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Provenance analysis of *Olivella biplicata* shell beads from the California and Oregon Coast by stable isotope fingerprinting

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Abstract

While *Olivella* beads are a common component of archaeological sites in California, and were widely traded in prehistory, no method has been developed to trace individual beads to a point of origin. This study examines the potential of stable carbon and oxygen isotopes to source *Olivella* beads from the Pacific coast. The study shows that 1) the oxygen isotopic composition of modern *Olivella biplicata* shells faithfully varies with ambient sea surface temperature and local upwelling, lending themselves to sourcing studies; 2) oxygen isotope ratios in modern shells can be used to identify shells that grow north versus south of Point Conception, California; and 3) shell carbon isotope ratios may further subdivide these two regions into more spatially restricted source zones. Analyses on a small sample of 10 beads found at various archaeological sites within the interior of California suggest that all were made in southern California.

Keywords: Stable isotopes; California; Oregon; Olivella; Provenance analysis; Prehistoric beads

1. Introduction

Tracing the movement of durable commodities within and between hunter-gatherer societies remains an important tool for archaeologists seeking to understand the nature and development of small-scale economies and the rise of social complexity. In the Great Basin and cismontane California, techniques such as X-ray fluorescence and neutron activation are commonly used to track the spatial and temporal distribution of prehistoric raw materials across broad geographic regions. Obsidian (volcanic glass) has been the primary focus of such sourcing studies, although chert [83], andesite [56], basalt [72,93], ceramics [33], and steatite [1] have also been studied. These provenance analyses have allowed archaeologists to explore various aspects of hunter-gatherer settlement mobility (e.g., refs. [12,15,29]), the organization of craft production [33,44], development of intra- and inter-regional exchange networks (e.g., refs. [19,21,35,39,51–55]), and the origins of complex social systems (e.g., refs. [2,54,60,97]), among other important topics.

Shell beads and ornaments are one of the most widely recognized items of exchange found in archaeological sites from California and the Great Basin [18,19,39,55]. By far, the most common shell beads reported in this region are made from the purple olive snail (*Olivella biplicata*), endemic to the Pacific coast from Vancouver

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Island to the northern Baja peninsula. *Olivella* shell beads were widely traded among Native Californians beginning at least 9000 to 10,000 years ago [13,14,19,37,85], and are regularly found at prehistoric sites across the west, occurring as far inland as eastern Nevada, Utah and Arizona [19,39,66,76,81]. The earliest shell beads from this region are simple spire-removed *Olivella* shells with little to no additional modification [13,14,37,39,85]. By the middle Holocene (ca. 5000 years ago), rectangular to oval-shaped beads cut from the body whorl were traded over a broad region [66,76,92], providing the foundation for a manufacturing industry and exchange network that developed through the late Holocene and culminated in the monetized systems of exchange reported ethnographically and archaeologically [2–5,9,10,19,24,52,55,60,61,65,66,91].

While it is clear that most *Olivella biplicata* beads found in the interior of the desert west are ultimately derived from the Pacific Coast, we are unaware of chemical studies that attempt to pinpoint the origin of beads to more specific locations along the more than 1100 miles of Pacific coastline. Yet, such a study would be invaluable in helping archaeologists to reconstruct not only the networks of exchange, but the development of subsistence and political economies and the emergence of ranked societies in California [11,52]. For example, Arnold [2–9] has linked the production of shell beads and chert microblades on the Santa Barbara Channel Islands to the development of powerful headmen, and the formation of small hunter-gatherer chiefdoms (see also refs. [36,60,61]).

2. Shell bead production

Centers of prehistoric shell bead production are thought to have existed in the Santa Barbara Channel area of southern California, in central California around Monterey Bay, and at Bodega Bay in northern California [19]. Yet, despite the ubiquity of *Olivella* shell beads in archaeological sites throughout California and the Great Basin, centers of bead production and exchange outside the Santa Barbara Channel region are poorly documented [19,79]. *Olivella* bead manufacturing in central and northern California is occasionally represented by small quantities of manufacturing waste and an occasional bead blank [19,28,48,81]. In contrast, sites located in southern California on Santa Cruz, San Miguel, and Santa Rosa Islands (the northern Channel islands) have produced as much as 150,000 pieces of bead manufacturing refuse and hundreds of production blanks from a single cubic meter of excavation [5,8,9,60,61]. As well, a tradition of specialized bead making tools, including micro-blade drills, is documented on the northern Channel Islands [2,3,36,60]. Nothing comparable to this level and regularity of production is evident at archaeological sites in central and northern California.

In fact, claims for large-scale prehistoric bead production outside the Santa Barbara Channel region are largely inferential, based on ethnographic descriptions of shell collecting and the regional distribution of certain bead types absent or uncommon in southern California, such as Saddle and Sequin beads [19]. There is some evidence from the Diablo Range and the southern North Coast Ranges that certain *Olivella* wall-beads were manufactured on the interior during the late Prehistoric period (i.e. post AD 1000), but this tradition appears to have been small-scale and could not account for the tens of thousands of *Olivella* beads recovered from central and northern California archaeological sites [19,48,77,78]. It is worth reiterating that despite extensive excavations along much of the central and northern California coast [57,80,96,97], particularly at Monterey Bay [23,27,79] and Bodega Bay [59], bead production on the massive scale evident in the Channel Islands region of southern California has not been documented. This would seem to indicate that shell bead production was highly localized along the southern California coast.

3. Sourcing shell

Olivella biplicata is an intertidal snail-shell that is abundant on sandy bottoms in lagoons, bays, and protected areas along the open coast of western North America from Vancouver Island, British Columbia, to northern Baja California [31,32,89]. Individual snails can live up to 15 years producing shells that reach up to 30 mm in length, though shells grow quickly during the first year of life, to approximately 15 mm. *Olivella* snails are generally found in waters less than five m in depth and at times are found in very high densities, up to 500 in an area less than one square meter in size [89].

Most previous studies of shell bead exchange in North America only trace shells back to bodies of water where particular species occur [70,76,81]. In California this approach would not be very informative as most species used for making beads, including *Olivella biplicata*, are available along the entire Pacific coastline. Thus, if provenance analysis of shell in California is to be archaeologically informative we must be able to track beads back to more specific regions of the Pacific coast.

