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Measurement of Significant Marine Paleotemperature Variation Using Black Abalone Shells from Prehistoric Middens

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The archaeological record from the last millennium in southern California indicates that a period of significant cultural change was associated with a reported marine paleoenvironmental disruption ca. 1150–1250 A.D. A lengthy warm-water anomaly may have in part precipitated more complex sociopolitical and economic responses. We develop independent verification of the perturbation (originally deduced from sediment core data) using archaeological data. Respiratory pore number allometry in the black abalone shell is known to vary clinally in modern populations in response to temperature-induced variation in rate of growth. We use developmental trajectories of abalone from dated, stratified archaeological deposits to reconstruct prehistoric seawater temperatures. ©1993 University of Washington.

INTRODUCTION

Recently recovered archaeological data from southern California indicate that important cultural developments were associated with a reported marine paleoenvironmental disruption ca. 1150–1250 A.D. Microfossils in marine sediment cores from the Santa Barbara Basin appear to document high Pacific water temperatures during this period (Pisias, 1978). Confirmation of this occurrence may be fundamental to understanding the path of increasing cultural complexity among the hunter–gatherer populations in the region (Arnold, 1991), so we developed a method to verify independently the perturbation with archaeologically derived materials. Because respiratory pore (trema) number allometry in the black abalone varies clinally in modern populations in response to temperature-induced variation in rate of growth, we were able to use developmental trajectories of abalone shells recovered from firmly dated archaeological sites on the Channel Islands to measure prehistoric seawater temperatures. The results confirm the occurrence of a warm-water period at this time and permit further inferences about prehistoric cultural change directly from radiocarbon-dated contexts. This new method is an effective complement to microfossil and oxygen isotope analyses for verifying paleotemperature variation from human-selected shell assemblages. The O^{18}–O^{16} method has not yet been applied by specialists to the black abalone shell, so comparative isotope date are not available. However, oxygen isotope analyses using mussel and possibly abalone are being developed for California, and we expect such studies will confirm the results presented here.

The greatest strength of our approach is its unambiguous association of dated abalone shells from *archaeological* contexts directly with paleotemperature information from the shells. Oceanic paleoenvironmental reconstructions from spatially separate sea-floor sediment samples are a source of more precisely datable, but more indirect, data for archaeologists to use. In this case, the new method can be used to verify observed sea-core trends independently.

ARCHAEOLOGICAL AND PALEOCLIMATIC CONTEXT

The Santa Barbara Channel region (Fig. 1) supported one of the most complex and populous hunter–gatherer cultures in the New World prior to European contact. To some extent, the unusual degree of cultural complexity among the Chumash peoples in this region was linked to the exceptional productivity of the cool, upwelling-dominated marine ecosystem. Food resources available to human populations included dozens of species of shellfish, seabirds, and marine mammals and one of the richest fisheries in the Pacific. In contrast, quite limited supplies of terrestrial resources could be obtained by the marine-dependent northern Channel Islanders. For these populations, lengthy or severe fluctuations in marine water temperatures that disrupted marine productivity could have precipitated important changes in subsistence, exchange, and related practices (Arnold, 1991, 1992). Marine perturbations may have stemmed from changes in oceanic currents, upwelling, or El Niño–Southern Oscillation (ENSO) phenomena.

