is done in the following way in the current analysis. The reconstructed network model has thirteen nodes and twenty-one edges, so I use the  $G(13,21)$  model, in which for each random graph, one picks eleven of the  $\frac{13(13-1)}{2} = \frac{13*12}{2} = \frac{156}{2} = 78$  possible edges between the thirteen vertices at random. From a more general mathematical perspective the Erdős-Rényi process is an unweighted link percolation process on the complete graph (Broadbent and Hammersley 1957; Bollobás 2001; Bollobás and Riordan 2006).

*Transitivity* measures the probability that adjacent vertices of a vertex are connected. This is sometimes also called the global clustering coefficient (see Wasserman 1994 for a mathematical definition). Empirical evidence suggests that in most real-world networks there are well connected subgroups (e.g., hubs, cliques, and motifs) that occur on average more often than would happen if ties (edges) were randomly established between pairs of nodes, such as is the case with  $G(n, M)$  Erdős-Rényi random graphs (Holland and Leinhardt 1971; Watts and Strogatz 1998). This suggests that if the transitivity of the reconstructed network model (Figure 7.1) is greater than would be expected in a  $G(13,21)$  model than the reconstructed network model is very likely representative of an organized system of exchange.

In an undirected graph, the shortest path between a pair of vertices is the path that connects the pair through a minimal number of vertices. *Average path length* in a graph is determined by calculating the shortest paths between all pairs of vertices in the graph. Average path length is an aspect of network topology that is defined as the average

number of steps along the shortest paths for all possible pairs between network nodes. It measures the efficiency of the movement of information, people or materials in a network. Most real networks have a short average path length, which is often called the small world effect, in which each node in the network is connected to all other nodes in the system via a short path.

Steps of the Analysis (see Appendix S for the R code used to implement these steps).

Step 1. Generate 10,000 Erdős-Rényi  $G(13,21)$  random graphs.

Step 2. Compute the transitivity and average path length for each random graph.

Step 3. Compute the transitivity and average path length for the reconstructed network graph.

Step 4. Construct histograms of the approximate sampling distributions for transitivity and average path length using the data from Steps 2 and 3 graphs.

Step 5. Compute estimates of the p-values for the transitivity and average path length values from the reconstructed network graph to test the null hypothesis.

The transitivity of the reconstructed network model (Figure 7.1) is larger than would be expected in a randomly generated system (p-value =  $4e-05$ , see Figure 7.2). This suggests there are subgroups in the graph that are highly interconnected, which is expected in an organized real-world system of exchange. This strongly supports the existence of a Hohokam/California transregional system.

The fact that the reconstructed network has a longer average path than would be expected in a randomly generated system (Figure 7.3) may relate to the network having two walktrap communities (described in next section), which are largely autonomous. In a future study I will compare the average path lengths of the coastal and interior communities to see if these values are significantly smaller than what would be expected

in a randomly generated system, but within the range expected in a small world system of their size. The much larger than expected ( $p\text{-value} = 0.0028$ ) average path length in the reconstructed network model (Figure 7.3) strongly suggests that the network model is representative of an exchange system that was not generated by random processes (i.e. the model is representative of an organized system of exchange). Based on these results the null hypothesis that the reconstructed network model of the Hohokam/California regional is representative of a randomly generated system (i.e. the Hohokam/California transregional system did not exist) is rejected at  $\alpha = 0.05$ .

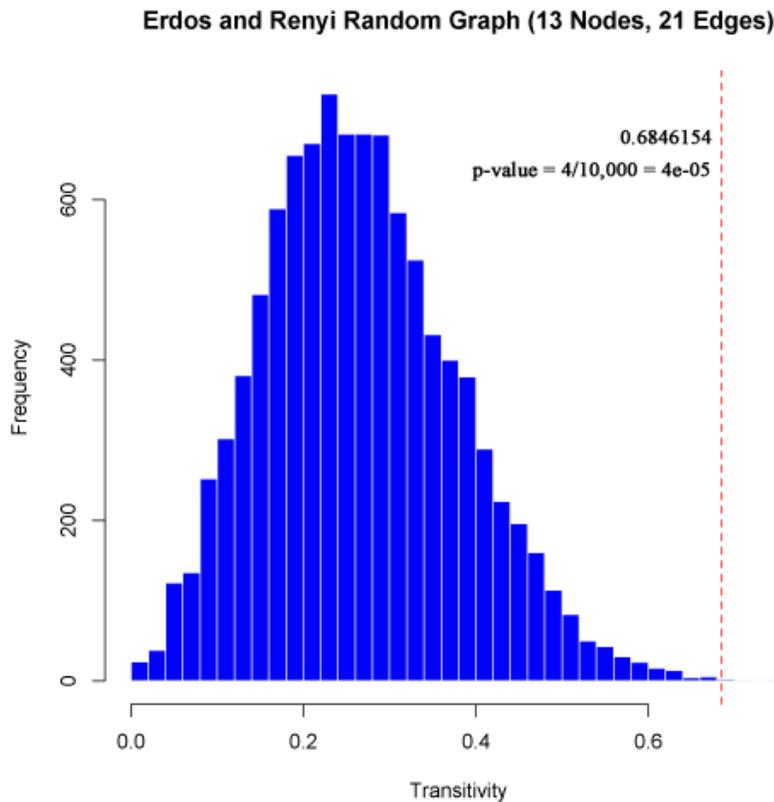


Figure 7.2. Approximate sampling distribution of transitivity for 10,000 Erdős-Rényi  $G(13,21)$  random graphs. Vertical dashed red line is the transitivity of the reconstructed network model (Figure 7.1).

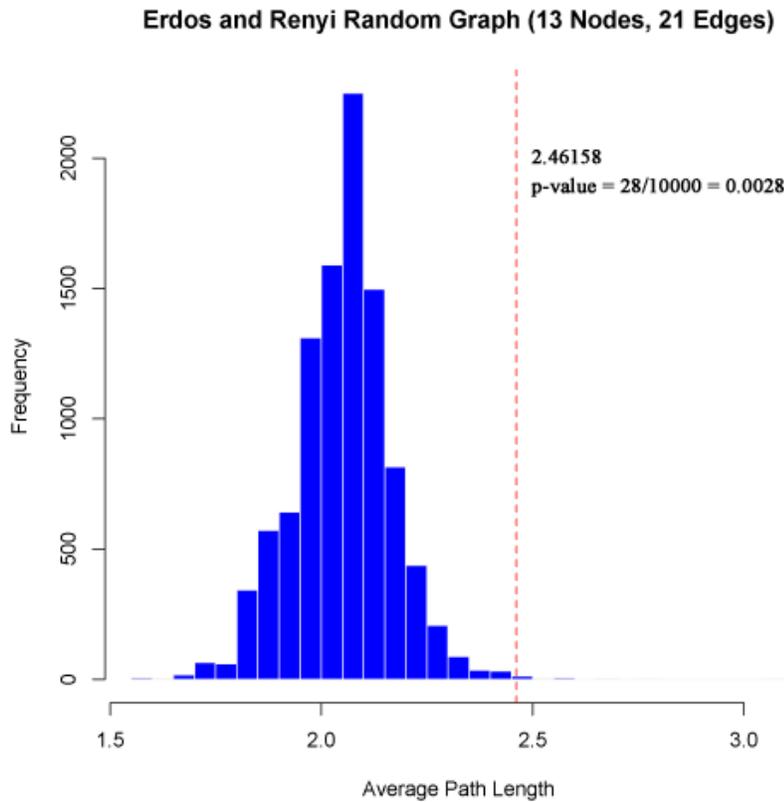


Figure 7.3. Approximate sampling distribution of the average path length for 10,000 Erdős-Rényi  $G(13,21)$  random graphs. Vertical dashed red line is the average path length of the reconstructed network model (Figure 7.1).

### Walktrap Community Detection Algorithm

The logical basis of the walktrap community detection approach is that it is reasonable that a random walker with a limited number of steps is more likely to remain within a community (consisting of a cluster of well connected community members) than to travel a less well-connected path into another community. Short random walks are more likely to not cross community boundaries than long walks. This is why the walktrap community detection algorithm (as implemented in the R `igraph` package) runs short random walks of three, four or five steps (depending on one of its parameters). I used the

default setting of four steps in my analysis. The walktrap algorithm uses the results of these random walks to merge separate communities in a bottom-up manner, which is an agglomerative hierarchical clustering process. In this process adjacent communities (having at least one edge in the graph connecting them) are merged based on their distance to each other. Also, in the walktrap algorithm, two communities are merged according to Ward's minimum variance method. Specifically, at each step  $k$  in the algorithm (see Pons and Latapy 2005:8-9), the algorithm merges the two communities that minimize the mean of the squared distances between each vertex and its community [where the squared distances are a special case of  $(r_{(i)C})^2$ , below, in which  $C$  is the community of  $i$ ]. Pons and Latapy (2005:4) define distances used in the walktrap algorithm in the following ways:

(1) the distance  $(r_{ij})$  between two vertices in a network graph with  $n$  vertices as:

$$\sqrt{\sum_{k=1}^n \frac{(P_{ik}^t - P_{jk}^t)^2}{d(k)}}$$

where  $P_{ik}^t$  is the probability of traveling in a random walk from a vertex  $i$  in the network to a vertex  $k$  in the network in  $t$  steps and  $P_{jk}^t$  is the probability of a random walk going from a vertex  $j$  in the network to a vertex  $k$  in the network in  $t$  steps.  $d(k)$  is the degree of vertex  $k$  (the number of connections between vertex  $k$  and other vertices in the network).

(2) the distance ( $r_{C_1C_2}$ ) between two communities in the network graph as:

$$\sqrt{\sum_{k=1}^n \frac{(P_{C_1k}^t - P_{C_2k}^t)^2}{d(k)}}$$

where  $P_{C_1k}^t$  is the probability of a random walk going from community  $C_1$  in the network to a vertex  $k$  in the network in  $t$  steps and  $P_{C_2k}^t$  is the probability of a random walk going from community  $C_2$  in the network to a vertex  $k$  in the network in  $t$  steps.  $d(k)$  is the same as before.

(3) the distance between a vertex  $i$  and community  $C$  in the network graph as:  $r_{iC} = r_{(i)C}$

$$\sqrt{\sum_{k=1}^n \frac{(P_{ik}^t - P_{Ck}^t)^2}{d(k)}}$$

where  $P_{ik}^t$ ,  $P_{Ck}^t$ , and  $d(k)$  follow from the definitions in (1) and (2).

The agglomerative hierarchical clustering process used by the walktrap algorithm produces a sequence of partitions of nodes (vertices) from the network graph (each of which is a community within a hierarchy of communities). The result of the algorithm is a hierarchical structure of communities that can be visually displayed as a dendrogram. The vertical distance on the y-axis of the dendrogram is the distance measure between two communities defined by Pons and Latapy [distance  $r_{C_1C_2}$  above]. In mathematical terms the Pons and Latapy distances are metrics (specifically Euclidean distances in  $\mathbb{R}^n$ ). This means that these distances are directly relatable to community membership. For example, the smaller the value of the distance  $r_{ij}$  [(1) above] between two vertices ( $i$  and

j) the greater the probability they belong to the same community. It is also necessary to decide which partitions in the sequence of partitions of vertices produced by the algorithm are most likely to correspond to actual communities. Pons and Latalpy 2005 (p. 10) use the maximal modularity score (introduced by Newman 2004 and Newman and Girvan 2004) as a stopping criterion for the number of merge steps (or, equivalently, where to cut the dendrogram), which, in turn, determines the number of communities detected.

### **Walktrap Communities and Modularity in the Hohokam/California Transregional Network**

In this section I use the walktrap algorithm to reveal structural and organizational elements of the Hohokam/California transregional system. In a graphical model of a network, communities are often conceptualized as highly cohesive or densely connected subgraphs, or equivalently as “subsets of vertices within which vertex-vertex connections are dense, but between which connections are less dense” (Girvan and Newman 2001:1).

As Girvan and Newman (2001:2) state.

The ability to detect community structure in a network could clearly have practical applications. Communities in a social network might represent real social groupings.

The walktrap communities in the following network graph of the Hohokam/California transregional system were detected (as mentioned earlier) using the R statistical igraph package (see Appendix R for more information). The two communities identified in the graph split the system into a coastal and interior community (Figure 7.4, also see Table 7.1). The interior community is where much of the interaction between Lake Cahuilla people and people in the Hohokam system would have occurred. Also, the division of the

system into two communities or modules, suggests relative autonomy between the coastal and interior communities, which may mean that neither was strongly dependent on the other, and that the collapse of one of the modules may not have resulted in a significant shock to the other. This suggests that the bioeconomic model developed and analyzed in the next chapter should focus on the interior community, since my primary interest concerns fragility/robustness tradeoffs in the Pre-Classic Hohokam system and how involvement of the Hohokam system in transregional exchange may have affected its stability and persistence.

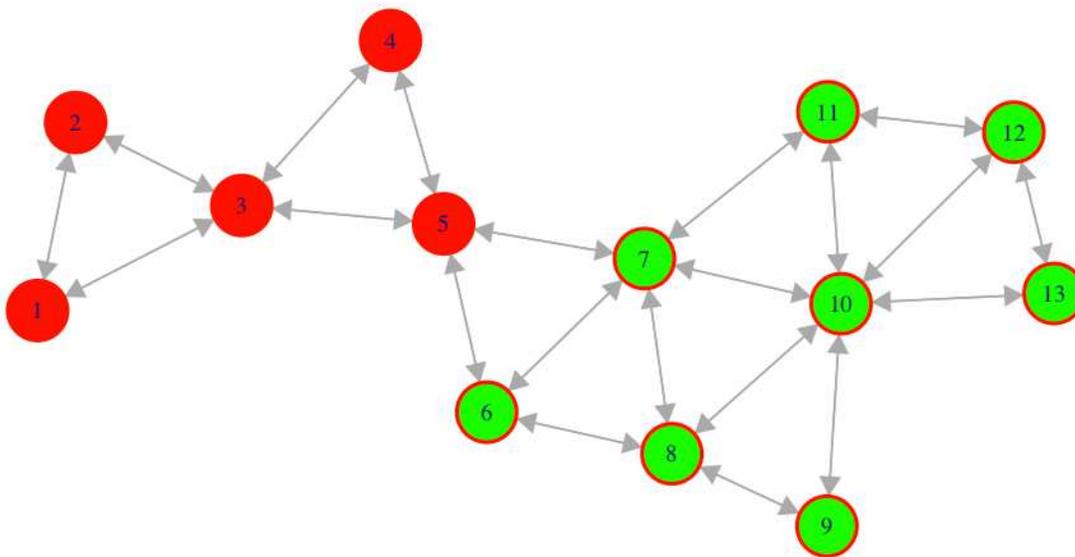


Figure 7.4. Hohokam/California transregional network graph with the two walktrap communities associated with the maximum (optimal) modularity. This division of the network identifies a coastal (red) group (Walktrap Community 1) and an interior (green) group (Walktrap Community 2).

For years, structures such as nested hierarchies (Sugihara and Ye 2009) and modularity in food-webs have been extensively studied and such studies suggest that these kinds of structures are tied to complexity in these types of systems, which, in turn, is strongly linked with persistence and stability (see Haldane and May 2011:351).

Recently, modularity has been an important topic in research on social networks and other types of complex systems (Newman 2006). The most widely used and accepted metric designed specifically for the purpose of measuring quality of a network subdivision into communities is modularity (for example, see Newman and Girvan, 2004). If edges in a network are randomly distributed modularity is expected to be close to zero. Newman and Girvan (2004) found that modularity in real-world networks typically ranges from about 0.3 to 0.7. Interestingly, the maximum modularity for my graphical model of the Hohokam/California network using the walktrap algorithm is 0.35 (Figure 7.5), which suggests a nonrandom structure based on the previous result. This supports the existence of the Hohokam/California transregional system. Also, the estimated p-value of 0.031 for the maximum modularity of the network model computed from the approximate sampling distribution of maximum modularity in an Erdős-Rényi random graph model with the same number of nodes and edges as the network model (see previous section for a detailed description of this model) also suggests a nonrandom structure (see Figure 7.6 and the end of Appendix R for the R code used to create Figure 7.6 and to compute the p-value).

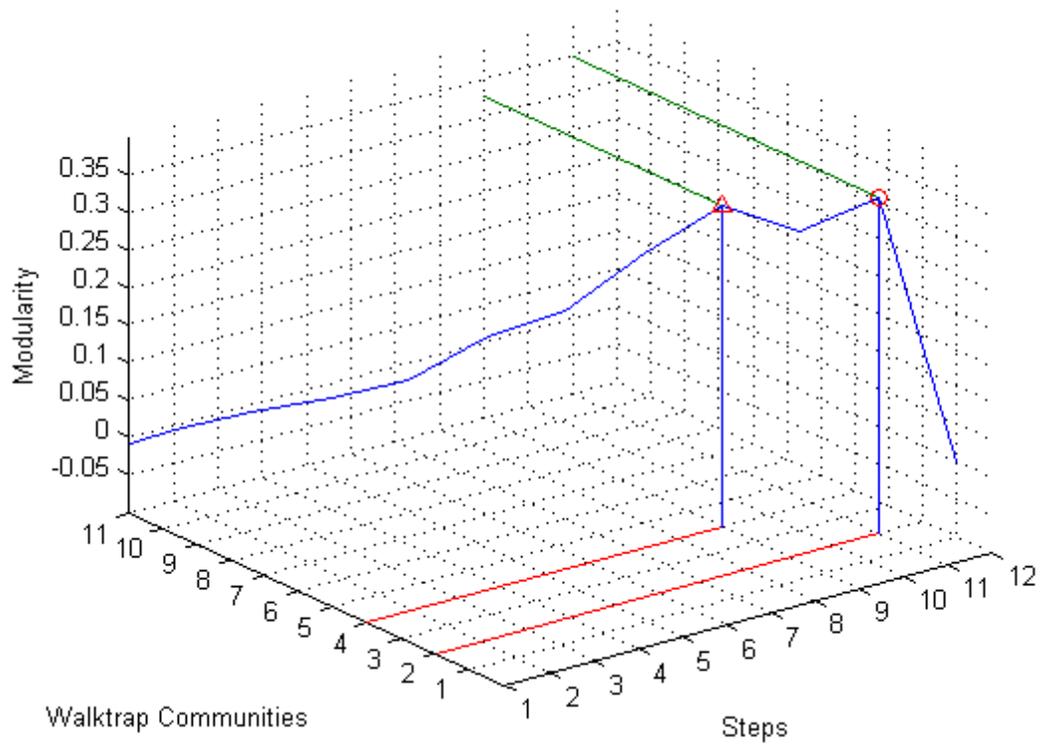


Figure 7.5. Plot of modularity, versus the number of walktrap communities and merge steps for the Hohokam/California transregional network graph. The maximum modularity (0.349206349) with eleven merge steps results in two walktrap communities. The next highest modularity (0.326530612) with nine merge steps detects four communities.

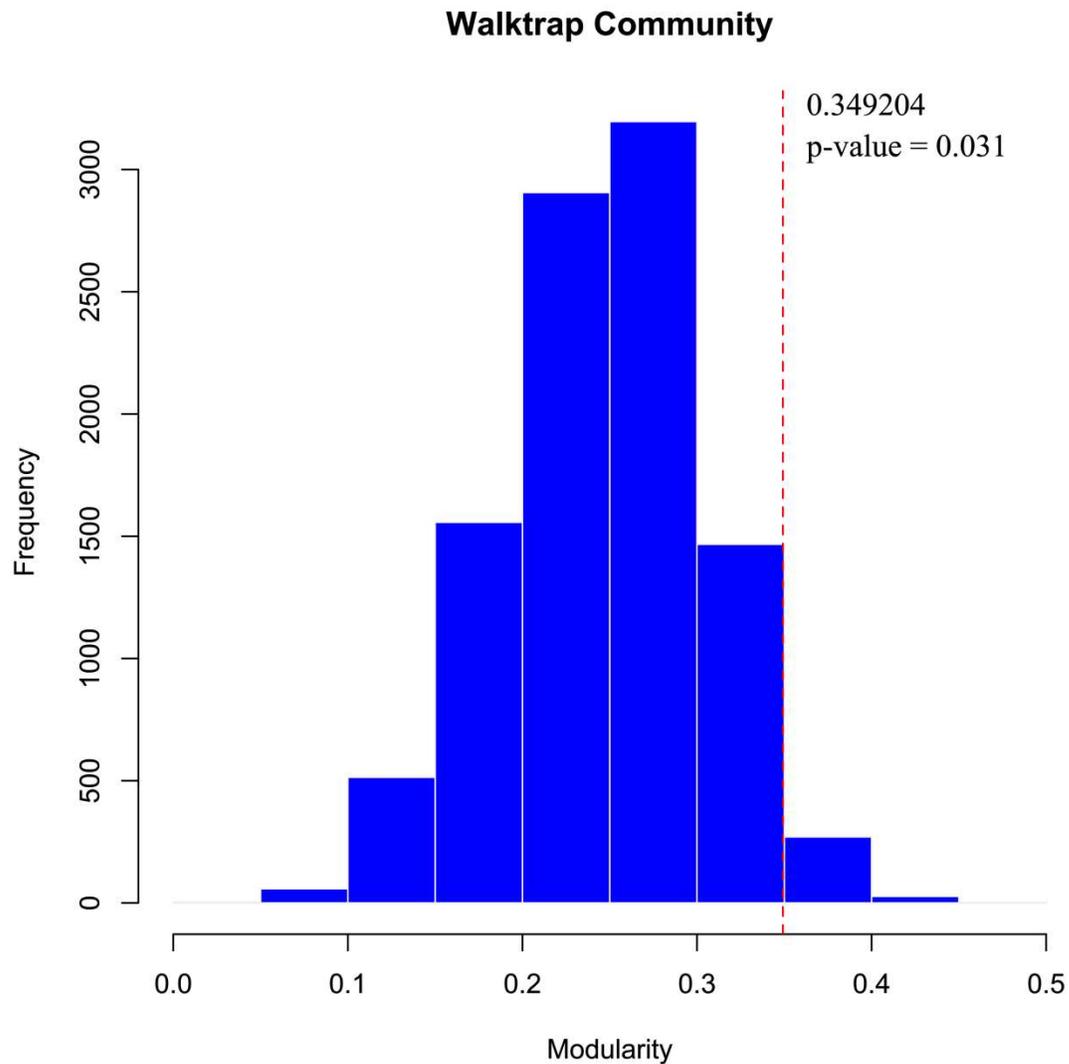


Figure 7.6. Approximate sampling distribution of the highest modularity resulting from using the walktrap community detection algorithm on 10,000 Erdős-Rényi random graphs. Vertical dashed red line is the highest modularity resulting from using the walktrap community detection algorithm on the reconstructed network model (Figure 7.1).

Considering the multiscalar structure of the California/Hohokam transregional network, the walktrap community dendrogram (Figure 7.7) makes ethnographic and archaeological sense. For example, in the dendrogram, 1 represents the Santa Barbara

Channel (SBC) Chumash, 2 the Northern Channel Island (NCI) Chumash, 3 the Santa Monica Mountains (SMM) Chumash, 4 the Southern Channel Island Tongva, and 5 the mainland Tongva. Ethnohistorically and archaeologically, the SBC and NCI Chumash are known to have had very strong ties through exchange and marriage (King 1976). In the Santa Barbara Channel and Northern Channel Island Chumash interaction sphere, the island Chumash (analogous to the peripheral Papagueria shell jewelry artisans in the Pre-Classic Hohokam system) specialized in manufacturing and exporting preciosities (especially shell “money” and jewelry) in exchange for staple items unavailable on the islands (e.g. deer and rabbit meat and a variety of plant foods) from mainland (analogous to the Pre-Classic Phoenix Basin component of the Hohokam system) sources (King 1978, 1990, 2000; Arnold 1992; Arnold and Munns 1994).

The dendrogram (Figure 7.7, also see Table 7.1) also suggests that the SMM Chumash had the closest non-Chumash ties to the Tongva on the southern Channel Islands, as well a very close relationship with the mainland Tongva. This prediction is supported by archaeological evidence provided by King (1971:38).

References in the previous section on trade with non-Chumash groups indicate that trade with the surrounding groups was limited to a rather small number of goods, and that the intensity of interaction was much less than within the Chumash area.

To the south, the Tongva groups may have been somewhat involved in the Chumash interaction system, but it appears from archaeological evidence that their main lines of interaction were between the mainland and the Southern Channel Islands, having close ties with the Chumash of the Santa Monica Mountains area [my emphasis].

The dendrogram also has predictive power. For example, it predicts close ties between Hopic and Cahuilla people, which have not yet been studied.

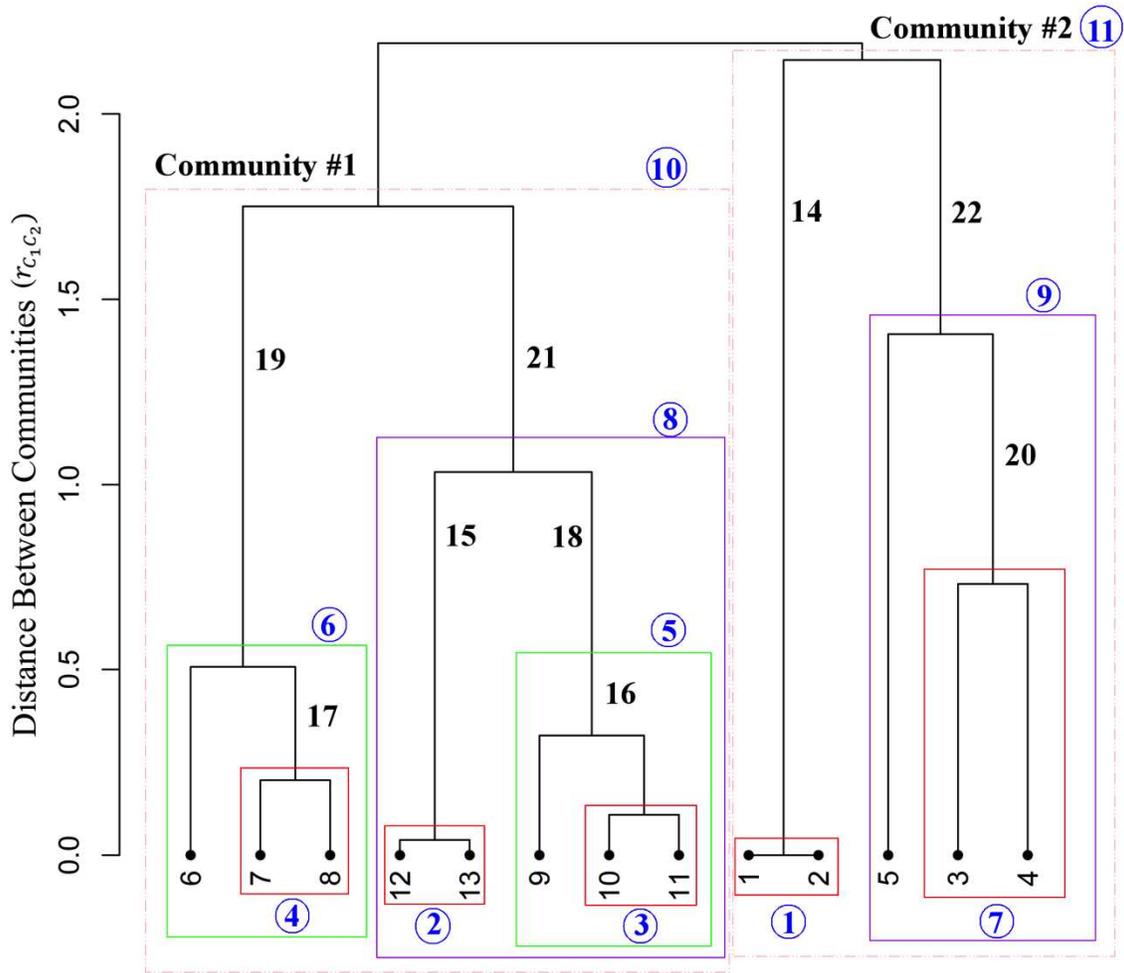


Figure 7.7. Walktrap community dendrogram for the Hohokam/California network graph. The numbers below the “leaves” (dots) of the dendrogram are regions in the Hohokam/California transregion (see Table 7.1). The merge steps in the clustering process are circled numbers (see earlier section in this chapter for a discussion of how the dendrogram is produced). Observe that with each merge step the distance ( between the pair of clusters being merged increases. Also, note that that the maximal modularity is at the eleventh merge step, see Figure 7.5 and Appendix R. Also, see Appendix R for the R script used to create the dendrogram.

At the finest (or most local) scale, the dendrogram also suggests that among the inland groups: (1) the Hopic and Cahuilla (7 and 8) were most strongly linked to each other, (2) the Lowland Patayan had their closest ties to the Upland Patayan (10 and 11), and (3) the Salt River and Gila River components of the Hohokam system (12 and 13)

were more strongly linked to each other than any of the other regions. Considering interaction between Lake Cahuilla people and the Hohokam system, at the finest scale, the dendrogram suggests a strong linkage between the Kumeyaay and Patayan groups (9, 10, and 11). At the next scalar level, the dendrogram shows the strongest linkage between the Kumeyaay and Patayan regions (9, 10, and 11) and the Hohokam system (12 and 13). This supports the idea that Kumeyaay and Patayan people of Lake Cahuilla had strong trade relations with each other and with the Hohokam system. This supports my idea that Lake Cahuilla fishers may have exchanged dried fish for Gulf of California shell artifacts from people of the Hohokam system. This result suggests that: (1) the interaction between the Kumeyaay, Patayan, and Hohokam elements of the Hohokam/California transregional system may have been important in terms of the fragility and persistence of this portion of the transregional system and (2) the bioeconomic model in the next chapter should focus on this component of the transregion and include trade between the Lake Cahuilla region and the Hohokam system.

## Directionality of the Transregional System

Directionality in the movement of shells is expected in an organized system of exchange. My question is: does the distribution of Pacific Coast and Gulf of California shell artifacts from contemporaneous sites in southern California and the Phoenix Basin and Gila Bend areas of Arizona suggest directionality and organization in exchange between the Hohokam system and southern California? To address this question, I use kriging to evaluate archaeologically observed patterns of shell distribution in Hohokam and southern California sites, to examine structure and directionality of these data. Kriging (Venables and Ripley 2002) applies to a variety of multiple regression based spatial analytic methods. For my study I will use ordinary kriging. Specifically, ordinary kriging is used to interpolate: (A) a variable  $z$  (in this case, either an  $n$  by 1 vector ( $n$ = the number of sampled sites) consisting of: (1) the total count of Pacific Coast shell artifacts divided by the sum of the total count of Pacific Coast and Gulf of California shell artifacts or (2) the total count of Gulf of California shell artifacts divided by sum of the total count of Pacific Coast and Gulf of California shell artifacts from an assemblage for  $n$  assemblages) and (B) a  $n$  by 2 matrix consisting of site locations in the form of forced (see Appendix B) and rescaled UTM coordinates ( $x$ =eastings/10000 and  $y$ =northing/10000) at unsampled locations  $x_i, y_i$  in the Hohokam/California transregion. The purpose of these analyses is to demonstrate empirically that the observed distribution of shell in the Hohokam/California transregion did not likely result from chance, and that movement of shell was directional. Table 7.3 provides the shell data used in the kriging analysis. See Appendix T for the raw data sets from Grewe, Snaketown, and Los Colinas

used for Table 7.3. Also, see Appendix T for detailed information on the Matlab functions and script used in the kriging analysis.

Table 7.3. Shell data used in kriging procedure. GoC = Gulf of California, PC= Pacific Coast.

Site	Region	GoC Shell Artifact/(GoC Shell Artifacts + PC Shell Artifacts)
Afton Canyon	Hopic	1/15
Oro Grande	Serrano	8/80
Indian Hill Rockshelter	Kumeyaay	5/6
Malibu (LAN-264)	Santa Monica Mountains	782/3874
	Chumash	
Oatman Flat	Lowland Patayan/Gila River	24/29
	Hohokam	
Escuela	Lowland Patayan/Gila River	32/115
	Hohokam	
ORA-225	Mainland Tongva	4/48
Grewe	Gila River Hohokam	1334/2368
Snaketown	Gila River Hohokam	634/638
Las Colinas	Salt River Hohokam	2785/2801

First the geographic positions of sites (x-y plane) and their corresponding values in column three of Table 7.3 (z component) are plotted with nine kriging results for scaled random fields (see Adler et al. 2007) with autocorrelation. This approach is often called the Monte Carlo method, which in this study the random fields correspond to spatially varying values of the ratio (relative frequency of Gulf of California shell artifacts) in

column three of Table 7.3. In this application of the Monte Carlo method, three-dimensional vectors of pseudo-random numbers are generated and scaled to the x, y, and z coordinates of the observed data space (see Appendix T for the Matlab code and additional explanation). The z component values of the random field are also generated so that they are spatially autocorrelated. This means that adjacent or near neighbors in the x-y plane have more similar z component values than more greatly separated points in the x-y plane. This is expected in many exchange contexts (e.g., down the line). In the kriging plots (Figures 7.8 and 7.9) red indicates a high, yellow a moderate, and blue a low relative frequency of Gulf of California shell artifacts (z component value) by geographic location. Examining twelve kriging results (Figure 7.8), the z component values for the actual data from the sites in the Hohokam system (Easting greater than 80) and the Indian Hill Rockshelter site (vicinity of Lake Cahuilla, near Easting 60 and Northing 360) have much greater proportions (larger z component values) than their corresponding pseudorandom z component values (or relative frequency of Gulf of California shell artifacts). The remaining sites (all from southern California) mostly have z component values that are significantly less than their corresponding pseudorandom z component values. These results suggest (at least by visual inspection) that the relative frequencies of Gulf of California shell artifacts from the Hohokam and Indian Hill Rockshelter sites are larger and the observed values from the remaining southern California sites are smaller than would be expected by chance. Also, the variation in the pseudorandom and spatially autocorrelated z component values in the kriging plots do not (as expected) suggest a consistent pattern of directionality (red “peak” to blue “valley” or source to recipient) in the movement of Gulf of California shell artifacts. In contrast the kriging plot for the

observed data (Figure 7.9) suggests strong directionality in the movement of Gulf of California shell artifacts from the Hohokam system to the Lake Cahuilla area (Indian Hill Rockshelter), and from Lake Cahuilla and vicinity to sites in the Serrano, Hopic, Tongva, and Chumash regions. A statistically rigorous analysis would generate the random field plots many times to produce an empirical sampling distribution of the pseudorandom values of the z component for each of the site locations and then compare the observed z component for each site with its empirical sampling distribution to compute an approximate p-value that the observed z component value would occur by chance. This will require adding additional Matlab code to that in Appendix T, which is a future goal.

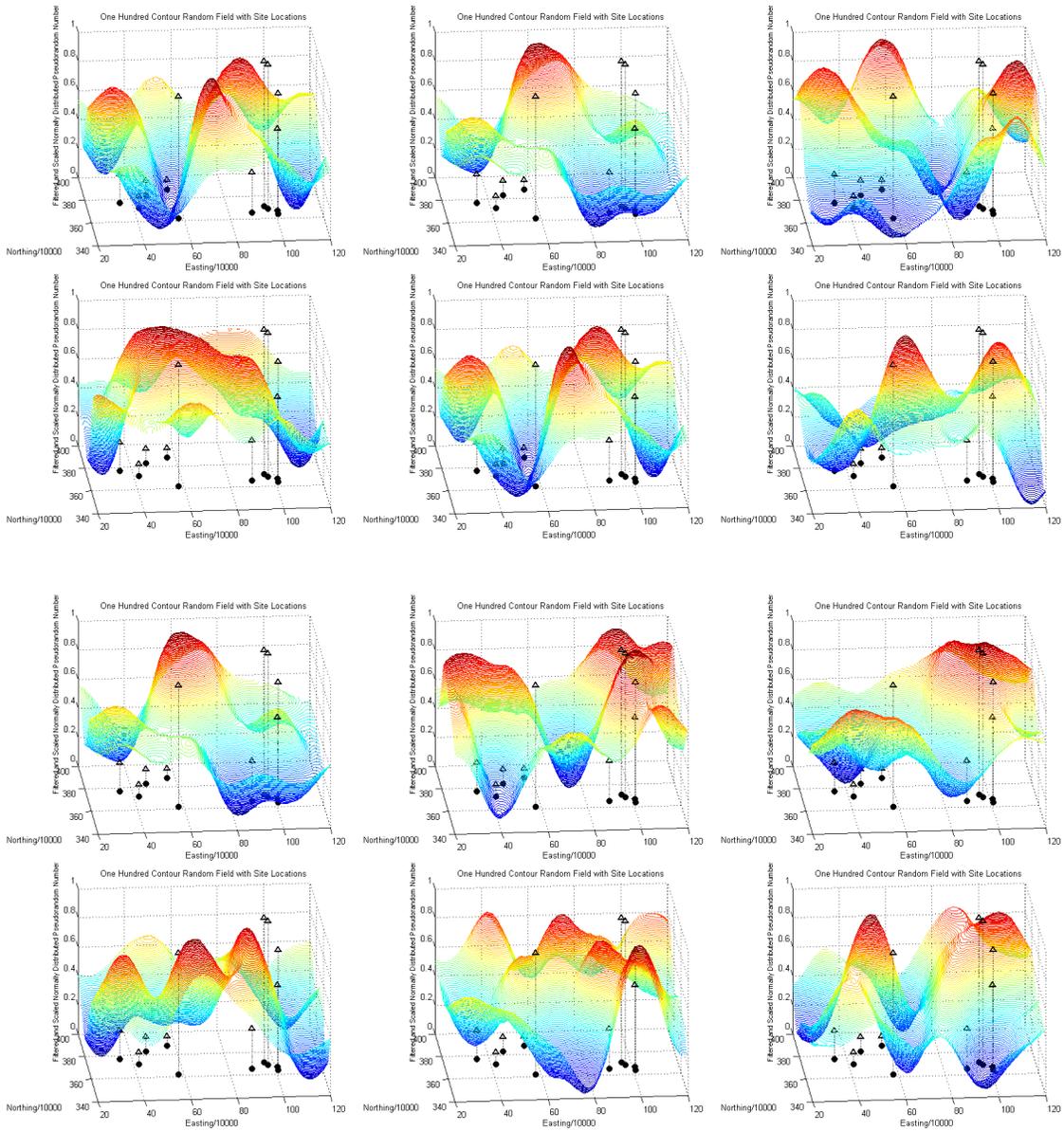


Figure 7.8. Sample of three-dimensional kriging contour plots that were computed on a scaled random field with autocorrelation. The mesh grid used is identical to the grid of the actual data (Figure 7.9). Actual data plotted for visual comparison.

