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Cultural transformations were key to long-term resilience of hunter-gatherer societies in the coastal Atacama Desert

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ABSTRACT

Hunter-gatherers thrived for millennia along the coastal Atacama Desert of northern Chile, often hailed as a prime example of resilience. In this paper, we examine which cultural strategies were preserved or evolved in response to significant environmental changes over the past 10,000 years, focusing on well-documented shell midden sites in coastal northern Chile (Caleta Vitor, ~18°S). Our findings reveal that different social groups not only restructured the extraction and consumption of marine resources, by diversifying their fishing tools but also innovated their worldview through funerary practices. These cultural shifts coincided with periods of variable marine productivity and major demographic transitions. We argue that these economic adaptations acted as strategies that enabled hunter-gatherers and fishermen to persist and thrive over time. Moreover, despite increasing environmental pressures and the growing influence of inland agriculture social systems, these communities maintained their traditional ways of life.

1. Introduction

Cultural continuities and discontinuities of hunter-gatherer groups in response to shifts in environmental conditions offer valuable insights into long-term adaptation and sustainability strategies (Aubry et al., 2015; Gamble, 2005). Several studies provide relevant examples of resilience in hunter-gatherer societies in various time windows and landscapes throughout the world (e.g; (Field, 2004; Ordonez and Riede, 2022; Ritchison et al., 2021; Scheinsohn et al., 2023; Uceda et al., 2021; Wilson et al., 2022). Resilience, in this context, refers to the ability of a system to absorb, adapt, anticipate and recover from (internal or external) perturbations while preserving its essential structure, function and feedback mechanisms (Walker et al., 2004). In hunter-gatherer groups, resilience can be manifested through the formation of new contact networks in response to the unpredictability of key resources, the development of new technologies, and the adjustment of resource selection as well as provisioning strategies under changing environmental scenarios (Lancelotti et al., 2016; Turck and Thompson, 2016; Yacobaccio et al., 2017).

Among diverse hunter-gatherer societies, coastal groups that depend extensively on marine resources deploy a specialized ecological niche with remarkable adaptive capacity to cope with littoral and coastal environmental fluctuations (Fitzhugh, 2012; Hudson et al., 2012; Turck and Thompson, 2016). Livelihood strategies include harvesting coastal benthic resources as well as procuring raw materials from inland areas. This requires a deep understanding of the predictability and productivity of local ecosystems as well as environmental factors affecting the dynamics of coastal hunter-gatherer communities across different time scales (Arriaza et al., 2008; Flores and Thakar, 2023; Santoro et al., 2017a).

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Studying coastal hunter-gatherer and fishermen communities in the Atacama Desert is key to understanding the complex interplay within socio-ecological systems. It provided valuable insights into human resilience, ecological adaptation, and the evolution of cultural practices. For instance, archaic groups that inhabited the Atacama coast were complex hunter-gatherers fishermen, with high population densities, semi-permanent settlements, and complex funerary rites (Arriaza et al., 2005, 2008; Arriaza and Standen, 2008; Marquet et al., 2012; Rivera and Rothhammer, 1991; Santoro et al., 2012, 2017a, 2017b; Standen, 1997). These hunter-gatherer-fisher communities that settled in coastal enclaves from Ilo, Peru to the El Loa coast Chile (17° and 21°S), demonstrate remarkable socio-cultural adaptability. Their versatility allowed them to capture, process, and consume a diverse array of Pacific coastal resources, sustaining an economic system acutely sensitive to environmental changes in one of the richest coastal environments on Earth coupled with the driest terrestrial ecosystems. These constraints, however, did not prevent them from developing complex mortuary practices, particularly during the Middle and Late Archaic periods, such as intricate mummification procedures of selected individuals of different ages and sexes. These practices, now known as the 'Chinchorro Culture', reflect profound and enigmatic ideological beliefs about life and death, rooted in conceptions that remain largely unknown (Arriaza et al. 2005, 2008; Arriaza and Standen, 2008; Marquet et al., 2012; Rivera and Rothhammer, 1991; Sanz et al., 2014; Standen et al., 2014). While these coastal groups largely preserved their hunter-gatherer way of life into later cultural periods, from the Formative Period onward (around 4.0 cal ka BP), they increasingly incorporated goods produced by inland farmer and pastoral groups through social exchanges, and the traditional archaic funerary practices were abandoned by the integration of new ideological cosmovisions (Carter, 2016; Montt et al., 2021, 2023; Muñoz Ovalle, 2011; Roberts et al., 2013; Santoro et al., 2012, 2017b).