Chemical analyses of shells is one possible approach to achieve this end. Strangely, this technique has not been widely applied in archaeological studies, even outside North America. We are aware of only two other studies that take a chemical approach to achieve these ends. Claassen [25,26] used neutron activation analysis to determine the chemical composition of *Busycon* sp. shells and artifacts in different parts of the American

Southeast. Claassen was able to track the movement of shell artifacts with some success using this technique, though it has not been repeated or extended since those studies. More analogous to the current study, Shackleton and Renfrew [86] were successful sourcing *Spondylus* sp. shell artifacts in Central Europe based on the ratio of stable oxygen isotopes in bulk shell samples. They found that different areas in the Black Sea region have characteristic isotopic signatures as a result of local temperature and salinity differences, which allowed them to trace the origin of *Spondylus* ornaments.

Interestingly, although much archaeological work with oxygen isotopes has been conducted along the California coast in recent years [45,58–60,62], the aim of these studies has been the reconstruction of prehistoric sea surface temperatures and/or occupational seasonality at individual archaeological sites, but not provenance analysis. Recent advances in isotope mass spectrometry over the last two decades, such as automated analysis and the ability to measure very small samples, make the tool highly effective and promising in provenance analysis of small and sometimes fragmented beads in California.

3.1. Approach

The current study examines the feasibility of using stable oxygen and carbon isotopes to source *Olivella* beads in California. The oxygen isotope ratio ($\delta^{18}O$) of biogenic carbonates such as aragonite depends strongly on calcification temperature and the $\delta^{18}O$ of the seawater ($\delta^{18}O_{sw}$) in which the organism precipitated its shell. The equation relating these factors has been determined empirically by Grossman and Ku [46] and can be described by

$$T\,(^{\circ}C) = 20.6 - 4.34\,(\delta^{18}O_{\text{aragonite (V–PDB)}} - \delta^{18}O_{\text{water (V–SMOW)}}) \quad \text{(eq1)}$$

where T is the temperature of calcification in degrees Celsius. We subtracted 0.2‰ from $\delta^{18}O_{sw}$ (V-SMOW) in Eq. (1) to account for differences between the V-SMOW (Vienna-Standard Mean Ocean Water) and V-PDB (Vienna-Pee Dee Belemnite) scales [16]. Here, isotopic data are expressed in standard delta (δ) notation, where

$$\delta\,(^{18}O \text{ or } ^{13}C) = [R_{sample}/R_{standard} - 1] \times 1000,$$

and R_{sample} and $R_{standard}$ are the oxygen (or carbon) isotopic ratios ($^{18}O/^{16}O$ or $^{13}C/^{12}C$) of the sample and the V-PDB (for calcite) or V-SMOW (for waters) standards, respectively, in ‰ units. Experiments have shown that calibrated temperature to $\delta^{18}O$ relationships can be used to reconstruct environmental seawater temperatures during the life of an organism if $\delta^{18}O_{sw}$ can be estimated or computed [16,20]. Field data show that salinity covaries linearly with $\delta^{18}O_{sw}$ [67,71,94]. For instance, the relationship between $\delta^{18}O_{sw}$ and salinity along the California coastline from Pt. Reyes (38 °N) to the Oregon-California border (42 °N) can be described by

$$\delta^{18}O_{sw} = 0.26 \times S - 8.96\ (n = 30;\ r^2 = 0.99) \quad \text{(eq2)}$$

[Spero unpublished data], whereas the relationship for ocean water between the southern California Bight and Monterey Bay is

$$\delta^{18}O_{sw} = 0.39 \times S - 13.23 \quad \text{(eq3)}$$

where S is salinity expressed in practical salinity units [88]. Differences between these equations reflect the geochemistry of the regionally controlled freshwater endmember (y-intercept) of the California coast range (Eq. (2)) and Sierra Nevada mountain range (Eq. (3)). Hence it is possible to reconstruct seawater temperature from shell $\delta^{18}O$ if salinity can be estimated or constrained. This geochemical approach has been successfully applied to studies of the shells of a variety of marine organisms including bivalve and gastropod mollusks, ostracods, forams, brachiopods and solitary corals [22,67,68,95]. In the case of mollusk shells, for example, serial microsampling around the spiral whorls from earliest to oldest growth reveals sinusoidal variations in isotope ratios, which result from shell deposition in a seasonal environment of changing seawater temperatures [46,49,50,67,94].

Although calculation of absolute environmental temperature is complicated by the influence of seasonal salinity variation along the California coast, one can determine unambiguously whether or not an individual shell inhabited warm southern California waters or cold northern California-Oregon waters because of the relative influence of the two environmental controls on shell $\delta^{18}O$. For example, salinities along the California coastline north of Pt. Reyes generally display fully oceanic salinities (33–34 psu), although slightly fresher salinities (31–32 psu) occur during the winter months. Using the slopes of the salinity relationships above, this equates to variation of ~0.6‰ in shell $\delta^{18}O$ during these low salinity periods. Southern California salinities vary little due to the absence of major river systems into the Santa Barbara Basin so these shells grow in fully marine conditions year round (33–34 psu). Temperature, on the other hand, has a very large influence on shell $\delta^{18}O$, with a slope of ~0.22‰/°C. Summer (i.e., maximum) temperatures in the Santa Barbara Basin usually reach 16–20 °C [64, Thunell unpublished data], whereas in Monterey Bay summer temperatures peak between 12–14 °C and in Oregon peak between 9–12 °C. Hence, outside of extreme runoff events that drastically change local salinities, the oxygen isotopic composition of shell

carbonate is primarily controlled by temperature differences between regions rather than salinity.