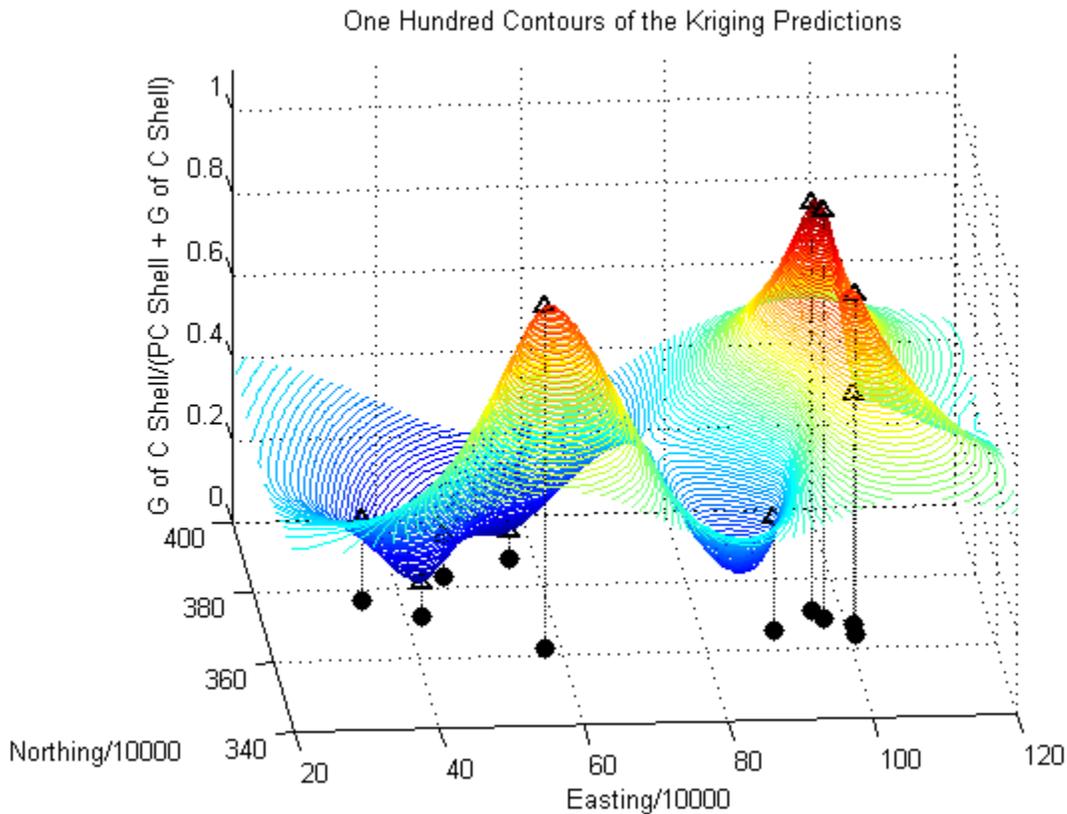


Figure 7.9. Three-dimensional kriging contour plot computed from actual data.

### Summary

The Erdős-Rényi random graph analyses provide rigorous and powerful results that strongly support the existence of the Hohokam/California transregional system. Based on my current information this may also be the first time this methodology has been used to evaluate the existence of a prehistoric exchange system using a network model constructed with ethnohistoric, ethnographic, and archaeological data.

The walktrap community analysis of an undirected network graph of the California/Hohokam transregional system revealed a multi-dimensional structure in the

inter-group relational ties, which is consistent with ethnohistoric, ethnohistoric, and archaeological evidence (Chapters 3 and 6). This supports the existence of the transregional system. The analysis also resulted in predictions of inter-group ties that can be studied in future research on the Hohokam/California transregional system.

The kriging analysis provided additional support for the existence of the Hohokam/California transregional system, since it showed strong directionality in the movement of shell (used as a proxy for interregional interaction), and (more so, with random field contour plots) that this directionality would not likely occur by chance. The kriging analysis also suggests that the transregional interaction of the Hohokam system was focused on the Lake Cahuilla region in southeastern California.

Both the network and the kriging analyses provide the important result that the Hohokam/California transregional system very likely existed. The walktrap community network analysis also provided the important results that: (1) the Hohokam/California transregional system had two modules (coastal and interior) whose susceptibility to shocks was probably largely independent and (2) there was probably a strong interdependence between the Lake Cahuilla region and the Hohokam system. These results shed light on some of what is needed in the bioeconomic model of the next chapter which are: (1) the interregional focus of the model should be limited to interaction between the Lake Cahuilla region and the Hohokam system and (2) trade between these regions should be included in the model to evaluate its effect on the stability and persistence of the Hohokam system.

## CHAPTER 8: A SIMPLE BIOECONOMIC MODEL OF RENEWABLE RESOURCE USE AND TRADE

The possible exchange of shell valuables manufactured in the Hohokam system for Lake Cahuilla fish is well supported by the archaeological evidence presented in the previous two chapters. Other lines of evidence that draw from ethnographic and oral histories in Papua New Guinea also lend support to the idea that shell valuables could be a fundamental item of exchange for protein-rich food from a distant place and across ethnic boundaries. For example, Connell (1977:81-82) provides the following oral account of the long-distance and cross-cultural exchange of shell valuables for protein rich foods (nuts and meat), in the Solomon Islands of Papua New Guinea (see Figure 8.1).

Within pre-contact Bougainville there was local trade as shell valuables manufactured in the Shortland islands, Buin and possibly elsewhere in Bougainville, were traded between different language groups and also inter-regional trade which incorporated shell armbands from Choiseul and possibly shell valuables from Malaita. These latter goods therefore had passed through a number of intermediaries before reaching a final destination in Bougainville. Oral accounts indicate that south Bougainvilleans exchanged agricultural produce (mainly pigs and almonds), clay pots and spears for these valuables.

Issues not considered by Connell and (for the most part) by other ethnographers and ethnohistorians that have studied traditional small-scale and middle range societies (and specifically ones that were still quite isolated and not yet interacting to a significant degree with complex or industrialized societies), are the short and long term effects of globalization processes (such as the scalar expansion of trading systems) on the stability of these kinds of social-ecological systems. In contrast, my focus in this chapter is to

examine how expanding the scale of the Pre-Classic Hohokam system could have contributed to its collapse.



Figure 8.1. The Bougainville, Choiseul, and Malaita Island exchange system.

With reference back to the first chapter of this study, the goal of this chapter is to evaluate how economic expansion of the Pre-Classic Hohokam system beyond the Hohokam region could have affected its long-term stability. That is, could increasing the scale of a pre-existing system (i.e. expanding beyond the Hohokam region) have reduced the efficacy of established robustness-fragility trade-offs, which, in turn, amplified the fragility of the system, increasing its risk of collapse? The context of economic

expansion will be limited to the trade of shell valuables manufactured in the Hohokam system to exchange for dried Lake Cahuilla fish. Systemic fragility of the Hohokam system in this context relates to the filling and emptying cycles of Lake Cahuilla combined with expansion of the spatial scale of trade, specialization in trade related activities, including the production of shell valuables to exchange for Lake Cahuilla fish, as well as the population size of the Hohokam regional system.

To accomplish this goal, I combine a qualitative analysis of the Hohokam social ecological system (ca. A.D. 850-1100) and a simple dynamic model of renewable resource use and trade, which builds on the model of Anderies (2006). Robustness to shocks and systemic fragility of the Hohokam system are key focal points in the modeling study of this chapter. As Anderies (2006) observes, the Colonial and early Sedentary Hohokam system became more robust to local dry periods because its scale of interaction increased, and more robust to small scale floods, because irrigation technology and infrastructure along with associated institutional arrangements permitted farmers to grow food away from flood zones (Figure 8.2, Table 8.1).

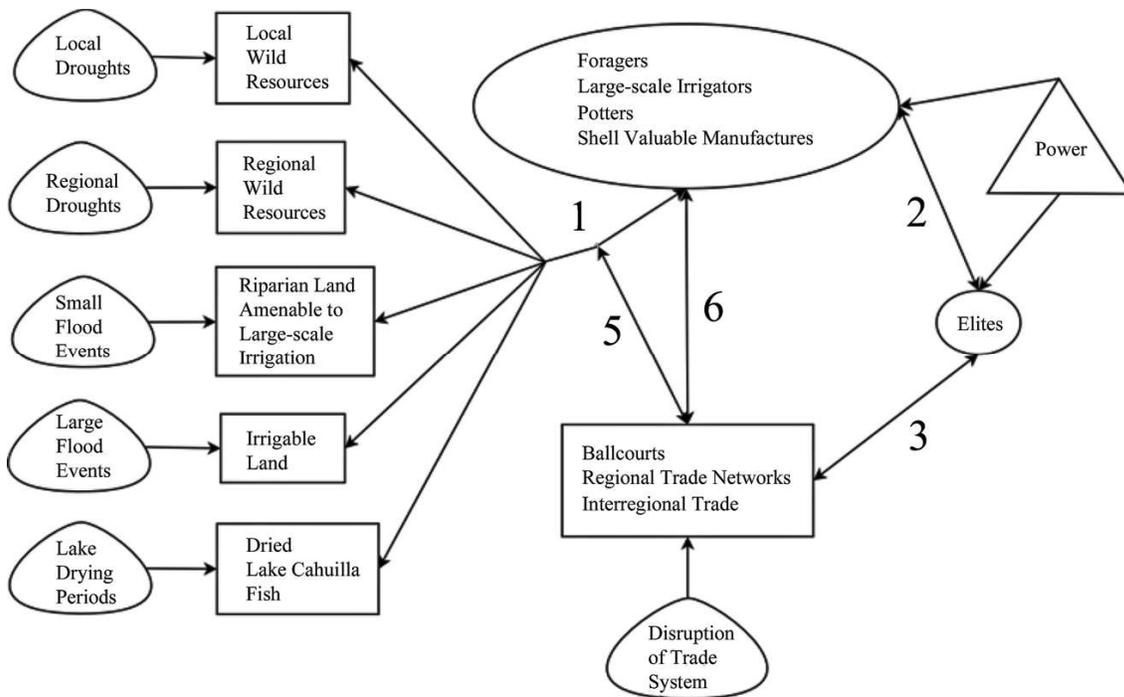


Figure 8.2. The general framework of Anderies et al. (2004) applied to the Hohokam system (circa A.D. 850-1100). The numbering matches Anderies et al. (2004). The framework shows the locations of different vulnerabilities in relation to system components.

But this also made the Hohokam system more vulnerable to larger scale (both longer in time and larger in area) shocks, such as regional droughts, severe flooding, and social problems that could impair trade within the Hohokam region and beyond.

It is not as clear how much the drying phases of the Lake Cahuilla drying/filling cycles (discussed in Chapter 4) could have disrupted the Hohokam system, by increasingly reducing the output potential of the Lake Cahuilla fishery over the course of several decades. Certainly, Lake Cahuilla people could have attempted to maintain the output of their fishery by building more fish traps and moving them with the receding shoreline of the lake, and/or adding or expanding other types of fishing (including active

approaches), such as boat and shore fishing using hook and line and bow and arrow methods.

Table 8.1. Robustness and vulnerabilities of the Hohokam/California transregional system in relation to spatial scale and rate of occurrence.

Robustness/Vulnerability Properties	Rate of Occurrence	Comments
Greater local robustness to drought and food shortages	Moderately slow, multi-year	Larger spatial scale of system
Increased robustness to small scale flooding	Rapid, over a period of days or weeks	Move irrigated land further from flood zones. [Increase capital devoted to building and maintaining irrigation infrastructure]
Vulnerability to social problems	Rapid	Disruption of trade systems
Vulnerability to environmental disturbances	Slow, multi-decadal	The cyclical waxing and waning of Lake Cahuilla; Long-term drought that would significantly reduce streamflow and the wild resource base.

It is also necessary to consider to what extent the social and environmental shocks in Figure 8.2 and Table 8.1 are independent. This will provide key insights that will help with interpreting the analysis of the bioeconomic model. For now, I will qualitatively examine the structure of the environmental shocks; in terms of a structural model of the risk space of the Hohokam system with Lake Cahuilla added (Figure 8.3). With the inclusion of Lake Cahuilla, it is clear that the risk space of the Hohokam system includes three independent (in that each is robust to shocks that usually do not co-occur) dimensions of variation: (1) the Lake Cahuilla filling and emptying dimension, which is

driven by seismic events in the Salton Basin; (2) the large-scale moisture availability dimension, which is determined by water input (rain and snowfall) into large areas of the Hohokam system; (3) the small-scale moisture availability dimension, which depends on local rain and snowfall. This means that robustness/fragility tradeoffs considered by Anderies (2006) need to be re-examined in the context of systemic fragility that couples the Hohokam social ecological system with the social ecological system of the Lake Cahuilla region.

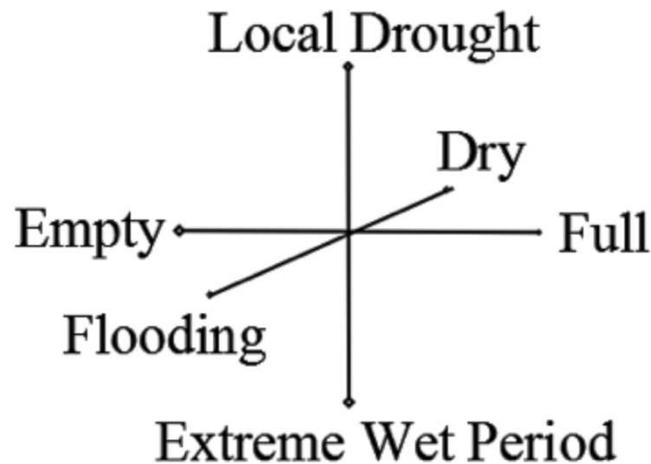


Figure 8.3. Three key environmental dimensions of the risk space of the Hohokam system, which are: (1) regional water availability (dry to flooding), (2) Lake Cahuilla filling/drying cycle (full to empty), and (3) local water availability (local drought to extreme local wet period).

Considering the independent nature of the dimensions of the risk space, the question of interest is: how could the inclusion of a Hohokam and Lake Cahuilla interaction sphere with only two trade items lead to system failure? Changes in the division of labor within the Hohokam system to produce large quantities of shell to enable the importation of Lake Cahuilla fish, and the labor required to export the shell

and import the fish must be key elements. This question is evaluated in the analysis of the bioeconomic model later in the chapter, where decisions related to labor allocation determine the model outputs.

### **Population Growth, Irrigation and Impacts on Local Wild Resources**

The increase in the population of the Hohokam system during the Late Colonial and Sedentary periods was probably a major factor in the collapse of the system around A.D. 1070. Population growth, especially at the core (Phoenix Basin) of the Hohokam system was likely the result of both internal and external (i.e. migration) inputs, as suggested by Nelson et al. (2010).

The regional economy in which they participated also supplied hunted and gathered resources from various ecological zones, and, with the expansion of the regional networks over time, it is likely that the irrigation communities in the lowlands became ever more dependent on nonlocal comestibles until the regional collapse. Prior to the collapse around AD 1070, there were no signs of environmental degradation along the Salt River. However, immediately following that time, the northern uplands overlooking the lower Salt River valley became depopulated, and settlements along the river rapidly swelled with migrants (e.g., Abbott and Foster 2003).

Nelson et al. also mention archaeological evidence of nutritional deficiencies (e.g., anemia related to shortfalls of wild protein in the diet) among residents of the Salt River area during this time and suggest a connection between a surge in population growth from migration and the degradation of local wild resources.

The effects on the local wild resource stock were substantial, with severe health consequences for the Salt River populations (Van Gerven and Sheridan 1994, James 2003, Kwiatkowski 2003, Sheridan 2003).

Nelson et al. (2010) also consider the interplay between population growth, density and irrigation intensification on wild resources, in the specific case of the Salt River component of the core region of the Pre-Classic Hohokam system.

By investing in large-scale irrigation technology, the Hohokam farmers in the lower Salt River valley assured themselves of a goodly supply of cultivated resources. At the same time, their infrastructure investments densely concentrated a large population in a single place, putting their local environment at risk for depletion and degradation. The Salt River inhabitants initially avoided that vulnerability by participating in a vast network of exchange [emphasis added].

The Hohokam in the Salt River valley invested in massive local infrastructure to suppress variation at annual frequencies and increase the productivity of the desert for agriculture. That advantage was achieved and supported a population that grew over several centuries. However, this success generated vulnerabilities to population growth that occurred on a generational timescale and led to the depletion of local resources [emphasis added].

### **The Coupling of Population and Technological Growth with Regional and Transregional Exchange**

As a coupled social-ecological system, there was a significant interplay (or feedbacks) between population and technological growth and the growth and organization of regional and transregional exchange systems in the Pre-Classic Hohokam system. For example, Nelson et al. (2010) comment on limitations on the growth of irrigation in the Sedentary period Hohokam system and its effect on trade (as well as the converse, the effect of trade [or lack of it] on the irrigation systems) that result from the interplay between limitations determined by  $R$  and  $S$  on the growth of the irrigation system and the capital labor ratio ( $K/h$ ).

The sustained agricultural success, however, may have encouraged substantial expansion of the hydraulic infrastructure sometime after AD 1000, at the height of the regional economy. A major irrigation complex, named the Lehi Canal System, was built around AD 1000 upstream of the other irrigation cooperatives on the river (Howard 1987), possibly by a migrant group from the middle Gila River valley to the south (Abbott 1995). The establishment of several new ballcourt villages and the addition of hundreds of irrigated hectares put new pressures on the water supply, which may have become a limiting resource at that time (J. Howard 1993). Diversion of the river flows by the Lehi farmers may have undercut the capacity of some downstream irrigation cooperatives to grow a surplus of corn and cotton for trade. In effect, the productive output in the valley as a whole after AD 1000 may have reached a maximum, while expanding local populations consumed their share and left a diminishing proportion of the total output for exchange with populations elsewhere in the region.

Although people [in the Hohokam system] were place focused, they acquired a wide array of resources and maintained access to a variety of resource areas for centuries through an extensive, pan-regional exchange network, which also provided a social environment conducive to maintaining their extensive canal network [emphasis added]. Once that extensive social network became fragmented, resources brought from afar were no longer available and the social relations that supported the canal systems changed.

Nelson et al. also consider the combined effect of ecological diversity with production and exchange in relation to the potential vulnerability of the Pre-Classic Hohokam system to rapid dissemination of environmental and social shocks throughout the entire system as a consequence of cohesion and interdependence in social and economic networks at the regional level [which again, I suggest was transregional].

Efficiencies of local specialization and the integration of diverse ecological zones, via the ballcourt rituals, underpinned webs of reliable dependencies, but at the risk of hypercoherence whereby local perturbations were felt throughout the region. When interconnections are too strong and too critical, local changes such as rising imbalances between supply and demand, sociopolitical strife that disrupts the movement of goods, and impairments to production capacities can cascade through the regional networks, causing regional-scale social, political, and economic transformation.

The Salt River Hohokam invested heavily in their irrigation infrastructure to supply a regional market [which I suggest was transregional] on which they, in turn, depended for vital resources. The interdependencies succeeded in building an efficient and productive regional economy, but at the risk of local perturbations, whose effects could cascade across the system.

## **Local Drought Cycles and the Need to Trade**

Frequent dietary stress as the result of local drought may also have been a major factor in the need for people in the Pre-Classic Hohokam system to look elsewhere for wild food. Specifically, it is necessary to identify patterns in the occurrences of persistent dry periods. To better understand the prevalence and potential; impact of drought cycles on wild food stocks in the Phoenix Basin during the Santa Cruz phase and Sedentary period of the Hohokam Cultural Sequence, I did two Fourier analyses. I used the Cooley-Tukey method of fast Fourier transforms to compute the power spectrum plots (Figures 8.4 and 8.6, also see Hameed et al. 1983 for an application of this method to the analysis of periodicities in precipitation; also see Appendix U for the Matlab code used in the Fourier analyses), one on reconstructed Salt River and the other on reconstructed Gila River annual streamflow data (provided by Scott Ingram to me in 2007; also see Graybill et al. 1989, 2006). I assume that annual streamflow is strongly correlated with yearly rainfall. Both of these analyses detect strong signals that correspond to high frequency and low frequency cycles in streamflow during A.D. 850-1100. For the A.D. 850-1100 period, the strongest signal recovered by the Fourier analysis of reconstructed streamflow for the Salt River is a 14.7-year period/cycle. The second strongest is a 22.7-year cycle (which also has a strong signal in the Gila River, see Figures 8.4 and 8.5). These appear to be drought cycles (Figure 8.5), with the most severe drought periods for the 14.7-year cycle occurring between A.D. 915-930, 1032-1047, and 1062-1076, and for the 22.7-year cycle during A.D. 1059-1081 (Figure 8.5). For the same period, the strongest signal recovered by the Fourier analysis of reconstructed streamflow for the Gila River is a 31.25-year period/cycle. This appears to be a multi-decadal drought cycle, with the worst drought

associated with this cycle occurring during A.D. 1023-1054 (see Figure 8.6). The most severe droughts associated with the cycle with the second strongest signal (11.4 years, see Figure 8.6 and 8.7) are during A.D. 966-978 and 1035-1046 (see Figure 8.7). The greatest overlap in drought period cycles between the two rivers occurs during A.D. 1032-1047, which is several decades after the time (ca. A.D. 1000) when the Hohokam system may have reached the limit of its irrigation capacity (see Nelson et al. 2010) as determined by available water from rivers, rain, and snowfall. Also the significant dry period in both river systems is coincident with the “down-cutting in the middle Gila riverbed during the 11th century [which] may have left some canal intakes high and dry, significantly reducing the agricultural outputs along the middle Gila River and the stability of the entire regional economy (Waters and Raveslout 2000)” [Nelson et al. 2010] may have also contributed to potential agricultural shortfalls and regional economic stress.

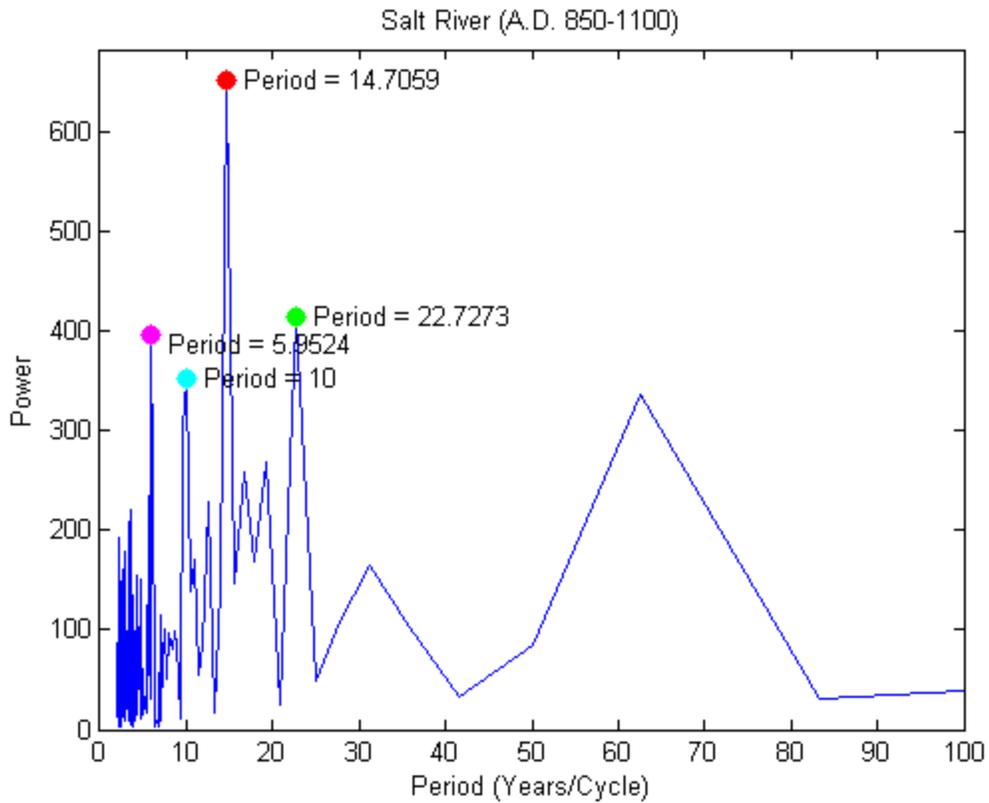


Figure 8.4. Fourier power spectrum of the periodicity of average annual streamflow in the Salt River (A.D. 850-1100).

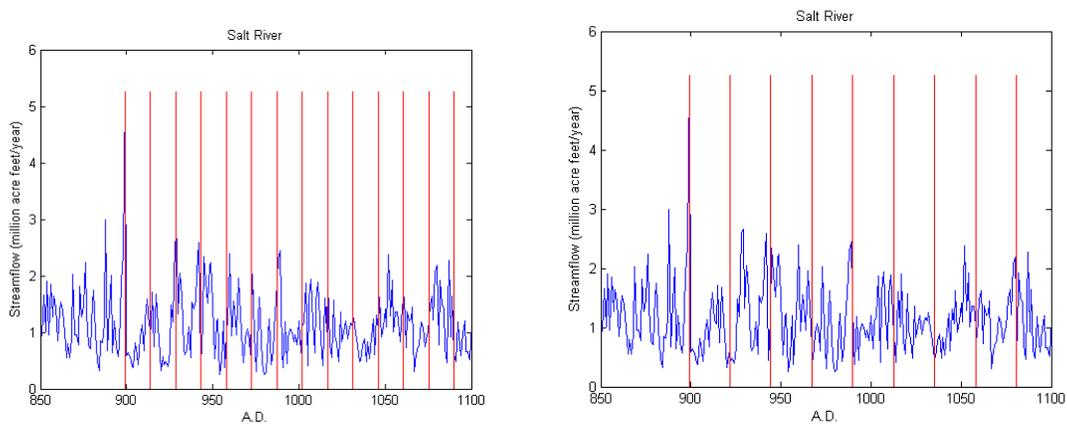


Figure 8.5. Reconstructed annual streamflow of the Salt River (A.D. 900-1100) partitioned into 14.7-year intervals (left) and 22.7-year intervals (right) corresponding to the two largest peaks in the periodicity of streamflow (Figure 8.4) predicted by the Fourier analysis.

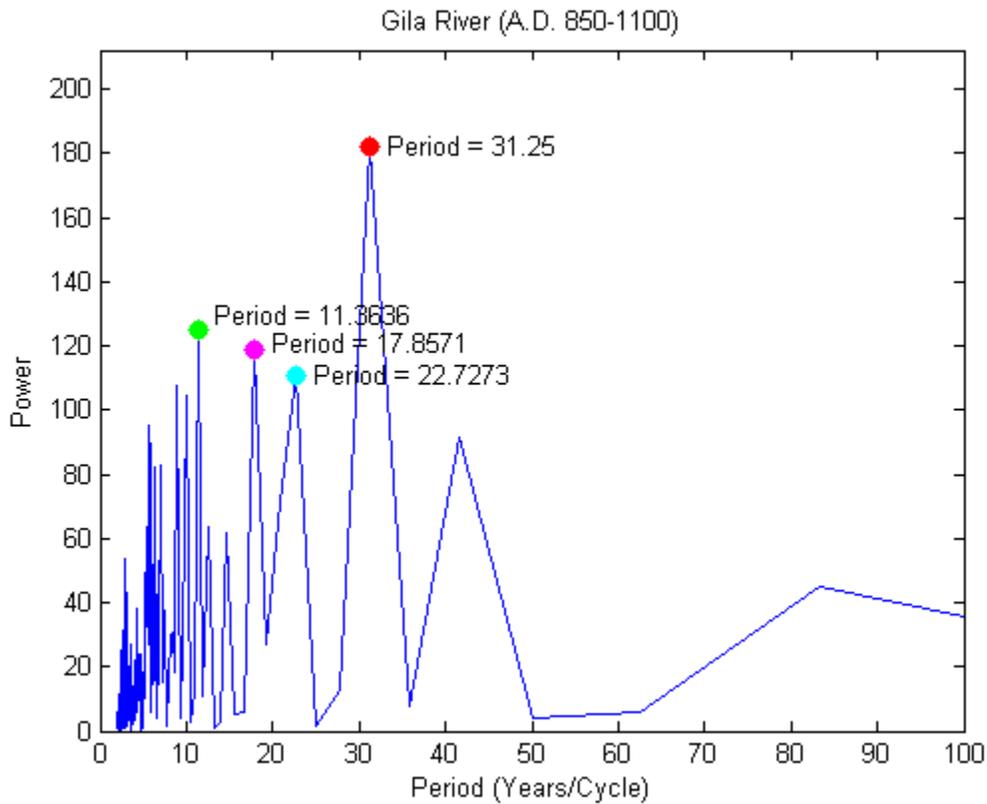


Figure 8.6. Fourier power spectrum of the periodicity of average annual streamflow in the Gila River (A.D. 850-1100).

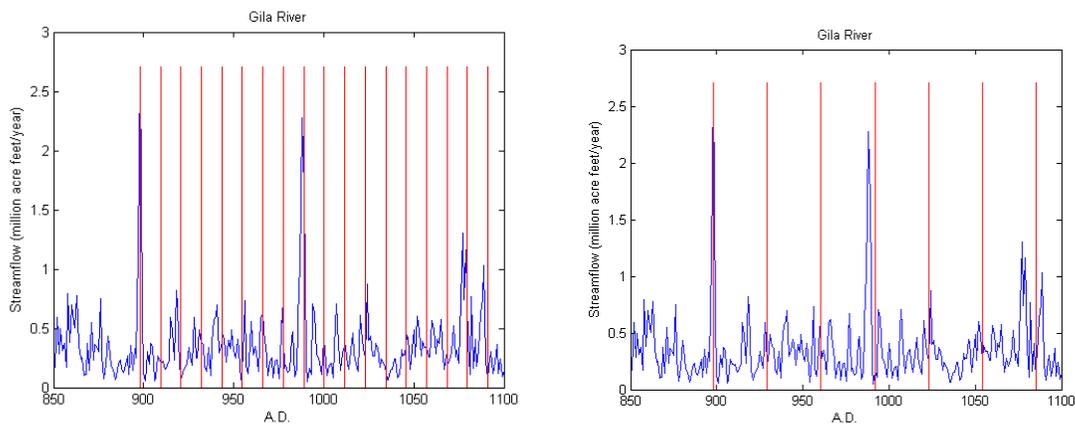


Figure 8.7. Reconstructed annual streamflow of the Gila River (A.D. 900-1100) partitioned into 11.4-year intervals (left) and 31.25-year intervals (right) corresponding to the two largest peaks in the periodicity of streamflow (Figure 8.6) predicted by the Fourier analysis.

In sum, the recurring multi-year drought cycles in the Phoenix Basin between A.D. 900 and 1100 identified by the Fourier analyses may have resulted in insufficient harvests of local wild protein sources to meet the minimal per-capita needs of people living in this area during that time. Extended droughts would probably also greatly decrease streamflow and, in turn, significantly reduce local fish stocks that may have been a major wild protein source for people in the Hohokam system. Also, increased levels of harvesting of these resources over time as the result of population growth may have further depleted them. Increased consumption of local wild foods accompanied by an increase in population during the Late Colonial and Sedentary period of the Hohokam cultural sequence (A.D. 850-1100) is supported by archaeological evidence (Bayman 2001; Crown 1991:147; Ford 1985; Gasser and Kwiatkowski, 1991a,b; White and Lekson 2001:104). It is plausible then to increase robustness against localized shortages of protein rich wild foods, people in the Pre-Classic Hohokam system re-allocated labor used to harvest local wild carbohydrate rich foods to pursuits that permitted the importation of protein rich dried fish from Lake Cahuilla. Also, the co-residence of Patayan people in major Hohokam settlements in the Phoenix Basin and Gila Bend (see Chapter 3), some of whom may have been specialist traders (i.e. middlemen) with kin and other ties to Patayan people living on the southern shores of Lake Cahuilla (see Chapter 3), could have lowered the transport and other (e.g., transaction) costs in the exchange of manufactured and other goods from the Phoenix Basin for dried Lake Cahuilla fish.

## Model

The model is broadly thematic and not detail oriented. Both extensive and intensive resource use are two elements of the model. The combination of these resource use strategies can reduce the effects of environmental variability by extending the spatial scale from which resources are obtained.

As Anderies (2006) states, which also applies to this model:

The reader should bear in mind that the model is not intended to capture specific features of the Hohokam system. The need for a sufficiently long temporal sequence to observe shifting vulnerabilities and large-scale change motivates our focus on an archaeological case such as the Hohokam, not the details of the case itself. Further, institutions are not formalized explicitly in the model; their role is implicit. For each biophysical configuration analyzed, institutions structure the suite of associated costs, benefits, vulnerabilities, and social interactions that generate the possible dynamical behaviors of the system. The formal model provides the link between institutional configurations (specified in qualitative terms) and social-ecological dynamics (specified in quantitative terms)[p. 142].

Trade is a component of this model. Trade in this model relates to a long distance riverine-based trade network, with two major categories (shell artifacts and dried fish) of exchange items. Wild resources (in general), such as fish provide a greater return of protein than agricultural products. Agriculture is (in general) expected to provide mostly carbohydrates. Local resource availability and loss becomes more of an issue as populations increase and are more settled. Intensifying agriculture and trade are two ways to deal with greater population size, but at the same time may enable further population increase. In particular, I extend Anderies (2006) Hohokam model to include trade of Lake Cahuilla dried fish (protein) for Hohokam shell preciosities.

As with the Anderies (2006) model, this model is a representative-agent, bioeconomic model of renewable resource use, inspired by other such models (Anderies 1998, 2003; Brander and Taylor 1998; Dalton and Coats 2000; Janssen and Scheffer

2004). As with the Anderies 2006 model, the qualitative analysis of the system I consider suggests the essential renewable resource types: local extensive (type 1), local intensive (type 2), and Lake Cahuilla fish (type 3). The states of the first two types in this model are the same as in the Anderies model, which he describes as:

The states of the extensive and intensive resources are measured in terms of harvestable biomass and soil fertility (Anderies, 1998, 2003), respectively. Society produces two types of output: protein rich (type 1) and carbohydrate rich (type 2). Although both can be produced from either resource type, wild resources may have higher productivity of type 1 output and irrigated agriculture may have higher productivity of type 2 output [p. 143].

In this model people in the Hohokam regional system try to meet their needs with minimum labor. Needs include those related to individual nutritional requirements, ritual and other types of social and economic obligations that include trade.

The mathematical representation of the system includes the regeneration of the renewable resources, the labor allocation to each resource type, and the dynamics of the periodic filling and emptying of Lake Cahuilla. Resource dynamics (including the filling and emptying cycles of Lake Cahuilla) are modeled using differential equations that describe the state of type 1, 2, and 3 resources,  $x_w$ ,  $x_a$  and  $x_{lc\_fish}$  (where  $w$  represents local wild resources,  $a$  irrigated agriculture, and  $lc\_fish$  Lake Cahuilla fish), and the carrying capacity of the Lake Cahuilla fishery (i.e. the size of Lake Cahuilla).

$$\frac{dx_w}{dt} = r_w(R) * x_w(1 - K_w(R) * x_w) - a_{wp} * Y_{wp} - a_{wc} * Y_{wc} \quad (1)$$

$$\frac{dx_a}{dt} = r_a(S) * x_a(1 - K_a(S) * x_a) - a_a * Y_a \quad (2)$$

$$\frac{dx_{lcf}}{dt} = r_{lcf} * x_{lcf} \left[ 1 - \left( \frac{x_{lcf}}{K_{LC_{scaled}}} \right) \right] - a_{lcf_p} * Y_{lcf_p} \quad (3)$$

$$\frac{du}{dt} = u * (1 - u^2 - v^2) - \left( \frac{2 * \pi}{p_1} \right) * v \quad (4)$$

$$\frac{dv}{dt} = v * (1 - u^2 - v^2) + \left( \frac{2 * \pi}{p_1} \right) * u \quad (5)$$

$$K_{LC_{scaled}}(u) = \frac{(\mu_1 + \alpha_1 * u)}{\mu_2} \quad (6)$$

The term  $r_w(R)$ , in equation (1) depends on rainfall,  $R$ , is the intrinsic regeneration rate of the wild resource stock. Unexploited wild resource stocks will increase to a rainfall-dependent carrying capacity. The subscript  $j$  has values  $p$ ,  $c$ , or  $p_{lcf}$ , which depict output type (protein rich local resource =  $p$ , carbohydrate rich local resource =  $c$ , protein rich Lake Cahuilla fish =  $lcf_p$ ). The subscript  $i$  is either  $w$  or  $a$  and depicts the resource type (extensive (wild) =  $w$ , intensive (irrigation) =  $a$ ).  $Y_{ij}$  represents output type  $j$  from resource type  $i$  and  $\alpha_{ij}$  the impact on resource type  $i$  of producing output type  $j$ .