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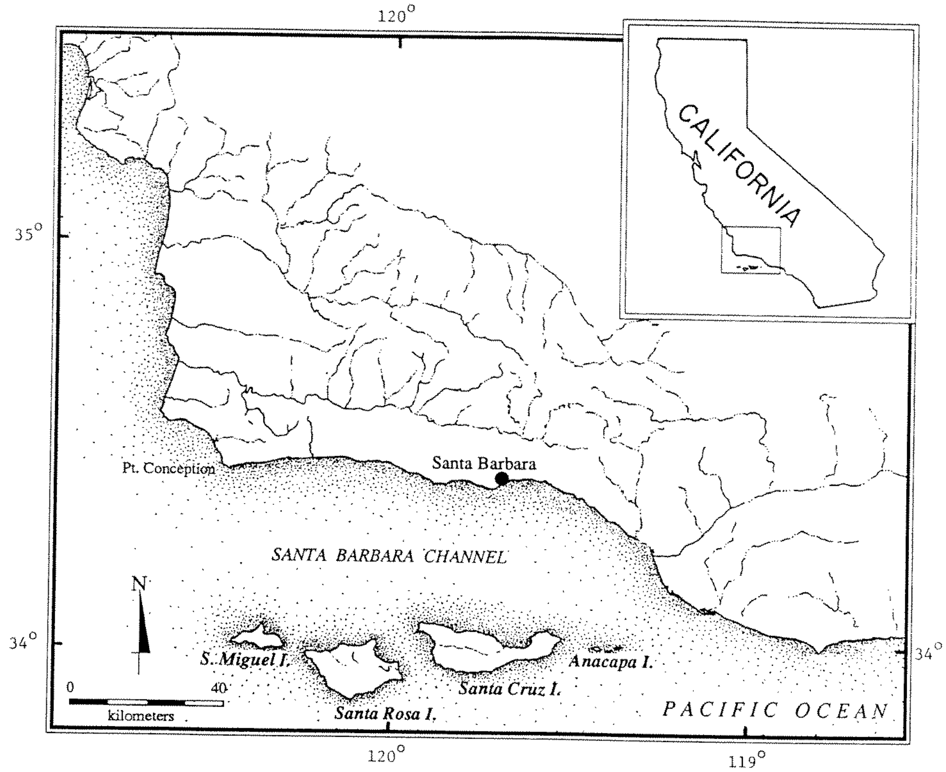

FIG. 1. Map of the study area, including the south-central California coastline and the northern Channel Islands. All samples were excavated from sites on western Santa Cruz Island.

Recent ENSO events on the American Pacific coast (1982–1984) have profoundly impacted marine ecosystems (Barber and Chavez, 1983; Dayton and Tegner, 1990; Glynn, 1988). Historical records from Peru (Quinn *et al.*, 1987) and reports based on varved sea-floor cores from the Santa Barbara Basin (Pisias, 1978) indicate that disruptions in marine productivity resulting from warm-water incursions have occurred during the last few millennia. Scholars using sediment cores from the Channel Islands region have noted assemblages of radiolarians and fish scales in the varved deposits (Pisias, 1978) that indicate occasional warm sea-surface temperatures (SSTs). A period of sustained high SST occurred ca. 1150–1250 A.D. (± 50 yr). The magnitude of temperature change in this period suggests that nutrient-poor warm water would have suppressed the high primary productivity normally generated by intense upwelling and cool currents.

This anomaly resembled an ENSO cycle in its apparent impacts, if not its unusual duration. Water temperatures, normally 14°–15°C, rose to perhaps 23°–24°C at times during this period, almost certainly causing large kelp-bed areas to be destroyed, as observed during recent ENSOs (Glynn, 1988). These conditions would have adversely affected marine species that depend upon kelp for food and shelter (Dayton and Tegner, 1990; Rollins *et al.*, 1987; Tissot, 1991). Many populations of marine organisms decline, and shifts in their ranges may occur, because of warm water, poor nutrient conditions, altered current patterns, or storm-induced mechanical disruption of habitat (Cowen, 1985; Radovich, 1961). This of course has important implications for availability of human food.

The warm-water period corresponded closely to a time of rapid cultural change in the channel region during the 12th–14th centuries. Dramatic increases in craft specialization and notable changes in regional economic integration, exchange, and social differentiation occurred at this time and can be explained as managerial responses to environmental stress and political actions by emerging leaders (Arnold, 1991). In this model, stress from resource depletion may have played a significant role in creating opportunities for individuals to begin regularly to manipulate labor and products in regionally integrated exchange. This proposed causal sequence for the rise of chiefdom-level complexity is discussed at length elsewhere (Arnold, 1992); here, our principal goal is to verify that temperature-related resource depletion problems did occur near the beginning of this sequence.