We gathered surface seawater temperature and salinity data for five locations along the California coast representing two locations north of Point Conception (Bodega Bay and Granite Canyon), two south of this location (Balboa and La Jolla), and one near this transition (Santa Barbara) [87, Thunell unpublished data]. While Santa Barbara records data between 1993 and 2003, the others include data gathered from 1980 through 1997. Fig. 1 shows the location of these sampling stations. Using Eqs. (1) and (2) we then computed predicted $\delta^{18}O$ values for shells produced in isotopic equilibrium, and plotted monthly average predicted values in Fig. 2 for these five locations. The figure lacks information in some areas due to missing data. Overall, the two series north of Point Conception on the lower part of the graph (Bodega Bay and Granite Canyon) are nearly identical and have very little overlap with the two southern California series (Balboa and La Jolla) and Santa Barbara, which are also quite similar to each other. As predicted there is minor overlap in predicted $\delta^{18}O$ values between summers north of Point Conception and winters in southern California, but even here, the overlap is minimal. The only major departure from this pattern occurred in March of 1983 and January-March of 1995 and 1996, when northern California $\delta^{18}O$ spiked to unusually low values during large El Niño Southern Oscillation (ENSO) events. Extremely low salinity values are recorded for these periods, indicating a period of high local rainfall and runoff of freshwater, especially into the central and northern California sites north of Point Conception. The mid 1990s part of the graph is expanded in the lower section of Fig. 2 to show an example of the effects of such an ENSO event on predicted isotopic values in shell. The southern California sites show a less marked decrease in $\delta^{18}O$ values, indicating that ENSO events are less pronounced in the isotopic signatures in this region. Similar, but less extreme ENSO events occurred during the late winters of 1982, 1986, 1992, and 1996, invoking similar but smaller-scale isotopic anomalies.

The data in Fig. 2 correlate quite well with our observed values (see below) and suggest that oxygen isotopic values from *Olivella biplicata* should have little overlap between areas to the north and south of Point Conception. During ENSO events, when extreme late winter runoff lowers salinity especially in central and northern California, these patterns are less marked or even disappear. Fortunately, these events are infrequent

Fig. 1. Sampling locations and places mentioned in text.

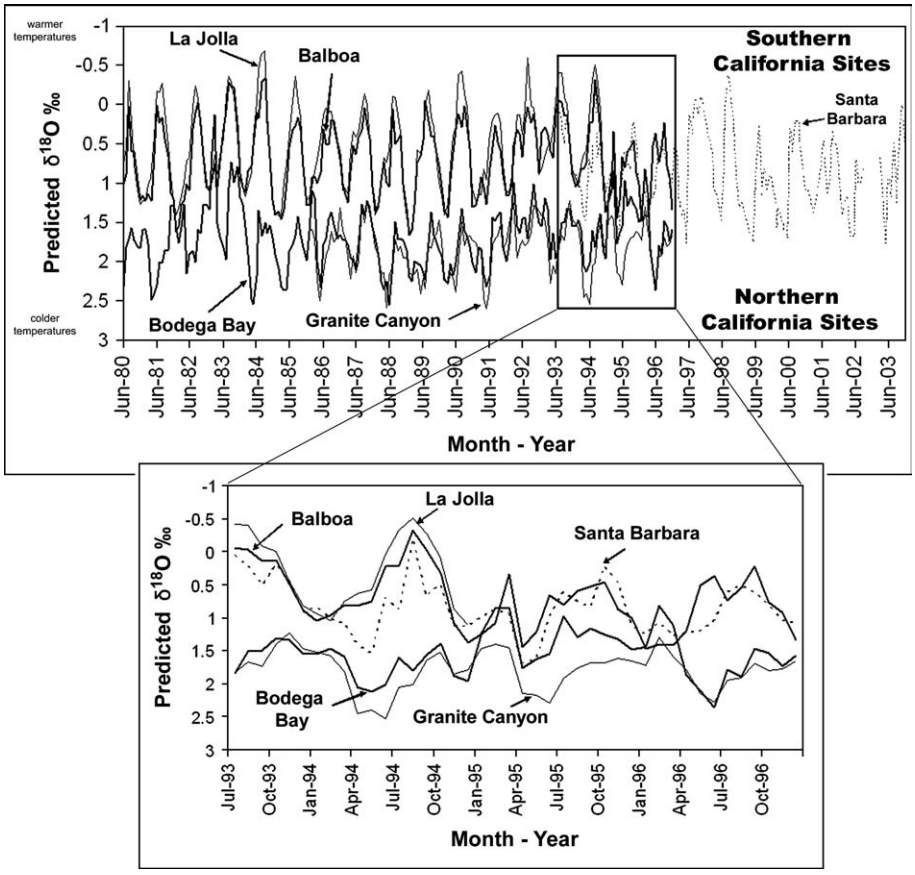

Fig. 2. Predicted aragonitic $\delta^{18}O$ based on salinity and temperature at five California locations. Note that northern and southern sites have minimal overlap.

and short in duration, and most beads will contain enough growth bands to span across such events, exceeding a single winter.

Within southern California, summer temperatures in the extreme south (i.e., La Jolla and the San Diego area) produce more negative $\delta^{18}O$ values than the Santa Barbara and Los Angeles regions to the north, in any given year. However, interannual variability makes it difficult to define this area as unique. In other words, there is too much overlap between predicted isotopic values in La Jolla and the other southern California sites to systematically differentiate this area from the others. Thus, at present we are not able to define additional source zones using predicted $\delta^{18}O$ values.

A second geochemical tracer is shell $\delta^{13}C$. In mollusks, shell $\delta^{13}C$ records may be influenced by metabolic rate, trophic level, and reproductive condition, although the processes by which this influence occurs are not well understood [30,42,68,73–75,84,95]. Another major source of shell $\delta^{13}C$ variation is changes in the $\delta^{13}C$ of dissolved inorganic carbon (ΣCO_2) in seawater. This parameter is ultimately controlled by the balance between photosynthesis and respiration in the water column. In surface waters, phytoplankton preferentially remove $^{12}CO_2$ during photosynthesis, thereby increasing $\delta^{13}C$ of ΣCO_2. Organic matter sinking below the photic zone is then metabolized by consumer organisms, thereby releasing ^{13}C depleted CO_2 back into the water column. When these ^{13}C-depleted waters return to the surface during seasonal upwelling events, the shell $\delta^{13}C$ records the decrease in $\delta^{13}C$ of ΣCO_2 [22,38,86]. In California, upwelling occurs most intensively between April and July [40,69]. Thus, shell $\delta^{13}C$ values may be distinctive of certain regions of the California coast that experience more intensive upwelling than others. Moreover, because upwelling occurs in certain seasons, patterns in $\delta^{13}C$ can be used in combination with $\delta^{18}O$ to isotopically fingerprint shells.