As is typical with bioeconomic models, wild resources are assumed to regenerate logistically (which is biologically reasonable). The regeneration rate of irrigated agricultural soil productivity is denoted by  $r_a(S)$  where  $S$  denotes stream water

transported into the soil through irrigation. The soil regeneration rate depends on  $S$  because irrigation water contains nutrients. Maximum soil fertility depends on the inorganic and organic composition of the soil and the complex interplay between the physical and chemical structure of the soil and the organisms that live in it.

In this model (to simplify the analysis), equations 1, 2, and 3 represent average conditions (i.e.  $R$  and  $S$  are constants, and  $K_{LC_{scaled}}(u)$  is the carrying capacity of the Lake Cahuilla fish stock that varies in a fixed 50-year cycle). Note that if  $K_{LC_{scaled}}(t)$ , were used (instead of equations 4 and 5, where  $u = u(t)$  and  $v = v(t)$  the system would be nonautonomous (i.e. the model's system of ordinary differential equations would explicitly depend on the independent variable  $t$ ). In equations 4 and 5,  $u$  and  $v$  generate an asymptotically stable orbit of the form  $(u(t), v(t)) = (\cos(\omega t + \phi), \sin(\omega t + \phi))$ , where  $\phi$  is an arbitrary phase-shift. Then by coupling  $u(t)$  to  $K_{LC_{scaled}}$  transforms the nonautonomous system into an equivalent autonomous (or time-invariant) and periodically driven system (see Ermentrout 2002:188-189). Figure 8.8 is a plot of the model 50-year Lake Cahuilla filling and emptying cycle.

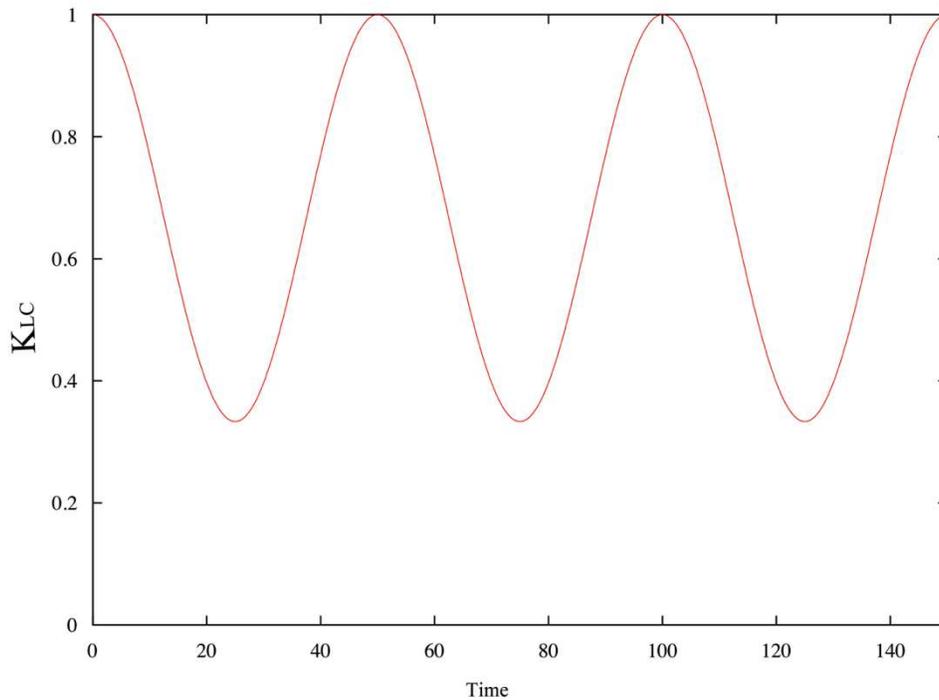


Figure 8.8. Lake Cahuilla fish stock without a fishery. Fluctuations in the fish stock result only from a 50-year filling and emptying cycle of the lake.

Local environmental shocks to the system correspond to changes in  $\mu$  and  $K$ . Variation in rainfall affects both the carrying capacity and growth rate of wild resources. Changes in the amount of stream water used for irrigation affects agricultural output and soil fertility. Changes in the productivity of the Lake Cahuilla fishery (as discussed earlier in the chapter) are the result of a 50-year long filling and emptying cycle of the lake (that is caused by seismic events in the Salton Basin that alter the course of the Colorado River to either fill or not to fill the lake) is a non-local environmental disturbance that is independent of  $\mu$  and  $K$ . Also, shocks resulting from  $\mu$  and  $K$  are rapidly felt by the system whereas the emptying cycles of Lake Cahuilla are multi-decadal and must have more subtle impacts on the system.

In the model, shocks to the system correspond to perturbations from average conditions. The objective of the analysis is to provide a preliminary study of the model (with numerical simulations) that will result in a better understanding of how environmental disturbances combined with corresponding changes in the population of the Hohokam system (for a fixed labor capital ratio) and the option to supplement wild protein with Lake Cahuilla fish, relate to robustness/fragility tradeoffs and the collapse of the system circa A.D. 1070. As with the Anderies (2006) model this model has a linear production structure. Lower- and upper-case letters depict *per capita* and total quantities, respectively (for example,  $Y_{wp} = h * y_{wp}$  represents total output of local wild protein rich resources). For per capita outputs,  $y_{wj} = A_{wj} * x_w * l_{wj}$ ,  $y_{aj} = A_{aj} * x_a * l_a * K$ ,  $y_{lcf} = A_{lcf} * x_{lcf} * l_{trade}$  where  $l_{wj}$  is the labor allocated to producing output  $j$  from resource type  $w$  (wild),  $l_a$  is the labor devoted to resource type  $a$ , and  $l_{trade}$  is the labor allocated for trade associated with the importation of dried Lake Cahuilla fish into the Hohokam system. No distinction is made between labor used for producing different types of output from resource type  $a$  - output is determined by a constant  $A_{aj}$ . Output from irrigated agricultural activity also depends on capital,  $K$ , which includes physical, social, and institutional infrastructure. People in the Hohokam system choose  $l_{wp}$ ,  $l_{wc}$ ,  $l_a$ , and  $l_{trade}$  in the following steps:

Step 1.

$$\text{Min } l_{wp} + l_{wc} + l_a \quad (8)$$

Subject to:

$$y_{wp} + y_{wc} \geq y_{wpcmin} + y_{wcmin} \quad (9)$$

$$y_{ap} + y_{ac} \geq y_{apmin} + y_{acmin} \quad (10)$$

$$l_{wp} + l_{wc} + l_a \leq \gamma * l_{max} \quad (11)$$

which produces optimal labor allocation as follows.

$$l_{a\_opt} = \min \left\{ \frac{1}{(A_{ap} * x_a * K)}, \frac{1}{(A_{ac} * x_a * K)} \right\} \quad (12)$$

$$\text{Then if } 1 - \frac{x_a * K}{x_w} \left( \frac{A_{ap}}{A_{wp}} + \frac{A_{ac}}{A_{wc}} \right) > 0 \quad (13)$$

$l_a = 0$ , else  $l_a = l_{a\_opt}$ . The preceding inequality (13) designates optimal labor allocation based on the state of the (wild resources and agricultural) conditions within the regional Hohokam system ( $x_w, x_a$ ) and technological constraints given by  $K$  and  $A_{ij}$ .

As Anderies (2006:144) says in relation to inequality (13).

This makes the conditions favoring a switch to irrigated agriculture clear: once the left hand side of inequality 13 becomes negative, society devotes some labor to irrigation. This becomes more likely as  $K$  increases (obviously), as the wild resource becomes degraded relative to irrigated agriculture (the ratio  $x_a/x_w$  increases), or the productivity of labor in irrigation is higher than in the wild resource sector.

After  $l_a$  is determined  $Y_{wp}, Y_{wc}, Y_{ap}$ , and  $Y_{ac}$  (which are the dynamical total outputs of wild protein and carbohydrate rich resources and protein and carbohydrate rich agricultural products) can be computed. These outputs are computed as follows.

$$Y_{wp} = A_{wp} * x_w * l_{wp} * h \quad (14)$$

$$Y_{wc} = A_{wc} * x_w * l_{wc} * h \quad (15)$$

$$Y_a = (A_{ap} + A_{ac}) * l_a * h * K \quad (16)$$

$$Y_{trade} = A_{lcf} * x_{lcf} * l_{trade} * h \quad (17)$$

Next, people in the Hohokam system decide whether to trade for Lake Cahuilla fish, using the following criteria.

$$\text{If } y_{wp} \geq y_{wpmin} \text{ then } l_{trade} = 0 \quad (18)$$

$$\text{else if } y_{wp} < y_{wpmin} \quad (19)$$

(i.e. minimum wild protein needs cannot be met) then Step 2.

In sum, Step 1 is a classic linear programming optimization problem, which is based on the realistic assumption that people in the Pre-Classic Hohokam system would try and meet their nutritional needs with either local wild resources or with a combination of wild resources and farming that minimizes labor. Then if all wild protein needs are met (18) there is no reason to trade for wild protein rich resources from sources outside of the Hohokam system. If these needs are not met (inequality 19) then implement Step 2. Step 2 is a heuristic and is based on the reasonable assumption that people will respond to local per-capita deficiencies in protein rich wild foods by transferring a maximum amount of available labor from procuring wild carbohydrate rich foods (determined by the following criteria and equations 20 and 21) to obtain protein from a non-local source that has an ample supply of protein rich wild food.

Step 2. If  $y_{wc} > y_{wcmin}$  and  $l_{wp} + l_{wc} + l_a < \gamma * l_{max}$  reduce  $l_{wc}$  to meet  $y_{wcmin}$  ( $\Delta L$ ) and then if  $l_{wp} + l_{wc} + l_a + \Delta L \leq \gamma * l_{max}$  allocate this amount of labor ( $\Delta L$ ) to  $l_{trade}$  where

$$\Delta L = \frac{(y_{wc} - y_{wcmin})}{A_{12} * x_1} = l_{trade} \quad (20)$$

else

$$l_{trade} = \gamma * l_{max} - l_{wp} - l_{wc} - l_a \quad (21)$$

In this analysis, I assume that the population of the Hohokam regional system (especially core area of the Phoenix or Salt-Gila Basin) increased between A.D. 900 and 1070. White and Lekson (2001:104) comment that the population in the Salt-Gila basin peaked during this time and was probably in the tens of thousands. Earle and Doyle (2008) provide an estimate of 30,000 for the Phoenix Basin. As with the Anderies (2006) model, I assume that population size and capital stocks are correlated and that the capital labor ratio ( $K/h$ , see Table 8.3) is constant. I also assume a high capital labor ratio considering the presumed peak in population and (presumed) major capital investments in (for example) the regional ballcourt network and irrigated agriculture. For comparative reasons, I use  $K/h = 0.2$ , which is the same value used by Anderies to represent a system with high investment in irrigation and other infrastructure. All of the remaining parameters in the model (see Table 8.3) were chosen to simplify the analysis and function to scale the units of measurement. As with the Anderies (2006) model, this model produces results that are robust over a broad range of parameter values.

Table 8.2. Model variables.

Variables	Definition
$x_w$	Biomass of wild resources in the Hohokam regional system.
$x_a$	Soil fertility of irrigated land in the Hohokam regional system.
$x_{lc\_fish}$	Biomass of Lake Cahuilla fish population.
$K$	Capital [which relates to the output of irrigated agriculture in the Hohokam system]. Used as a constant in the current model.
$K_{LC}(u)$	Carrying capacity of Lake Cahuilla fishery as a function of $u$ . $K_{LC}$ is a periodic function, with periodicity equal to $p_1$ .
$l_{ij}$	Labor devoted to producing output $j = p$ or $c$ from resource $i = w, a$ , or $lc$ .
$l_a$	Labor devoted to agriculture.
$l_{trade}$	Labor devoted to trade by the Hohokam system. Implicitly includes labor allocated to the procurement, manufacture, transport of shell preciosities and associated equipment (e.g., burden baskets), by middlemen, and labor and equipment devoted to transporting dried Lake Cahuilla fish.

The model parameters of Table 8.3 determine the magnitude and range of population values ( $h \in [0, \sim 2.5]$ ) useful for studying the model dynamics. The magnitude of the population values of this model are scaled so that (for example) a population of 10,000 is represented by  $h = 1$  and a population of 25,000 by  $h = 2.5$ . Equivalent to the Anderies model both: (1) the growth rates of the resource types (there are three in this model compared to two in the Anderies model) and (2) the productivities in procuring wild resources and producing crops with irrigated agriculture are assumed to be 1.

Table 8.3. Model parameters.

Parameters	Definition	Default Value
$r_w$	Intrinsic regeneration rate of wild resources in the Hohokam system [rainfall].	1
$r_a$	Intrinsic regeneration rate of agriculture [stream flow].	1
$r_{lc\_fish}$	Intrinsic rate of natural increase of Lake Cahuilla fish population	1
$l_{max}$	Total available labor per individual (e.g., 20 hours/day).	20
$\gamma$	Scaling factor for $l_{max}$ .	0.9
$h$	Total human population in Hohokam system.	1.5
$K$	Capital, which includes physical, social, and institutional infrastructure.	0.3
$K_i$	Carrying capacity of resource $i$ , where $i = a$ or $w$ ( $a =$ agriculture [streamflow] and $w =$ wild resources [rainfall]).	1
$A_i$	Output type $p$ (protein rich) or $c$ (carbohydrate rich) per unit labor in $w$ (harvesting local wild resource), $lc_f$ (harvesting Lake Cahuilla fish), or $a$ (agricultural production).	1 for all $i = wp, wc, ap, ac,$ or $lc_f\_p$
$a_i$	Impact on resource $w, a,$ or $lc_f$ as the result of producing $p$ or $c$ .	0.1 for all $i = wp, wc, ap, ac,$ or $lc_f\_p$
$y_{wpmin}$	Minimum per-capita requirement for protein rich wild resources.	1
$y_{wcmin}$	Minimum per-capita requirement for carbohydrate rich wild resources	1
$p_1$	Lake Cahuilla filling and emptying cycle.	50
$\alpha_1$	Scaling parameter for $K_{LC_{scaled}}(u)$ .	1
$\mu_1$	Scaling parameter for $K_{LC_{scaled}}(u)$ .	2
$\mu_2$	Scaling parameter for $K_{LC_{scaled}}(u)$ .	3

## Model Analysis

The model was analyzed with numerical simulations using XPPAUT (Ermentrout 2002); see Appendix V for the XPPAUT code. The purpose of the simulations is to identify how trade for Lake Cahuilla fish may have affected long-run dynamics of the Pre-Classic Hohokam system (ca. A.D. 900-1100) and how this relates to robustness/vulnerability tradeoffs. This is also only a preliminary analysis of this model, which I will study in greater depth in the future with bifurcation analyses.

It is important to identify the different robustness/vulnerability tradeoffs that are represented in the model. In the model, capital ( $K$ ) relates to irrigation infrastructure whose output depends on the design of irrigation systems, labor investment in their construction and operation, and streamflow.  $K$  is associated with vulnerabilities in the system that include: (1) reductions in streamflow (extended drought) that lower agricultural productivity; (2) social problems that interfere with the construction and maintenance of irrigation systems; and (3) floods. Investments in  $K$  (increasing  $K$ ) make the system more robust to short term local drought, but more vulnerable to the preceding three types of disturbances. Becoming involved in long distance trade relations with Lake Cahuilla residents that result in the importation of dried Lake Cahuilla fish: (1) increases the potential resource base for people in the Hohokam system and (in turn) the robustness to maintain a minimum desired level of wild protein rich food (also see Freeman et al. 2014:99-100), (2) increases the systems robustness to short and long term droughts that lower the productivity of local wild resources, and (3) to environmental and social perturbations (above) that can reduce the productivity of irrigated agriculture. Vulnerabilities of trading for Lake Cahuilla fish include: (1) social disturbances (e.g.,

conflict among Lake Cahuilla residents and disease epidemics) that can disrupt trade, (2) environmental disturbances (e.g., desiccation of Lake Cahuilla as the result of periodic changes in the course of its primary water source [the Colorado River]) that can reduce the output of the Lake Cahuilla fishery, and (3) potential degradation of local resources from increases in population that may result from protein surpluses generated by the importation of Lake Cahuilla fish.

The model is evaluated with a constant capital labor ratio  $K/h = 0.2$  (which corresponds to a major investment in irrigation infrastructure, see Anderies 2006:147) and four population sizes: (1) small ( $h=1$ , which corresponds to a population of 10,000), (2) a medium-sized population of 15,000 ( $h=1.5$ ), (3) a large population of 25,000 ( $h=2.5$ ), and (4) at a population threshold (25,050,  $h=2.505$ ) where the system bifurcates from long-term stability to collapse after 144 years. For the small population case the long-run equilibrium is characterized by a small reduction in wild resource stocks from harvesting (between 0.7 and 0.8 of the carrying capacity, see Figure 8.9), an average of about 2.75 hours per day per person devoted to harvesting these resources, and virtually no labor devoted to agriculture or Lake Cahuilla trade (Figures 8.10 and 8.11). At this population level with a significant investment in irrigation infrastructure the population is highly robust to local environmental shocks, although very little per-capita labor is devoted to agriculture and only a small per-capita labor investment per day is required to maintain the output of wild resources at minimal levels.

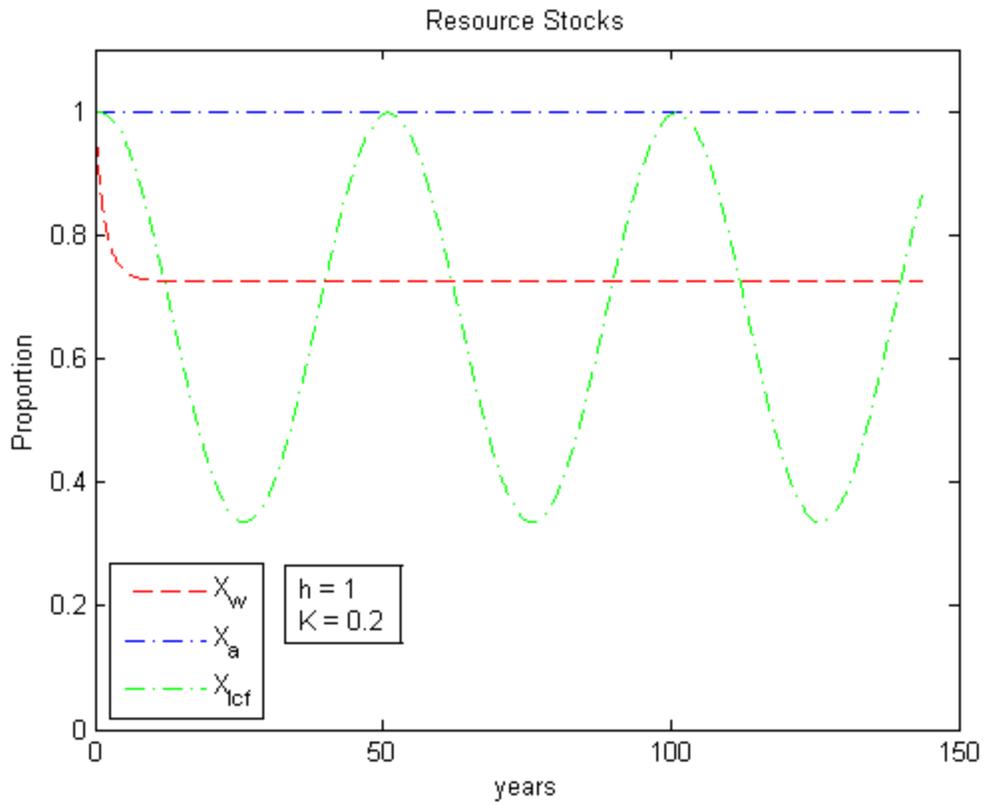


Figure 8.9. Wild and agricultural resource stocks and Lake Cahuilla fish stock over a 150-year period, with  $h = 1$  and  $K = 0.2$  (small population with intensified irrigation).

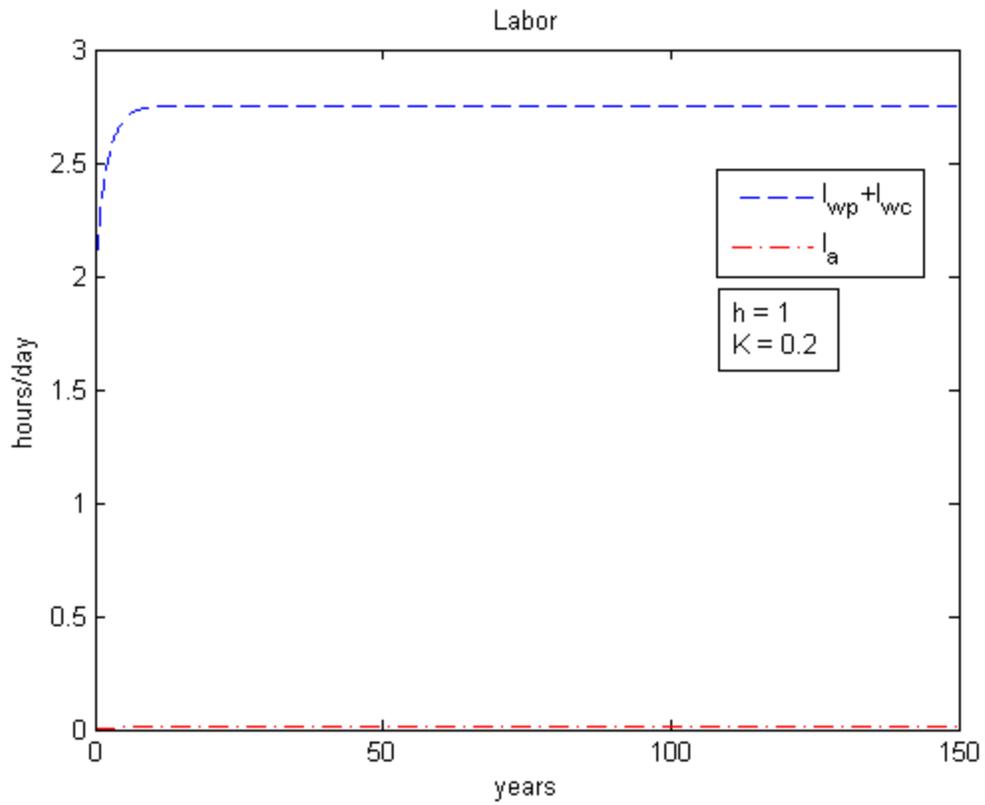


Figure 8.10. Labor devoted to wild resources and agriculture for a small population.

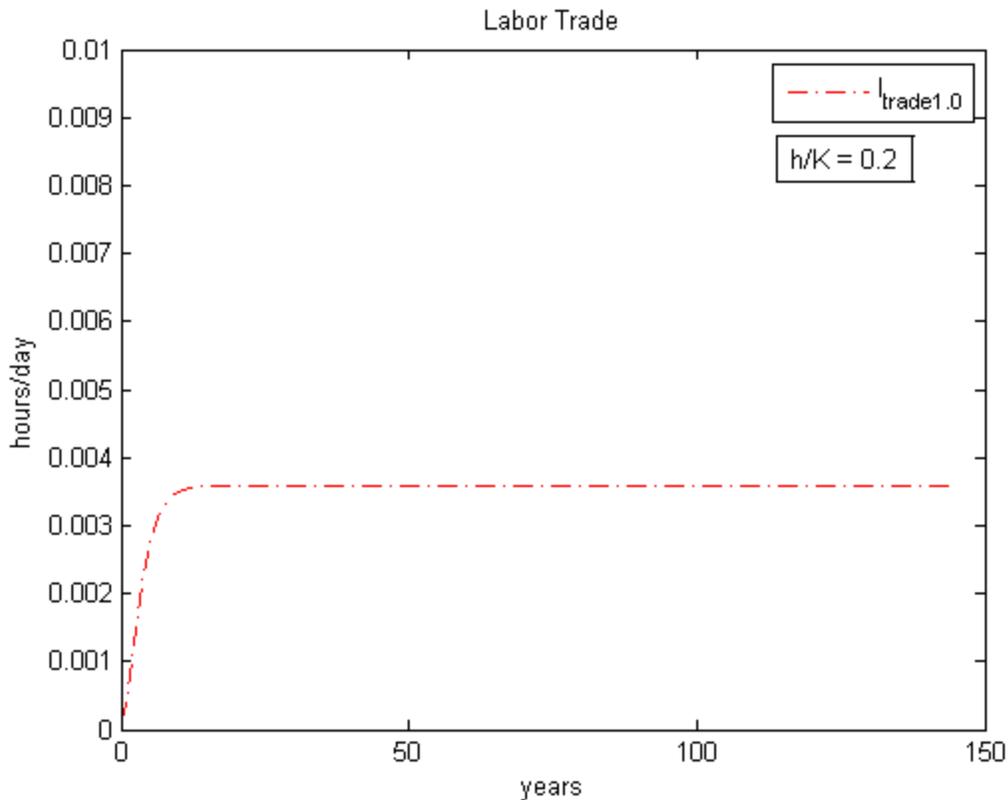


Figure 8.11. Labor devoted to Lake Cahuilla trade for a small population.

For the medium-sized population ( $h=1.5$ ) the long-run equilibrium for the wild resource stock is reduced to about 0.6, soil fertility is reduced slightly to about 0.9, and the Lake Cahuilla fish stock is barely affected (Figure 8.12). Compared to the small population case, the long-run equilibrium of the per-capita allocation of labor for obtaining wild resources is slightly reduced to about 2.5 hours per day, about 0.8 hours per day per-capita is devoted to agriculture, and about 0.3 hours/day per-capita is used for Lake Cahuilla trade (Figure 8.13). This amounts to a small total per-capita labor investment of about 3.5 hours/day to maintain minimal levels of production. Under these conditions the Hohokam system is very robust to environmental shocks as the result of increased agricultural production and the import of dried Lake Cahuilla fish.

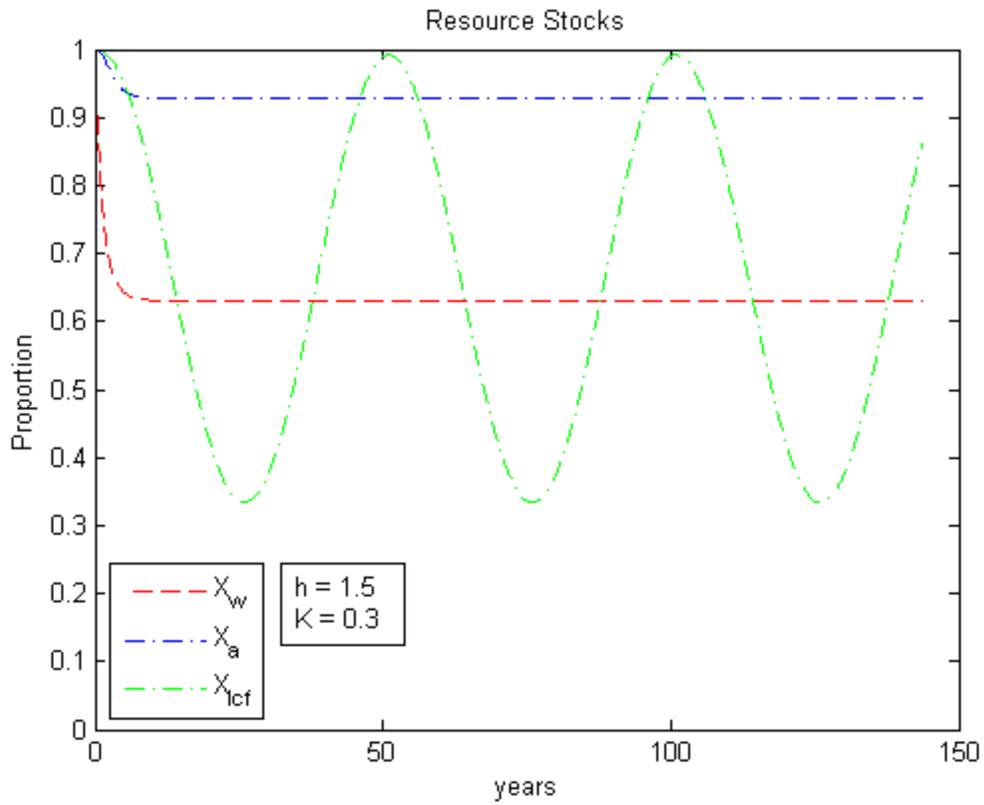


Figure 8.12. Wild and agricultural resource stocks and Lake Cahuilla fish stock over a 150-year period, with  $h = 1.5$  and  $K = 0.2$  (medium sized population with intensified irrigation).

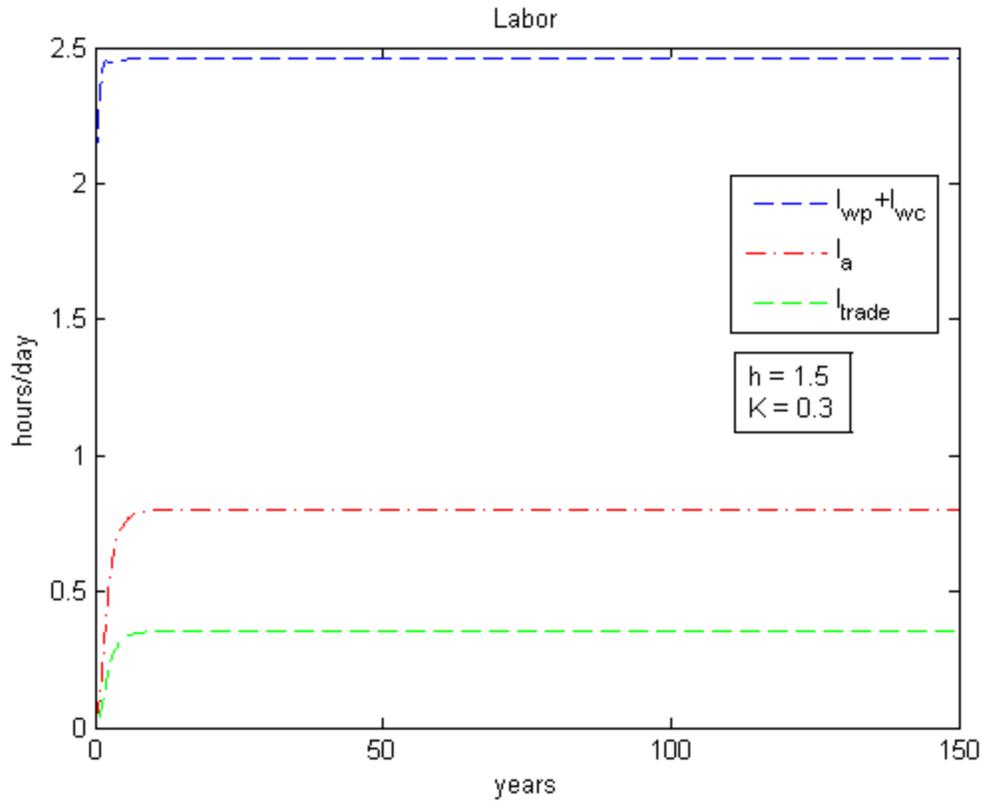


Figure 8.13. Labor devoted to wild resources, agriculture, and Lake Cahuilla trade for medium-sized population.

For the large population ( $h=2.5$ ) the long-run equilibrium of both the wild resource stock and soil fertility drops to about half their respective carrying capacities after about 50 years (Figure 8.14). The Lake Cahuilla fish stock is now slightly reduced but at the peak of its cycle it is still close to its maximum carrying capacity of 1 when the lake is at its greatest extent during its 50-year cycle (Figure 8.14). After about 50 years per-capita labor allocation stabilizes when the system reaches equilibrium (Figure 8.15). Compared to the medium-level population at the long-run equilibrium per-capita labor devoted to agriculture has increased from about 0.8 to approximately 2 hours per day, per-capita labor devoted to wild resources is reduced to about 2 hours per day, and per-capita labor

for Lake Cahuilla trade has increased from about 0.3 hours per day to nearly 1 hour per day (Figure 8.15). To meet their minimum daily requirements of protein and carbohydrates people now on average need to work about 5 hours per day, which is only a moderate labor investment. Even though the local wild resource stock and soil fertility are nearly reduced by half at equilibrium the Lake Cahuilla fish stock remains near its carrying capacity and the system is sustainable. In this case on average about 20 percent of a person's labor is devoted to activities related to Lake Cahuilla trade. Together agriculture and Lake Cahuilla dried fish have made the system very robust to environmental disturbances such as drought and floods.

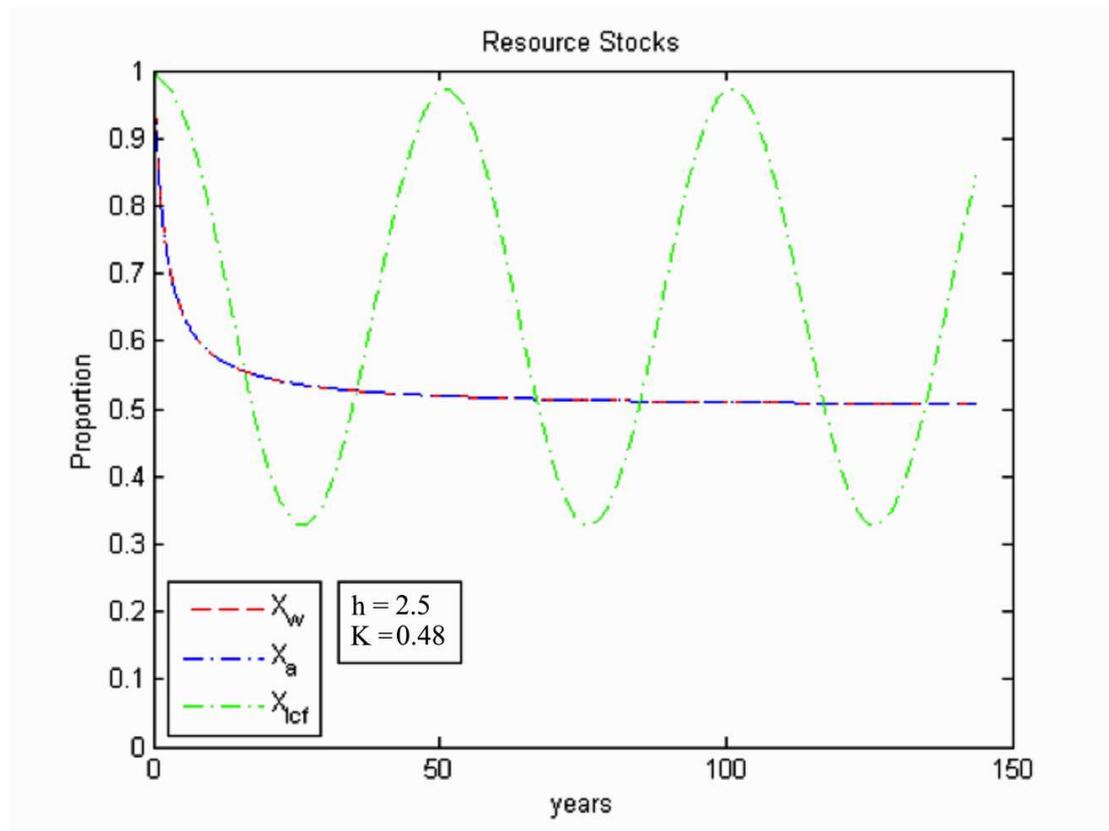


Figure 8.14. Wild and agricultural resource stocks and Lake Cahuilla fish stock over a 150-year period, with  $h = 2.5$  and  $K = 0.48$  (large population with intensified irrigation).