A METHOD FOR DERIVING MARINE PALEOTEMPERATURES

We introduce a new method to document water paleotemperature cycles using archaeological specimens.

The developmental pattern of living gastropods in various water temperature zones can be measured to understand responses to warm-water conditions. Tissot (1988a) has measured ontogenetic trajectories—measures of developmental change in a trait as a function of time (Alberch *et al.*, 1979)—in the black abalone (*Haliotis cracherodii*) across a range of populations representing different water temperatures. Developmental variability in trema number was found to be related directly to temperature in this species (Tissot, 1988b). We assume that if parallel ontogenetic changes occur in specimens from archaeological sites in the same regions, then it can be inferred that changing water-temperature conditions account for the observed differences.

The shell of *H. cracherodii* is an accretionary structure that provides a record of previous growth within its whorls. Because shell growth is irregular (Tissot, 1991), growth rate cannot be inferred from shell microstructure, as in other marine molluscs (Jones, 1988). However, measurement of the ontogenetic trajectory does reveal significant patterning. Among black abalone, the number and spacing of the tremata on the shell display strong allometric (unequal) variation with shell size (Tissot, 1988a,b). Based on seven shell characters, multivariate trajectories for trema structure (number, size, and spacing) were calculated using linear relationships between scores derived from principal components analysis (Table 1). The slope of the trajectories displays a latitudinal cline along the Pacific coast of North America: measurements from more than 2400 living abalone from four regions between 27° and 37°N latitude reveal that populations in warm Baja California exhibit more numerous, small, closely spaced tremata than cooler-water populations of the central California coast (Table 2).

Because the rate of trema addition increases with the rate of shell growth, high growth rates result in steeper trajectory slopes and more numerous tremata (Tissot, 1991). Moreover, because the rate of calcium carbonate deposition is strongly influenced by temperature, the growth rates of marine molluscs almost invariably increase with increasing temperature (Vermeij, 1978). This phenomenon has been demonstrated for black abalone in the laboratory and is largely independent of food availability (Pacific Gas and Electric, 1982; Tissot, 1991). The slopes of trajectories of abalone shells therefore can be used as indicators of environmental conditions under which shell deposition occurred, principally marine water temperature.

TABLE 1

Results of Principal Components Analysis on 2564 Individual *H. cracherodii* from Six Localities along the Pacific Coast

Variable	Variable loadings		
	PC1	PC2	PC3
Length	0.97	0.01	0.03
Width	0.98	0.01	0.01
Height	0.93	0.11	−0.07
Tremata number	0.36	0.88	−0.04
Tremata length	0.96	0.09	0.01
Tremata spacing	0.68	−0.42	−0.50
Tremata diameter	0.72	−0.32	0.52
Percentage variation	68.60	15.50	7.60
Cumulative variation (%)	68.60	84.10	91.70

Note. Variable loadings are indicated for seven variables used to measure size and shape variation in abalone shells (see Tissot, 1988a).

TABLE 2

Developmental Trajectories of *H. cracherodii* Shells Derived from Recent Populations in Relation to Environmental Conditions

Population	*N*	Latitude (°N)	Trema number allometry	Average annual temperature (°C)
Guadalupe Island (MX)	64	28	0.326	20
Natividad Island (MX)	41	27	0.092	18
Santa Cruz Island (CA)	1470	34	−0.037	15
Año Nuevo Island (CA)	904	37	−0.070	12

Note. Measures of shell size and trema number were derived from principal components analysis of seven shell traits. Ontogenetic trajectories were calculated using linear regression of the second axis scores (PC2) on the first axis scores (PC1) (after Tissot, 1988b).