For this isotopic sourcing technique to be feasible for archaeological analyses, it is necessary to 1) establish that $\delta^{18}O$ and $\delta^{13}C$ in *Olivella biplicata* are affected by sea temperature and upwelling and 2) determine the intra- and interannual overlap in water temperature and upwelling between different regions of the coast. The former will demonstrate that the sourcing technique we propose is technically feasible. The latter will determine the size of the "source zones" for which we will be able to establish isotopic fingerprints. The less interannual overlap in temperature and upwelling for different regions of the coast,

the finer our resolution of source zones (i.e., smaller source zones).

3.2. Methods

Samples for isotopic analysis were processed in the stable isotope laboratory at UC Davis on a Micromass Optima isotope ratio mass spectrometer (IRMS). Powdered carbonate samples were drilled from the shell surface in shallow grooves (<0.3 mm deep) which ran parallel to the growth lines using a 0.5 mm bit attached to a hand-held drill. Powdered carbonate samples ranged from 50 to 80 μg in weight. Sampling began at the *Olivella* shell lip (most recent growth) and continued until we reached the parietal callus (earlier growth), and included at least one whole whorl revolution. The linear distance between samples ranged from 0.5 mm to 2.5 mm depending on the size of the shell and how intensively it was sampled. The analysis of beads required determining the axis of growth, orienting the artifacts in the same way as complete shells, and making sure to sample consecutive growth bands. In all cases, anomalous isotope values were rechecked by subsampling at a finer spatial resolution.

Prior to analysis on the IRMS, powdered aragonite samples were gently heated at 75 °C in vacuo for 30 minutes to remove adsorbed water and subsequently reacted in 105% orthophosphoric acid at 90 °C using an ISOCARB automated common acid bath system. The resulting CO_2 was then purified through a series of cryotraps and introduced into the IRMS through a dual inlet system.

External precision for $\delta^{18}O$ and $\delta^{13}C$ values is ± 0.09 and ± 0.07 (one standard deviation), respectively, based on multiple ($N = 138$) analyses of standards NBS-19 and UCD-SM92. The precision for $\delta^{18}O$ is equivalent to a 2σ temperature uncertainty of ± 0.75 °C when oxygen isotope data are converted to sea surface temperature.

For this study we microsampled 20 *Olivella biplicata* shells from various locations between Santa Barbara, California and southern Oregon. Four specimens were collected from the Santa Barbara mainland near the University of California, Santa Barbara campus, three from Santa Cruz Island, and one from Santa Rosa Island. The remaining twelve shells are from locations north of Point Conception, including two from Big Sur, five from Monterey Bay, one from Bodega Bay, one from Point Reyes, one from Fort Bragg, and two from southern Oregon. All shells were collected between 1999 and 2003, with the exception of the Bodega Bay sample, which was collected in the 1970s, and a prehistoric shell from Santa Barbara. In addition, a single modern *Olivella dama* shell from Puerto Peñasco, Mexico, on the northern edge of the Gulf of California, was sampled for comparative purposes. Because the Puerto Peñasco isotopic data are so divergent, they are only mentioned briefly below. Finally, we also sampled ten prehistoric beads from the southern Sacramento and Santa Clara valleys in northern California ($n = 4$) and from Owens Valley in southern California ($n = 6$). Fig. 1 also plots the sites from which these beads were drawn.

4. Results and discussion

4.1. Establishing the seasonality of Olivella biplicata

Because *Olivella biplicata* is a shallow-water gastropod species, its oxygen isotopic signature should be directly controlled by sea-surface temperature. Fig. 3 shows a series of 45 oxygen (triangles) and carbon (squares) isotope measurements collected at ~0.5 mm intervals along the growth trajectory of a modern *Olivella* shell, beginning with the outermost shell lip, or most recent, growth. The shell was collected from the intertidal zone of Santa Barbara, California. Higher

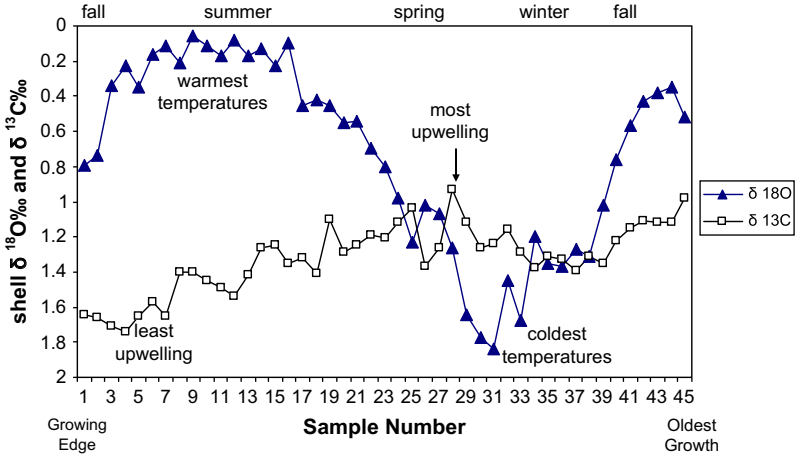

Fig. 3. Microsampling of a single modern *Olivella biplicata* shell from Santa Barbara. Note: Sample numbers represent 0.5 mm increments along shell whorl.

(more positive) $\delta^{18}O$ values indicate colder SST and/or higher, more oceanic-like salinities. Lower (more negative) $\delta^{18}O$ values indicate warmer SST and/or lower salinities. This data set records a little over one year's growth for this particular shell. These data begin with the season in which the animal died (i.e., when the shell was collected) in the early fall (sample = 1) and are preceded by summer (samples 7–17), spring into winter (samples 18–34), fall (samples 35–41), and terminate at the end of the penultimate summer (samples 42–45). These data show that *Olivella biplicata* is recording seasonal fluctuations in $\delta^{18}O$, which we interpret as changes in SST.