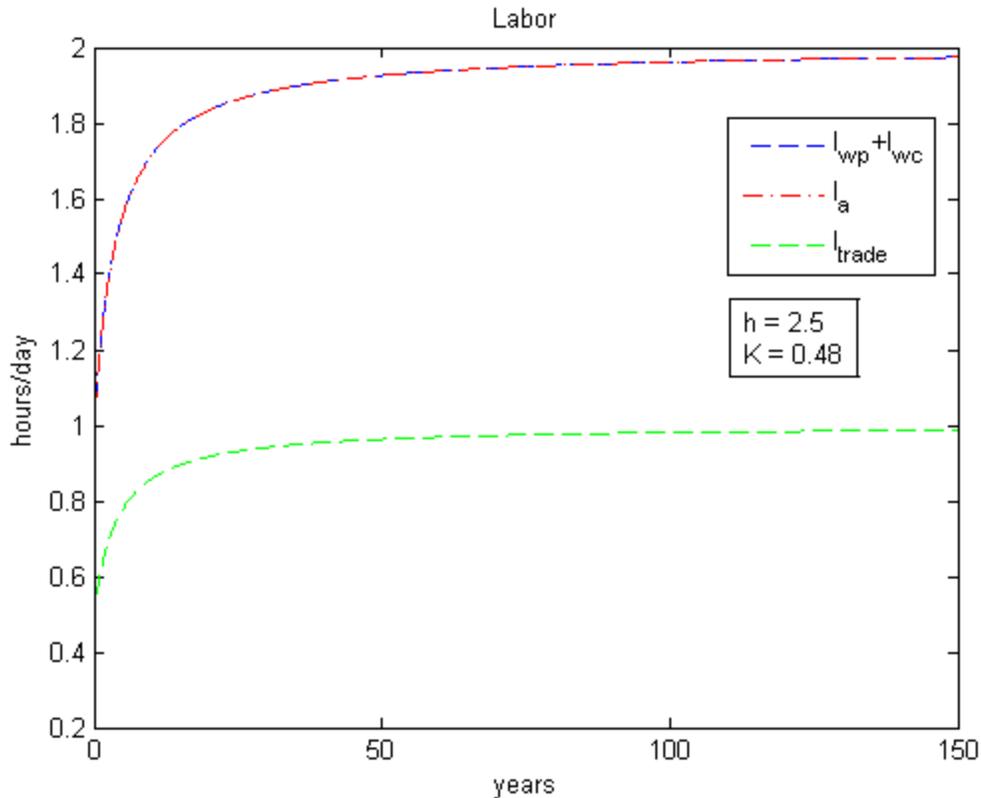


Figure 8.15. Labor devoted to wild resources, agriculture, and Lake Cahuilla trade for a large population,  $h=2.5$ ,  $K = 0.48$ .

The final case is a population size (25,050) and capital ( $K=0.501$ ) combination that constitutes a very slight increase from the values of these parameters in the previous case that produces a radical change in the system dynamics. In this case adding only an additional 50 people after reaching a population of 25,000 results in the very rapid collapse of the system in which the local resource base is destroyed and in contrast the Lake Cahuilla fish stock remains near full capacity (see Figure 8.16). Under these conditions the model predicts that people would not respond fast enough to re-organize the system in order to delay or prevent the exhaustion of local resources. At 135.7 years total labor reaches the model's maximum per-capita daily labor allocation ( $l_{max}$ ) of 18 hours/day, where it remains until the system has completely collapsed at 143.6 years.

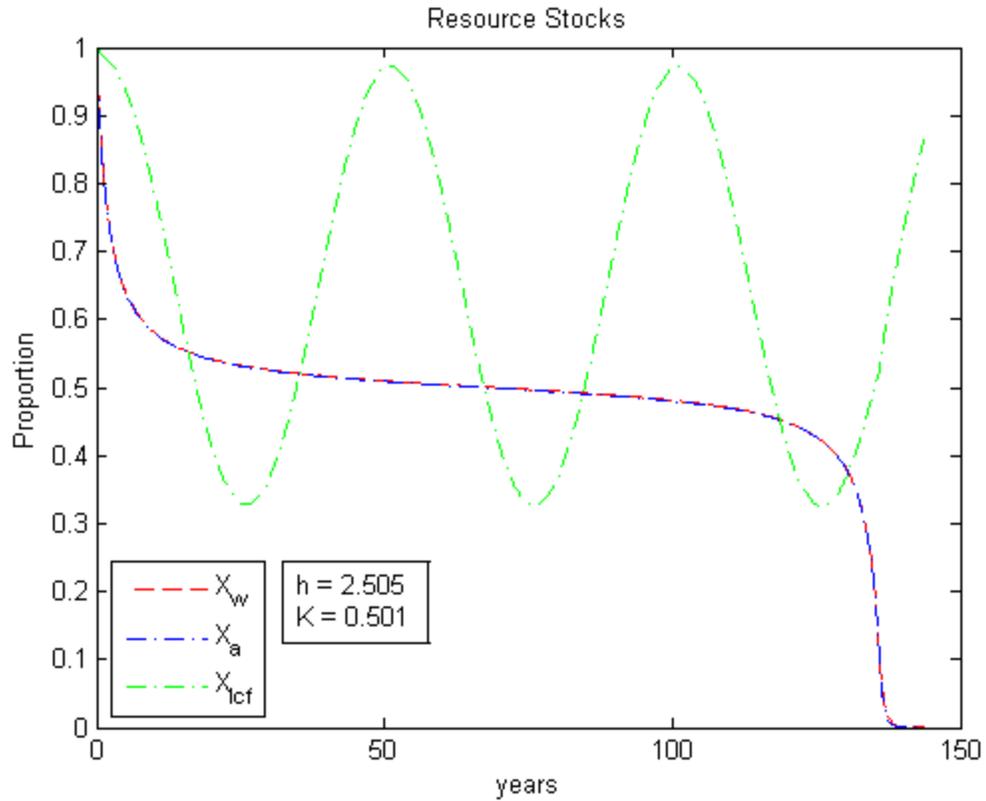


Figure 8.16. Wild and agricultural resource stocks and Lake Cahuilla fish stock over a 150-year period, with  $h = 2.505$  and  $K = 0.501$  (critically large population with intensified irrigation).

In fact near the time of collapse society incorrectly deploys all its labor (probably an issue of sunk-cost related to investments in existing institutional arrangements and irrigation infrastructure) to agricultural production (carbohydrate rich foods) and the harvest of local protein rich wild foods (see Figure 8.17). Slightly more labor is devoted to agricultural production (see Figure 8.17), but to no avail. Labor devoted to obtaining carbohydrate rich wild resources rapidly drops to zero, a very short time after the cessation of labor devoted to Lake Cahuilla trade (Figure 8.17). During this time, labor devoted to trade achieves the long-term maximum of 3.57 hours/day at 135.6 years, followed by a complete cessation of trade at 136.2 years (see Figure 8.17).

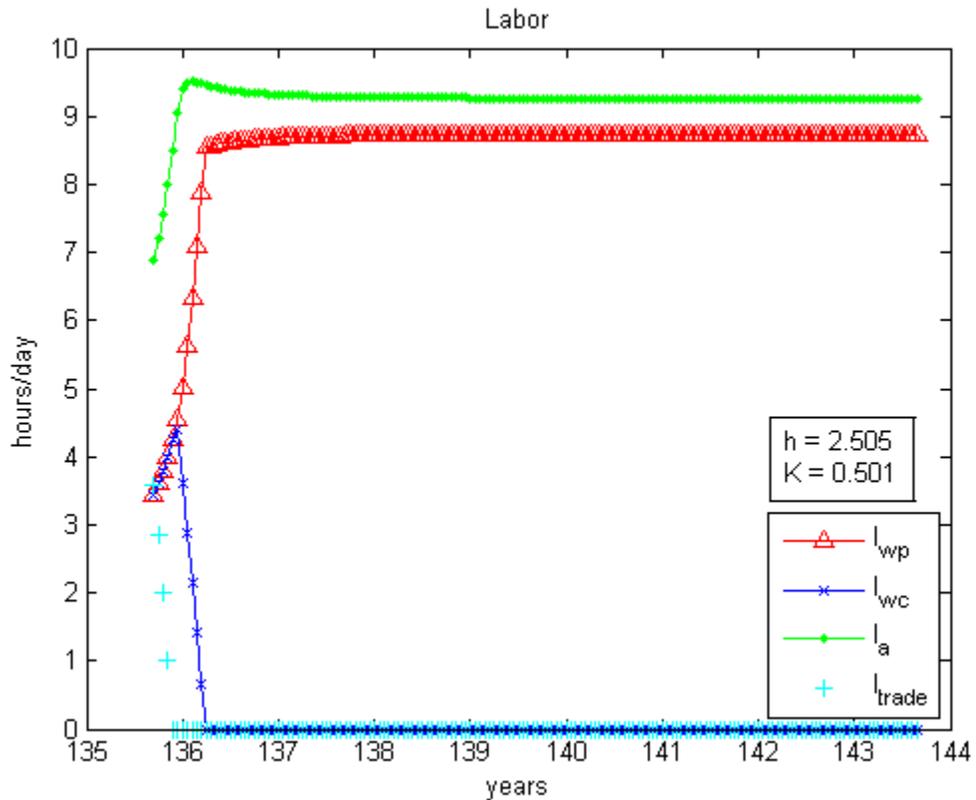


Figure 8.17. Labor allocated to protein rich wild resources (wp), carbohydrate rich wild resource (wc), agriculture (a), and Lake Cahuilla trade (trade) for critically large ( $h=2.505$ ) population.

Devoting much more labor to the import of Lake Cahuilla fish would have been a far better choice for sustaining the local resource base, considering that the Lake Cahuilla fish stock was still near its cyclical carrying capacity (see Figure 8.16). Also, the predicted rate of the collapse of the Pre-Classic Hohokam system (~20 years) by the model could be evaluated with archaeological evidence. In particular, if the model run begins a few years (~25) after A.D. 900 given  $h=2.505$  and  $K=0.501$ , the model predicts the system will completely collapse by A.D. 1070, which is consistent with the most recent archaeological estimates. In Chapter 2 archaeological evidence was provided that

suggests much of the large-scale irrigation infrastructure (e.g., canals and water control systems) may have completed by A.D. 950 (Howard and Huckleberry 1991) accompanied by continuing population growth (previous section this chapter). This supports the idea that critical values of  $h$  and  $K$  could have been reached during the Sedentary period where the system bifurcated from long-term stability to rapid collapse dynamics. So what is the role of the Lake Cahuilla fish trade in the collapse?

Framed in the context of systemic fragility and robustness/fragility tradeoffs, as the first three cases demonstrate, the long distance trade for Lake Cahuilla fish would help to make the Hohokam system highly robust to local drought, floods and protein shortages, but (as the last case shows) with the tradeoff of much higher vulnerability to the catastrophic degradation of local resources as the result of population growth. In relation to population growth a key result from the final case is that just a minute population difference (50 people or equivalently a slight population increase of just 0.2 percent) shifted the modeled Pre-Classic Hohokam system from long-term stability to rapid collapse. It seems reasonable that people within the system would not recognize this (especially since their minimal needs were being met with the added bonus of a wild protein surplus from Lake Cahuilla fish, see Figure 8.18), which makes this a rather subtle kind of systemic fragility tied to expanding the scale of interaction through trade for Lake Cahuilla fish. Also, surpluses of protein resulting from the import of Lake

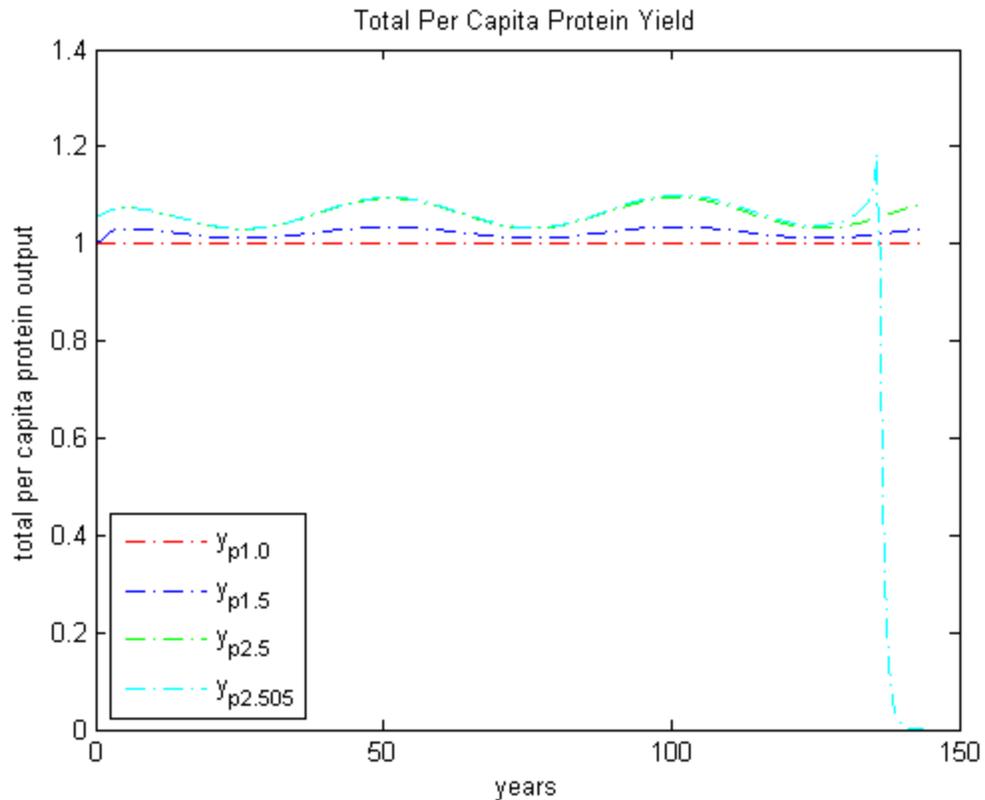


Figure 8.18. Total per capita protein yields for the four cases studied in the model analysis.

Lake Cahuilla fish may have contributed not only to the growth of the human population of the Hohokam system directly (as food) but possibly also in an institutional setting as staple finance (D'Altroy et al. 1985) that facilitated the growth of infrastructure (e.g., irrigation systems) that amplified the human carrying capacity of the local system.

Possibly the most compelling result from the analysis of the final case ( $h=2.505$ ,  $K=0.501$ ) is that people did not dramatically increase labor for Lake Cahuilla trade near the onset of a rapid collapse of the system to possibly overt catastrophe. Explaining this result is a future research goal that should include a deeper study of the parameter space of the model through bifurcation analysis.

## Summary and Conclusion

In this chapter a simple bioeconomic model was developed and analyzed using the conceptual frameworks of robustness-vulnerability tradeoff properties of SESs and institutional economics to evaluate the systemic fragility of the Pre-Classic Hohokam system (ca. A.D. 900-1100) in relation to trade with Lake Cahuilla. Prior to this chapter ethnohistoric, ethnographic, and archaeological evidence was used to establish the likelihood and contexts of trade between the Hohokam system and Lake Cahuilla fishers during this time. Key robustness and vulnerability properties of the expanded Hohokam system were also identified as the result of network analyses in Chapter 7. These analyses suggested a strong connection between the Hohokam system and Lake Cahuilla fishers that was vulnerable to environmental disruptions (the drying of Lake Cahuilla) and social disturbances that would disrupt trade between the two regions. Prior to the analysis of the model it seemed intuitive that the loss of Lake Cahuilla as the result of the diversion of the Colorado River by periodic earthquakes was strongly linked to the systemic fragility of the expanded Hohokam system. Interestingly the model analysis provided a very different insight that revealed an unexpected and critical vulnerability of the system that directly relates to theory concerned with sunk cost and path dependence (which I discuss in detail in the next chapter).

As the model analysis suggests, in many cases people may have more than enough resources to provide for their needs well into the future, even with a rapidly growing population. The problem is being able to detect important and sometimes very subtle or unexpected feedbacks from the environment and being able to respond in ways that maximize the robustness of the system. In the case of the Hohokam system, institutional

arrangements and infrastructure that had developed over centuries were probably optimized for maintaining stability in the output and for sustaining local wild resources and agriculture. Expanding the scale of interaction provided new vulnerabilities for the Hohokam system that required changes in established norms and rules. Institutional change, considering the great success of the Hohokam system for many generations, probably did not come easy or quickly. In fact, the model analysis suggests it was not the filling and drying cycles of Lake Cahuilla or any other environmental shock that likely was a major factor in the collapse of the Pre-Classic Hohokam system. Rather the analysis provides the unexpected result that the failure of the system was tied to the social realm. Specifically that people and institutions, considering their major investments and trust in infrastructure and technology that had sustained them for at least a thousand years, would not respond adequately or rapidly enough to increase development of infrastructure related to the import of dried Lake Cahuilla fish. This is because in doing so would require reduction in infrastructure and output in other sectors and time proven technologies, specifically agricultural infrastructure (e.g., large-scale irrigations systems) and the harvest of local wild resources. Finally, another and possibly more compelling insight from the model analysis is there may have been a very narrow range of population increase beyond some critical threshold that may not have been detectable, even with major alterations in the Hohokam system that would afford greater flexibility in responding to crises of this type. This may be a more general issue and concern for all human societies that should be the focus of future research.

## CHAPTER 9: INCREASING SCALES OF SOCIAL INTERACTION AND THE ROLE OF LAKE CAHUILLA IN THE SYSTEMIC FRAGILITY OF THE HOHOKAM SYSTEM (A.D. 700-1100)

In this study I have provided a fresh examination of Hohokam archaeology that considers far more than just material evidence from the archaeological record within the Hohokam system. The aim of this study is to provide a better understanding of the systemic fragility of the Pre-Classic Hohokam system in relation to the growth of the system and expansion of interaction beyond the regional scale. To accomplish this I used multiple lines of evidence and (in some cases) applied or developed analytical methods that are new to archaeology. Qualitative data from ethnohistory, ethnography, and archaeology was analyzed in conjunction with formal analyses of archaeological data to: (1) construct a network model of what I call the Hohokam/California transregional system and (2) suggest that much of the expansion of the Pre-Classic Hohokam system beyond the regional scale was driven by local deficiencies of wild protein rich food that resulted from the combined and interacting processes of climate change, human population growth and capital investment in irrigation infrastructure. Production of shell preciosities to trade for dried fish from a large fishery at Lake Cahuilla in the Salton Basin of southeastern California was identified as a likely response to increase robustness of the Hohokam system to local wild protein shortfalls. Additional ethnohistoric and archaeological evidence identified the Gila River as the most likely trade route between the Phoenix Basin (the core of the Hohokam system) and Lake Cahuilla.

The network model was analyzed using two network analytic methods (walktrap communities and the Erdős-Rényi random graph model) to: (1) strongly argue for the

existence of the transregional system and (2) study its organizational structure in relation to the fragility of the system. Archaeologists have not previously used these methods. Results from the archaeological and network analyses suggest significant interaction between the Pre-Classic Hohokam system and Lake Cahuilla fishers. This result was used in a stylized bioeconomic model where the Hohokam system manufactures and trades shell preciosities for dried Lake Cahuilla fish to supplement the harvest of local wild protein rich food. Analysis of the bioeconomic model provided key insights into robustness-fragility tradeoffs resulting from trade with Lake Cahuilla fishers and how these tradeoffs may have contributed to the rapid collapse of the Pre-Classic Hohokam system circa A.D. 1070.

### **Reconstructing and Analyzing the Hohokam/California Transregional System**

The inter-linked process of identifying the types of data and analyses that were needed to accomplish the goals of this study required innovation, original thinking, and sometimes a lot of patience and persistence. Early in the research process I realized that data from ethnohistoric, ethnographic and archaeological sources was needed. The archaeological data proved to be the most challenging. Of all the material categories I considered I determined that shell artifacts were the most useful for constructing a network model of interaction between southern California societies and the Hohokam system. Compiling the shell data to do this was a lengthy and sometimes frustrating process, since the majority of archaeological samples from southern California and (especially) Hohokam sites were obtained using  $\frac{1}{4}$  inch screens, which prevented the recovery of the great majority of the most important shell artifact types (e.g., *Olivella biplicata* saucer/disc and *Olivella dama* small barrel beads) for my purposes.

In the daunting search for shell artifacts of the types I needed, I am very grateful for the help of Arthur Vokes (Arizona State Museum), Chester King (Topanga Anthropological Consultants), and Margaret Hardin and Lindsey Groves (Los Angeles County Museum of Natural History). I am also most grateful for the help from Betsy Brandt and Chester King with the ethnohistoric and ethnographic data.

To develop and implement the variety of analytical methods used in this work required knowledge and experience from several theoretical and methodological areas of research that include: social ecological systems, institutional economics, the archaeology, ethnohistory and ethnography of exchange, ethnohistoric and institutional analysis, stylized mathematical modeling using ordinary differential equations, simulation based mathematical statistics, mathematical seriation, signal processing, network analysis, fisheries biology, malacology, and geometric morphometrics. The specific theory and methodology required from each of these areas is introduced prior to their use throughout this work with additional details provided in appendices. Summaries of the findings are given at the end of each chapter. The purpose of this section is to provide a summary of the important findings from each of the chapters of this study and (in particular) how they relate to the four research goals addressed by this work, which are: (1) Document the transregional system of interaction that linked the Hohokam region and California during the centuries from AD 700 to 1100; (2) determine whether the transregional exchange system was directional and structured or was largely stochastic using simulation, network, and statistical analysis; (3) identify regions in the network model that are probably strongly tied to the Hohokam system and each other through regular interaction; and (4) use mathematical modeling to evaluate the effects of additional labor allocations

for specialized production and trade, population size, and the filling/drying cycles of Lake Cahuilla on the stability of Hohokam social ecological system.

I addressed Goals 1 and 3 in Chapter 3 with the synthesis of ethnohistoric, ethnographic and archaeological data on exchange relations between each of the regions in the Hohokam California transregion. This process also resulted in the recognition and definition of what may be the territory of Hopi ancestors prior to A.D. 1100 in a large region that includes part of southeastern California, central and northern Arizona, southeastern Nevada, and southwestern Utah. Shell artifacts and pottery data were used to suggest archaeological group identity and intra and interregional exchange patterns that were compared with or supplemented by ethnohistoric and ethnographic data on exchange within and among California and Arizona societies between A.D. 700 and 1100. This resulted in the construction of an undirected and preliminary network model of the California/Hohokam transregion amenable to additional study using graph theoretic and network analytic methods.

Chapter 6 is characterized by the use of statistical methods not commonly or previously used by archaeologists. Most of them required writing original computer code or implementing (and often modifying) code published in peer-reviewed journal supplements or other published sources. The computer code for each of these procedures is provided in an appendix. Because of this the reader should refer to the appropriate appendices as well as the descriptions of these methods prior to their use in Chapter 6 and to the interpretation of the results following their use. In this summary I emphasize the collective result, which is the efficacy of their synthesis into a directed network model, which is consistent with the preliminary undirected model in Chapter 3. Together these

models support the accuracy of the other. Individually and collectively the statistical analyses of Chapter 6 use shell artifacts as a proxy for exchange. They provided many additional details on interregional exchange relations in the Hohokam/California transregion that include information on the intensity and directionality of exchange. Some of the results from Chapter 6 also suggest that most of the interregional interaction of the Pre-Classic Hohokam system in California was with Lake Cahuilla residents, and that Gulf of California shell artifacts (probably made by artisans in the Hohokam system) are a major import item, which addresses Goals 1, 2, and 3.

In Chapter 4, I provided archaeological ethnographic and ethnohistoric evidence of the importance of dried fish as a protein source in recent and prehistoric societies in the Great Basin, Arizona, the Colorado River, and Lake Cahuilla. I also provided archaeological evidence that may suggest the long distance transport and consumption of Gulf of California fishes by Classic Mimbres people in the ancient U.S. Southwest. The Mimbres case and an ethnohistoric and archaeological example (cui-ui fishery) from the Great Basin (which I also discuss in Chapter 4) suggest that people in desert regions of the U.S. may often have traveled long distances to acquire fish. In Chapter 4, I also examined the role of Lake Cahuilla in the economic expansion of the Pre-Classic Hohokam system, which addresses Goal 3. I also provided evidence that the Gila River was an efficient and direct trade route between the Phoenix Basin and Lake Cahuilla that offered an abundance of freshwater and wild resources that facilitated long distance travel across the desert, which addresses Goal 3. In addition, I provided recent seismological evidence that the Lake Cahuilla filling and emptying cycles were the result of earthquakes in the Salton Basin that altered the course of the Colorado River (the lake's

primary water source), and which are independent of climatic events such as drought. Finally, I provided archaeological evidence (e.g., stone fish traps and fish bone) from Lake Cahuilla shoreline sites that suggest a substantial fishery existed at the lake during the Late Colonial and Sedentary periods of the Hohokam system.

In Chapter 5, I used diagnostic morphological attributes of *Olivella dama* (a gastropod endemic to the Gulf of California and commonly recovered as small barrel and spire ground beads from Pre-Classic Hohokam deposits), *Olivella flecherae* (a Gulf of California endemic often found in Pre-Classic Hohokam sites as small barrel beads), *Olivella tergina* and *zoenata* (Gulf of California species whose distribution overlaps with *dama*) and *Olivella biplicata* shell (a Pacific Coast endemic) that show a sample of small *Olivella* sp. barrel beads from burials (A.D. 900-1050) in a coastal southern California site (Humaliwo or LAn-264) are very likely species *dama*. I then used three size based (maximum length) univariate analyses (dot plot, box plot and 2 sample Smirnov test) to evaluate the origin of the Malibu *Olivella dama* small barrel beads. The results of all of these analyses suggest that some of the Malibu barrels may have originated in the Gila River area of the Hohokam system. Finally, I used a landmark based geometric morphometric procedure (geodesic principal components analysis) to compare the two-dimensional shape of the Malibu beads with the shape of *O. dama* small barrel beads from several contemporary Hohokam sites. I then used two statistical tests (robust one-way MANOVA and pivotal bootstrap), which (in these analyses) compare the mean shape between two populations. Both tests were used to evaluate the null hypothesis that sample pairs of *Olivella dama* barrel beads are from the same population. The null hypothesis was not rejected for four of the burial samples compared to some of the

samples from the Phoenix area. This suggests that some of the Malibu barrels may have come from Phoenix area of the Hohokam system. Combined, these analyses suggest the transport of these beads from one end (the Hohokam system) to the other end (Chumash area) of the transregion, which addresses Goals 1 and 3.

Chapter 6 begins with the study of M5a-b (A.D. 900-1050) burials from the Chumash Malibu site (LAn-264) that contain several to hundreds of *Olivella dama* small barrel beads. In Chapter 5 many of these beads were shown to have probably come from the core area (Phoenix Basin) of the Hohokam system. Initially I used a new quantitative method (Porčić 2013) to show that the relative frequencies of the shell artifact types from the burials were probably mostly patterned by time (which is a pre-requisite for a chronological seriation). The burials were then mathematically seriated and subdivided into temporal groups with the aid of radiocarbon dates. This allowed me to evaluate if shape consistency (measured with variation in bead diameter) of the Malibu *O. dama* barrels increased (which is expected if production of the beads intensified) during a period when this kind of bead may have often been traded for dried Lake Cahuilla fish. The coefficient of variation statistic was used to evaluate this hypothesis, which also posits that specialized and intensified production of *Olivella dama* small barrel beads in the Hohokam system occurred during an extended high stand of Lake Cahuilla and during a time (A.D. 900-1000) that the regional Hohokam system was expanding. The results of the analysis do not reject the null hypothesis and suggest that the production of *O. dama* barrels in the Hohokam system intensified between A.D. 900 and 1100 (see Figure 6.9, Burial Partition 2). This addresses Goals 2 and 3.

The remainder of the regional cases studied in Chapter 6 involves a large variety of statistical analyses whose purpose and outcomes are best understood by reviewing the appropriate sections in Chapter 6. It is sufficient here to only mention the purpose of these analyses (which was to address Goals 1, 2, and 3) and to briefly summarize their results, which are: (1) produce a directed network model of interaction between regions in the Hohokam/California transregion and (2) provide strong support for the idea that much of the shell preciosities exported from the Hohokam system were traded to people living in the vicinity of Lake Cahuilla.

In Chapter 7, I analyzed the network model produced in Chapters 3 and 6 using two network analytic methods to address Goals 1, 2, and 3. The first network analyses (using the Erdős-Rényi random graph model and the graph-theoretic measures: transitivity and average path length) showed that the Hohokam/California transregional network model does not have an organizational structure that would likely result from random (stochastic) processes, which addresses Goal 2. The second network analytic method (walktrap communities) revealed two distinct communities (or modules) that are expected to be largely independent (or equivalently that they are not mutually interdependent), which addresses Goals 3 and 4. One of the communities consists of regions in coastal southern California (which is the portion of the transregion with the greatest ecological richness and diversity) and the other is composed of interior regions that include those associated with Lake Cahuilla and the Hohokam system. The modularity measure from this analysis is in the observed range for real world networks (which is expected if the transregional system existed), and is also shown statistically to be too large to likely occur by chance, which addresses Goal 2. The partitioning of the

network into two communities suggested that the study of the systemic fragility of the Hohokam system with a mathematical model in Chapter 8 should focus on the interior community or (more specifically) on trade between the Hohokam system and Lake Cahuilla, which addresses Goal 4. In sum, the results of this analysis address all four goals.

Finally, kriging was used to show that the proportions of Gulf of California and Pacific Coast shell are likely the result of directional exchange, which addresses Goal 2. This supports the idea of an organized (or structured) system of interaction in the Hohokam/California transregion. This analysis also suggested strong directionality in the movement of Gulf of California shell artifacts from the Hohokam system to the Lake Cahuilla area, which addresses Goals 2 and 3. Such directionality in the movement of Gulf of California shell artifacts is also expected if these items were often traded for dried Lake Cahuilla fish.

In Chapter 8, I used the results of the preceding chapters along with a qualitative analysis of the A.D. 850-1100 Hohokam social-ecological system (SES) to help construct a bioeconomic model of the Hohokam SES (ca. A.D. 900-1100) that included trade with Lake Cahuilla fishers. I also used a Fourier analysis of reconstructed streamflow in two major rivers (the Gila and Salt) in the Phoenix Basin to help explain how variability in streamflow (rainfall) would have contributed to the establishment of trade for Lake Cahuilla fish. The result of the qualitative analysis of the Hohokam SES based on the framework of Anderies et al. 2004 helped identify in part how the Hohokam SES with trade to Lake Cahuilla was robust to perturbations and in what ways it was vulnerable to disturbances (environmental and social). Key vulnerabilities of the Hohokam SES

identified by this analysis are extended environmental shocks (e.g., multi-decadal droughts) and social disturbances that could disrupt trade. I used the theoretical result from Chapter 2 that minimal systemic fragility requires minimal redundancy in the types of items traded between regions to support my use in the bioeconomic model of only two kinds of items for trade between the Hohokam system and Lake Cahuilla. I also interpreted the results of the model using the robustness-fragility trade-off property from Chapter 2. Results from the model analysis that relate to the systemic fragility of the Hohokam system are: (1) trade for Lake Cahuilla fish makes the system highly vulnerable to exceeding a very narrow human population ceiling, since the trade for fish facilitates population growth to a population threshold that when slightly exceeded will result in the rapid collapse of the system as the result of the degradation of the local resource base; and (2) sunk costs (see Janssen et al. 2003; Janssen and Scheffer 2004) in the infrastructure of the local system that may deter people from rapidly and sufficiently increasing non-local trade to a level that would increase the sustainability of the system. Although preliminary, these results are a major contribution that shed new light on the long-standing debate on the reasons for the rapid collapse of the Pre-Classic Hohokam system during the middle to latter Sedentary period? In sum, the analyses and modeling of this chapter address Goal 4.

## **What More Can Be Learned from the Network Model?**

Much of this study involves the organization and evaluation of data to construct a network model of transregional exchange in what I call the Hohokam/California transregion between A.D. 700 and 1100. To accomplish this required the compilation and analysis of a diverse array of ethnohistoric, ethnographic and archaeological data using both qualitative and quantitative methods. The network model produced in this study is also a valuable data set that can be analyzed with a large variety of network analytic and graph theoretic measures (e.g., dominating sets and betweenness centrality, see Hage and Harary 1996) to provide a more nuanced understanding of the organization of the Hohokam/California transregional system and to address specific research questions, such as: where did middlemen concentrate in the system and why? Much more can be learned about the robustness-fragility properties of the Pre-Classic Hohokam transregional system by further study of the Hohokam/California network model. I provide two examples that demonstrate this as well as complement and add to results from earlier chapters of this work.

### *Example 1: Network Motifs*

*Network motifs* are: “recurring significant patterns of interconnections” (Milo et al. 2002:824). In terms of network models they are classes of subgraphs that represent the basic functional building blocks of complex systems (Milo et al. 2002). Network motifs arise because of the special constraints under which the network has developed (Callaway 2001; Milo et al. 2002:828). They have been shown to occur (see Milo et al. 2002) in biological (e.g., protein interactions, foodwebs, and neural networks) and engineered systems (e.g., internet routers and electrical circuits). They presumably occur in most

social systems. Figure 9.1 provides an example of a three-node and four-node motif detected in the Hohokam/California transregional network model (see Appendix W for the R code used to do this). Figure 9.2 shows the approximate sampling distributions of Motifs 3 and 4 in an Erdős-Rényi random graph with thirteen nodes and twenty-one edges. The estimated p-values for the observed frequency of Motifs 3 and 4 in the Hohokam/California network model are significantly different than what would likely occur by chance (Figure 9.2, also see Appendix W for the R code used to compute the approximate sampling distributions and estimate the p-values).

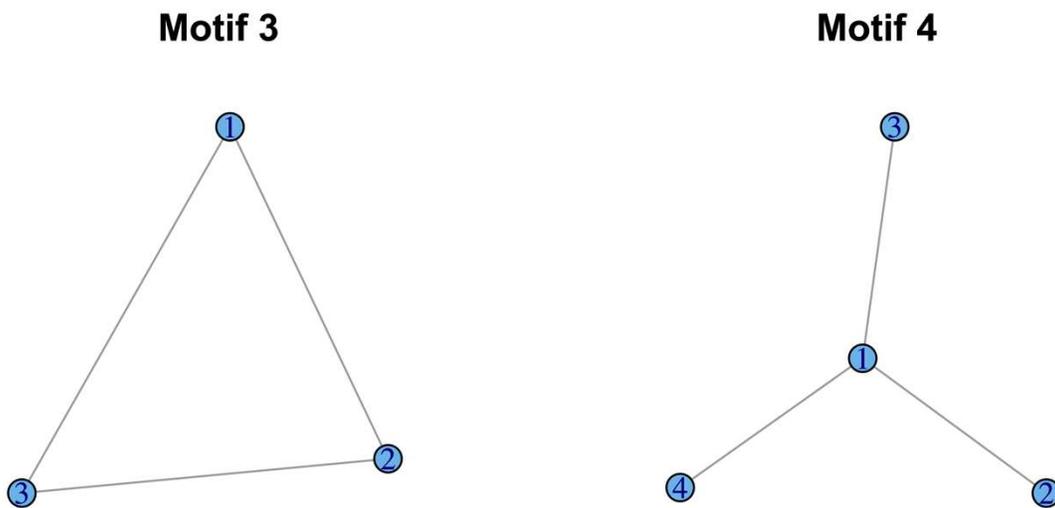


Figure 9.1. Examples of a three-node and four-node motif in the Hohokam/California transregional network model.

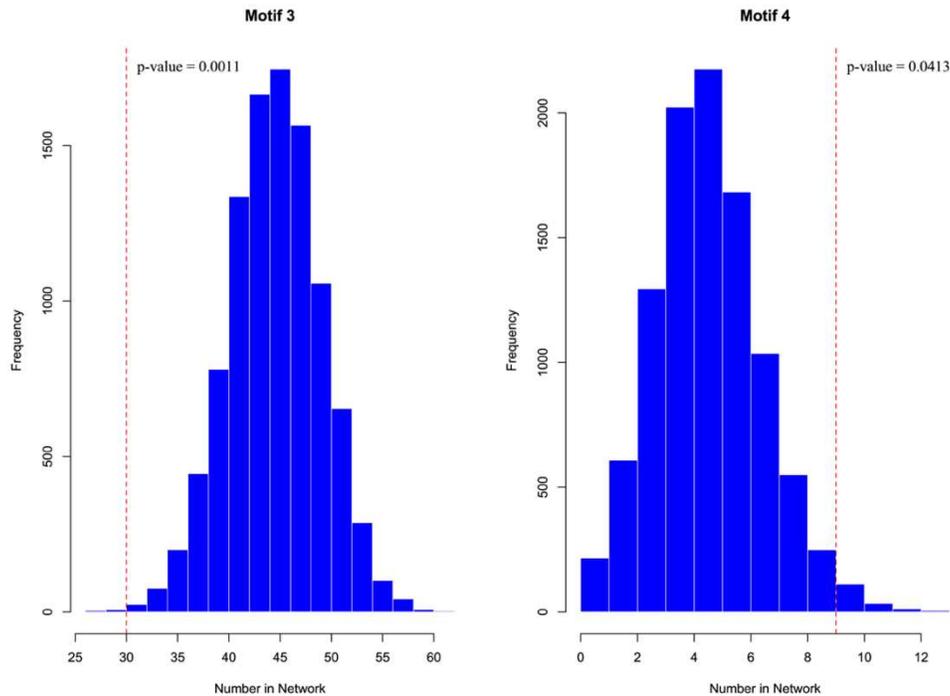


Figure 9.2. Approximate sampling distributions of Motifs 3 and 4 in an Erdős-Rényi random graph with thirteen nodes and twenty-one edges. The dashed red vertical line is the observed frequency of each motif in the Hohokam/California transregional network model with its estimated p-value.