ANALYSIS AND RESULTS

Prehistoric occupants of the Santa Barbara Channel region used the black abalone for many purposes, including, most importantly, subsistence and making shell beads and ornaments. Large numbers of well-preserved, unmodified, and unbroken shells were deposited in Channel Islands sites beginning thousands of years ago, and these afford the opportunity to measure varying patterns of abalone development during this interval. Samples in the analysis consist of nearly 700 whole abalone specimens (Table 3) from four sites on western Santa Cruz Island (Fig. 1). Shells were acquired by manual excavation under highly controlled conditions from dated cultural lenses ranging from 500 to 1790 A.D. (Arnold, 1992). These four sites (SCRI-191, -192, -330, and -474) were the first on the northern Channel Islands to generate detailed paleoenvironmental information—including the systematic collection of whole black abalone shells—designed explicitly to assess prehistoric water temperature variation (Arnold, 1992). The sites were selected for investigation because each spans the period of the warm-water anomaly and/or immediately precedes or follows it, thus providing data that should represent both baseline (cool water) and warm-water conditions.

TABLE 3
Archaeological Samples of *H. cracherodii* Shells, Santa Cruz Island

Level	N	Depth (cm)		Age assignment
Morse Point (SCRI-192)				
A	66	05–10		Historic
B	86	10–20		Historic
C	39	25–40		Historic/Protohistoric
D	54	40–60		Late Period (ca. 1528–1953 A.D.)
E	7	65–75		Late Period
F	14	75–100		Late Period (follows ca. 1281–1413 A.D.)
Forney Cove (SCRI-330)				
Level	N	Depth (cm)		Age assignment
A	21	10–15		Historic
B	26	20–45		Late Period
C	23	55–85		Late Period (ca. 1325–1430 A.D.)
D	22	90–125		Late Period
E	10	125–140		Early Late Period
Christy Ranch (SCRI-191)				
Level	N	Excavation unit[a] 35S,2W	35S,3W	Age assignment
A	77	Lens B	15–20	Late Period (ca. 1455–1650 A.D.)
B	20	Lens C	—	Late Period (ca. 1421–1437 A.D.)
C	27	Lens D	30–35	Late Period (ca. 1327–1465 A.D.)
D	29	Lens E-up	35–45	Transitional (ca. 1284–1405 A.D.)
E	22	Lens E-lo	—	Transitional (ca. 1277–1385 A.D.)
F	19	Lens F/G-up	—	Late Middle Period
G	24	Lens G-l0	65–70	Middle Period
H	9	—	70–80	Middle Period
I	13	—	85–90	Middle Period
Posa Anchorage (SCRI-474)				
Level	N	Depth (cm)		Age assignment
A	24	5–30		Late Middle Period (ca. 1042–1256 A.D.)
B	16	35–50		Middle Period (ca. 993–1221 A.D.)
C	23	50–60		Middle Period (ca. 777–996 A.D.)
D	4	70–75		Middle Period (ca. 410–640 A.D.)

Note. Age assignments are based on artifact assemblages and dendrocalibrated charcoal radiocarbon dates, based on 1 sigma statistic (see Arnold, 1992, for published dates).

[a] Excavation units at this site were excavated using two systems, and depth is recorded either by lens (discrete stratigraphic level) or by cm below surface.