Shell $\delta^{13}C$ values also vary seasonally. We observe lowest values during spring (sample 25–31), when local upwelling brings nutrient rich, ^{13}C-depleted thermocline waters to the surface, thereby decreasing the $\delta^{13}C_{DIC}$ of the mixed layer. If we accept the seasonal interpretation described above, upwelling is at a maximum during late winter and spring and at a minimum during summer and fall when $\delta^{13}C$ values are most positive. We can see in Fig. 3 that as upwelling increases, surface waters attain their lowest temperatures, with temperatures increasing again thereafter as upwelling slows. These data are consistent with water temperature and upwelling patterns recorded in the Santa Barbara area.

Thus, Fig. 3 demonstrates that the stable isotope composition of *Olivella* reflects SST and upwelling conditions. Because seasonal SST and upwelling vary along the California margin, shells which grew in different regions should contain distinct paired carbon and oxygen isotope values that can be used to fingerprint the shell source. We predict that *Olivella* growing in coastal regions north of Point Conception will have higher $\delta^{18}O$ values (enriched in ^{18}O) because calcification temperatures will be lower than at more southerly sites. For application purposes, it will be necessary to establish that summer temperatures from northern regions do not significantly overlap with winter temperatures from more southern locales. Although independent interpretation of $\delta^{13}C$ values on a regional level are difficult, when combined with $\delta^{18}O$ data, the carbon data can help distinguish between nearby sites such as the Channel Islands of Santa Barbara because of differences in upwelling (and reduced $\delta^{13}C$ values) compared to mainland areas [40,69].

4.2. Regional isotopic signatures

To test this hypothesis, we collected $\delta^{13}C$ and $\delta^{18}O$ data from 19 additional shells from locations along the California and Oregon coast. All shells, with the exception of a single sample from the Santa Barbara mainland, are modern and were sampled at moderate spatial resolution (>0.5 mm increments along the shell surface). The one exception is an unmodified whole shell collected from an undated prehistoric midden on Devereaux Beach, Santa Barbara (lat: 34° 25′ 16″, long: 119° 53′ 18″) and sampled with similar spatial resolution. Nevertheless, we refer to the group collectively as "modern shells" in the discussion below to distinguish them from modified prehistoric beads. All shells were sampled to collect data from more than one year's growth, thereby capturing the full range of

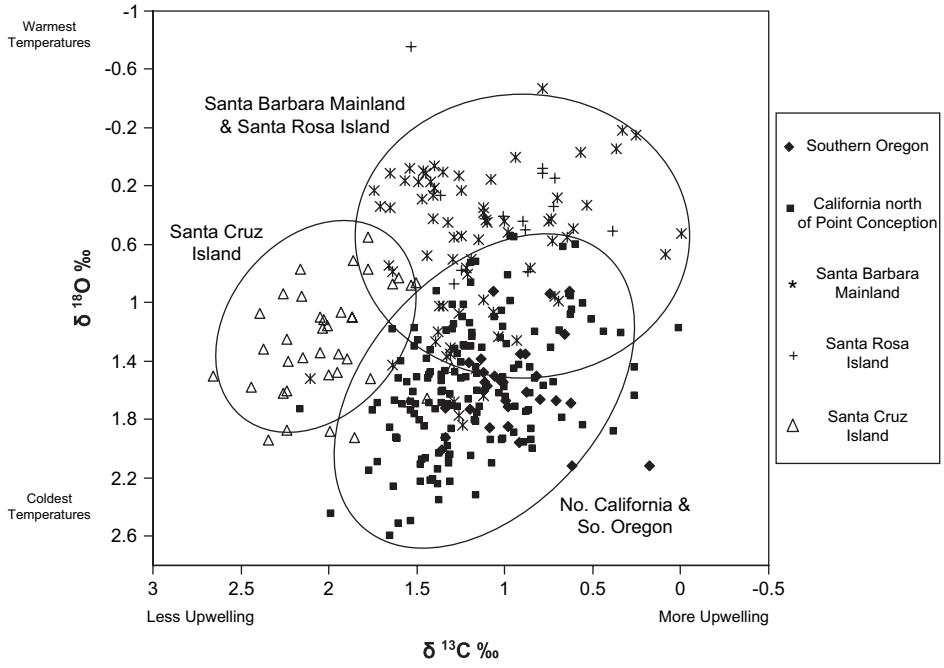

Fig. 4. $\delta^{18}O$ and $\delta^{13}C$ values for 20 whole *Olivella biplicata* shells.

isotopic values for that location over at least one year. An average of 15 isotopic analyses were made on each shell. These data are plotted in Fig. 4.

Although the number of shells sampled is small ($n = 21$ shells comprising 328 isotopic measurements), Fig. 4 shows that there are regional isotopic fingerprints for modern *Olivella* shells. In particular, shells from northern and central California and southern Oregon are largely distinguished from those shells collected in the southern California Bight (south of the Santa Barbara Basin) by $\delta^{18}O$ on the Y-axis, as we had predicted. Thus, shells from sites in Oregon have similar $\delta^{18}O$ values to shells collected to the north of Point Conception (e.g., Big Sur) because these sites are both influenced by the cold California Current that flows along the western margin of North America. In contrast, the Santa Barbara and Santa Cruz Island sites are influenced by the California Current during the spring and earliest summer only [17]. During the remainder of the year, the Davidson Current advects warm water into the basin from the south which is recorded as low $\delta^{18}O$ values by *Olivella*. Interestingly, the one shell collected from Puerto Peñasco, Mexico (not graphed) is highly divergent (see Table 1) with very low $\delta^{18}O$ and relatively high $\delta^{13}C$ values characteristic of warmer and/or less saline waters that may reflect an estuarine influence, with nominal upwelling. These data suggest that beads made from shells collected in the Gulf of California should be isotopically distinct and readily identifiable.

Carbon isotope values provide additional separation between the two regions. Among southern California shells, $\delta^{13}C$ values distinguish Santa Cruz Island samples from mainland Santa Barbara and Santa Rosa Island. The former have much higher values indicating a smaller upwelling influence near Santa Cruz Island. Unfortunately, shell $\delta^{13}C$ values do little to help distinguish northern and central California sites into more distinct regional signatures. Table 1 gives the range of isotopic values for each of the 21 shells analyzed in this study.