Motif 3 is a graphical representation of what are called transitive triplet interactions, which means in the Hohokam/California transregional network model if an exchange occurs between regions 1 and 2 and regions 2 and 3 then it also occurs between regions 1 and 3. An abundance of transitive triplet interactions indicates that trade items can be transported both directly between regions as well as several intermediate regions. This kind of network structure is associated with redundancy of links and robustness to link failure between regions (Kaluza et al. 2010). However, while advantageous for the robustness of localized inter-regional trade, an abundance of transitive triplets will likely increase the systemic fragility of the network, since the effects of localized disturbances can more easily and quickly move through the entire system. Figure 9.2 shows that Motif

3 occurs far less frequently in the Hohokam/California transregional network model than is expected in an Erdős-Rényi random graph model with the same number of nodes and edges. This is expected if the Hohokam/California transregional system was organized to be robust to system wide shocks.

Motif 4 is a graphical representation of a localized hub topology where node 1 is the hub (see Figure 9.1). Figure 9.3 shows that Motif 4 occurs far more frequently than expected in an Erdős-Rényi random graph model with an identical number of nodes and edges. This is expected if the Hohokam/California transregional system had middlemen (who often facilitate the robustness of exchange systems by lowering transaction costs, see Coase 1937 and North 1992) at the local regional scale, which might reduce systemic fragility.

#### *Example 2: Betweenness Centrality*

*Betweenness centrality* (Freeman 1979; Newman 2004) is a measure that identifies hubs in a network and predicts where middlemen will likely concentrate. Hubs have a direct bearing on the robustness of networks (Wasserman 1994). More generally, betweenness centrality indicates the importance of a node in a network graph and in this study, the importance of a region to the movement of goods, people, and information. A plot of the betweenness centrality values for the Hohokam/California network model (Figure 9.3) identifies the Santa Monica Mountains Chumash (node 3) and the Mainland Tongva (node 5) regions as the most important nodes in the walktrap coastal community and the Hopic (node 7) and Lowland Patayan (node 10) as the most important nodes in the walktrap interior community (see Chapter 7). The Hopic and Mainland Tongva have the highest betweenness centrality scores and are *connector hubs* (Bassett et al. 2006,

Guimera and Amaral 2005; Sporns et al. 2007) because they link the coastal and interior communities to one another (see Chapter 7). The Santa Monica Mountains Chumash and Lowland Patayan regions are *provincial hubs* (see preceding references) because they tend to link the other regions in their respective communities.

Remembering that in Chapter 8 the focus of trade in the bioeconomic model is between the Hohokam system (nodes 12 and 13) and the Lake Cahuilla area (nodes 8, 9, and 10) this analysis suggests that the Lowland Patayans were very important to the stability of interaction between the Hohokam system and Lake Cahuilla. Also in Chapter 3, I provided recent archaeological evidence that showed Lowland Patayans were residents in some Hohokam communities (ca. A.D. 900-1100). This analytical result also provides another line of evidence that Lowland Patayans residing in Hohokam settlements and elsewhere may have been middlemen. In sum, this analysis identifies another and very specific vulnerability of the Pre-Classic Hohokam system in relation to trade with Lake Cahuilla (i.e. shocks that could disrupt interaction with Lowland Patayans).

Finally, using the Erdős-Rényi random graph model for a network with thirteen nodes and twenty-one edges (see Chapter 7) to: (1) generate betweenness centrality approximate sampling distributions for nodes 3, 5, 7, and 10, (2) plot each of the observed betweenness values for these nodes in the Hohokam/California network model in its corresponding histogram, and (3) compute the estimated p-values for each of the observed betweenness centrality values (see Figure 9.4 and Appendix X for the R code used to make Figures 9.3 and 9.4 and to compute the p-value estimates), strongly suggests that it is highly unlikely that any of the observed betweenness centrality values

for nodes 3, 5, 7, and 10 would be as large as they are by chance. This provides an additional line of evidence that the Hohokam/California transregional network model is representative of an organized system of interaction.

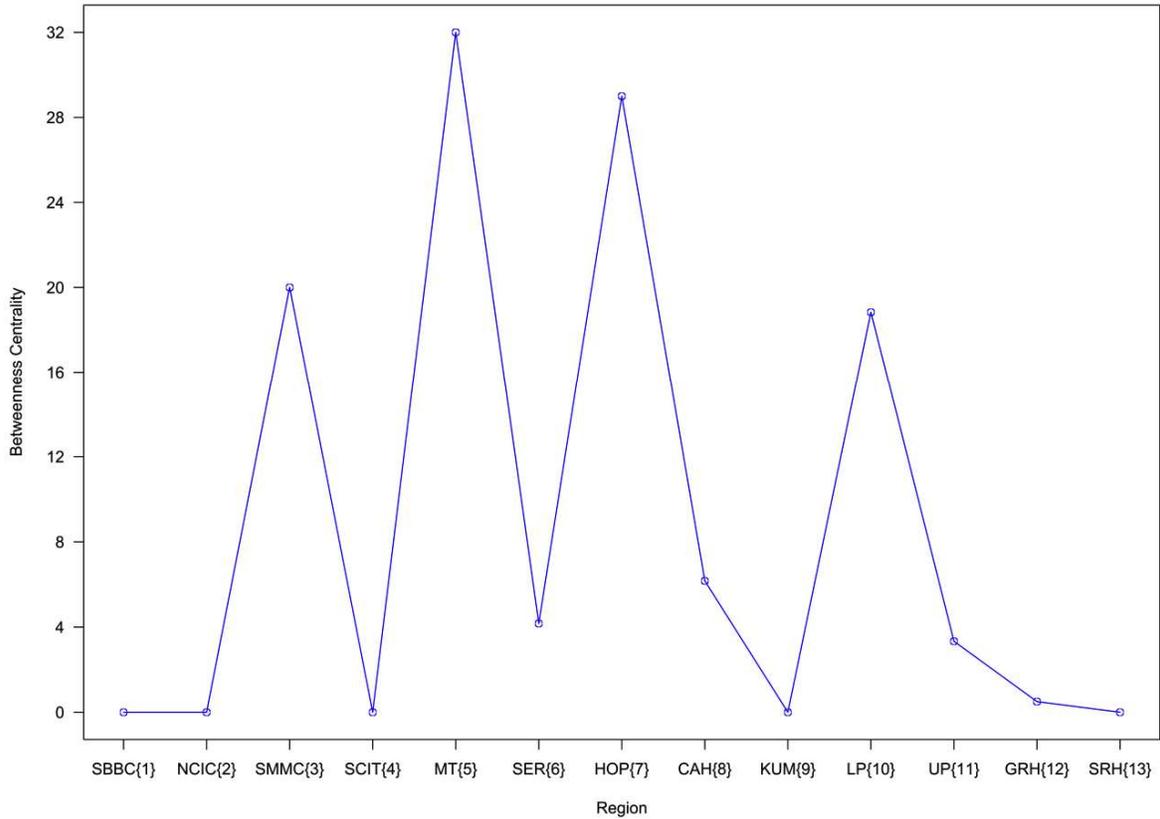


Figure 9.3. Betweenness centrality scores for each of the regions in the Hohokam/California transregional network model.

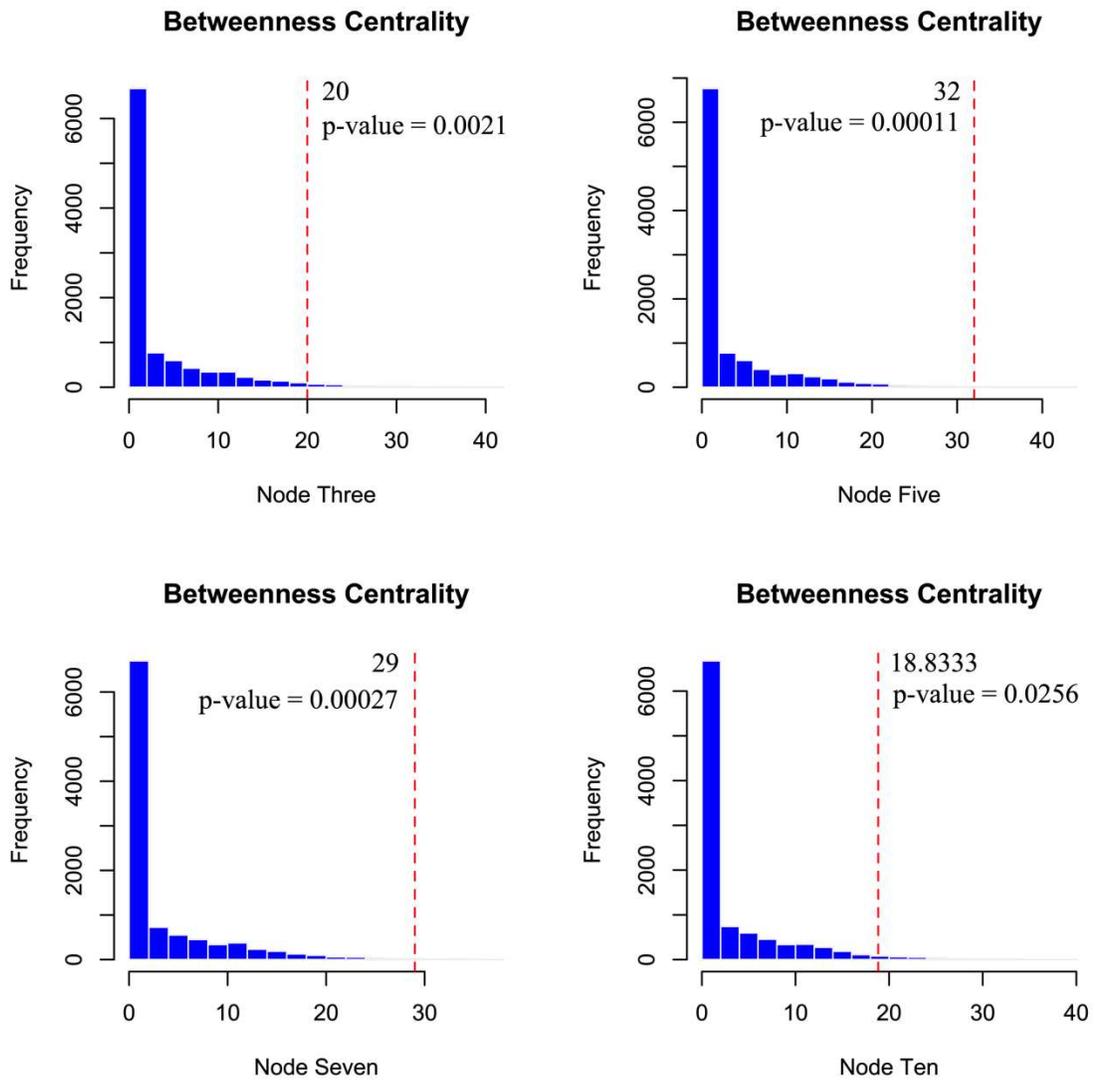


Figure 9.4. Approximate sampling distributions of the betweenness centrality score for nodes three five, seven, and ten in an Erdős-Rényi random graph with thirteen nodes and twenty-one edges. The dashed red vertical line is the observed betweenness centrality score with estimated p-value for each of these nodes in the Hohokam/California transregional network model.

## **Path Dependence, Trade, Systemic Fragility, and the Collapse of the Pre-Classic Hohokam System**

A major result from the bioeconomic model of Chapter 8 suggests that after surpassing a very narrow window of population growth the Pre-Classic Hohokam system would be on a certain trajectory of collapse that could only be stopped or delayed by investing a lot more labor into activities related to trade for Lake Cahuilla fish. The model incorporated the realistic reaction heuristic that the people and institutions (whether they were based on quasi-voluntary compliance or coercion, although a bias for coercive governance would afford an advantage for sustaining the Pre-Classic Hohokam system) in the Hohokam system would respond to shortfalls in the supply of wild protein by diverting a maximum amount of available labor from the procurement of carbohydrate rich wild resources to activities (e.g., manufacture of shell preciosities and burden baskets for the long distance transport of trade items) related to obtaining Lake Cahuilla fish. In turn, the highest level decision process in the model of how much labor should optimally be allocated to agriculture verses wild resources to meet minimum needs would probably not provide a sufficient amount of spare labor to sustain the system with trade in a rapidly developing crisis situation. Ostrom (2005) provides the following insight about the relationship between institutional (organizational) response and the pace of exogenous [as well as endogenous] change.

Individuals who have adapted an effective way of coping with a particular technological, economic, or social environment may be able to adjust to slow changes in one or several variables if substantial feedback is provided about the consequences of these changes for the long term sustainability of the resource and/or set of institutions for governing the resource (Gupta and Tiwari 2002). They may even be able to adjust to changes in these variables that occur at a moderate rate. The faster the key variables change and the more variables that change at the same time, the more demanding the problem of adaption to new circumstances. These kinds of threats are difficult for all organizations. Those that

rely to a greater extent on quasi-voluntary compliance are however, more threatened than those who are able to coerce contributions (Bromley and Chapagain 1984; Goodland, Ledec, and Webb 1989) [pp. 272-273].

So one question pertaining to the sustainability of the Pre-Classic Hohokam system is: how much and what kinds of feedback would have been necessary to allow organizations and institutions to move enough labor from economic sectors with major capital and other investments in infrastructure (e.g., ballcourt markets and agriculture) to the Lake Cahuilla fish trade to sustain the system? A second and more daunting question is: was the social, political, economic and institutional organization and structure of the Pre-Classic Hohokam system flexible enough to accomplish this? Ideas and methodology from the Institutional Analysis and Development Framework or IAD (Ostrom 2011) are useful for addressing the first question and ideas from the concept of *path dependence* (see North 1990; Krugman 1990, 1991) may be helpful for answering the second question. I will discuss path dependence in relation to the Hohokam system and leave the first question for future research.

Hegmon (2013) provides a good summary of path dependence.

Path dependence connotes a sense of becoming increasingly stuck in a particular way of doing things, and theories of path dependence attempt to explain how this happens.

Hegmon also observes in the case of the Pre-Classic Hohokam system “growth [in terms of technology and human population size] might have involved a feedback loop that led to path dependence”. Hegmon further suggests why theory based on the concept of path dependence is useful for addressing the second question: “theorizing path dependence is important because it provides insights into how and why some situations remain on narrow trajectories while others retain more flexibility”. Hegmon argues that reliance on

irrigated agriculture, which facilitated the growth of the human population of the Hohokam system, may have created a constrained and nearly inflexible form of path dependence. She provides the following discussion on path dependence in the Hohokam case that emphasizes the interplay between the labor required to construct, maintain and manage irrigation infrastructure and a growing population, which assumes that, once a critical population threshold was reached, there were no options but to continue along that trajectory.

Earlier comparative work had suggested the Hohokam decline could be understood as a path-dependent downward spiral involving increasing reliance on a single risky technology (Hegmon et al. 2008: 322), although recent work (McClelland and Lincoln-Babb 2011) suggests the decline was less severe, in terms of human health, than originally thought. Hohokam irrigation was investigated in a transdisciplinary project called “Change is Hard: The Challenges of Path Dependence,” which focused on the deep and recent history of the Phoenix area (e.g., Bolin et al.’s [2005] historical geography of the emergence environmental injustice in the late 19<sup>th</sup> century and York et al.’s [2011] institutional analysis of the development of recent land use patterns). Analyses of Hohokam irrigation (described in more detail in the following discussion of lock-in) considered feedback between the labor required to build and maintain the system and the population that would be supported by it (Hegmon et al. 2013). Although this self-reinforcing trajectory fits with the general concept of path dependence, it does not technically exhibit the properties of increasing returns. Rather, the trajectory continued because—once the large population was established in the area—there was no other way of producing enough food.

The constraints of the past are evident in an analysis of one of the largest Hohokam irrigation systems, known as Canal System 2 (Hegmon et al. 2013; Howard 1993; Figure 1), which grew rapidly early in the sequence (i.e., between the Pioneer [ca. A.D. 1-750] and Colonial periods [ca. A.D. 750-950]). Several lines of evidence and argument support the assumption that the irrigation system would not have been constructed if it had not been needed to water fields and feed a growing population, thus the infrastructure growth was linked to both increasing labor inputs and population.

The system can also be understood as carrying technological momentum, involving the physical technology intertwined with the population that both supported the system and was supported by it.

As my analysis of the model in Chapter 8 suggests, the Hohokam system may have had another option, which was a bifurcating (or dichotomous) trajectory with an optional path that added long distance trade. So at this juncture the question becomes: given the option of long distance trade, was the developmental trajectory of the Pre-Classic Hohokam system not so heavily path dependent on agriculture to accomplish a timely and large enough divestiture of that system and its infrastructure in favor of investment in trade with Lake Cahuilla fishers that could possibly have sustained the Pre-Classic Hohokam system? The preliminary analysis of the model in Chapter 8 suggests that the Hohokam system would not have been flexible enough even on the path where trade with Lake Cahuilla is added, without a major restructuring of the institutional arrangements associated with agriculture and the harvest of local wild resources. Also, as discussed in Chapter 8 and the beginning of this section, the model analysis suggests that the rapid rate at which local resources would be degraded following a very small increase in population over some critical threshold is a type of systemic fragility that could not be effectively managed through institutional design or change. More specifically, as I suggested in Chapter 8, in the case of the Pre-Classic Hohokam system there may not be enough feedback to detect the impending collapse let alone respond to it.

### **The Contributions of this Study and Its Value to Future Research**

This study resulted in the introduction of new analytical techniques to archaeology that will likely contribute to future archaeological research. The need to develop and apply novel methods of analysis relates to the complexity or problematic nature of the data and to the research questions being addressed with these analyses. For

example, some of the shell artifact samples were small which necessitated the use of appropriate and computationally intensive statistical methods such as Barnard's exact test, which have not [to my knowledge] been previously used by archaeologists. Also in this study, I examined the Pre-Classic Hohokam system in a new way that considers the development and persistence of the system in relation to a much larger transregional scale than the local and regional scales that have been the focus of previous archaeological research on this system. This required organizing a large body of archaeological data on shell artifacts from sites in the Hohokam/California transregion to help produce [as mentioned earlier] a network model of the system and identify elements of the transregional system that are consonant with the systemic fragility of the Hohokam system. The large shell artifact database produced by this study is also a valuable resource for future research.

In addition, the operationalization and application of many of the statistical methods used to analyze these data in this study required writing or restructuring previously written R and Matlab code (available in the appendances and in the future in an online data repository and hopefully as part of a book on archaeological analysis). The R and Matlab code for each of these methods are useful analytical tools for future archaeological research.

Finally, another important contribution of this study is the bioeconomic model and the XPPAUT code used to simulate and analyze it (see Appendix V). Future and deeper study of the current model using bifurcation analysis (see Doi et al. 2010; Ermentrout 2002; Krysolova and Earn 2013; Kuznetsov 1995; McLennan-Smith and Mercer 2013) and later by adding a reconstructed rainfall signal, population and capital

dynamics, and estimates of the intrinsic rate of natural increase carrying capacity of Lake Cahuilla fishes are expected to produce additional insights into how systemic fragilities of the Pre-Classic Hohokam system may have contributed to the collapse of the system.

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APPENDIX A

ASM *OLIVELLA* BARREL BEAD DATA

Table A.1.

Location	Context	Phase/Period	Catalog No:	Bag	<i>Olivella</i> species	Bead Type	Width (mm)
Snaketown	Non-Mortuary	/Pioneer	A- 25762		<i>dama</i>	Barrel	6.26
Snaketown	Non-Mortuary	/Sweetwater	A- 25611		<i>dama</i>	Barrel	6.85
Las Colinas	Non-Mortuary	Sedentary		4- 1398	<i>dama</i>	Barrel	6.42
Las Colinas	Non-Mortuary	Sedentary		4- 2394	<i>dama</i>	Barrel	6.4
Las Colinas	Non-Mortuary	Sedentary		4- 0669	<i>dama</i>	Barrel	6.77
Las Colinas	Non-Mortuary	Sedentary		4- 0224	<i>dama</i>	Barrel	6.24
Las Colinas	Non-Mortuary	Sedentary		4- 0966	<i>dama</i>	Barrel	5.98
Las Colinas	Non-Mortuary	Sedentary		5- 2918	<i>dama</i>	Barrel	5.83
Las Colinas	Non-Mortuary	Sedentary		7- 0455	<i>dama</i>	Barrel	7.06
Las Colinas	Non-Mortuary	Sedentary		5- 2938	<i>dama</i>	Barrel	6.6

Las Colinas	Non-Mortuary	Sedentary		5- 1659	<i>dama</i>	Barrel	4.76
Las Colinas	Non-Mortuary	Sedentary		5- 1015	<i>dama</i>	Barrel	6.76
Las Colinas	Non-Mortuary	Sedentary		7- 1140	<i>dama</i>	Barrel	5.89
Tanque Verde Wash Site	Pithouse	Sedentary/Rincon	90		<i>dama</i>	Barrel	6.99

## APPENDIX B

### DATA AND R CODE FOR DOT PLOT

Raw Data.

File: O\_dama\_AZ\_CA.txt

Period\_Phase Diameter\_mm  
Location

M5a-b 3.6 B68	M5a-b 4.6 B45	M5a-b 5 B51	M5a-b 5.9 B51
M5a-b 4 B68	M5a-b 4.6 B45	M5a-b 5 B51	M5a-b 6 B51
M5a-b 4.1 B68	M5a-b 4.6 B45	M5a-b 5 B51	M5a-b 6 B51
M5a-b 4.2 B68	M5a-b 4.6 B45	M5a-b 5 B51	M5a-b 6 B51
M5a-b 4.2 B68	M5a-b 4.6 B45	M5a-b 5 B51	M5a-b 6.5 B51
M5a-b 4.4 B68	M5a-b 4.7 B45	M5a-b 5 B51	M5a-b 4.8 B73a
M5a-b 4.7 B68	M5a-b 4.7 B45	M5a-b 5 B51	M5a-b 5.1 B73a
M5a-b 4.9 B68	M5a-b 4.7 B45	M5a-b 5.2 B51	M5a-b 5.1 B73a
M5a-b 5 B68	M5a-b 4.7 B45	M5a-b 5.2 B51	M5a-b 5.2 B73a
M5a-b 5.2 B68	M5a-b 4.7 B45	M5a-b 5.2 B51	M5a-b 5.2 B73a
M5a-b 5.3 B68	M5a-b 4.7 B45	M5a-b 5.2 B51	M5a-b 5.2 B73a
M5a-b 5.9 B68	M5a-b 4.7 B45	M5a-b 5.2 B51	M5a-b 5.2 B73a
M5a-b 6.2 B68	M5a-b 4.7 B45	M5a-b 5.2 B51	M5a-b 5.3 B73a
M5a-b 6.5 B68	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.3 B73a
M5a-b 3.7 B45	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.3 B73a
M5a-b 3.8 B45	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.3 B73a
M5a-b 4 B45	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.3 B73a
M5a-b 4.1 B45	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.3 B73a
M5a-b 4.2 B45	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.3 B73a
M5a-b 4.2 B45	M5a-b 4.7 B45	M5a-b 5.3 B51	M5a-b 5.4 B73a
M5a-b 4.2 B45	M5a-b 4.8 B45	M5a-b 5.4 B51	M5a-b 5.4 B73a
M5a-b 4.2 B45	M5a-b 4.8 B45	M5a-b 5.4 B51	M5a-b 5.4 B73a
M5a-b 4.2 B45	M5a-b 4.8 B45	M5a-b 5.4 B51	M5a-b 5.5 B73a
M5a-b 4.3 B45	M5a-b 4.9 B45	M5a-b 5.4 B51	M5a-b 5.5 B73a
M5a-b 4.3 B45	M5a-b 4.9 B45	M5a-b 5.4 B51	M5a-b 5.5 B73a
M5a-b 4.3 B45	M5a-b 5 B45	M5a-b 5.4 B51	M5a-b 5.5 B73a
M5a-b 4.4 B45	M5a-b 5.1 B45	M5a-b 5.5 B51	M5a-b 5.5 B73a
M5a-b 4.4 B45	M5a-b 5.1 B45	M5a-b 5.5 B51	M5a-b 5.5 B73a
M5a-b 4.4 B45	M5a-b 5.2 B45	M5a-b 5.5 B51	M5a-b 5.5 B73a
M5a-b 4.4 B45	M5a-b 5.3 B45	M5a-b 5.5 B51	M5a-b 5.5 B73a
M5a-b 4.4 B45	M5a-b 5.3 B45	M5a-b 5.6 B51	M5a-b 5.6 B73a
M5a-b 4.4 B45	M5a-b 5.4 B45	M5a-b 5.6 B51	M5a-b 5.6 B73a
M5a-b 4.5 B45	M5a-b 5.5 B45	M5a-b 5.7 B51	M5a-b 5.6 B73a
M5a-b 4.5 B45	M5a-b 4.7 B51	M5a-b 5.7 B51	M5a-b 5.6 B73a
M5a-b 4.5 B45	M5a-b 4.7 B51	M5a-b 5.7 B51	M5a-b 5.6 B73a
M5a-b 4.5 B45	M5a-b 4.7 B51	M5a-b 5.7 B51	M5a-b 5.7 B73a
M5a-b 4.5 B45	M5a-b 4.7 B51	M5a-b 5.8 B51	M5a-b 5.7 B73a
M5a-b 4.5 B45	M5a-b 4.7 B51	M5a-b 5.8 B51	M5a-b 5.7 B73a
M5a-b 4.6 B45	M5a-b 4.8 B51	M5a-b 5.8 B51	M5a-b 5.7 B73a
M5a-b 4.6 B45	M5a-b 4.8 B51	M5a-b 5.9 B51	M5a-b 5.7 B73a

```
#Raw data cont.
```

```
Sedentary 3.3 Snaketown_4  
Sedentary 3.3 Snaketown_4  
Sedentary 3.4 Snaketown_4  
Sedentary 3.5 Snaketown_4  
Sedentary 3.6 Snaketown_4  
Sedentary 3.6 Snaketown_4  
Sedentary 3.6 Snaketown_4  
Sedentary 3.6 Snaketown_4  
Sedentary 3.7 Snaketown_4  
Sedentary 3.7 Snaketown_4  
Sedentary 4 Snaketown_4  
Sedentary 2.85 Snaketown_5  
Sedentary 3.21 Snaketown_5  
Sedentary 3.43 Snaketown_5  
Sedentary 3.45 Snaketown_5  
Sedentary 3.51 Snaketown_5  
Sedentary 3.65 Snaketown_5  
Sedentary 3.71 Snaketown_5  
Sedentary 3.77 Snaketown_5  
Sedentary 3.79 Snaketown_5  
Sedentary 4.23 Snaketown_5
```

```
#R commands for Figure
```

```
library(lattice)  
a <-read.table("O_dama_AZ_CA.txt",header=TRUE)  
dotplot(Period_Phase~Diameter_mm, data=a, groups=Location, main="Olivella sp.  
Barrel Beads")  
dotplot(Diameter_mm, data=a, groups=Location, main="Olivella sp. Barrel Beads")  
dotplot(Location~Diameter_mm, data=a, groups=Period_Phase, main="Olivella sp.  
Barrel Beads")
```

APPENDIX C

2-SAMPLE SMIRNOV TEST WITH COMPUTATION OF P-VALUES USING  
SIMULATION

Two or more empirical cumulative distribution functions are useful for examining the distribution of a sample of data. However, when plotted together they are also useful for the qualitative assessment of differences over portions of the range of a variable for two or more samples (for example, see Shorak and Wellner 1986). What follows is a brief overview and description of the empirical cumulative distribution function, and the assessment of the similarity of two such functions using a randomization model and a Monte Carlo procedure. This approach does not make any unverified assumptions about the distribution of the data, does not require continuity in the distribution of the data, and is appropriate for use with small samples.

The empirical cumulative distribution function (or empirical CDF) of a sample of  $n$  numbers  $\{x_1, x_2, \dots, x_n\}$  is defined as follows:  $ECDF(x) = \text{Proportion of } x_i \text{'s } \leq x$  for all real numbers  $x$ .

For example, if  $n = 28$  and given the ordered set of integers  $Q = [2, 3, 4, 4, 4, 4, 5, 5, 5, 5, 5, 6, 6, 6, 6, 6, 6, 6, 7, 8, 8, 8, 8, 9, 9, 12, 13]$ . It follows that  $ECDF(x)$  is a step function with values in this example of: 0 when  $x < 2$ ,  $1/28$  when  $2 \leq x < 3$ ,  $2/28$  when  $3 \leq x < 4$ ,  $6/28$  when  $4 \leq x < 5$ ,  $12/28$  when  $5 \leq x < 6$ ,  $19/28$  when  $6 \leq x < 7$ ,  $20/28$  when  $7 \leq x < 8$ ,  $24/28$  when  $8 \leq x < 9$ ,  $26/28$  when  $9 \leq x < 12$ ,  $27/28$  when  $12 \leq x < 13$ , and  $28/28$  when  $x \leq 13$ .

The Smirnov two sample test is a pair-wise comparison of empirical CDFs. For example, let  $ECDF1$  and  $ECDF2$  be the empirical CDFs of two samples, say Sample 1 and Sample 2. The Smirnov statistic  $S$  is the maximum absolute difference between the empirical CDFs. Values of  $S$  lie in the interval  $0 \leq S \leq 1$ . Observed values of  $S$  near 0

support the null hypothesis that the two samples are drawn from the same population and large observed values of this statistic support the alternative. In this rendition of the Smirnov test, a *randomization model* is used. In this model the data are measurements taken from  $n + m$  individuals from two distinct groups of sizes  $n$  and  $m$ , respectively. The randomization test employed here consists of a Monte Carlo analysis that uses 2000 random partitions (that includes the observed partition of the  $m + n = 20$  scores). [For more details, for example, see Baglivo 2005, pp.147-149; 151-152] The results of the test from a single simulation of this case are that 0.6% (12/2000) of the partitions produced a Smirnov statistic that was greater than or equal to the observed value of the statistic (0.708333). Note that each time the test is applied the number of partitions that will produce a Smirnov statistic greater than or equal to the observed value will vary over a small range due to the stochastic nature of the sampling procedure. This procedure is implemented using Mathematica code provided by Baglivo (2005).

APPENDIX D

DATA FOR GEODESIC PRINCIPAL COMPONENTS ANALYSIS

Raw data.

TPS File: O\_dama\_LAN264\_LC\_TVWS\_ST.tps

LM=7	LM=7	LM=7	LM=7
204 95	298 100	273 107	226 108
216 174	320 239	293 216	236 159
204 289	304 331	284 254	233 280
36 286	40 316	28 272	45 302
12 148	25 120	22 201	22 206
36 40	68 23	63 53	59 37
190 41	282 44	258 40	212 50
ID_B35_5	ID_B35_4	ID_45_4	ID_45_8
LM=7	LM=7	LM=7	LM=7
231 57	221 80	218 60	242 125
262 176	236 107	236 102	244 220
257 267	220 237	229 242	234 262
65 260	31 220	43 248	36 253
28 155	23 177	24 148	26 219
56 45	41 46	43 28	54 34
230 54	189 35	211 52	212 64
ID_B35_1	ID_45_1	ID_45_5	ID_45_9
LM=7	LM=7	LM=7	LM=7
240 110	244 136	215 93	214 64
258 208	254 197	232 177	231 142
248 310	246 322	227 234	216 210
34 298	30 309	40 242	40 209
17 174	21 249	27 180	34 92
44 41	74 35	64 37	55 33
235 48	226 66	197 43	214 66
ID_B35_2	ID_45_2	ID_45_6	ID_45_10
LM=7	LM=7	LM=7	LM=7
242 62	218 42	214 52	212 48
270 213	233 159	225 156	230 179
256 242	230 201	225 194	228 252
32 230	50 216	48 224	54 260
19 93	19 99	28 126	29 175
47 37	37 36	55 26	40 32
238 59	215 39	204 40	204 41
ID_B35_3	ID_45_3	ID_45_7	ID_45_11

LM=7	LM=7	LM=7	LM=7
232 64	231 120	217 74	218 76
245 153	247 210	228 149	237 145
226 243	226 326	200 281	229 245
81 262	48 323	50 287	38 228
22 168	34 171	26 152	26 145
61 29	60 50	49 29	50 52
216 24	222 50	218 48	206 56
ID_45_12	ID_45_16	ID_45_20	ID_45_24
LM=7	LM=7	LM=7	LM=7
253 106	237 69	247 68	256 66
269 174	256 186	293 234	274 160
249 268	250 221	280 304	264 255
32 250	30 212	62 296	50 259
22 201	28 137	38 179	36 190
64 56	81 27	65 46	48 46
232 45	234 62	232 40	256 37
ID_45_13	ID_45_17	ID_45_21	ID_45_25
LM=7	LM=7	LM=7	LM=7
280 114	262 66	226 64	228 78
295 218	270 160	239 152	242 182
285 302	246 270	221 262	241 231
38 304	60 288	50 248	50 254
32 155	28 151	28 190	25 196
56 72	72 40	39 35	34 36
272 76	255 36	228 62	210 52
ID_45_14	ID_45_18	ID_45_22	ID_45_26
LM=7	LM=7	LM=7	LM=7
250 82	282 100	218 82	236 116
268 164	287 195	232 167	249 230
256 260	258 324	202 288	222 350
36 246	32 285	52 294	63 326
36 136	29 232	30 161	31 264
50 51	72 60	54 35	46 77
242 48	278 56	223 59	224 55
ID_45_15	ID_45_19	ID_45_23	ID_45_27

LM=7	LM=7	LM=7	LM=7
201 34	202 61	295 128	317 128
234 128	216 142	306 234	320 212
216 233	204 218	299 323	296 341
52 216	34 215	45 317	57 335
24 109	20 137	22 170	20 207
35 34	40 39	42 35	48 40
214 40	193 44	268 35	287 66
ID_45_28	ID_45_32	ID_45_36	ID_45_40
LM=7	LM=7	LM=7	LM=7
226 106	256 114	260 108	288 139
238 180	270 216	268 185	304 204
234 285	246 326	252 322	298 326
43 304	40 272	50 318	40 342
26 163	28 151	18 204	24 199
56 50	50 55	33 40	45 48
220 51	238 46	247 43	252 39
ID_45_29	ID_45_33	ID_45_37	ID_45_41
LM=7	LM=7	LM=7	LM=7
264 68	263 112	307 174	254 116
278 180	272 194	310 201	272 236
262 267	258 326	280 361	254 350
35 258	44 338	34 339	68 366
28 177	13 194	24 294	30 232
55 32	36 40	57 82	58 32
250 45	236 46	284 46	245 84
ID_45_30	ID_45_34	ID_45_38	ID_45_42
LM=7	LM=7	LM=7	LM=7
228 72	300 154	287 98	268 147
250 129	313 268	300 174	282 196
238 223	292 368	286 296	264 348
34 230	67 381	50 332	48 323
24 137	30 258	28 207	13 198
34 37	43 96	58 39	42 35
212 32	275 25	281 64	208 40
ID_45_31	ID_45_35	ID_45_39	ID_45_43

LM=7	LM=7	LM=7	LM=7
292 131	318 172	251 107	329 166
302 172	327 272	272 192	339 236
287 298	301 417	260 311	327 345
52 307	60 423	39 314	43 416
34 225	37 230	17 188	11 238
62 32	84 44	46 44	35 50
266 38	286 40	232 47	297 60
ID_45_44	ID_45_48	ID_45_52	ID_45_56
LM=7	LM=7	LM=7	LM=7
316 148	271 119	264 96	253 72
329 230	286 204	278 178	278 158
320 314	262 328	252 313	260 286
73 369	42 315	42 309	38 265
32 196	16 189	20 162	19 160
73 40	47 47	50 27	42 32
282 43	257 38	248 32	234 30
ID_45_45	ID_45_49	ID_45_53	ID_45_57
LM=7	LM=7	LM=7	LM=7
298 136	289 103	252 90	301 170
309 198	302 176	271 184	306 232
301 289	273 332	253 324	296 338
57 392	54 324	65 308	48 338
25 223	15 185	28 165	29 227
50 26	51 34	52 28	53 71
298 92	273 40	238 43	281 30
ID_45_46	ID_45_50	ID_45_54	ID_45_58
LM=7	LM=7	LM=7	LM=7
248 88	250 78	287 150	301 176
260 152	271 173	294 207	304 208
246 264	242 326	274 318	278 369
68 297	62 330	40 348	16 314
36 158	20 176	26 206	14 261
38 24	38 24	77 38	52 58
222 29	250 76	274 70	273 29
ID_45_47	ID_45_51	ID_45_55	ID_45_59

LM=7	LM=7	LM=7	LM=7
301 105	312 139	282 118	244 111
314 184	328 248	295 217	258 200
298 324	297 398	284 304	228 309
50 358	46 359	55 330	30 260
52 58	23 208	32 172	25 168
44 32	52 51	73 34	60 50
274 42	289 32	267 62	280 52
ID_45_60	ID_45_64	ID_45_68	ID_45_72
LM=7	LM=7	LM=7	LM=7
257 136	256 121	259 109	285 74
272 218	268 188	268 184	301 182
244 334	250 286	240 308	289 308
76 347	58 322	39 279	54 330
20 202	24 196	14 162	18 154
86 26	46 37	35 32	24 28
232 41	243 56	232 34	276 46
ID_45_61	ID_45_65	ID_45_69	ID_45_73
LM=7	LM=7	LM=7	LM=7
286 107	301 93	320 126	232 69
302 186	319 200	328 199	290 189
286 294	283 384	251 339	254 320
46 272	38 292	49 322	83 353
31 150	21 176	26 188	29 171
58 40	58 28	57 39	57 57
272 69	272 37	296 28	232 68
ID_45_62	ID_45_66	ID_45_70	ID_45_74
LM=7	LM=7	LM=7	LM=7
275 118	275 96	308 99	277 98
296 195	286 156	328 226	290 212
279 327	258 269	317 337	268 356
60 354	66 305	58 319	44 304
24 146	21 140	23 184	26 197
54 52	24 23	68 18	52 40
277 31	256 42	276 86	259 31
ID_45_63	ID_45_67	ID_45_71	ID_45_75

LM=7	LM=7	LM=7	LM=7
276 66	238 74	287 117	244 100
296 186	255 156	297 185	254 192
294 246	239 251	261 359	230 300
69 265	47 261	34 300	40 274
23 136	21 170	20 164	25 149
34 36	36 33	38 59	34 67
266 48	226 33	261 27	229 54
ID_45_76	ID_45_80	ID_45_84	ID_65_3
LM=7	LM=7	LM=7	LM=7
282 62	289 135	239 95	322 151
294 161	298 218	256 173	330 248
268 295	283 288	239 300	293 423
66 289	38 348	41 325	53 411
27 109	21 170	16 150	30 258
29 37	64 32	30 44	73 57
279 50	264 34	229 60	311 82
ID_45_77	ID_45_81	ID_45_85	ID_65_4
LM=7	LM=7	LM=7	LM=7
306 126	272 67	296 120	218 63
318 230	293 200	318 248	245 176
279 434	258 364	313 320	238 258
60 372	56 398	46 292	51 261
22 279	16 254	29 139	24 150
60 71	41 60	52 30	42 34
266 61	257 42	277 30	217 54
ID_45_78	ID_45_82	ID_65_1	ID_68_1
LM=7	LM=7	LM=7	LM=7
272 96	266 71	290 80	322 98
304 228	284 175	319 231	336 186
288 330	273 251	308 330	326 317
57 324	50 283	52 320	72 340
24 198	29 158	32 180	38 143
54 32	58 30	52 42	66 34
264 83	254 35	284 75	306 56
ID_45_79	ID_45_83	ID_65_2	ID_68_2

LM=7	LM=7	LM=7	LM=7
357 181	228 55	316 171	255 104
376 285	238 146	324 259	270 224
350 444	229 250	296 402	255 254
73 412	58 226	51 402	26 260
42 290	27 66	36 220	18 170
68 64	40 40	86 46	36 38
326 49	226 47	284 36	234 35
ID_68_3	ID_68_7	ID_75_3	ID_LC_4
LM=7	LM=7	LM=7	LM=7
241 100	225 58	222 110	263 109
264 204	256 165	239 194	284 203
249 290	245 244	230 289	271 303
52 302	48 255	24 302	36 276
28 198	18 153	14 212	26 202
50 57	48 25	56 32	50 32
229 63	224 48	194 26	244 34
ID_68_4	ID_68_8	ID_LC_1	ID=LC_5
LM=7	LM=7	LM=7	LM=7
293 120	303 134	289 94	248 134
318 250	317 205	310 194	266 226
302 350	303 346	302 290	257 286
47 340	46 322	44 297	50 354
25 224	31 234	22 184	24 219
56 44	55 73	39 42	77 22
268 43	276 43	280 44	223 44
ID_68_5	ID_75_1	ID_LC_2	ID_LC_6
LM=7	LM=7	LM=7	LM=7
251 66	302 127	185 78	277 112
266 164	315 239	202 151	298 230
255 270	300 280	183 244	248 370
71 282	81 308	41 279	45 354
32 177	34 139	8 169	21 209
55 46	65 45	56 10	56 23
246 56	306 101	158 22	248 22
ID_68_6	ID_75_2	ID_LC_3	ID_LC_7

LM=7  
262 103  
286 202  
279 242  
34 258  
21 181  
38 45  
238 32  
ID\_TVWS\_1  
LM=7  
178 36  
209 153  
186 268  
64 252  
12 106  
29 22  
172 27  
ID\_ST\_1  
LM=7  
77 34  
82 71  
77 102  
10 94  
4 57  
14 8  
64 5  
ID\_ST\_2  
LM=7  
91 28  
109 66  
98 105  
14 106  
9 75  
13 26  
75 14  
ID\_ST\_3

## APPENDIX E

### R CODE FOR GEODESIC PRINCIPAL COMPONENTS ANALYSIS

R functions needed for GPC analysis.