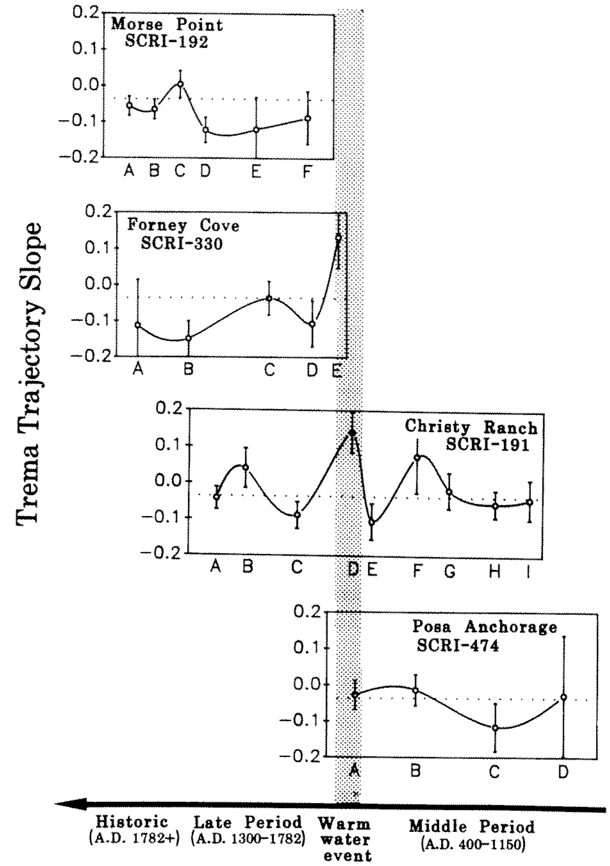

FIG. 2. Mean slopes of trema ontogenetic trajectories (± 1 SE) of *H. cracherodii* shells recovered from dated archaeological deposits at four Santa Cruz Island sites. The slope of trajectories varies in response to the rate of shell growth, which covaries with seawater temperature. Steeper slopes result from faster growth rates under warmer water conditions. These are seen as higher positive values. The mean slope of trema trajectories for recent Santa Cruz Island shells is indicated at −0.037. Archaeological deposits are arranged chronologically relative to the reported warm-water event at ca. 1150–1250 A.D. Shells from this 1150–1250 A.D. period verify the presence of warm-water conditions.

The results of our analysis show that these samples display considerable variation in the slope of developmental trajectories through time (Fig. 2). Shells recovered from deposits absolutely dated to the reported warming event consistently display elevated trajectory slopes (higher peaks, Fig. 2). These results firmly support sediment–core data from the Santa Barbara Channel (Pisias, 1978), which indicate that the marine environment was considerably warmer during this period. Current morphology–temperature patterns suggest that conditions when human populations collected these shells around Santa Cruz Island at ca. 1150–1250 A.D. were similar to those of southern Baja California today (Table 2), where temperatures average 19°–20°C and range up to 24°C (Robinson, 1976). Trajectories (Fig. 2) indicate that cold-water periods bracketed the warming event, and less marked high SST occurred in the past as well. The quite cool conditions dating to ca. 1300–1400 A.D. (dips immediately to the left of the stippled area, Fig. 2) appear also to be consistent with the Little Ice Age confirmed by Davis (1992) for southern California.

Other archaeological data gathered by Arnold (1991) show that there were many settlement disruptions on Santa Cruz Island at the time of the warm-water period, indicated by numerous cases of site abandonments and interruptions in artifact seriations. Referring to Figure 2, it can be observed that site SCRI-474 was abandoned as this period began, and SCRI-330 and SCRI-192 were established as, and just after, it closed. The occupation at SCRI-191 apparently continued through the perturbation, but artifact assemblages may suggest a brief discontinuity. This pattern of settlement disruption occurs islandwide, which further highlights the likelihood that paleotemperature anomalies had a profound effect on prehistoric communities in the area.

Abalone development, archaeological data, and paleotemperature sequences permit reconstruction of the context of cultural change. These data represent significant independent confirmation of other environmental indicators and are important because SST variability played a role in prehistoric cultural evolution along the California coast. Archaeologists examining the prehistoric impact of warm-water events in Peru (e.g., Moseley *et al.*, 1981; Sandweiss, 1986; Yesner, 1980) have argued that SST disruptions may have affected cultural developments in those regions as well. These phenomena are increasingly important in paleoenvironmental–archaeological research throughout the Pacific Rim.

CONCLUSION

Our results contribute to interpretations of paleoenvironmental change and later Holocene ocean temperature dynamics. Developmental patterns of *H. cracherodii* have proven to be sensitive indicators of water temperature conditions under which growth occurs. The method is applicable to samples of abalone shells excavated from specific stratigraphic contexts worldwide to reconstruct the changing water temperature conditions in which human populations foraged.

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