4.3. Analysis of prehistoric beads

We analyzed 10 *Olivella* beads from interior California to evaluate our shell bead isotopic fingerprinting method (Table 2). Six of these beads are from Owens Valley located in southeastern California, whereas four are from interior northern California. Beads from the Owens Valley comprise four types including two Tiny Saucers (Type G1), one Oblique Spire-Lopped, one Callus Cup (Type K1), and two Large Saucers (Type G2). Types are after Bennyhoff and Hughes [19]. Two Tiny Saucers and one Large Saucer were analyzed from contexts at site CA-INY-3806, radiocarbon-dated to AD 850. This assay is consistent with the purported age of these bead types elsewhere in southern California [19,66]. The other three beads from the Owens Valley were recovered from a house floor and house fill at site CA-INY-5207, radiocarbon dated to AD 1700. This date is considerably later than typically ascribed to these bead forms [19] and suggests they are related to an older occupation component also recognized at this site.

Beads from northern California include three from the southern Sacramento Valley and one from the

Table 1
Modern shells analyzed and range of isotopic values recorded

Area of collection	Shell ID	No. samples taken	Sample spacing (mm)	$\delta^{18}O$ range	$\delta^{18}O$ average	$\delta^{13}C$ range	$\delta^{13}C$ average
Puerto Peñasco	PPA	23	1.0	[0.77, −4.05]	−1.00	[2.26, 0.38]	1.71
Santa Rosa Island	SBA2	14	1.0	[0.87, −0.76]	0.35	[1.53, 0.39]	0.97
Santa Barbara	SBA	45	0.5	[1.84, 0.06]	0.72	[1.74, 0.93]	1.32
Santa Barbara*	DSA	9	1.5	[1.52, 0.26]	0.77	[2.11, 0.73]	1.35
Santa Barbara	SBA30	9	2.0	[0.99, −0.47]	0.37	[0.94, 0.00]	0.59
Santa Barbara	SBA33	10	1.5	[0.95, −0.18]	0.24	[1.46, 0.25]	0.69
Santa Cruz Island	SCB	8	1.5	[1.40, 0.71]	1.07	[2.24, 1.60]	1.97
Santa Cruz Island	SCRI195	15	2.0	[1.68, 0.55]	1.20	[2.44, 1.30]	2.00
Santa Cruz Island	SCA	16	2.5	[1.94, 0.86]	1.44	[2.66, 1.44]	1.98
Big Sur	BSA	14	2.0	[2.04, 1.17]	1.59	[1.60, 1.16]	1.41
Big Sur	BSB	10	2.5	[2.00, 0.86]	1.56	[1.36, 0.84]	1.02
Monterey Bay	RMN	24	0.75	[2.60, 1.61]	2.13	[1.99, 1.01]	1.49
Monterey Bay	MBB	17	1.0	[1.94, 1.14]	1.46	[1.51, 0.74]	1.20
Monterey Bay	MMB20	9	2.0	[1.64, 0.55]	1.02	[1.38, 0.94]	1.09
Monterey Bay	MMB28	16	1.5	[1.88, 0.90]	1.23	[1.36, 0.38]	0.95
Monterey Bay	MMB34	12	2.0	[1.89, 0.62]	1.37	[0.94, 0.01]	0.50
Bodega Bay	BBA	21	2.0	[2.10, 0.94]	1.46	[1.64, 0.63]	1.07
Point Reyes	PR32	13	1.5	[2.11, 1.25]	1.71	[2.16, 1.02]	1.53
Fort Bragg	PBM29	12	2.0	[2.23, 1.26]	1.70	[1.51, 1.02]	1.29
Southern Oregon	SCO1	14	2.0	[2.12, 0.92]	1.55	[1.06, 0.18]	0.76
Southern Oregon	ORS31	17	1.5	[2.00, 0.92]	1.61	[1.36, 0.88]	1.11

Notes: * = prehistoric unmodified shell.

Table 2
Beads analyzed and range of isotopic values recorded

Bead type	Bead No.	Site	Approx. date	Number samples taken	$\delta^{18}O$ range	$\delta^{13}C$ range
Tiny Saucers (G1)	OV D	INY-3806	AD 850	2	[0.8, 0.6]	[1.9, 1.7]
Tiny Saucers (G1)	OV E	INY-3806	AD 850	2	[0.8, −0.2]	[2.3, 1.9]
Large Saucer (G2a)	OV F	INY-3806	AD 850	3	[0.6, 0.3]	[2.1, 1.8]
Large Saucer (G2b)	OV A	INY-5207	prehistoric	4	[0.4, −0.5]	[2.1, 1.4]
Callus Cup (K1)	OV B	INY-5207	prehistoric	2	[0.8, 0.4]	[2.7, 2.3]
Spire Lopped (A2a)	OV C	INY-5207	prehistoric	8	[0.2, −0.5]	[1.9, 1.5]
Semi-Ground Disk (H1b)	YOL-69 A	YOL-69	AD 1810	8	[0.7, −0.3]	[1.7, 1.3]
Semi-Ground Disk (H1b)	YOL-69 B	YOL-69	historic	9	[0.6, 0.1]	[0.9, 0.2]
Semi-Ground Disk (H1b)	YOL-69 C	YOL-69	AD 1870	3	[−0.1, −0.7]	[2.6, 2.4]
Semi-Ground Disk (H1b)	SCL-30	SCL-30	AD 1825	3	[0.4, 0.2]	[1.5, 1.6]

southern Santa Clara Valley. All four of these are needle-drilled disk beads (Type H), a type that was manufactured during the early historic period in California [8]. Specimens sampled from site CA-YOL-69 in Sacramento Valley, were each associated with large burial lots which have been radiocarbon dated to between AD 1700 and 1810 [47,98]. The single disk bead from Santa Clara Valley was recovered from an historic-period trash pit at Santa Clara mission (CA-SCL-30). A portion of this bead was AMS-dated to AD 1825 [47].