#ishapes (available from: <http://www.stochastik.math.uni-goettingen.de/index.php?id=huckemann>) R files needed:

Figure2PreShape.R  
GPC1.R  
GPC2.R  
GPCA.R  
GPCr.R  
GSimulate.R  
Mean.R  
OptimalPosition.R

R script for GPC analysis.

```
#load R Shapes package
#load R source code for read.tps

c<-read.tps("O_dama_LAN264_LC_TVWS_ST.tps")

control=list(trace=1)
g.shape.shell <- ShapeGPCA(c,control=control)

par(mfrow=c(2,2))

plot(-
g.shape.shell$Scores[,1],g.shape.shell$Scores[,2],type="n",xlab="GPC1",ylab="GPC2",
main="Geodesic PC scores")
text(-g.shape.shell$Scores[,1],g.shape.shell$Scores[,2],1:116)

plot(-
g.shape.shell$Scores[,1],g.shape.shell$Scores[,3],type="n",xlab="GPC1",ylab="GPC3",
main="Geodesic PC scores")
text(-g.shape.shell$Scores[,1],g.shape.shell$Scores[,3],1:116)

plot(-
g.shape.shell$Scores[,2],g.shape.shell$Scores[,3],type="n",xlab="GPC2",ylab="GPC3",
main="Geodesic PC scores")
text(-g.shape.shell$Scores[,2],g.shape.shell$Scores[,3],1:116)

g.shape.shell$CurvEst #curvature estimate
```

```
g.shape.shell$Mperc  
g.shape.shell$Pperc[1:5]  
g.shape.shell$Rperc[1:5]
```

```
write.table(g.shape.shell$Scores[,1:3], file = "LAN264_LC_TVWS_STPC_.csv", sep =  
",", col.names = NA) #writes first three GPC scores to a comma delimited file.
```

APPENDIX F  
GEODESIC PRINCIPAL COMPONENT SCORES

Table F.1 GPC Scores.

	Locality	scoreGPC1	scoreGPC2	scoreGPC3
1	B35	0.016618	0.102787	0.019201
2	B35	-0.06616	0.008146	-0.05123
3	B35	0.00244	0.008963	0.019907
4	B35	-0.20709	-0.06854	0.033468
5	B35	-0.10143	0.022941	0.063748
6	B45	0.073632	-0.08992	-0.10339
7	B45	0.164029	-0.04036	-0.01966
8	B45	-0.16843	-0.03699	0.007712
9	B45	-0.00384	-0.17373	0.041708
10	B45	-0.00971	0.024317	-0.10228
11	B45	0.063106	-0.08761	0.031071
12	B45	-0.07227	-0.05015	0.030745
13	B45	0.109488	0.019255	-0.00706
14	B45	0.091725	-0.15255	0.03726
15	B45	-0.16079	-0.01308	-0.02392
16	B45	0.010654	0.005842	-0.03809
17	B45	0.050919	0.034672	-0.00822
18	B45	-0.01385	-0.0751	-0.00581
19	B45	-0.11664	-0.03818	0.015099
20	B45	-0.08349	-0.04925	-0.03135
21	B45	0.038243	0.111116	0.041947
22	B45	-0.07767	-0.13798	0.0003
23	B45	-0.01659	0.046005	-0.03067
24	B45	0.07697	-0.07929	-0.10952
25	B45	0.030038	0.129117	-0.05028
26	B45	-0.02709	0.004782	0.015265
27	B45	0.029732	-0.0304	-0.12626
28	B45	0.0259	0.121964	-0.04261
29	B45	-0.04832	-0.04289	-0.06659
30	B45	0.000996	-0.08737	-0.07388
31	B45	0.015193	-0.1078	0.000947
32	B45	0.145607	0.026265	-0.06308
33	B45	-0.1104	0.041589	-0.10288
34	B45	0.007153	0.061885	0.031666
35	B45	-0.01159	-0.08043	-0.05004
36	B45	-0.04757	-0.06789	-0.02387
37	B45	-0.03755	-0.04471	-0.04891
38	B45	-0.03262	0.007032	0.001364
39	B45	0.030004	0.043956	0.012415

	Locality	scoreGPC1	scoreGPC2	scoreGPC3
40	B45	0.064834	-0.01891	0.051633
41	B45	-0.03127	-0.0317	0.07165
42	B45	0.050773	0.022898	-0.02581
43	B45	0.157035	-0.108	-0.05054
44	B45	0.005295	-0.02275	-0.03163
45	B45	-0.00096	-0.02398	-0.00979
46	B45	0.020804	-0.01886	0.05535
47	B45	0.0659	0.083403	0.004743
48	B45	0.080117	0.034171	0.043769
49	B45	0.095079	-0.07266	0.002495
50	B45	0.004112	-0.00656	0.118106
51	B45	-0.00956	-0.0149	0.057648
52	B45	0.019717	0.059765	0.033721
53	B45	0.086158	0.086684	0.085157
54	B45	0.024325	0.002849	0.004839
55	B45	0.019445	0.032271	-0.03251
56	B45	-0.01447	0.114475	-0.06871
57	B45	0.01945	0.012084	0.006532
58	B45	0.015413	0.051893	-0.00083
59	B45	0.014312	0.093801	-0.01535
60	B45	0.046057	-0.00502	0.048974
61	B45	0.00644	-0.03205	0.080999
62	B45	-0.00978	-0.01612	-0.04891
63	B45	0.060228	-0.06704	0.063353
64	B45	0.146787	-0.10152	-0.0205
65	B45	-0.17701	0.161514	0.097833
66	B45	0.118518	0.102797	0.079402
67	B45	-0.081	-0.05294	-0.01932
68	B45	-0.04341	0.093135	0.055758
69	B45	0.030649	0.02321	0.012854
70	B45	0.035092	0.009843	0.038719
71	B45	0.014388	0.02001	-0.08034
72	B45	-0.05992	0.038554	0.028417
73	B45	-0.02449	0.013054	0.061756
74	B45	0.01448	0.007159	-0.00132
75	B45	0.046282	0.009296	-0.01767
76	B45	-0.05328	-0.01945	-0.01138
77	B45	0.010566	-0.02892	-0.05239
78	B45	-0.07818	0.039584	-0.01169
79	B45	-0.04979	0.15593	-0.02551
80	B45	0.045464	0.015055	-0.04287

81	B45	-0.14356	-0.06246	0.013391
82	B45	-0.14244	0.070024	-0.0516
83	B45	0.117203	0.044351	-0.09864
84	B45	-0.03449	0.000111	-0.01872
85	B45	0.007149	-0.03563	-0.02626
86	B45	-0.0037	-0.0079	0.127865
87	B45	0.071811	0.082752	-0.07591
88	B45	-0.04051	-0.03737	0.016502
89	B45	0.000859	0.028038	-0.0443
90	B45	-0.05241	0.092056	0.004622
91	B65	-0.08013	-0.04758	0.086395
92	B65	-0.08553	-0.01441	-0.02926
93	B65	-0.06165	0.019031	-0.02611
94	B65	0.06707	0.055476	-0.03234
95	B68	-0.05703	0.013812	-0.02313
96	B68	-0.09283	0.037694	0.016215
97	B68	0.088085	-0.01682	0.015245
98	B68	0.006046	-0.01221	-0.00313
99	B68	0.031486	-0.03417	0.025935
100	B68	-0.02267	0.011711	-0.06367
101	B68	-0.19733	0.086922	-0.03201
102	B68	-0.04568	-0.02245	-0.02484
103	B75	0.048424	-0.06886	-0.03159
104	B75	-0.16935	-0.04147	0.069141
105	B75	0.083617	0.066344	0.081401
106	LC	0.13561	-0.01184	0.046901
107	LC	-0.04706	-0.07833	-0.00887
108	LC	0.14661	0.099268	0.057573
109	LC	-0.03121	-0.1277	0.071595
110	LC	0.053181	-0.07738	-0.00129
111	LC	0.110301	0.012235	0.137659
112	LC	0.094356	0.076747	0.017062
113	TVWS	-0.03079	-0.16288	0.058178
114	ST	-0.04386	0.202761	-0.03249
115	ST	0.066375	0.019108	0.061753
116	ST	0.001556	-0.06632	-0.03897

## APPENDIX G

### MATLAB CODE FOR 3D GPC PLOT

Matlab code used for 3D GPC Plot.

% Need the RGB triple of color name, version 2, m file, available from the Matlab file  
%exchange.

```
X=[0.016618368      0.064833942      -0.049790411
-0.207094639      -0.031270808      0.045464168
0.164029102       0.050772917      -0.14356124
-0.009713992      0.157035347      -0.142444325
0.109487778      0.005294693      0.117203403
0.010654339      -0.000961123     -0.034494803
-0.11664014      0.020803697      0.007148718
-0.077674797     0.065899658     -0.003704933
0.030037931      0.080116852      0.071810877
0.025899845      0.095079445     -0.040509127
0.015192648      0.004111897      0.000858629
0.007152502      -0.00955555      -0.052407563
-0.037552007     0.019717431     -0.080133418
-0.06615539      0.086158225     -0.085525006
-0.101433602     0.024324641     -0.061649036
-0.168430597     0.01944482      0.067069928
0.063105589     -0.014468972     -0.057033327
0.091725002     0.019449758     -0.09282808
0.050919434     0.015412787     0.088085496
-0.083490063     0.01431235      0.006046352
-0.016591855     0.046056594     0.031486031
-0.027094183     0.006439511     -0.022671358
-0.048319809     -0.009784029     -0.197325511
0.145607494     0.060227841     -0.045675669
-0.011591297     0.146786896     0.048423907
-0.032621536     -0.177005488     -0.169348654
0.00243993      0.118517884     0.08361735
0.073631913     -0.08100116     0.135609957
-0.003841096     -0.043413522     -0.047062029
-0.072268786     0.030648685     0.14661047
-0.160785476     0.035092195     -0.031213061
-0.013847106     0.014387994     0.053181289
0.038242574     -0.059924867     0.11030097
0.076969994     -0.024490455     0.094355876
0.029731578     0.014480469     -0.030787619
0.000995831      0.046282199     -0.043862206
-0.110397467     -0.053281003     0.066374759
-0.047571065     0.010565752     0.001556199];
```

Y=[0.102787219	0.034171044	0.013811888
0.008146365	-0.07265867	0.037693538
0.008962942	-0.006556932	-0.016816926
-0.068539437	-0.014898998	-0.012211415
0.022941312	0.059764787	-0.03417018
-0.089916396	0.086683966	0.011711244
-0.040360467	0.002849303	0.086922191
-0.036985984	0.032270813	-0.022448986
-0.173733407	0.114475365	-0.068859262
0.024317256	0.012083638	-0.04147225
-0.087610824	0.051892691	0.066344137
-0.050149155	0.093800727	-0.01183876
0.01925464	-0.005024676	-0.078334059
-0.152552294	-0.03204593	0.09926773
-0.013076399	-0.016115644	-0.127696748
0.005842006	-0.067039582	-0.077381436
0.034671634	-0.101520478	0.012235035
-0.075100727	0.161513903	0.076747491
-0.038175833	0.102796557	-0.162879495
-0.049247878	-0.052937787	0.202760996
0.111116472	0.093135474	0.019108173
-0.137984083	0.023209675	-0.06631574];
0.046004502	0.009842699	
-0.07929262	0.0200104	
0.129116959	0.038554163	
0.004782168	0.01305406	
-0.03039924	0.007158709	
0.121964285	0.00929579	
-0.04289278	-0.019452501	
-0.087373026	-0.028920807	
-0.107796863	0.039584289	
0.026265467	0.155929678	
0.041589314	0.015055243	
0.06188455	-0.06245795	
-0.080434307	0.070024481	
-0.0678897	0.044350515	
-0.044707057	0.000111175	
0.007031628	-0.035633083	
0.043955851	-0.007904886	
-0.018907746	0.082751984	
-0.031704577	-0.037369064	
0.022897538	0.028038199	
-0.108001856	0.09205576	
-0.022753126	-0.047584111	
-0.023981628	-0.014410853	
-0.018861564	0.019030532	
0.083403389	0.055476159	

Z=[0.019200967	0.002494685	0.015245004
-0.051231394	0.118106117	-0.003133319
0.01990703	0.05764846	0.025934519
0.033467798	0.033721297	-0.063669232
0.063747649	0.085156744	-0.032014081
-0.103394834	0.004838685	-0.024835992
-0.019661394	-0.032505499	-0.031586217
0.007711747	-0.068714218	0.069141017
0.041707993	0.006531941	0.08140054
-0.102281003	-0.0008282	0.046901213
0.0310713	-0.01534944	0.046901213
0.030745301	0.048973572	-0.008870226
-0.007064433	0.080998622	0.057572724
0.037260306	-0.048912914	0.071594985
-0.023919425	0.063352791	-0.001291106
-0.038085488	-0.020498381	0.137659113
-0.008222071	0.097833404	0.017061981
-0.005806871	0.079402222	0.058177775
0.015098684	-0.019319702	-0.032488615
-0.031351686	0.055758065	0.061753207
0.041946957	0.012854492	-0.038971198];
0.00030028	0.038718698	
-0.030674165	-0.080335963	
-0.10951911	0.028416875	
-0.050284199	0.061756005	
0.015265064	-0.001320876	
-0.126258646	-0.01767299	
-0.042614249	-0.011377292	
-0.066588816	-0.052390329	
-0.073875622	-0.011686332	
0.000946541	-0.025505417	
-0.06307563	-0.042865724	
-0.102883114	0.013391067	
0.031665885	-0.051599439	
-0.05004142	-0.098642625	
-0.023872784	-0.018716749	
-0.048908291	-0.026257369	
0.001364404	0.127865272	
0.012414522	-0.075910433	
0.051633145	0.016501918	
0.071649805	-0.044301004	
-0.025806386	0.00462177	
-0.050535847	0.086395189	
-0.031634386	-0.029261758	
-0.009793766	-0.026110326	
0.055350207	-0.032336805	
0.004742852	-0.02313165	
0.043768585	0.016215215	

```

plot3(X(1:5),Y(1:5),Z(1:5),'r+'),view(-60,60)
view(40,35)
hold on;
plot3(X(6:90),Y(6:90),Z(6:90),'bo'),view(-60,60)
view(40,35)
hold on;
plot3(X(91:95),Y(91:95),Z(91:95),'gP'),view(-60,60)
view(40,35)
hold on;
p0=plot3(X(96:102),Y(96:102),Z(96:102),'c*'),view(-60,60)
set(p0,'Color',rgb('maroon'))
view(40,35)
hold on;
plot3(X(103:105),Y(103:105),Z(103:105),'m^'),view(-60,60)
view(40,35)
grid on;
hold on;
p=plot3(X(106:112),Y(106:112),Z(106:112),'yh'),view(-60,60)
set(p,'Color',rgb('gold'))
view(40,35)
hold on;
p1=plot3(X(113),Y(113),Z(113),'kd'),view(-60,60)
set(p1,'Color',rgb('black'))
view(40,35)
hold on;
plot3(X(114:116),Y(114:116),Z(114:116),'rs'),view(-60,60)
view(40,35)
grid on;
for j=1:5,
    hold all; plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)],'r:') , view(-60,60)
view(40,35)
end
for j=6:90,
    hold all; plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)],'b:') , view(-60,60)
view(40,35)
end
for j=91:95,
    hold all; plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)],'g:') , view(-60,60)
view(40,35)
end
for j=96:102,
    hold all; q0=plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)],'c:') , view(-60,60)
set(q0,'Color',rgb('maroon'))
view(40,35)
end
end

```

```

for j=103:105,
    hold all; plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)], 'm:') , view(-60,60)
view(40,35)
end
for j=106:112,
    hold all; q=plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)], 'y:') , view(-60,60)
set(q,'Color',rgb('gold'))
view(40,35)
end
for j=113,
    hold all; q1=plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)], 'k:') , view(-60,60)
set(q1,'Color',rgb('black'))
view(40,35)
end
for j=114:116,
    hold all; plot3([X(j); X(j)], [Y(j); Y(j)], [-0.2; Z(j)], 'r:') , view(-60,60)
view(40,35)
end
xlabel('GPC Score 1 (29.94%)')
ylabel('GPC Score 2 (24.11%)')
zlabel('GPC Score 3 (13.73%)')

legend('B35', 'B45', 'B65', 'B68', 'B75', 'Las Colinas', 'TVWS', 'Snaketown')

title('Olivella dama Barrel Beads')

```

## APPENDIX H

### ROBUST ONE-WAY MANOVA AND PIVOTAL BOOTSRAP TEST

#Example of raw data for one-way MANOVA comparing GPC1 and GPC2 scores of the *Olivella dama* barrel beads from LAn-264 Burial 35 with those from Las Colinas.

```
Location GPC1 GPC2
B35 0.0166183680840283 0.102787218565642
B35 -0.06615538954363 0.00814636505726161
B35 0.00243992974579816 0.00896294207028367
B35 -0.207094639483624 -0.0685394374901909
B35 -0.101433602213706 0.0229413117021865
LC 0.135609956806496 -0.0118387601988104
LC -0.0470620294265891 -0.0783340590614058
LC 0.146610470291907 0.099267730071095
LC -0.0312130614398089 -0.127696748076196
LC 0.0531812892519583 -0.0773814364460503
LC 0.1103009700218 0.0122350346482705
LC 0.0943558755573164 0.0767474913577316
```

#R script for robust one-way MANOVA.

```
x<-read.table("B35LC.txt",header=T)

#Need R package rrcov

library(rrcov)

grp <- as.factor(x[,1])

x <- as.matrix(x[,2:3])

Wilks.test(x,grouping=grp,method="mcd")
```

#Example of two *Olivella dama* barrel bead landmark data sets used in the pivotal bootstrap test.

LC.tps (Las Colinas)

B68.tps (LAn-264 Burial 68)

LM=7	LM=7	LM=7	LM=7
222 110	263 109	218 63	293 120
239 194	284 203	245 176	318 250
230 289	271 303	238 258	302 350
24 302	36 276	51 261	47 340
14 212	26 202	24 150	25 224
56 32	50 32	42 34	56 44
194 26	244 34	217 54	268 43
ID_LC_1	ID=LC_5	ID_68_1	ID_68_5
LM=7	LM=7	LM=7	LM=7
289 94	248 134	322 98	251 66
310 194	266 226	336 186	266 164
302 290	257 286	326 317	255 270
44 297	50 354	72 340	71 282
22 184	24 219	38 143	32 177
39 42	77 22	66 34	55 46
280 44	223 44	306 56	246 56
ID_LC_2	ID_LC_6	ID_68_2	ID_68_6
LM=7	LM=7	LM=7	LM=7
185 78	277 112	357 181	228 55
202 151	298 230	376 285	238 146
183 244	248 370	350 444	229 250
41 279	45 354	73 412	58 226
8 169	21 209	42 290	27 66
56 10	56 23	68 64	40 40
158 22	248 22	326 49	226 47
ID_LC_3	ID_LC_7	ID_68_3	ID_68_7
LM=7		LM=7	LM=7
255 104		241 100	225 58
270 224		264 204	256 165
255 254		249 290	245 244
26 260		52 302	48 255
18 170		28 198	18 153
36 38		50 57	48 25
234 35		229 63	224 48
ID_LC_4		ID_68_4	ID_68_8

#Example R script used for pivotal bootstrap test.

#Need R shapes package

#Need R source code for read.tps

A<-read.tps("LC.tps")

B<-read.tps("B68.tps")

resampletest(A,B,resamples=1000) #set for 1000 bootstrap resamples

Selected output ( $\lambda_{min}$ , and  $\lambda_{min}$  p-value)

\$lambda

[1] 25.30161

\$lambda.pvalue

[1] 0.4125874

Note that the estimated  $\lambda_{min}$  p-value will vary slightly each run of the procedure (with the same data) because of stochastic variation resulting from the bootstrap resampling.

APPENDIX I  
PORČIĆ METHOD

#R script for performing the permutation significance test (or Porčić method) from Porčić 2013.

```
library(ca) #library ca has to be installed
library(plyr) #library plyr has to be installed
Perm <- 100000 # Perm sets the number of permutations for the randomization test. Set
#at 100,000 permutations.
PERM <- c(1:Perm)
```

#Function for counting modes (copy and past to R gui)

```
localMaxima <- function(x) {
  # Use -Inf instead if x is numeric (non-integer)
  y <- diff(c(-.Machine$integer.max, x)) > 0L
  rle(y)$lengths
  y <- cumsum(rle(y)$lengths)
  y <- y[seq.int(1L, length(y), 2L)]
  if (x[[1]] == x[[2]]) {
    y <- y[-1]
  }
  y
}
```

#Copy and save using plain text editor as LAN264\_Porcic.csv to working directory to  
# which R is set.

```
15,727,0,0,0,198,1,1,7,0
0,94,8,5,0,33,1,1,0,0
3,24,5,2,0,1,2,0,240,0
1,31,2,0,0,5,0,0,14,0
1,3,8,2,0,0,2,1,200,0
0,0,234,4,0,0,1,40,0,0
0,28,119,112,0,3,7,9,1,0
0,0,36,130,0,0,0,0,2,0
2,12,4,355,2,15,0,120,301,3
7,69,294,1994,1,0,12,20,3,0
```

```
data<-read.csv(file="LAN264_Porcic.csv",header=F)
#Performing correspondence analysis (CA) on the data and calculating the number of
modes for the CA solution
```

#Enter the following code in the R gui

```
M <- length(data[1,])
a <- c(1:M)
b <- c(1:M)
data2 <- as.matrix(data)
ord <- ca(data)$rowcoord[,1]
data <- as.matrix(data)
data1 <- cbind(ord, data)
data1 <- as.data.frame(data1)
G <- arrange(data1, desc(ord))
matr <- G[,2:(M+1)]/(apply(G[,2:(M+1)],1, sum))
```

```
for(j in 1:M) {
```

```
  a[j] <- length(localMaxima(matr[,j]))
```

```
}
```

```
sum(a) #gives the observed total of modes
```

```
# R code to generate the distribution of total number of modes with randomized data
```

```
for(i in 1:Perm) {
  for(j in 1:M) {
    data2[,j] <- sample(data[,j], replace = FALSE)}
  ord <- ca(data2[which(rowSums(data2)>0),])$rowcoord[,1]
  data2 <- as.matrix(data2)
  data3 <- cbind(ord, data2[which(rowSums(data2)>0),])
  data3 <- as.data.frame(data3)
  G <- arrange(data3, desc(ord))
```

```
  matr <- G[,2:(M+1)]/(apply(G[,2:(M+1)],1, sum))
```

```
  for(j in 1:M) {
```

```
    b[j] <- length(localMaxima(matr[,j]))}
```

```
  PERM[i] <- sum(b)}
```

```
quantile(PERM, 0.05) # Gives the value of the 5th percentile of the randomized
distribution of total number of modes
```

```
sum(a) → 26 modes
```

```
quantile(PERM,0.05) → 5% 26.
```

Result is that the 5th percentile of the randomized distribution occurs at 26 modes, which means that the 26 modes in the LAN-264 burial data is statistically significant at  $\alpha = 0.05$ . This means that the LAN-264 data is very likely structured mostly by time.

```
#Creates histogram of results.
```

```
hist(PERM, breaks=16, col = 4, border = terrain.colors(1), xlab = "Total Number of Modes", main = "Distribution of the Total Number of Modes of 100,000 Randomized (Permuted) Data Tables") # Draws a histogram of randomized total number of modes
```

```
abline(v = 26, col=2, lty=2)
```

APPENDIX J  
SERIATION METHODS

## Procedure for the Oro Grande Sample

Kendall's 1-mode multidimensional scaling method (or "horse-shoe method", see Kendall (1963, 1969a, b, 1971), in combination with a traveling salesman problem solver, was used to sequence the Oro Grande residential loci sample. I chose this method, because of the very small sample size of the shell artifacts from residential loci 6, 7, 8, and 10, and because there (fortunately) are very good temporally diagnostic types of shell (that occur in very low frequencies  $n [1, 3]$ ) in the samples from the loci. Small sample size makes the use of an abundance matrix very problematic (due to sampling error). Also, the choice of a method (such as Kendall's) that uses an incidence (presence/absence) matrix seems preferable, because of the issue with sampling error (which is less confounding when magnitude is removed), and also because distinct and temporally diagnostic shell artifact types are present in each of the loci.

### **R code to compute the Oro Grande burial seriations. The R packages seriation, TSP, MASS, and vegan are required.**

#For MS Windows, download and unpack concorde.exe (The Traveling Salesman Problem or TSP solver used to find the seriation) from <http://www.tsp.gatech.edu/concorde/downloads/downloads.htm>, and place it in a directory where it can be called by R. It is also necessary to have Cygwin (<http://www.cygwin.com/>) in the same directory.

```
library(seriation)
```

```
#Kendall's square symmetric matrix
```

```
S <- function(x, w = 1) {  
  sij <- function(i, j) w * sum(pmin(x[i,], x[j,]))  
  h <- nrow(x)  
  r <- matrix(ncol = h, nrow = h)  
  for(i in 1:h) for(j in 1:h) r[i,j] <- sij(i,j)  
  r  
}
```

```

SoS <- function(x) S(S(x))

#To establish a path for R to call concorde.exe

concorde_path("directory where concorde.exe is located")

#e.g. concorde_path("E:/OroGrande") or

concorde_path("/Users/macuser/Desktop/Concorde/TSP")

OG<-read.table("OG.txt", header=F)

#Kendall's horse shoe (Hamiltonian arc)

horse_shoe_plot <- function(mds, sigma, threshold = mean(sigma), ...) {

plot(mds, main = paste("Kendall's horse shoe with th =", threshold), ...)
l <- which(sigma > threshold, arr.ind=TRUE)
for(i in 1:nrow(l)) lines(rbind(mds[l[i,1],], mds[l[i,2],]))
}

#shuffle data

x <- OG[sample(nrow(OG)),]

sigma <- SoS(x)

#Two different options for computing the mds matrix, but use only one at a time in the
following code

#Option 1: multidimensional scaling algorithm for 'primary treatment of ties' or ptt
# (Kendall 1971 pp. 229-233; Kruskal 1964).
#“ probably much preferred when any one value (for example, zero) occurs frequently
#in the similarity matrix” (Kendall 1971 p. 229)

library(MASS)

mds<-isoMDS(1/(1+sigma))$points

#Option 2: multidimensional scaling algorithm for 'secondary treatment of ties' or stt
#(Kendall 1971 pp. 229-232; Kruskal 1964).

library(vegan)

mds <- monoMDS(1/(1+sigma),model="local")$points

```

```

#plot Kendall's horse shoe

horse_shoe_plot(mds, sigma)

#find order using a TSP

library(TSP)

tour <- solve_TSP(insert_dummy(TSP(dist(mds)), label = "cut"), method = "concorde",
control = list(rep = 15))

tour <- cut_tour(tour, "cut")

lines(mds[tour,], col = "red", lwd = 2)

#because of the shuffling of the original data matrix OG, need to look at both x and
#mds to determine the identity of the points in the plot

```

## **R Code for LAN-264 Seriation**

### **Detrended Correspondence Analysis**

```

#decorana_264.csv (below)

O.b._2.3_3.3,
O.b._3.4_4.9,O.b._5.0_7.1,O.b._7.2_12.4,Myt._2.4_3.4,Myt._3.5_4.9,Myt._5.0-
7.1,Myt._7.2_8.9,O._dama_barrel,O.b._barrel
35,15,727,0,0,0,198,1,1,7,0
48,0,94,8,5,0,33,1,1,0,0
51,3,24,5,2,0,1,2,0,240,0
68,1,31,2,0,0,5,0,0,14,0
73a,1,3,8,2,0,0,2,1,200,0
10,0,0,234,4,0,0,1,40,0,0
64,0,28,119,112,0,3,7,9,1,0
61,0,0,36,130,0,0,0,0,2,0
45,2,12,4,355,2,15,0,120,301,3
43,7,69,294,1994,1,0,12,20,3,0

library(vegan)

x<-read.csv(file="decorana_264.csv",header=T)

LAN264.dca<-decorana(x)
summary(LAN264.dca)

```

```

scores(LAN264.dca)

plot(LAN264.dca, disp = "sites", type = "n")

ordipointlabel(LAN264.dca,disp="sites",col="blue")

points(LAN264.dca, disp = "sites", pch = 21, col = "red", bg = "yellow", cex = 1)

abline(v=-0.7130,col=3,lty=3)

```

### **TSP Seriation**

```

library(MASS)

library(seriation)

LAN264<-t(matrix(c(15,727,0,0,0,198,1,1,7,0,
0,94,8,5,0,33,1,1,0,0,
3,24,5,2,0,1,2,0,240,0,
1,31,2,0,0,5,0,0,14,0,
1,3,8,2,0,0,2,1,200,0,
0,0,234,4,0,0,1,40,0,0,
0,28,119,112,0,3,7,9,1,0,
0,0,36,130,0,0,0,0,2,0,
2,12,4,355,2,15,0,120,301,3,
7,69,294,1994,1,0,12,20,3,0),10,10))

concorde_path("/Users/macuser/Desktop/Concorde/TSP")

x1 <-prop.table(LAN264,1)

x1a<-round(x1,digits=4)

x1b<-as.table(x1a)

write.csv(x1b, file = "LAN264Prop_1914_10_Burials.csv")

y<-dist(x1)

y<-as.matrix(y)

write.csv(y, file = "y.csv", fileEncoding = "macroman") #MAC Excel

write.csv(y, file = "y.csv", fileEncoding = "UTF-16LE") #Windows Excel

```

```
order<-c(seriate(dist(x1),method="TSP",control=list(method="concorde")))
get_order(order)
[1] 6 7 8 10 9 5 3 4 2 1 #seriation ordering of burials.
```

Corresponding LAn-264 burials for the get\_order(order) result (above).

```
1 = B35
2 = B48
3 = B51
4 = B68
5 = B73a
6 = B10
7 = B64
8 = B61
9 = B45
10 = B43
```

TSP seriation result with the correct chronological direction.

```
B35->B48->B68->B51->B73a->B45->B43->B61->B64->B10
```

#metric MDS to generate x-y coordinates for showing the burials and Hamiltonian path

```
loc<-cmdscale(y)
x_1 <- loc[,1]
y_1 <- loc[,2]
```

%Matlab Code to make a plot (Figure 6.5) of the TSP results.

```
%Raw data for LAn-264 seriation plot
A=[-0.219210195991725 -0.635320911141974;
-0.14694394734727 -0.55920210399092;
-0.566882125462284 0.414450230179661;
-0.316707260810887 -0.326564764855316;
-0.575056595225354 0.501664980062944;
0.291384116990324 -0.0293107321595351;
0.368799902041548 -0.000587402683148962;
0.556921439925786 0.179621486940755;
0.044956156372251 0.287571490120415;
0.562738509507611 0.167677727527119];
```

%labels correspond to their seriation order.

```

labels = cellstr( num2str([35 48 51 68 73 10 64 61 45 43]') );

plot(A(:,1), A(:,2), 'r.')

%Need Matlab function drawarrow.m

function drawarrow(x1,x2,y1,y2,len)
%DRAWARROW connecting two points with a line with arrowhead
%drawarrow(x1,x2,y1,y2,len) draw an arrowed line from (x1,y1) to (x2,y2),and len is the
length of the arrow side.
%(x1,y1)-->(x2,y2)

cita=pi/12; % default angle between the two sides of arrow is 30
cos_cita=cos(cita);
sin_cita=sin(cita);

x=[x1 x2];
y=[y1 y2];

% r is the ratio of the length of arrow side to the distance between the two points.
r=len/sqrt((x1-x2)*(x1-x2)+(y1-y2)*(y1-y2));
% you can change the color of line here, default color is black.
hdl_line=line(x,y,'color',[0 0 0]);
p1_x=x2;
p1_y=y2;
p2_x=x2+r*(cos_cita*(x1-x2)-sin_cita*(y1-y2));
p2_y=y2+r*(cos_cita*(y1-y2)+sin_cita*(x1-x2));
p3_x=x2+r*(cos_cita*(x1-x2)+sin_cita*(y1-y2));
p3_y=y2+r*(cos_cita*(y1-y2)-sin_cita*(x1-x2));
% you can change the color of arrow here, default color is black.
hdl_head=patch([p1_x p2_x p3_x],[p1_y p2_y p3_y],'k');

```

```

%Commands to draw the labeled Hamiltonian path for the LAN-264 TSP seriation using
%function drawarrow.m
drawarrow(A(1,1),A(2,1),A(1,2),A(2,2),0.045)
hold on;
drawarrow(A(2,1),A(4,1),A(2,2),A(4,2),0.045)
hold on;
drawarrow(A(4,1),A(3,1),A(4,2),A(3,2),0.045)
hold on;
drawarrow(A(3,1),A(5,1),A(3,2),A(5,2),0.045)
hold on;
drawarrow(A(5,1),A(9,1),A(5,2),A(9,2),0.045)
hold on;
drawarrow(A(9,1),A(10,1),A(9,2),A(10,2),0.045)
hold on;
drawarrow(A(10,1),A(8,1),A(10,2),A(8,2),0.01)
hold on;
drawarrow(A(8,1),A(7,1),A(8,2),A(7,2),0.045)
hold on;
drawarrow(A(7,1),A(6,1),A(7,2),A(6,2),0.045)
text(A(1,1), A(1,2), labels(1), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','right');
text(A(2,1), A(2,2), labels(2), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','left');
text(A(3,1)-0.015, A(3,2)-0.02, labels(3), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','right');
text(A(4,1), A(4,2), labels(4), 'VerticalAlignment','top', ...
      'HorizontalAlignment','right');
text(A(5,1), A(5,2), labels(5), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','right');
text(A(5,1), A(5,2), labels(5), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','right');
text(A(6,1), A(6,2), labels(6), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','right');
text(A(7,1)+0.025, A(7,2)-0.075, labels(7), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','right');
text(A(8,1)-0.005, A(8,2)-0.025, labels(8), 'VerticalAlignment','top', ...
      'HorizontalAlignment','left');
text(A(9,1), A(9,2), labels(9), 'VerticalAlignment','top', ...
      'HorizontalAlignment','right');
text(A(10,1)-0.02, A(10,2)+0.02, labels(10), 'VerticalAlignment','bottom', ...
      'HorizontalAlignment','left');
xlabel('metric MDS Dimension 1')
ylabel('metric MDS Dimension 2')
title('LAN 264 M5a-b Burials')

```

APPENDIX K  
FORD DIAGRAM

## Ford Diagram

```
#Ford_1914.csv
```

```
15,727,0,0,0,198,1,1,7,0  
0,94,8,5,0,33,1,1,0,0  
1,31,2,0,0,5,0,0,14,0  
3,24,5,2,0,1,2,0,240,0  
1,3,8,2,0,0,2,1,200,0  
2,12,4,355,2,15,0,120,301,3  
7,69,294,1994,1,0,12,20,3,0  
0,0,36,130,0,0,0,0,2,0  
0,28,119,112,0,3,7,9,1,0  
0,0,234,4,0,0,1,40,0,0
```

```
#R script
```

```
library(plotrix)  
x<-read.csv(file="Ford_1914.csv",header=F)  
x1<-as.matrix(x)  
x2<-prop.table(x1,1)  
x3<-100*x2  
dimnames(x3) <- list(NULL, NULL)  
xaxlab=c("Oliv_2.3-  
3.3","Oliv_3.4_4.9","Oliv_5.0_7.1","Oliv_7.2_12.4","Myt_2.4_3.4","Myt_3.5_4.9","Myt_5.0_7.1","Myt_7.2_8.9","O_dama_barrel","O_bip_barrel")  
yaxlab=c("35","48","68","51","73a","45","43","61","64","10")  
battleship.plot(x3,,mar=c(2,5,5,1),xaxlab=xaxlab,yaxlab=yaxlab,maxxspan=0.60,maxyspan=0.48)
```

## APPENDIX L

### FIEDLER VECTOR SPECTRAL PARTITIONING ANALYSIS

%Matlab code to convert the Brainerd-Robinson probability matrix (BRP) for the Malibu  
%data to an adjacency matrix, using a p-value cut-off (threshold) of 0.05.

```
BRP=[0 0.84903 0 0.77838 0 0 0 0 0;  
0.84903 0 0 0.55415 0 0 0.00002 0 0;  
0 0 0 0.4155 0.82429 0 0 0 0.21306;  
0.77838 0.55415 0.4155 0 0.1248 0 0 0 0.14685;  
0 0 0.82429 0.1248 0 0 0 0 0.29932;  
0 0 0 0 0 0.3278 0.00012 0 0;  
0 0.00002 0 0 0 0.3278 0 0.45502 0.2323 0.23425;  
0 0 0 0 0.00012 0.45502 0 0.40675 0.90496;  
0 0 0.21306 0.14685 0.29932 0 0.2323 0.40675 0 0.01359;  
0 0 0 0 0 0.23425 0.90496 0.01359 0];
```

```
l=length(BRP);  
threshold = 0.05;  
for m = 1:l  
    for n = 1:l  
        if BRP(m,n)<=threshold  
            A(m,n) = 0;  
        else  
            A(m,n)=1;  
        end  
    end  
end  
end
```

The following Matlab code computes the Fiedler vector  $v$  (the eigenvector corresponding to the 2nd smallest eigenvalue  $d$  of the Laplacian of the graph of  $A+A'$ ).  $p$  is the permutation obtained when  $v$  is sorted. In my analysis  $p$  provides a seriation of the Malibu M5a-b burials, where the order of the burials cannot be determined because their values in  $v$  (and likewise in  $p$ ) are equal.  $A$  should be the adjacency matrix of a connected graph.

```
%Matlab code for Fiedler vector analysis
```

```
A=[0 1 0 1 0 0 0 0 0 0;  
1 0 0 1 0 0 0 0 0 0;  
0 0 0 1 1 0 0 0 1 0;  
1 1 1 0 1 0 0 0 1 0;  
0 0 1 1 0 0 0 0 1 0;  
0 0 0 0 0 0 1 0 0 0;  
0 0 0 0 0 1 0 1 1 1;  
0 0 0 0 0 0 1 0 1 1;  
0 0 1 1 1 0 1 1 0 0;  
0 0 0 0 0 0 1 1 0 0];
```

```
n = size(A,1);  
opt.disp = 0; %turn off printing to eigs  
opt.tol = sqrt(eps);  
S = A\A'\speye(n); %compute the Laplacian of A  
S=diag(sum(S))-S;  
[v,d] = eigs(S,2,'SA',opt); %find the Fiedler vector v  
v=v(:,2);  
d=d(2,2);  
[ignore p] = sort(v); %sort it to get p
```

```
%Matlab code to plot the results
```

```
%need vline2.m
```

```
set(gcf,'Color',[1 1 1])  
subplot(1,2,1)  
plot(sort(v),'-');  
xlabel('index i')  
ylabel('fv(i)')  
title('Sorted Fiedler Vector')  
set(gca, 'XTick',1:10, 'XTickLabel',{'48' '35' '68' '73a' '51' '45' '61' '64' '43' '10'})  
axis('tight')  
axis('square')  
vline2([2 6], {'m--', 'g:'}, {'first cut', 'second cut'}, opts)  
subplot(1,2,2)  
spy(A(p,p),'r')  
title('Sorted Adjacency Matrix')
```

Table L.1. Laplacian of A.

2	-1	0	-1	0	0	0	0	0	0
-1	2	0	-1	0	0	0	0	0	0
0	0	3	-1	-1	0	0	0	-1	0
-1	-1	-1	5	-1	0	0	0	-1	0
0	0	-1	-1	3	0	0	0	-1	0
0	0	0	0	0	1	-1	0	0	0
0	0	0	0	0	-1	4	-1	-1	-1
0	0	0	0	0	0	-1	3	-1	-1
0	0	-1	-1	-1	0	-1	-1	5	0
0	0	0	0	0	0	-1	-1	0	2

v (Fiedler vector)=

-0.4187  
 -0.4187  
 -0.1593  
 -0.2519  
 -0.1593  
 0.5086  
 0.3060  
 0.2497  
 -0.0032  
 0.3470

sorted v =

-0.4187  
 -0.4187  
 -0.2519  
 -0.1593  
 -0.1593  
 -0.0032  
 0.2497  
 0.3060  
 0.3470  
 0.5086

d = 0.3983

p = [2 1 4 5 3 9 8 7 10 6]

APPENDIX M  
BAXTER AND COOL METHOD

Baxter and Cool 2010:2384 provide the following R script. Copy and paste into R.

```
data.boot <- function(y,h){boot(y, peak.test, R=9999, sim = "parametric", ran.gen = shrunk.gen,
mle = c(length(y),h),h = h)}
peak.test <-function(y,h)
{dens <-density(y,h)
length(peaks(dens$y))
}
peaks <-function(x){
l <-length(x)
xm1 <-c(x[-1],x[l])
xp1 <-c(x[1],x[-1])
x[x>xm1 & x>xp1]
}
shrunk.gen<-function(d,mle){
n<-mle[1];h <-mle[2]
v<-var(d)
i<-sample(n,n,replace=T)
(d[i]+h*rnorm(n))/sqrt(1+h^2/v)}
```

Also need R packages boot and MASS.

For example, the diameters for the *Olivella dama* small barrel beads from LAn-264 Burial 68 are entered into R as the vector: a<-(3.6, 4.1, 4.2, 4.2, 4.4, 4.7, 4.9, 5, 5.2, 5.3, 5.9, 6.2, 6.5).

The critical bandwidth  $h_0$  is determined by using the function peak.test. To determine the critical bandwidth for the Burial 68 data to four decimal places using peak.test, start by determining the critical bandwidth to two decimal places. Then, compute the midpoint  $(0.39+0.38)/2=0.3850$ .

Then compute peak.test(a, 0.385) in R and repeat the bifurcation procedure until convergence on the critical bandwidth to four decimal places (see Table M.1 for the sequence for Burial 68).

Table M.1. Sequence for determining the optimal bandwidth of the kernel density estimate of the diameter distribution of the *Olivella dama* barrel bead sample from LAn-264 Burial 68.

Bandwidth	Number of Modes	
0.39	1	
0.38	2	
0.3850	2	
0.3875	2	
0.3888	1	
0.3881	2	
0.3884	2	
0.3886	1	$h_0$
0.3885	2	

Hall and York 2001 provide a correction formula  $\lambda_\alpha$  for  $h_0$  (also see Baxter and Cool 2010:2381).

Use the following R script to compute  $\lambda_\alpha$  (lamda\_alpha), where  $\alpha$  in this case is 0.05 (b, below).

```

a1<- 0.94029
a2<-1.59914
a3<- 0.17695
a4<- 0.48971
a5<- 1.77793
a6<- 0.36162
a7<- 0.42423
b<-0.05
lamda_alpha <-(a1*b^3+a2*b^2+a3*b+a4)/(b^3+a5*b^2+a6*b+a7)

```

Henderson et al. 2008 suggest using the formula  $\lambda_\alpha * h_0$  to compute the corrected critical bandwidth  $h_0(\text{corrected})$  [h0\_corrected].

Use the following R code to test if the Burial 68 data is unimodal using the bootstrapping procedure provided by Baxter and Cool 2010:2384.

```

ho<-0.3886

```

```
h0corrected<- lamda_alpha*ho
```

```
data.boot(a,h0corrected)
```

The following output is produced.

Call:

```
boot(data = y, statistic = peak.test, R = 9999, sim = "parametric",  
      ran.gen = shrunk.gen, mle = c(length(y), h), h = h)
```

Bootstrap Statistics :

```
original bias std. error  
t1*      1 0.4137414 0.5197973
```

Table M.2. Interpretation of above output.

original	This identifies the number of modes being evaluated, which is 1 mode in this case.
t1* 1	
bias 0.4137414	This is the p-value, which in this case is not significant at $\alpha=0.05$ . Conclude that the Burial 68 data is unimodal.

Table M.3. LAn-264 *Olivella dama* barrel bead diameter (mm).

Burial	68	45	51	73a
1	3.6	3.7	4.7	4.8
2	4	3.8	4.7	5.1
3	4.1	4	4.7	5.1
4	4.2	4.1	4.7	5.2
5	4.2	4.2	4.7	5.2
6	4.4	4.2	4.8	5.2
7	4.7	4.2	4.8	5.2

8	4.9	4.2	5	5.3
9	5	4.2	5	5.3
10	5.2	4.3	5	5.3
11	5.3	4.3	5	5.3
12	5.9	4.3	5	5.3
13	6.2	4.4	5	5.3
14	6.5	4.4	5	5.3
15		4.4	5.2	5.4
16		4.4	5.2	5.4
17		4.4	5.2	5.4
18		4.4	5.2	5.5
19		4.5	5.2	5.5
20		4.5	5.2	5.5
21		4.5	5.3	5.5
22		4.5	5.3	5.5
23		4.5	5.3	5.5
24		4.5	5.3	5.5
25		4.6	5.3	5.5
26		4.6	5.3	5.6
27		4.6	5.3	5.6
28		4.6	5.4	5.6
29		4.6	5.4	5.6
30		4.6	5.4	5.6
31		4.6	5.4	5.7
32		4.7	5.4	5.7
33		4.7	5.4	5.7
34		4.7	5.5	5.7
35		4.7	5.5	5.7
36		4.7	5.5	5.7
37		4.7	5.5	5.7
38		4.7	5.6	5.7
39		4.7	5.6	5.7
40		4.7	5.7	5.8
41		4.7	5.7	5.8
42		4.7	5.7	5.8
43		4.7	5.7	5.8
44		4.7	5.8	5.8
45		4.7	5.8	5.8

46	4.7	5.8	5.8
47	4.8	5.9	5.8
48	4.8	5.9	5.8
49	4.8	6	5.8
50	4.9	6	5.9
51	4.9	6	5.9
52	5	6.5	5.9
53	5.1		5.9
54	5.1		5.9
55	5.2		5.9
56	5.3		5.9
57	5.3		5.9
58	5.4		5.9
59	5.5		6
60			6
61			6
62			6
63			6
64			6
65			6
66			6
67			6.1
68			6.1
69			6.1
70			6.1
71			6.2
72			6.2
73			6.2
74			6.2
75			6.2
76			6.3
77			6.3
78			6.4
79			6.4
80			6.5
81			6.5
82			6.6
83			6.7

APPENDIX N

BOOTSTRAPPED AND JACKKNIFED COEFFICIENT OF VARIATION

R script to compute the Bootstrap and Jackknife CV and CV Confidence Intervals, and histograms. The histograms require the R package MASS.

```
CV <- function(x) sqrt(var(x))/mean(x)
```

```
boot <- numeric(10000)
```

```
for (i in 1:10000) boot[i] <- CV(sample(x,replace=T))
```

```
mean(boot)
```

```
var(boot)
```

```
truehist(boot,nbins="Scott",prob=FALSE,xlab = "Coefficient of Variation (10,000 Bootstrap Replications)", ylab="Frequency",main="Amavisca Burial #4 Olivella biplicata Wall Bead Diameter (mm)")
```

```
truehist(boot,nbins="FD",prob=FALSE,xlab = "Coefficient of Variation (10,000 Bootstrap Replications)", ylab="Frequency",main="Burial 64 Mode 3 Olivella biplicata Wall Bead Diameter (mm)")
```

```
quantile(boot,0.975)
```

```
quantile(boot,0.025)
```

```
bias <- mean(boot) - CV(x)
```

```
CV(x) - bias
```

```
#Normality
```

```
CV(x) - bias - 1.96*sqrt(var(boot))
```

```
CV(x) - bias + 1.96*sqrt(var(boot))
```

```
#Efron
```

```
quantile(boot,0.025)
```

```
quantile(boot,0.975)
```

```

#Halls
2*CV(x) - quantile(boot,0.975)
2*CV(x) - quantile(boot,0.025)

#Jackknife
jack <- numeric(length(x)-1)

pseudo <- numeric(length(x))

for (i in 1:length(x))
{ for (j in 1:length(x))
{if(j < i) jack[j] <- x[j] else if(j > i) jack[j-1] <- x[j]}
pseudo[i] <- length(x)*CV(x) -(length(x)-1)*CV(jack)}

mean(pseudo)

var(pseudo)

hist(pseudo)

truehist(pseudo,nbins="Scott",prob=FALSE,xlab = "Pseudovalue",
ylab="Frequency",main="Burial 64 Mode 3 Olivella biplicata Bead Diameter (mm)")

var(pseudo)/length(x)

mean(pseudo) - qt(0.975,length(x)-1)*sqrt(var(pseudo)/length(x))

mean(pseudo) + qt(0.975,length(x)-1)*sqrt(var(pseudo)/length(x))

```

Example of shell diameter vector file used as raw data to compute the CV value with the preceding R code.

```
## Example. Raw data vector for Burial 68 (Table).
```

```
x<-c(3.6,4,4.1,4.2,4.2,4.4,.47,4.9,5,5.2,5.3,5.9,6.2,6.5)
```

Table N.1. LAn-264 *Olivella dama* barrel bead counts from four burials. Each cell in the first row consists of the burial number of the sample. The first column is the bead diameter (cm). Raw data for mode detection and CV analysis.

Diam.	68	45	51	73a
3.6	1			
3.7		1		
3.8		1		
4.0	1	1		
4.1	1	1		
4.2	2	5		
4.3		3		
4.4	1	6		
4.5		6		
4.6		7		
4.7	1	15	5	
4.8		3	2	1
4.9	1	2		
5.0	1	1	7	
5.1		2		2
5.2	1	1	6	4
5.3	1	2	7	7
5.4		1	6	3
5.5		1	4	8
5.6			2	5
5.7			4	9
5.8			3	10
5.9	1		2	9
6.0			3	8
6.1				4
6.2	1			5
6.3				2
6.4				2
6.5	1		1	2
6.6				1
6.7				1
Total	14	59	52	83

Figure N.1 *Olivella dama* barrel bead diameter CV bootstrap histograms.

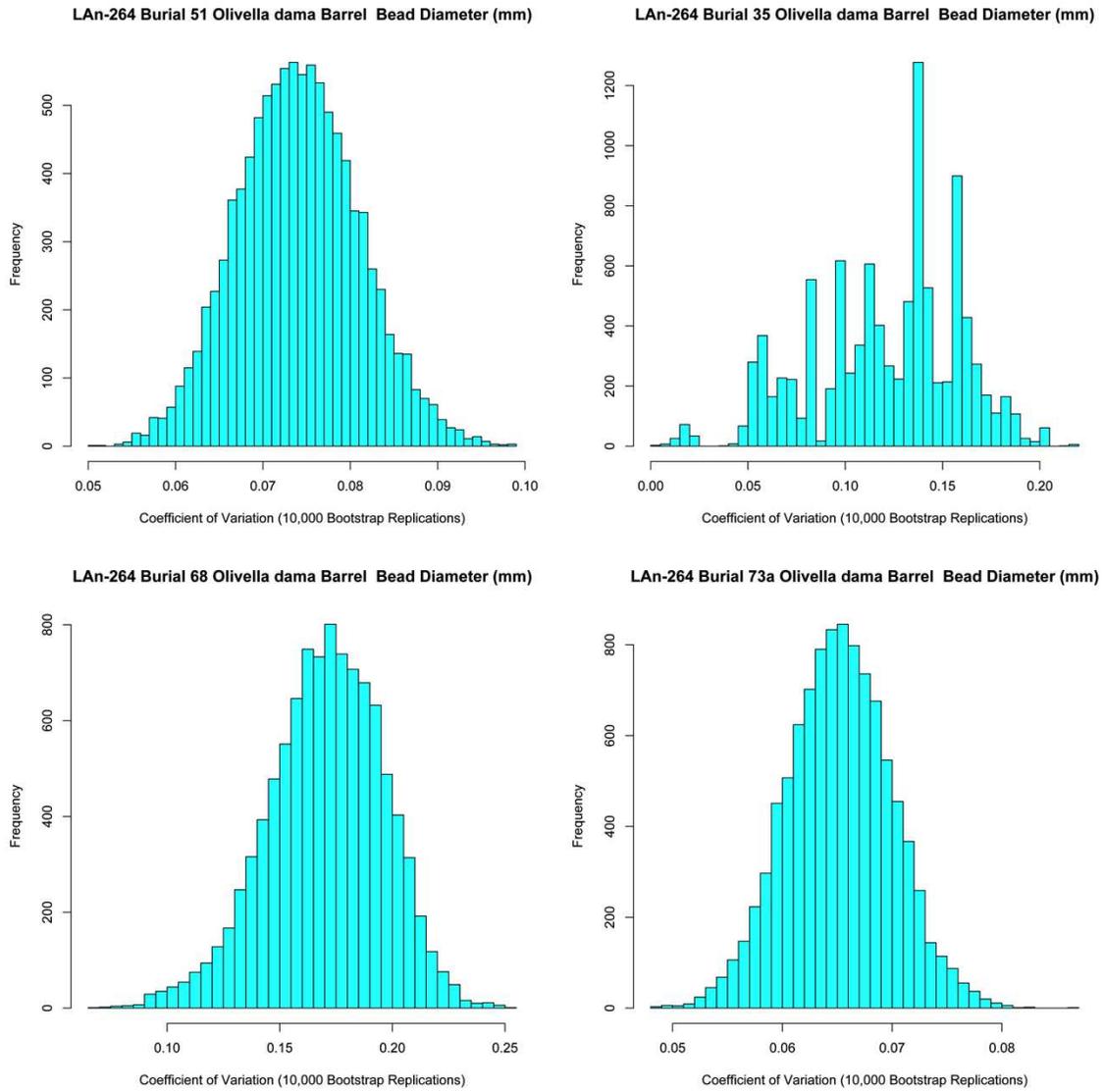


Figure N.2 *Olivella dama* barrel bead diameter CV bootstrap histogram.

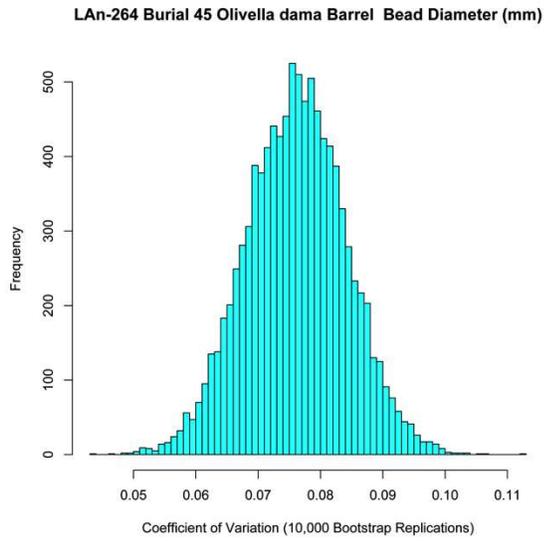


Figure N.3. *Olivella dama* barrel bead diameter CV jackknife Histograms.

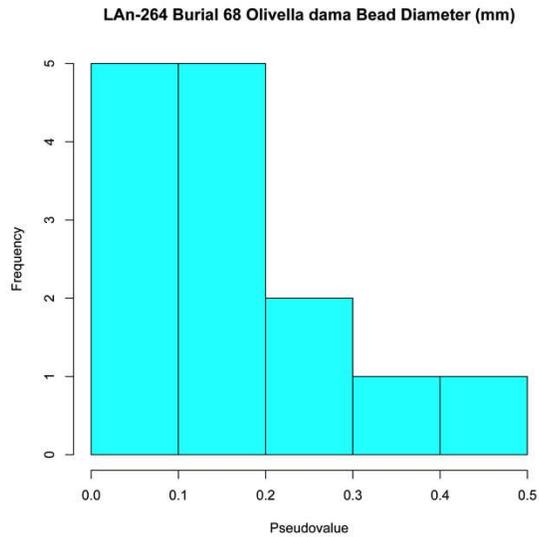
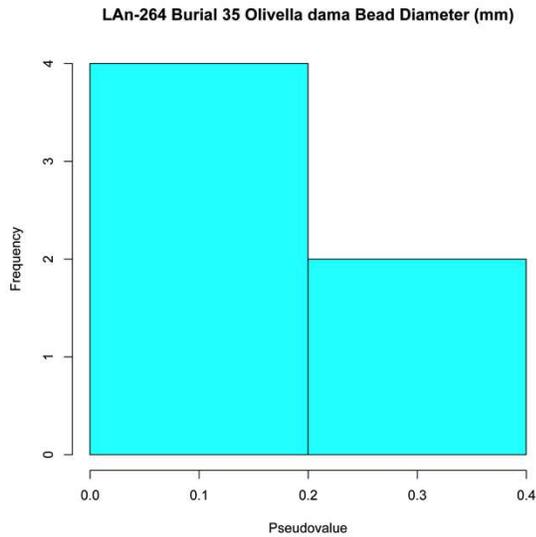
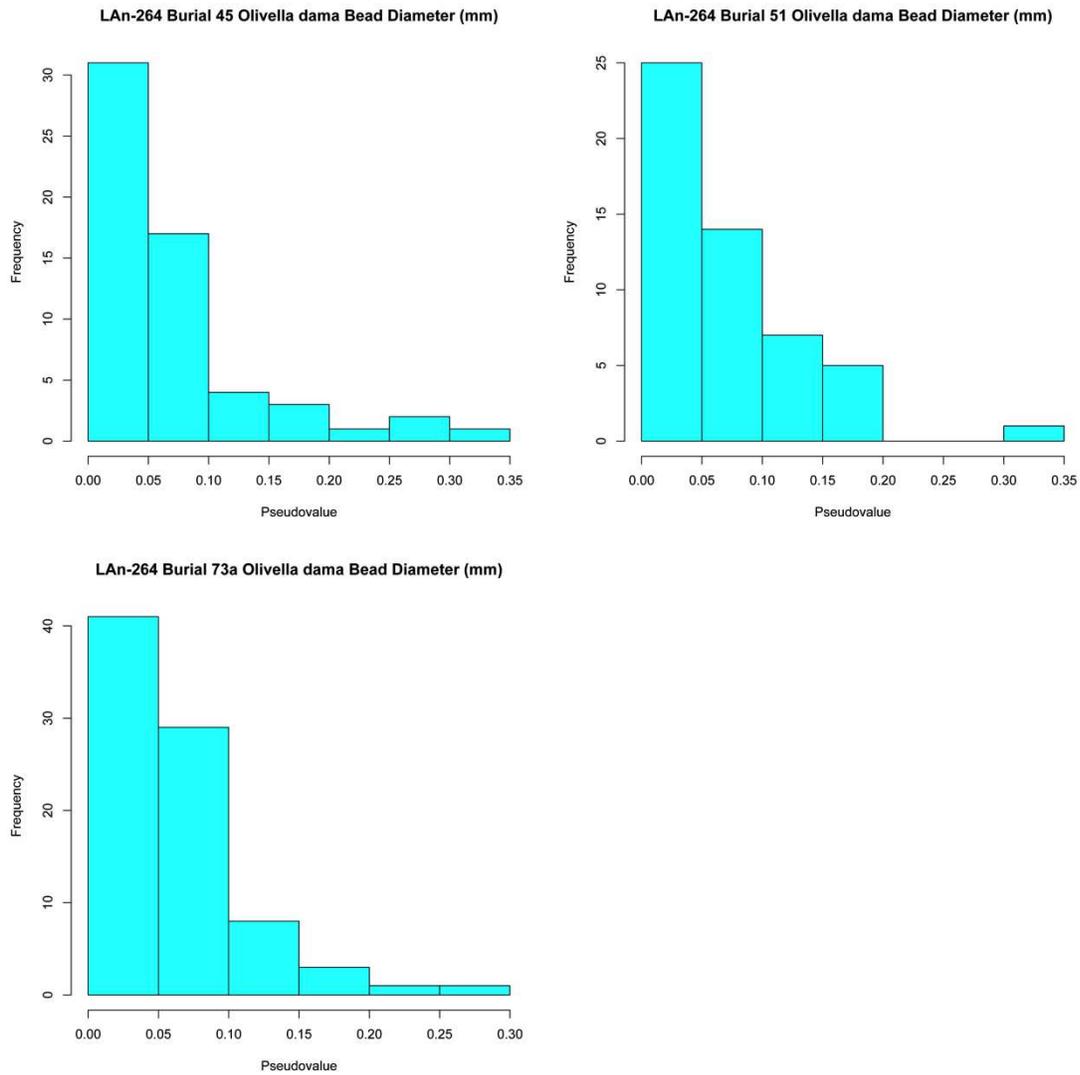


Figure N.4. *Olivella dama* barrel bead diameter CV jackknife histograms.



APPENDIX O

BOSCHLOO'S AND BARNARD'S EXACT TEST

I used the R Exact package and the following code for Boschloo's exact test.

```
#LAn-264 B35 vs. B48
```

```
data<-matrix(c(7,950,0,142),2,2,byrow=TRUE)
```

```
#LAn-264 B48 vs. B68
```

```
data<-matrix(c(0,142,14,39),2,2,byrow=TRUE)
```

```
#LAn-264 B68 vs. B51
```

```
data<-matrix(c(14,39,240,37),2,2,byrow=TRUE)
```

```
#LAn-264 B51 vs B73a
```

```
data<-matrix(c(240,37,200,17),2,2,byrow=TRUE)
```

```
#LAn-264 B73a vs. B45
```

```
data<-matrix(c(200,17,301,513),2,2,byrow=TRUE)
```

```
#LAn-264 B45 vs. B43
```

```
data<-matrix(c(301,513,3,2397),2,2,byrow=TRUE)
```

```
#LAn-264 B43 vs. B61
```

```
data<-matrix(c(3,2397,2,166),2,2,byrow=TRUE)
```

```
#LAn-264 B61 vs. B64
```

```
data<-matrix(c(2,166,1,278),2,2,byrow=TRUE)
```

```
#LAn-264 B64 vs. B10
```

```
data<-matrix(c(1,278,0,279),2,2,byrow=TRUE)
```

```
exact.test(data,alternative="two.sided",interval=FALSE,beta=0.001,npNumbers=100,method="Boschloo",to.plot=TRUE)
```

Barnard's exact test is appropriate for analyzing 2 x 2 contingency tables consisting of very small samples. This test is virtually unknown in the social sciences and is often more powerful for analyzing 2 x 2 contingency tables (see below) than the well-known Fisher's Exact Test. This test is computationally intensive and was performed using the MyBarnard Matlab function by Cardillo (2010), which is available at:

<http://www.mathworks.com/matlabcentral/fileexchange/25760-mybarnard>. Barnard's exact test can also be performed using the R Barnard and the R Exact packages which are less computationally efficient than the Cardillo program. I used the MyBarnard function.

### **Background and Overview of Test**

Barnard's test is an alternative to Fisher's exact test. It is generally more powerful (for 2x2 tables) than Fisher's test, but is also more computationally intensive. The test was first published by George Alfred Barnard (1945). Mehta and Senchaudhuri (2003:5) explain why Barnard's test is more powerful than Fisher's under certain conditions.

When comparing Fisher's and Barnard's exact tests, the loss of power due to the greater discreteness of the Fisher statistic is somewhat offset by the requirement that Barnard's exact test must maximize over all possible p-values, by choice of the nuisance parameter,  $\pi$ . For 2 x 2 tables the loss of power due to the discreteness dominates over the loss of power due to the maximization, resulting in greater power for Barnard's exact test. But as the number of rows and columns of the observed table increase, the maximizing factor will tend to dominate, and Fisher's exact test will achieve greater power than Barnard's.

APPENDIX P

DATA AND SAS CODE FOR ANALYSIS OF MEANS (ANOM) TEST

#SAS code for the ANOM analysis in Chapter 6

```
data OGAfton; input Location$ Bead_Diam;
```

```
datalines;
```

```
OGL5 4.2  
OGL5 4.2  
OGL5 4.2  
OGL5 4.3  
OGL5 4.4  
OGL5 4.4  
OGL5 4.4  
OGL5 4.4  
OGL5 4.5  
OGL5 4.5  
OGL5 4.5  
OGL5 4.5  
OGL5 4.6  
OGL5 4.6  
OGL5 4.6  
OGL5 4.7  
OGL5 4.8  
OGL5 4.8  
OGL5 4.8  
OGL5 4.8  
OGL5 4.9  
OGL5 4.9
```

OGL5 4.9  
OGL5 4.9  
OGL5 4.9  
OGL5 5.0  
OGL5 5.0  
OGL5 5.0  
OGL5 5.1  
OGL5 5.1  
OGL5 5.2  
OGL5 5.9  
OGL5 6.2  
OGL5 7.1  
OGL5 7.4  
OGL5 7.6  
OGL5 9.1  
Afton 4.3  
Afton 4.4  
Afton 4.6  
Afton 5  
Afton 5.2  
Afton 5.3  
Afton 5.4  
Afton 5.4  
Afton 6.2  
Afton 7.3  
Afton 7.3  
Afton 8.1  
;

title 'ANOM Chart for Olivella biplicata Disc Bead';

proc anom data=OGAfton;

xchart Bead\_Diam\*Location / alpha=.1 method=smm;

label Bead\_Diam = 'Diameter\_mm'

Location = 'Site';

run;

APPENDIX Q

DATA AND R CODE FOR FIGURE 7.1

#To install this package, start R and enter:

```
source("http://bioconductor.org/biocLite.R")
  biocLite("Rgraphviz")
```

```
library(Rgraphviz)
```

```
seq<-c(0,1,1,0,0,0,0,0,0,0,0,0,0,
1,0,1,0,0,0,0,0,0,0,0,0,0,
1,1,0,1,1,0,0,0,0,0,0,0,0,
0,0,1,0,1,0,0,0,0,0,0,0,0,
0,0,1,1,0,1,1,0,0,0,0,0,0,
0,0,0,0,1,0,1,1,0,0,0,0,0,
0,0,0,0,1,1,0,1,0,1,1,0,0,
0,0,0,0,0,1,1,0,1,1,0,0,0,
0,0,0,0,0,0,1,0,1,0,0,0,
0,0,0,0,0,1,1,1,0,1,1,1,
0,0,0,0,0,0,1,0,0,1,0,1,0,
0,0,0,0,0,0,0,0,1,1,0,1,
0,0,0,0,0,0,0,0,1,0,1,0)
```

```
HohokamCA.matrix<-matrix(seq,nrow=13,ncol=13,byrow=T)
```

```
rownames(HohokamCA.matrix)<-c("Santa Barbara Channel Chumash {1}", "Northern Channel
Island Chumash {2}", "Santa Monica Mountains Chumash {3}", "Southern Channel Island
Tongva {4}", "Mainland Tongva {5}", "Serrano {6}", "Hopic {7}", "Cahuilla {8}", "Kumeyaay
{9}", "Lowland Patayan {10}", "Upland Patayan {11}", "Salt River Hohokam {12}", "Gila
River Hohokam {13}")
```

```
colnames(HohokamCA.matrix)<-c("Santa Barbara Channel Chumash {1}", "Northern Channel
Island Chumash {2}", "Santa Monica Mountains Chumash {3}", "Southern Channel Island
Tongva {4}", "Mainland Tongva {5}", "Serrano {6}", "Hopic {7}", "Cahuilla {8}", "Kumeyaay
{9}", "Lowland Patayan {10}", "Upland Patayan {11}", "Salt River Hohokam {12}", "Gila
River Hohokam {13}")
```

```
am.graph<-new("graphAM", adjMat=HohokamCA.matrix, edgemode="undirected")
```

```
plot(am.graph, attrs = list(node = list(shape="plaintext", fillcolor = "white",
fontSize=80)))
```

APPENDIX R

DATA AND R CODE FOR COMPUTING THE WALKTRAP COMMUNITIES OF THE  
RECONSTRUCTED HOHOKAM/CALIFORNIA TRANSREGIONAL NETWORK

Raw data (UCINET DL file, which defines the adjacency matrix used to compute the Walktrap Communities, and plot the Walktrap Community dendrogram and colored graph of the reconstructed Hohokam/California transregional network. Copy and paste the following text to Notepad in MS Windows or TextEdit in Mac OSX. In TextEdit also do: Format -> Make Plain Text. In Notepad save as: PanRegNet.dat (with the settings in the bottom of the Notepad: All Type, and Encoding: ANSI) and in TextEdit save as the same file name (but uncheck the box net to: if no extension is provided, use “.txt”).

```
DL N = 13
Data:
0 1 1 0 0 0 0 0 0 0 0 0 0
1 0 1 0 0 0 0 0 0 0 0 0 0
1 1 0 1 1 0 0 0 0 0 0 0 0
0 0 1 0 1 0 0 0 0 0 0 0 0
0 0 1 1 0 1 1 0 0 0 0 0 0
0 0 0 0 1 0 1 1 0 0 0 0 0
0 0 0 0 1 1 0 1 0 1 1 0 0
0 0 0 0 0 1 1 0 1 1 0 0 0
0 0 0 0 0 0 0 1 0 1 0 0 0
0 0 0 0 0 0 1 1 1 0 1 1 1
0 0 0 0 0 0 1 0 0 1 0 1 0
0 0 0 0 0 0 0 0 0 1 1 0 1
0 0 0 0 0 0 0 0 0 1 0 1 0
```

install R package igraph and change directory (File → Change Dir...) to where the raw data file PanRegNet.dat is located.

R script for walktrap community analysis

```
library(igraph)
```

```
G<-read.graph("PanRegNet.dat", format = c("dl")) #raw data input
```

```

wt <- walktrap.community(G, steps = 4, merges = TRUE, modularity=TRUE,
membership=TRUE) # computes Walktrap Communities with modularity and default
membership
dend <- as.dendrogram(wt, use.modularity=TRUE) # computes Walktrap Community
dendrogram
#Output from typing dend in R command window: 'dendrogram' with 2 branches and 13 #
members total, at height 2.190476
plot(dend, nodePar=list(pch=c(NA, 20))) # plots Walktrap Community dendrogram
wmemb <- community.to.membership(G, wt$merges,steps=which.max(wt$modularity)-1) #
determines Walktrap Community membership corresponding to the maximum (optimal)
modularity.
a <- wmemb$membership
G$layout <- layout.kamada.kawai # use force-based Kamada-Kawai 2D graph drawing
algorithm
V(G)$color <- rainbow(3)[a+1] # the nodes of the network graph for each Walktrap community
are assigned a unique color.
plot(G)

```

To orient the graph (G) interactively (which in my case was to rotate the graph to a reasonable geographic orientation), use the following R script, provided in the igraph package. In a Mac, a new interactive plot of the graph will appear in an X window (I used XQuartz, which is available at: <http://xquartz.macosforge.org/landing/>).

tkplot(G) #check orientation of G in the X window, which you will need to estimate the number of degrees to rotate the graph.

```
id <- tkplot(G)
```

```
tkplot.rotate(id,225) # For example, this command rotates the graph 225 degrees clockwise.
```

```
tkplot.center(id) #this command centers the graph in the X window after it is rotated.
```

From the X window I exported the network as a postscript file, and re-opened it with the with the generic Mac picture file viewer, from which I saved the file as a .jpeg (maximum quality).