Fig. 5 shows three of these bead types (5a–c) and a whole shell (5d), displaying a range in sizes and shapes typically encountered. Due to the small size of some beads (e.g., 5a = Callus Cup; 5b = Semi-Ground Disk) only two to three isotope samples could be taken across growth bands. On others (e.g., 5c = Spire Lopped) up to nine isotopic samples were taken. Obviously, our confidence in attributing a bead to a source area is higher on beads that were sampled across a greater range of growth bands (i.e., growth time). The whole shell (5d) is typical of the size available along the California coast for bead manufacture.

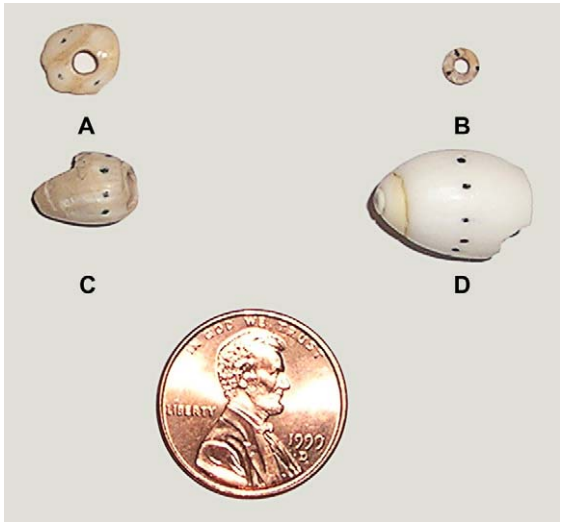

Fig. 5. Three *Olivella biplicata* beads (a–c) and a whole shell (d) from California, showing range in size. Black mark indicates sampling location.

Fig. 6 shows the 44 isotopic samples that were obtained from the 10 beads, plotted with the modern shell data distribution and regional ellipses in Fig. 4. The most important observation is that the bead isotopic fingerprints do not fall within the range of values observed among modern *Olivella biplicata* shells from northern and central California and southern Oregon. This suggests that the source shells for these beads were all collected in the warmer waters south of Point Conception. Significantly, these results support ethnographic information indicating that needle-drilled disk beads were manufactured at southern California Missions during the early Historic period [8,43,65,66]. The presence of these beads in the Santa Clara and Sacramento valleys also indicates that they were transported very far from their likely southern California source. The results also support those of Arnold [3–5] who suggests that southern California, particularly the Channel Islands area, was of great importance in the production of beads.

Nine of the ten beads have $\delta^{13}C$ values that cluster near the upper extreme for the Santa Barbara mainland and the general range for Santa Cruz Island. Only one of the beads, which records low $\delta^{13}C$ values (represented by '+' symbols) does not overlap with $\delta^{13}C$ values from modern shells from Santa Cruz Island. Although we have not extensively sampled modern shells from Santa Rosa Island to evaluate whether the range of $\delta^{13}C$ values typically encountered there overlap with Santa Cruz Island, it is unlikely given the more westerly location of Santa Rosa Island which places it closer to the influence of the California Current and its lower $\delta^{13}C$ upwelling signal. Given the data we have collected to date, we believe this bead (YOL-69 B) was manufactured on Santa Rosa Island, San Miguel Island, or the Santa Barbara mainland. The three other historic needle-drilled beads (YOL-69 A, YOL-69 B, and SCL-30) also have isotopic readings consistent with Santa Rosa Island, San Miguel Island, or Santa Barbara mainland production, but fall close to the range of Santa Cruz Island as well.

The remaining six beads from Owens Valley (OV A through OV F) have $\delta^{13}C$ signatures consistent with

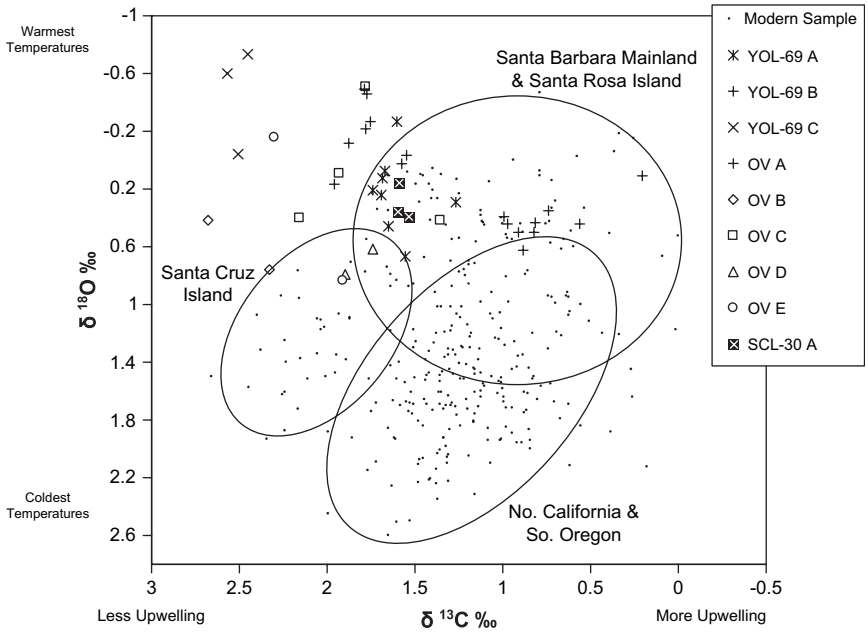

Fig. 6. Results of stable isotopic analysis of *Olivella biplicata* beads.

a Santa Cruz Island source. However, only three of those (OV B, OV D, and OV F) have $\delta^{18}O$ values consistent with our findings for modern shell from that island. We tentatively assign those three to a Santa Cruz Island source. Sources for the remaining three beads (OV A, OV C, and OV E) in the upper left-hand part of Fig. 6 are less clear. Although carbon isotopic values overlap with Santa Cruz Island, oxygen isotopes do not. Two explanations present themselves. First, we have previously noted that modern *Olivella dama* collected in the Gulf of California have a combined fingerprint with lower $\delta^{18}O$ and higher $\delta^{13}C$ values than anywhere in California or Oregon. These three beads fall close to this isotopic range, suggesting the possibility of an unidentified bead source to the south of the Santa Barbara Basin. Alternatively, the Santa Barbara Basin is very sensitive to ENSO events. During an El Niño year, maximum SST in the Basin can increase as much as 2–3 °C (=0.5 to 0.75‰ reduction in shell $\delta^{18}O$) [90] while the $\delta^{13}C$ of the dissolved CO_2 increases because of a reduction in local upwelling. Taken together, it is possible that the shells used to make the beads in the upper left of Fig. 6 grew during an ENSO event in the past.

4.4. Potential data interpretation issues

There are several biological factors that can confound interpretations of shell bead geochemistry. Mollusks are not passive recorders of their environment but interact dynamically with it. As a result, the sourcing of shell beads is unlike that of more passive materials such as obsidian, or even pottery. When sampling shell for sourcing studies, several issues should be considered.

First, growth rates change daily, seasonally, and over the lifespan of an animal, biasing which conditions are recorded in its shell. An animal that only secretes shell carbonate in the summer at temperate latitudes may have an identical isotopic range as an animal that grows only in the winter and spring at subtropical or tropical latitudes. For example, *Urosalpinx cinerea* from a mid-Atlantic site in Virgina, U.S.A. has a warmer range of isotopic values than its congener, *Urosalpinx perrugata*, which occurs at a more southerly site along the Gulf of Mexico [49]. As well, reproducing organisms invest less energy into growth [41], and shells of reproductive age may record a lower range of values (shorter seasonal calcification period) than ontogenetically younger and smaller shells [49]. Our empirical data from modern shells along the California and Oregon coast do not suggest this is an issue for *Olivella biplicata*, however, it is possible that shells growing south of California and north of Oregon may display alternative patterns.

Second, it is also important to establish whether the species under investigation is mobile and can migrate. Most bivalve mollusks are infaunal, or permanently attached to a substrate and can be assumed to have lived near the place they were collected. However, some larger gastropods are mobile, thereby allowing them to move between the shallow nearshore and offshore environments on a seasonal basis. Such movement could obscure a seasonal isotopic signature. Similarly, some mollusks, including the pelagic gastropod *Janthina*, are suspended on a mass of bubbles, and other species may travel great distances attached to floating mats of seaweed, wood, or other floating debris. Thus, it is important to consider the physiology

and life habit of the species under study. For the species studied here, *Olivella biplicata* migrates less than one to two kilometers in its lifetime up or down the coast and remains at similar water depths [31,32,89].

Third, many gastropod mollusks have an outermost shell composed of three layers of crossed lamellar aragonite (e.g., *Olivella*). Other species have an outermost layer of calcite in addition to the crossed lamellar aragonite. Calcite and aragonite precipitated under identical environmental circumstances have different isotopic ratios due to fractionation differences between the two mineral forms of calcium carbonate [20,63]. While the slopes of the temperature vs. $\delta^{18}O$ values are nearly identical, the y-intercepts are considerably different. Thus, care must be taken when directly comparing calcitic and aragonitic bead $\delta^{18}O$ values for provenance analysis, and one must drill samples from the same mineralogic layers in species with complex mineralogies. Standardizing bead orientation when drilling samples is one way to avoid sampling different parts of the shell with different mineralogies. *Olivella biplicata* contains only aragonitic shell layers, although our sampling strategy is still standardized by utilizing only the outermost shell layer. Moreover, this issue points out the drawbacks of crushing entire shells or beads and obtaining a single isotopic reading for sourcing studies.

5. Conclusions

Our analyses suggest that sourcing *Olivella biplicata* shell beads from the California and Oregon coast using stable isotope fingerprinting holds much promise. However, to date our defined source zones are much more expansive than typically observed for other archaeological materials such as obsidian or even pottery. For example, one of our source zones encompasses the entire coastline from Point Conception to Southern Oregon. Thus, the spatial resolution of shell bead sourcing using this technique will necessarily be much lower than for other artifact categories. However, even such rough divisions will be useful in California archaeology to bring a better understanding to prehistoric patterns in bead production, distribution, exchange, and consumption.

It is clear that a more comprehensive sampling of modern *Olivella* geochemistry is needed along the Pacific coastline, especially south of Santa Barbara and north of southern Oregon. Moreover, although the isotopic patterns we have outlined differentiate northern from southern source zones in the present (and likely the recent part of prehistory), it remains to be shown that these patterns hold for all of prehistory. Thus, it is possible that ocean circulation and coastal conditions varied during the past several millennia [10,58,60,62] or that patterns in upwelling were different [82]. Such effects would have important implications for interpreting isotopic data and sourcing of *Olivella biplicata*. However, the single prehistoric shell we analyzed from the Santa Barbara mainland did not have noticeably different isotopic values than from modern shells we analyzed from that area. Similarly, short-term ENSO events could also influence the isotopic signature of beads collected from northern coastal areas as a result of the northward shift of warm-water currents. Our future research will seek to address these issues. As well, we are also examining chemical composition using Inductively Coupled Plasma-Mass Spectrometry on these same shells to see if there are other chemical signatures distinguishing different parts of the California coast [34].

Our analyses suggest that sampling beads in multiple locations will help to alleviate problems associated with isotopic overlap between summer conditions north of Point Conception and winter conditions in southern California. A single isotopic reading from a shell or a homogenized sample (i.e., crushing an entire bead and obtaining a single measurement) will lead to higher rates of errors in source assignment. This is because it is the extremes in oxygen isotopes, especially the cold winter temperatures (and isotopic signatures) north of Point Conception and warm summer waters of southern California, that help to define source zones. Trends in carbon isotopes along such growth bands can help to identify problematical ENSO events that confound these patterns, further limiting errors in source identification. On the other hand, a single reading or a homogenized average may reflect an ambiguous region of the isotopic variation in shell, for example, the area where the ellipses associated with southern and northern California overlap in the central part of Fig. 4. The best chance for successful provenance analysis of shell beads in California will be to serially sample beads across several growth lines, that is, in several locations that are likely to represent different seasons.

Finally, application of our isotopic fingerprinting technique to six beads from Owens Valley and four from the Central Valley suggests that all were manufactured from shells that grew south of Point Conception. Three of the ten have isotopic signatures consistent with source sites on Santa Cruz Island, four of them consistent with Santa Rosa Island or the Santa Barbara mainland, and the remaining three in either of these places, perhaps during El Niño years, or intriguingly, an alternate source zone that has not been identified yet.

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