#Sequence of merges (merge matrix) of pairs of communities by the walktrap community algorithm (see Chapter 4, Figure 4.2).

```
wt$merges
```

```
      [,1] [,2]
[1,]   1   2
[2,]  12  13
[3,]  10  11
[4,]   7   8
[5,]   9  16
[6,]   6  17
[7,]   3   4
[8,]  15  18
[9,]   5  20
[10,]  19  21
[11,]  14  22
[12,]  23  24
```

#Modularity scores. Note that in the following the first merge step has a score of # -  
0.04535148 and the eleventh merge step has the maximal score of 0.34920639.

```
wt$modularity
```

```
[1] 0.00000000 -0.04535148 -0.00453515 0.02267573 0.04761904 0.07482994 0.13945578
0.17800452 0.25850341 0.32653061 0.29931974 0.34920639 0.00000000
```

```
#Walktrap algorithm summary output.
```

```
wt
```

```
Graph community structure calculated with the walktrap algorithm
```

```
Number of communities (best split): 2
```

```
Modularity (best split): 0.3492064
```

```
Membership vector:
```

```
[1] 1 1 1 1 1 2 2 2 2 2 2 2 2
```

```
length(wt)
```

```
[1] 2          # two communities detected
```

```
sizes(wt)
```

```
Community sizes
```

```
1 2
```

```
5 8
```

```
#Which means, Community 1 has five members and Community 2 has 8 members.
```

```
#Determine approximate sampling distribution of walktrap community modularity for Erdős-
#Rényi G(13,21) random graph and compare to walktrap community modularity of actual
#network model. Compute approximate p-value that observed modularity would likely occur by
#chance.
```

```

library(igraph)

G<-read.graph("PanRegNet.dat", format = c("dl"))

wt_2 <- walktrap.community(G, steps = 4, merges = TRUE, modularity=TRUE,
membership=TRUE)

N<-10000

(sum1 <- rep(0, N))

for(i in 1:N) {
  g <- erdos.renyi.game(13, 21, type="gnm")

  wt <- walktrap.community(g, steps = 4, merges = TRUE, modularity=TRUE,
membership=TRUE)

  sum1[i] <- max(wt$modularity)
}

hist(sum1, breaks=16, col = 4, border = terrain.colors(1), xlab = "Modularity", main="Walktrap
Community")

abline(v = max(wt_2$modularity), col=2, lty=2)

sum2<-0

for(i in 1:N) {
  if (max(wt_2$modularity)<=sum1[i]) sum2 <-sum2+1
}

p_value_1 <-sum2/N

```

## APPENDIX S

DATA AND R CODE FOR ERDŐS- RÉNYI RANDOM GRAPH ANALYSIS PART I:

TRANSITIVITY AND AVERAGE PATH LENGTH

```
DL N = 13
```

```
Data:
```

```
0 1 1 0 0 0 0 0 0 0 0 0 0 0
1 0 1 0 0 0 0 0 0 0 0 0 0 0
1 1 0 1 1 0 0 0 0 0 0 0 0 0
0 0 1 0 1 0 0 0 0 0 0 0 0 0
0 0 1 1 0 1 1 0 0 0 0 0 0 0
0 0 0 0 1 0 1 1 0 0 0 0 0 0
0 0 0 0 1 1 0 1 0 1 1 0 0 0
0 0 0 0 0 1 1 0 1 1 0 0 0 0
0 0 0 0 0 0 1 0 1 0 0 0 0 0
0 0 0 0 0 0 1 1 1 0 1 1 1 1
0 0 0 0 0 0 1 0 0 1 0 1 0 1
0 0 0 0 0 0 0 0 0 1 1 0 1 1
0 0 0 0 0 0 0 0 0 1 0 1 0 1
```

```
library(igraph)
```

```
G<-read.graph("PanRegNet.dat", format = c("dl"))
```

```
G2<-as.undirected(G)
```

```
N<-10000
```

```
(sum1 <- rep(0, N))
```

```
(sum2 <- rep(0,N))
```

```
for(i in 1:N) {
```

```
  g <- erdos.renyi.game(13, 21, type="gnm")
```

```
  sum1[i] <- average.path.length(g)+sum1[i]
```

```
  sum2[i] <-transitivity(g, type="average")+sum2[i]
```

```
}
```

```
sum3<-0
```

```
sum4<-0
```

```
for(i in 1:N) {
```

```
  if (average.path.length(G2)<=sum1[i]) sum3 <-sum3+1
```

```
}
```

```
for(i in 1:N) {
```

```
  if (transitivity(G2, type="average")<=sum2[i]) sum4 <-sum4+1
```

```
}  
  
p_value_1 <-sum3/N  
  
p_value_2 <-sum4/N  
  
hist(sum1, breaks=16, col = 4, border = terrain.colors(1), xlab = "Average Path Length", main =  
"Erdos and Renyi Random Graph (13 Nodes, 21 Edges)")  
  
abline(v = average.path.length(G2), col=2, lty=2)  
  
hist(sum2, breaks=16, col = 4, border = terrain.colors(1), xlab = "Transitivity", main = "Erdos  
and Renyi Random Graph (13 Nodes, 21 Edges)")  
  
abline(v = transitivity(G2, type="average"), col=2, lty=2)
```

## APPENDIX T

### DATA AND MATLAB CODE USED IN KRIGING ANALYSES

The Matlab function wgsutm.m was used to convert WGS84 coordinates (Latitude,Longitude) for each of the following sites into UTM coordinates. All coordinates were forced into the same UTM zone and hemisphere (11S), for analysis using this function (Table T.1).

Matlab script used to generate the forced UTM coordinates in Table.

```
Lat=[ 35.043627 34.640669 32.738964 34.03897 32.755761 32.948094 33.611708 32.99869
33.187047 33.428864];
```

```
Lon=[-116.285902 -117.340629 -116.147392 -118.677229 -111.5549251 -112.717072 -
117.835807 -111.514665 -111.919597 -112.065064];
```

```
[x2,y2,utmzone2,utmhemi2] = wgs2utm(Lat,Lon,11,'N')
```

Table T.1. UTM coordinates for California and Arizona sites used in the kriging analysis.

Site	Easting (Forced Zone 11N)	Northing (Forced Zone 11N)
Afton Canyon	565100	3878000
Oro Grande	468800	3833000
Indian Hill Rockshelter	579800	3623000
Malibu (LAn-264)	345200	3768000
Oatman Flat	1010400	3637000
Escuela	900500	3654000
ORA-225	422500	3719000
Grewe	1012700	3664500
Snaketown	973800	3683500
Las Colinas	959000	3709700

Table T.2. Van Bergin Grewe Site Gulf of California shell. Source: Curated collection currently at the Los Angeles County Museum of Natural History, Los Angeles, California.

Number/Location	<i>Glycymeris</i> bracelet fragment	<i>Laevicardium elatum</i> fragment	<i>Argopecten</i> <i>ventricosus</i>	Total
A.4431-113 Site II No Provenience	1		258	259
A.4431-114 Site II No Provenience			34	34
A.4431-118 Site II No Provenience		1	382	383
A.4431-120 Site II No Provenience	109			109
A.4431-121 Site II	74		54	128
A.4431-144 Site II No Provenience			1	1
A.4431-1850 Site II House 2-J-3	2			2
A.4431-1851 Site II (#4)	3			3
A.4431-1855 Site II	1			1
A.4431-44	1			1
Total	190	1	729	921

Table T.3 Van Bergin Grewe Site Gulf of California shell. Source: Curated collection currently at the Los Angeles County Museum of Natural History, Los Angeles, California.

Number/Location	<i>Glycymeris</i> bracelet fragment	<i>Laevicardium elatum</i> fragment	Total
A.4431-1834 Site II Fill (#28)	2	1	3
A.4431-124 Site II (203/22)		48	48
A.4431-125 Site II	13	335	348
A.4431-1843 Cremation Area 3 (#14)	1		1
Total	16	384	400

Table T.4 Van Bergin Grewe Site Gulf of California shell. Source: Curated collection currently at the Los Angeles County Museum of Natural History, Los Angeles, California.

Number/Location	<i>Turitella</i> leucostoma	<i>Turitella</i> lentiginosa	<i>Columbella</i> sp.	<i>Conus</i> sp.	Total
A.4431-144 Site II No Provenience	1	1	1	1	4
Total	1	1	1	1	4

Table T.5 Van Bergin Grewe Site Gulf of California shell. Source: Curated collection currently at the Los Angeles County Museum of Natural History, Los Angeles, California.

Number/Location	<i>Callinax (Olivella) dama</i> Spire-ground bead	<i>Oliva spicata</i> (probable species identification)	<i>Crassadoma gigantea</i>	Total
A.4431-54	7			7
A.4431-1857 Site II #28		1		1
A.4431-1832 Site II No Provenience			1	1
Total	7	1	1	9

Table T.6. Table T.4 Van Bergin Grewe Site Gulf of California shell. Source: Curated collection currently at the Los Angeles County Museum of Natural History, Los Angeles, California.

Number/Location	<i>Callinax (Olivella) biplicata</i> "Barrel" Bead	<i>Callinax (Olivella) biplicata</i> Spire-Ground Bead	<i>Haliotis</i> sp. worked	Total
A.4431-125 Site II			5	5
A.4431-1830	763	266		1029
Total	763	266	5	1034

Table T.7. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation.

House/Phase	<i>Glycymeris</i> sp.	<i>Laevicardium</i> <i>elatum</i>	<i>Pecten</i> sp.	<i>Olivella</i> <i>dama</i>	<i>Turitella</i> sp.	Total
5F:7 Sacaton	67	3				70
5G:1 Sacaton	14	6				20
5G:10 Sacaton	27	2		1		30
5G:2 Sacaton	24	1	1		1	27
5G:4 Sacaton	4					4
5G:12 Sacaton	4					4
6G:1 Sacaton	58	3				61
6G:2 Santa Cruz	10	1				11
6G:3 Sacaton	23	28				51
Total	231	44	1	1	1	278

Table T.8. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation.

House/Phase	<i>Glycymeris</i> sp.	<i>Laevicardium</i> <i>elatum</i>	<i>Olivella</i> sp.	<i>Cowrie</i> sp.	<i>Pecten</i> sp.	Total
8B:1 Sacaton	55		1	1		57
8E:16 Santa Cruz	2	1				3
8F:4 Sacaton	1	1				2
8F:5 Sacaton	9	3				12
9E:7 Santa Cruz	2					2
9E:9 Santa Cruz	2		1			3
9F:3 Sacaton	7	1				8
9F:4 Sacaton	5					5
9F:10 Sacaton	4	2				6
9G:2 Santa Cruz	2				1	3
9G:3 Sacaton	10					10
Total	99	8	2	1	1	111

Table T.9. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation.

House/Phase	<i>Glycymeris</i> sp.	<i>Laevicardium elatum</i>	<i>Spondylus</i> sp.	Total
10D:3 Sacaton	6			6
10D:4 Santa Cruz	14	1		15
10F:1 Sacaton		1		1
10F:2_Complex Sacaton	1			1
10F:4 Sacaton	1			1
10F:5 Sacaton	3			3
10F:6 Sacaton			1	1
10F:8 Sacaton	22	3		25
10F:11 Sacaton	1			1
Total	48	5	1	54

Table T.10. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation. (cont.).

House/Phase	<i>Glycymeris</i> sp.	<i>Laevicardium</i> <i>elatum</i>	<i>Pecten</i> sp.	<i>Olivella</i> sp.	<i>Spondylus</i> sp.	Total
10F:12 Sacaton	5					5
10F:18-Complex Sacaton	4					4
10F:22 Sacaton				1		1
10F:23 Sacaton	7	1				8
10G:3 Sacaton					1	1
10G:4 Sacaton	2		1			3
10G:7 Santa Cruz	4					4
10G:8 Sacaton	7	2				9
Total	29	3	1	1	1	35

Table T.11. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation.

House/Phase	<i>Glycymeris</i> sp	<i>Laevicardium</i> <i>elatum</i>	<i>Pecten</i> sp.	<i>Olivella</i> sp.	<i>Cerithidea</i> sp.	Tota
10G:13 Sacaton	6	1				7
10G:15 Santa Cruz	9		1			10
10I:1 Sacaton	41	2				43
10I:2 Sacaton	4					4
10I:3 Sacaton	2	3		3		8
10J:1 Sacaton	1	2	1			4
10J:2 Sacaton		4	1			5
10J:3 Sacaton	2	5			2	9
10J:9 Sacaton	3					3
11F:1 Sacaton	1 (bilobed bead)					1
11F:5 Sacaton	12	3		2		17
11F:10	1					1
Total	82	20	3	5	2	112

Table T.12. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation.

House/Phase	<i>Glycymeris</i> sp.	<i>Laevicardium elatum</i>	<i>Argopecten</i> sp.	<i>Olivella</i> sp.	Total
11F:14 Sacaton	11	2			13
11H:1 Late Santa Cruz		1	1	1	3
11I:3 Sacaton	3				3
11J:2 Sacaton	23	2			25
Total	37	5	1	1	44

Table T.13. Snaketown data used in kriging analysis. Source: Snaketown shell data from Seymour 1990:797-976, Appendix E (House and floor fill artifacts), 1964-1965 excavation.

House/Phase	<i>Haliotis rufescens</i>	<i>Haliotis</i> sp.	Total
5G:1 Sacaton	1		
9E:9 Santa Cruz		2	
10F:21 Sacaton		1	
Total	1	3	4

Table T.14. Las Colinas Pre-Classic Gulf of California shell. Source: Vokes 1988:321, Table 9.1.

Type(s)	Count
<i>Glycymeris gigantea, maculata, multicosata</i>	1426
<i>Laevicardium elatum</i>	1116
<i>Argopecten circularis</i>	54
<i>Pecten vogdesi</i>	40
<i>Dosinia ponderosa</i>	2
<i>Spondylus/Chama</i>	2
<i>Olivella dama</i>	88
<i>Conus perplexis, regularis</i>	30
<i>Turritella gonostoma, leucostoma</i>	6
<i>Cerithidea albonodosa, mazatlanica</i>	6
<i>Columbella strombiformis, fuscata</i>	5
<i>Nassarius moestus</i>	3
<i>Crucibulum</i>	2

<i>Theodoxus luteofasciatus</i>	2
<i>Oliva incrassata</i>	1
<i>Opalia</i>	1
<i>Morula lugubris</i>	1
Total	2785

Table T.15. Las Colinas Pre-Classic Pacific Coast shell. Source: Vokes 1988:321, Table 9.1.

Type(s)	Count
<i>Haliotis cracherodii, rufescens</i>	15
<i>Dentalium</i> sp.	1
Total	16

Table T.16. Raw shell count data (with context) used in kriging analysis.

Site	Context	Pacific Coast Shell	Gulf of California Shell
Afton Canyon	Residential	14	1
Oro Grande	Residential	72	8
Indian Hill Rockshelter	Residential	1	5
Malibu (LAn-264)	Cemetery	3092	782
Oatman Flat	Burial	5	24
Escuela	Burial	83	32
ORA-225	Residential	44	4
Grewe	Burial/Residential	1034	1334
Snaketown	Residential	4	634
Las Colinas	Residential/Burial	16	2787

**Matlab .m files, script and raw data used in kriging analyses.**

%Need the following matlab functions (.m files) from the Mathworks Exchange

%consolidator.m

%fminsearchbnd.m

%kriging.m (Ordinary Kriging by Wolfgang Schwanghart)

%parseargs.m

%variogram.m

%variogramfit.m

%must open the above files (file->open)

%and then

%publish them (file-> publish filename.m)

%before the following will work

% Ratio of total number of Gulf of California Shell artifacts in each of the ten assemblages

% divided by the total shell sample size (PC Shell + GofC Shell) for the corresponding

%assemblage ( $0 < z < 1$ )

%Raw data for kriging analysis

```
S=[56.51 387.81; 46.88 383.32; 57.99 362.27; 34.52 376.77; 101.04 363.74; 90.05 365.37; 42.25  
371.94; 101.27 366.45; 97.38 368.35; 95.9 370.97];  
r1=1/15; r2=8/80; r3=5/6; r4=782/3874; r5=24/29; r6=32/115; r7=4/48; r8=1334/2368;  
r9=634/638; r10=2785/2801;  
z = [r1 r2 r3 r4 r5 r6 r7 r8 r9 r10];
```

%Matlab script used to perform kriging analysis.

```
x = S(:,1);  
y = S(:,2);  
z = transpose(z);  
[X,Y] = meshgrid(20:120,340:400);
```

% X is a 61-by-101 matrix, with the first column all 20's, with each subsequent column consisting of values of the previous column + 1 (so, for example, the second column is all 21's) up to 120's for the last (101<sup>st</sup>) column.

%Y is also a 61-by-101 matrix, with the same structure as X, accept the first column is all 340, and the final column is all 400.

%Calculates 3D random field contour plots with site locations plotted

%Create random field with autocorrelation and scaled to [0,1]

Z = randn(size(X)); % returns an m-by-n matrix containing pseudorandom values drawn from the standard normal distribution, with an array the same size as X, which is 61-by-101.

```
Z = imfilter(Z,fspecial('gaussian',[40 40],8));
```

```

%imfilter(Z,h) filters the multidimensional array Z
%with the multidimensional filter h = fspecial('gaussian',[40 40],8). The result Z (or Z filtered)
%has the same size and class as the original Z (or Z unfiltered). In this case, h returns a
%rotationally symmetric Gaussian lowpass filter of size hsize = [40 40] with standard deviation
%= 8.

ZmaxCol = max(Z,[],1);
ZmaxColT = transpose(ZmaxCol);
MaxZ = max(ZmaxColT) %maximum value in array Z
ZminCol = min(Z,[],1);
ZminColT = transpose(ZminCol);
MinZ = min(ZminColT) %minimum value in array Z
j = 61;
k = 101;
Zstand = zeros(j,k);    % Preallocate matrix
for m = 1:j
    for n = 1:k
        Zstand(m,n) = (Z(m,n) - MinZ)/(MaxZ - MinZ); %Scales the values of Zstand to [0,1]
    end
end
Zp = Zstand; % 61-by-101 array of normally distributed and autocorrelated pseudorandom
numbers between 0 and 1
contour3(X(1,:),Y(:,1),Zp,100)
view(-15,25)
hold on;
plot(x,y,'k','MarkerSize',25)
for i = 1:length(z)
    zp = 0:0.01:z(i);
    plot3(x(i),y(i),zp, 'k','MarkerSize',4.5)
    plot3(x(i),y(i),z(i),'^k','LineWidth',2)
end
title('One Hundred Contour Random Field with Site Locations')
xlabel('Easting/10000')
ylabel('Northing/10000')
zlabel('Filtered and Scaled Normally Distributed Pseudorandom Numbers','FontSize',8)

```

```

% 3D kriging prediction plot

v = variogram([x y],z,'plotit',false,'maxdist',75);
[dum,dum,dum,vstruct] = variogramfit(v.distance,v.val,[],[],[],'model','stable');
[Zhat,Zvar] = kriging(vstruct,x,y,z,X,Y);
contour3(X(1,:),Y(:,1),Zhat,100)
zlim([0 1.1])
view(-5,25) % view(-175,15)
hold on;
plot(x,y,'k','MarkerSize',25)
for i = 1:length(z)
zp = 0:0.01:z(i);
plot3(x(i),y(i),zp, 'k','MarkerSize',4.5)
plot3(x(i),y(i),z(i),'^k','LineWidth',2)
end
title('One Hundred Contours of the Kriging Predictions')
xlabel('Easting/10000')
ylabel('Northing/10000')
zlabel('G of C Shell/(PC Shell + G of C Shell)')

```

APPENDIX U

FOURIER ANALYSIS OF RECONSTRUCTED STREAMFLOW DATA

```
%Fourier analysis of reconstructed streamflow data. Required for both the Salt and Gila River
%analyses.
```

```
year=x(:,1);
relNums=x(:,2);
Y = fft(relNums);
Y(1)=[];
n=length(Y);
power = abs(Y(1:floor(n/2))).^2;
nyquist = 1/2;
freq = (1:n/2)/(n/2)*nyquist;
period=1./freq;
plot(period,power);
axis([0 100 0 max(power)+30]);
ylabel('Power');
xlabel('Period (Years/Cycle)');
```

```
%Label four strongest signals (with the corresponding period for each) in the plot of the Fourier
%analysis of the reconstructed Salt River streamflow data.
```

```
hold on;
index=find(power==max(power));
mainPeriodStr=num2str(period(index));
plot(period(index),power(index),'r.', 'MarkerSize',25);
text(period(index)+2,power(index),['Period = ',mainPeriodStr]);
A=power;
[~, idx] = sort(A,'descend');
mainPeriodStr2=num2str(period(idx(2)));
plot(period(idx(2)),A(idx(2)),'g.', 'MarkerSize',25);
text(period(idx(2))+2,A(idx(2)),['Period = ',mainPeriodStr2]);
mainPeriodStr3=num2str(period(idx(3)));
plot(period(idx(3)),A(idx(3)),'m.', 'MarkerSize',25);
text(period(idx(3))+2,A(idx(3))-10,['Period = ',mainPeriodStr3]);
mainPeriodStr4=num2str(period(idx(4)));
plot(period(idx(4)),A(idx(4)),'c.', 'MarkerSize',25);
text(period(idx(4))+2,A(idx(4)),['Period = ',mainPeriodStr4]);
hold off;
title('Salt River (A.D. 850-1100)')
```

```

%Plot of reconstructed Salt River streamflow with the strongest cycle detected by the Fourier
%analysis for A.D. 850-1000.
B=relNums;
[~, idx] = sort(B,'descend');
plot(year,relNums)
title('Salt River')
xlabel('A.D.')
ylabel('Streamflow (million acre feet/year)')
xstart=year(idx(1));
ystart=0;
height=max(relNums);
line([xstart xstart],[ystart ystart+height],'Color','r');
A=power;
[~, idx] = sort(A,'descend');
hold on;
range=floor((1100-900)/period(idx(1)));
for i = 1:range
    x = xstart+i*period(idx(1));
    line([x x],[ystart ystart+height],'Color','r');
end
hold off;

```

```
%Plot of reconstructed Salt River streamflow with the second strongest cycle detected by the  
%Fourier analysis for A.D. 850-1000.
```

```
B=relNums;  
[~, idx] = sort(B,'descend');  
plot(year,relNums)  
title('Salt River')  
xlabel('A.D.')  
ylabel('Streamflow (million acre feet/year)')  
xstart=year(idx(1));  
ystart=0;  
height=max(relNums);  
line([xstart xstart],[ystart ystart+height],'Color','r');  
A=power;  
[~, idx] = sort(A,'descend');  
hold on;  
range=floor((1100-900)/period(idx(2)));  
for i = 1:range  
    x = xstart+i*period(idx(2));  
    line([x x],[ystart ystart+height],'Color','r');  
end  
hold off;
```

```
%Label four strongest signals (with the corresponding period for each) in the plot of the Fourier
%analysis of the reconstructed Gila River streamflow data.
```

```
hold on;
index=find(power==max(power));
mainPeriodStr=num2str(period(index));
plot(period(index),power(index),'r.', 'MarkerSize',25);
text(period(index)+2,power(index),['Period = ',mainPeriodStr]);
A=power;
[~, idx] = sort(A,'descend');
mainPeriodStr2=num2str(period(idx(2)));
plot(period(idx(2)),A(idx(2)), 'g.', 'MarkerSize',25);
text(period(idx(2))+2,A(idx(2))+4,['Period = ',mainPeriodStr2]);
mainPeriodStr3=num2str(period(idx(3)));
plot(period(idx(3)),A(idx(3)), 'm.', 'MarkerSize',25);
text(period(idx(3))+2,A(idx(3))+2,['Period = ',mainPeriodStr3]);
mainPeriodStr4=num2str(period(idx(4)));
plot(period(idx(4)),A(idx(4)), 'c.', 'MarkerSize',25);
text(period(idx(4))+2,A(idx(4)),['Period = ',mainPeriodStr4]);
hold off;
title('Gila River (A.D. 850-1100)')
```

```
%Plot of reconstructed Gila River streamflow with the strongest cycle detected by the Fourier
%analysis for A.D. 850-1100.
```

```
B=relNums;
[~, idx] = sort(B,'descend');
plot(year,relNums)
title('Gila River')
xlabel('A.D.')
ylabel('Streamflow (million acre feet/year)')
xstart=year(idx(1));
ystart=0;
height=max(relNums);
line([xstart xstart],[ystart ystart+height],'Color','r');
A=power;
[~, idx] = sort(A,'descend');
hold on;
range=floor((1100-900)/period(idx(1)));
for i = 1:range
    x = xstart+i*period(idx(1));
    line([x x],[ystart ystart+height],'Color','r');
end
hold off;
```

```

%Plot of reconstructed Gila River streamflow with the second strongest cycle detected by the
%Fourier analysis for A.D. 850-1100.
B=relNums;
[~, idx] = sort(B,'descend');
plot(year,relNums)
title('Gila River')
xlabel('A.D.')
ylabel('Streamflow (million acre feet/year)')
xstart=year(idx(1));
ystart=0;
height=max(relNums);
line([xstart xstart],[ystart ystart+height],'Color','r');
A=power;
[~, idx] = sort(A,'descend');
hold on;
range=floor((1100-900)/period(idx(2)));
for i = 1:range
    x = xstart+i*period(idx(2));
    line([x x],[ystart ystart+height],'Color','r');
end
hold off;

```

APPENDIX V  
BIOECONOMIC MODEL  
XPPAUT CODE

#simple bioeconomic model with individual entry.

#define parameters-----

par a11=0.1,a12=0.1,a2=0.1,a3=0.1,A11=1,A12=1,A21=1,A22=1,AK=1,Ko=0.5

par S=1,h=1.5,dk=0.05,I=0.05,K=0.3,spow=10,Lmax=20,ypmin=1,ycmin=1,gamma=0.9

par alpha1=1,alpha2=1

par p1=50

par mu1=2,mu2=3

#-----

#define some hidden variables and functions-----

f(x,a,b) = if(x>0)then(x\*\*b/(a\*\*b + x\*\*b))else(0)  
g1(y2,x2) = if(y2<x2)then(1)else(0)  
g2(y3,x3,z3) = if(y3>x3)then(z3)else(0)  
g3(y4) = if(y4>0)then(y4)else(20)  
g4(y5,x5) = if(y5<x5)then(y5)else(x5)  
l2max = min(1/(A21\*x2\*K), 1/(A22\*x2\*K))  
svar = (A21/A11 + A22/A12)\*x2\*K/x1  
l2opt = l2max\*f(svar,1,spow)  
l11opt = (1 - A21\*x2\*l2opt\*K)/(A11\*x1)  
l12opt = (1 - A22\*x2\*l2opt\*K)/(A12\*x1)  
l2 = min(l2opt, gamma\*Lmax)  
l11 = min(l11opt, gamma\*Lmax-l2)  
l12 = min(l12opt, gamma\*Lmax-l2-l11)  
l12eval1 = l12-g1(yp\_local,ypmin)\*g2(yc\_local,ycmin,delta\_12)  
l12eval2 = g3(l12eval1)  
l12t = g4(l12, l12eval2)  
l3\_r = gamma\*Lmax-(l11 + l12t + l2)  
l3 = min(abs(delta\_12)\*g1(yp\_local,ypmin),l3\_r)  
Y11 = A11\*x1\*l11\*h  
Y12 = A12\*x1\*l12t\*h  
Y2 = (A21+A22)\*x2\*l2\*h\*K  
Y21 = A21\*x2\*l2\*h\*K  
Y22 = A22\*x2\*l2\*h\*K  
Y3 = A3\*l3\*x3\*h  
delta\_12 = (yc\_local - ycmin)/(A12\*x1)

```

Klc = Ko*(1 + alpha2*u)
yc_local = A12*x1*l12t
yp_local = A11*x1*l11
yc_a = A22*x2*l2*K
yp_a = A21*x2*l2*K
LCpro = A3*x3*l3
LCpt = x3*l3
totl = l11+l12t+l2+l3
r1=1
r2=1
r3=1
Klc2 = (mu1 + alpha1*u)/mu2

#define auxiliary quantities-----

#define right hand sides-----

dx1/dt = r1*x1*(1-x1) - a11*Y11 - a12*Y12
dx2/dt = r2*x2*(1-x2) - a2*Y2
#dh/dt = b(Y1,Y2) - d(Y1,Y2)
#dK/dt = AK*l2-dK*K
dx3/dt = r3*x3*(1-x3/Klc2)-a3*Y3
du/dt = u*(1 - u^2 - v^2) - (2*Pi/p1)*v
dv/dt = v*(1 - u^2 - v^2) + (2*Pi/p1)*u

#set initial conditions

init x1=1,x2=1,x3=1,u=1,v=0

#define some auxiliary variables
aux totlab = l2+l11+l12t
aux totlab_t = l2+l11+l12t+l3
aux lwp = l11
aux lwc = l12t
aux la = l2
aux lw = l11+l12t
aux switch = svar
aux tot1out = Y11+Y21
aux tot2out = Y12+Y22
aux tot12out = Y11+Y21+Y12+Y22
aux LCtradeout = Y3
aux LCF = Klc

```

```
aux LCF2 = KLc2
aux ltrade = l3
aux ltrader = l3_r
aux yp = yp_local
aux yc = yc_local
aux yca = yc_a
aux ypa = yp_a
aux yp_w_a = yp_local+yp_a
aux yc_w_a = yc_local+yc_a
aux yp_t = yp_local+LCpro+yp_a
aux lcp = LCpro
aux delta12 = l12-l12t
aux delta_p = abs(yp_local-LCpro)
aux delta_12out = delta_12
aux delta_yc = yc_local-ycmin
```

```
#-----
```

```
@ xlo=0,ylo=0,zlo=0,xhi=1.1,yhi=1.1,zhi=1.1
@ xp=x1,yp=x2,zp=x3
@ ulo=0,vlo=0,uhi=1,vhi=1
@ up=u,vp=v
@ bounds=100000
```

```
done
```

APPENDIX W

DATA AND R CODE FOR ERDŐS- RÉNYI RANDOM GRAPH ANALYSIS PART II:

MOTIFS

```
DL N = 13
```

```
Data:
```

```
0 1 1 0 0 0 0 0 0 0 0 0 0 0
1 0 1 0 0 0 0 0 0 0 0 0 0 0
1 1 0 1 1 0 0 0 0 0 0 0 0 0
0 0 1 0 1 0 0 0 0 0 0 0 0 0
0 0 1 1 0 1 1 0 0 0 0 0 0 0
0 0 0 0 1 0 1 1 0 0 0 0 0 0
0 0 0 0 1 1 0 1 0 1 1 0 0 0
0 0 0 0 0 1 1 0 1 1 0 0 0 0
0 0 0 0 0 0 1 0 1 0 0 0 0 0
0 0 0 0 0 0 1 1 1 0 1 1 1 1
0 0 0 0 0 0 1 0 0 1 0 1 0 1
0 0 0 0 0 0 0 0 0 1 1 0 1 1
0 0 0 0 0 0 0 0 0 1 0 1 0 1
```

```
library(igraph)
library(R.utils)
```

```
G<-read.graph("PanRegNet.dat", format = c("dl"))
```

```
G2<-as.undirected(G)
```

```
#example of a three node motif in the Hohokam/California transregional network model
motif_3 <- graph.isocreate(size=3,number=3,directed=F)
#example of a four node motif in the Hohokam/California transregional network model
motif_4 <- graph.isocreate(size=4,number=4,directed=F)
plot(motif_3,main="Motif 3")
plot(motif_4,main="Motif 4")
```

```
N<-10000
```

```
(sum3 <- rep(0, N))
(sum4 <- rep(0,N))
```

```
for(i in 1:N) {
  g <- erdos.renyi.game(13, 21, type="gnm")
  mygraphmotifs <- graph.motifs(g,3)
  motif_3 <- mygraphmotifs[3]
  motif_4 <- mygraphmotifs[4]
  sum3[i] <- motif_3+sum3[i]
  sum4[i] <- motif_4+sum4[i]
```

```

}

subplots(nrow=1, ncol=2)

mygraphmotifs_2 <- graph.motifs(G2,3)

hist(sum3, breaks=16, col = 4, border = terrain.colors(1), xlab = "Number in Network",
main="Motif 3")

abline(v = mygraphmotifs_2[3], col=2, lty=2)

hist(sum4, breaks=16, col = 4, border = terrain.colors(1), xlab = "Number in Network",
main="Motif 4")

abline(v = mygraphmotifs_2[4], col=2, lty=2)

sum1<-0
sum2<-0

for(i in 1:N) {
  if (mygraphmotifs_2[3]>=sum3[i]) sum1 <-sum1+1
  if (mygraphmotifs_2[4]<=sum4[i]) sum2 <-sum2+1
}

p_value_3 <-sum1/N
p_value_4 <-sum2/N

```

## APPENDIX X

DATA AND R SCRIPT FOR ERDŐS- RÉNYI RANDOM GRAPH ANALYSIS PART III:

BETWEENNESS CENTRALITY

DL N = 13

Data:

```
0 1 1 0 0 0 0 0 0 0 0 0 0 0
1 0 1 0 0 0 0 0 0 0 0 0 0 0
1 1 0 1 1 0 0 0 0 0 0 0 0 0
0 0 1 0 1 0 0 0 0 0 0 0 0 0
0 0 1 1 0 1 1 0 0 0 0 0 0 0
0 0 0 0 1 0 1 1 0 0 0 0 0 0
0 0 0 0 1 1 0 1 0 1 1 0 0 0
0 0 0 0 0 1 1 0 1 1 0 0 0 0
0 0 0 0 0 0 1 0 1 0 0 0 0 0
0 0 0 0 0 0 1 1 1 0 1 1 1 0
0 0 0 0 0 0 1 0 0 1 0 1 0 0
0 0 0 0 0 0 0 0 0 1 1 0 1 0
0 0 0 0 0 0 0 0 0 1 0 1 0 0
```

```
library(igraph)
```

```
library(R.utils)
```

```
G<-read.graph("PanRegNet.dat", format = c("dl"))
```

```
G2<-as.undirected(G)
```

```
a<-betweenness(G2)
```

```
N<-10000
```

```
(sum3 <- rep(0, N))
```

```
(sum5 <- rep(0, N))
```

```
(sum7 <- rep(0, N))
```

```
(sum10 <- rep(0, N))
```

```
for(i in 1:N) {
```

```
  g <- erdos.renyi.game(13, 21, type="gnm")
```

```
  bc <- betweenness(g)
```

```
  sum3[i] <- bc[3]+sum3[i]
```

```
  sum5[i] <- bc[5]+sum5[i]
```

```
  sum7[i] <- bc[7]+sum7[i]
```

```
  sum10[i] <- bc[10]+sum10[i]
```

```
}
```

```

subplots(nrow=2, ncol=2)

hist(sum3, breaks=16, col = 4, border = terrain.colors(1), xlab = "Node Three",
main="Betweenness Centrality")

abline(v = a[3], col=2, lty=2)

hist(sum5, breaks=16, col = 4, border = terrain.colors(1), xlab = "Node Five",
main="Betweenness Centrality")

abline(v = a[5], col=2, lty=2)

hist(sum7, breaks=16, col = 4, border = terrain.colors(1), xlab = "Node Seven",
main="Betweenness Centrality")

abline(v = a[7], col=2, lty=2)

hist(sum10, breaks=16, col = 4, border = terrain.colors(1), xlab = "Node Ten",
main="Betweenness Centrality")

abline(v = a[10], col=2, lty=2)

sumA<-0
sumB<-0
sumC<-0
sumD<-0

for(i in 1:N) {
  if (a[3]<=sum3[i]) sumA <-sumA+1
  if (a[5]<=sum5[i]) sumB <-sumB+1

  if (a[7]<=sum7[i]) sumC <-sumC+1
  if (a[10]<=sum10[i]) sumD <-sumD+1
}

p_value_3 <-sumA/N
p_value_5 <-sumB/N
p_value_7 <-sumC/N
p_value_10 <-sumD/N

```

```

#Make plot and turn off axes and annotations (axis labels) to label them as desired

plot(a, type="o", col="blue", axes=F, ann=F)

#Calculate range from 0 to max value of a

g_range <- range(0, a)

#Make x axis using abbreviated regions and their corresponding numbers
axis(1, at=1:13,
lab=c("SBBC{1}", "NCIC{2}", "SMMC{3}", "SCIT{4}", "MT{5}", "SER{6}", "HOP{7}", "CAH{
8}", "KUM{9}", "LP{10}", "UP{11}", "GRH{12}", "SRH{13}"))

#Make y axis with horizontal labels that display ticks at
#every 4 marks. 4*0:g_range[2] is equivalent to c(0,4,8,12).
axis(2, las=1, at=4*0:g_range[2])

#Create box around plot
box()

#Label the x and y axes
title(xlab="Region")
title(ylab="Betweenness Centrality")

```