Past fluctuations in key environmental drivers of modern interannual and interdecadal variability in the Atacama Desert (Crispín-De la Cruz et al., 2022; Feldberg and Mix, 2002; Moy et al., 2002; Rein, 2004; Salvatteci et al., 2019; Salvatteci et al., 2022; Valero-Garcés et al., 1996, 2003) appear to have significantly influenced the dynamics of human-environment interactions among coastal hunter-gatherers (e.g., Santoro et al., 2017a, 2017b). The El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), modulate not only the trophic structure and community dynamics of coastal ecosystems but also regional hydrological patterns (Castilla and Camus, 1992; Garreaud et al., 2009; Houston, 2006a, 2006b; Thiel et al., 2007). Archaeological evidence from both Chinchorro-associated sites in northern Chile and hunter-gatherer settlements in southern Peru indicates that resource exploitation patterns likely adapted to these environmental fluctuations (Fontugne et al., 2004; Lavallée et al., 2011; Santoro et al., 2012). While ENSO/PDO-type climatic shifts may have influenced emergent properties in these interactions across different cultural periods, these changes were not always directly tied to population boom-and-bust cycles (Uceda et al., 2021). Still, theoretical models suggest that a positive feedback loop between cultural complexity, paleoenvironmental conditions, demographic trends, and technological innovations was crucial in driving adaptive strategies in the Atacama Desert over the past 14,000 years, ultimately leading to socio-cultural continuities and discontinuities (Gayo et al., 2023; Santoro et al., 2017a).

Capturing the effects of these patterns on socio-ecological systems is, however, challenging when relying on traditional disciplinary methods, as such approaches may overlook the intricate feedback loops that have historically shaped these systems. Interdisciplinary research, therefore, becomes essential -integrating diverse methodologies across both micro and macro scales and leveraging paleoenvironmental records tailored to specific research questions. This approach enables a deeper understanding of resilience within socio-ecological systems, revealing the adaptive strategies that past communities employed to navigate significant environmental shifts. That is, here we examine the long-term coevolutionary relationships among adaptations in material culture among marine hunter-gatherer communities from the Atacama Desert, paleodemographic trends and large-scale climatic variations, including shifts in marine productivity, hydroclimate and ENSO-like fluctuations. We especially explore how pre-Columbian coastal societies adapted to fluctuating marine productivity and environmental pressures, thereby enhancing our understanding of resilience in coastal hunter-gatherer groups throughout the Holocene socio-cultural sequence (ca. 10 to 0.5 cal ka BP).

We focus on Caleta Vitor (CV; 18°45′S, 70°20′W, Fig. 1), one of the best-documented archaeological sites along the western coast of subtropical South America, known for its extensive long-term occupational sequence spanning almost the entire Holocene (Carter, 2016; Carter and Santoro, 2016). The complex of archaeological settlements at CV reveals both burial and habitation areas, with evidence of nearly continuous occupation dating back approximately 9.4 cal ka BP (Carter, 2016; Disspain et al., 2016; Roberts et al., 2013 Swift et al., 2015). Previous studies show that the people of CV adapted their shellfish provisioning strategies in response to changes in marine productivity throughout the Holocene, with malacological diversity increasing during periods of reduced productivity (Carter, 2016; Santoro et al., 2017b).

Due to the lack of direct data on environmental fluctuations, traditional archaeological interpretation of CV social evolution emphasized that hunter-gatherer groups maintained a permanent subsistence coastal economy, with some variation in their technologies and resource procurement methods. It was also stated that the integration of horticultural crops and other elements (e.g., textiles, pottery, metallurgy) produced by nearby farming social groups in coastal valleys, like Vitor of Chaca, did not change the subsistence economy (Carter and Santoro, 2016; Roberts et al., 2013). It was recognized, however, that cultural shifts did occur at CV in burial practices that integrated goods yielded by new technologies such as ceramics and complex weavings, cultivated crops (Carter and Santoro, 2016; Gayo et al., 2020; Martens, 2019; Roberts et al., 2013). Hence, in this article, we present a step forward to understand and explain the socioeconomic strategies adopted by coastal hunter-gatherer and fishermen communities at CV in the littoral of the Atacama Desert. By examining the extensive archaeological record of CV, we explore how these communities navigated environmental changes, maintained a stable coastal economy, and integrated foreign cultural innovations over millennia. We aim to shed light on the complex interactions between humans and the environment, as well as on the resilience and adaptability of these past societies in one of the most arid regions on Earth.

2. Materials and methods

2.1. Study area

CV is situated on the coast of the Atacama Desert, at the mouth of the valley bearing the same name. The area features a semi-perennial river, which supports a riparian formation at the base of a deeply incised canyon (quebrada) that dissects the longitudinal valley (Gajardo, 1994; Luebert and Pliscoff, 2006; Villagrán et al., 1999). The mouth of the valley is flanked by imposing, unvegetated cliffs rising between 700 and 1000 masl, with a narrow marine terrace extending along its southern margin (Martens et al., 2021). Despite the overall hyperaridity, isolated patches of *Lomas* vegetation -remarkably diverse and highly endemic-persist on the steep slopes of the Coastal Range at elevations between 400 and 1000 masl. These "fog oases" are sustained by a thick stratocumulus cloud held in place by a marine boundary layer (García et al., 2021; Muñoz-Schick et al., 2001; Rundel et al., 1991), the influence of which in the vicinity of the study area is spatially constrained -extending northwards to Punta Madrid (18°S) and southwards to localities such as Chipana Hill (21°S) (Gayo et al., 2020).

As part of the western Andean slope, environmental conditions over CV are driven by ENSO. Changes in tropical Pacific Sea Surface Temperatures (SST) influence zonal atmospheric circulation, impacting

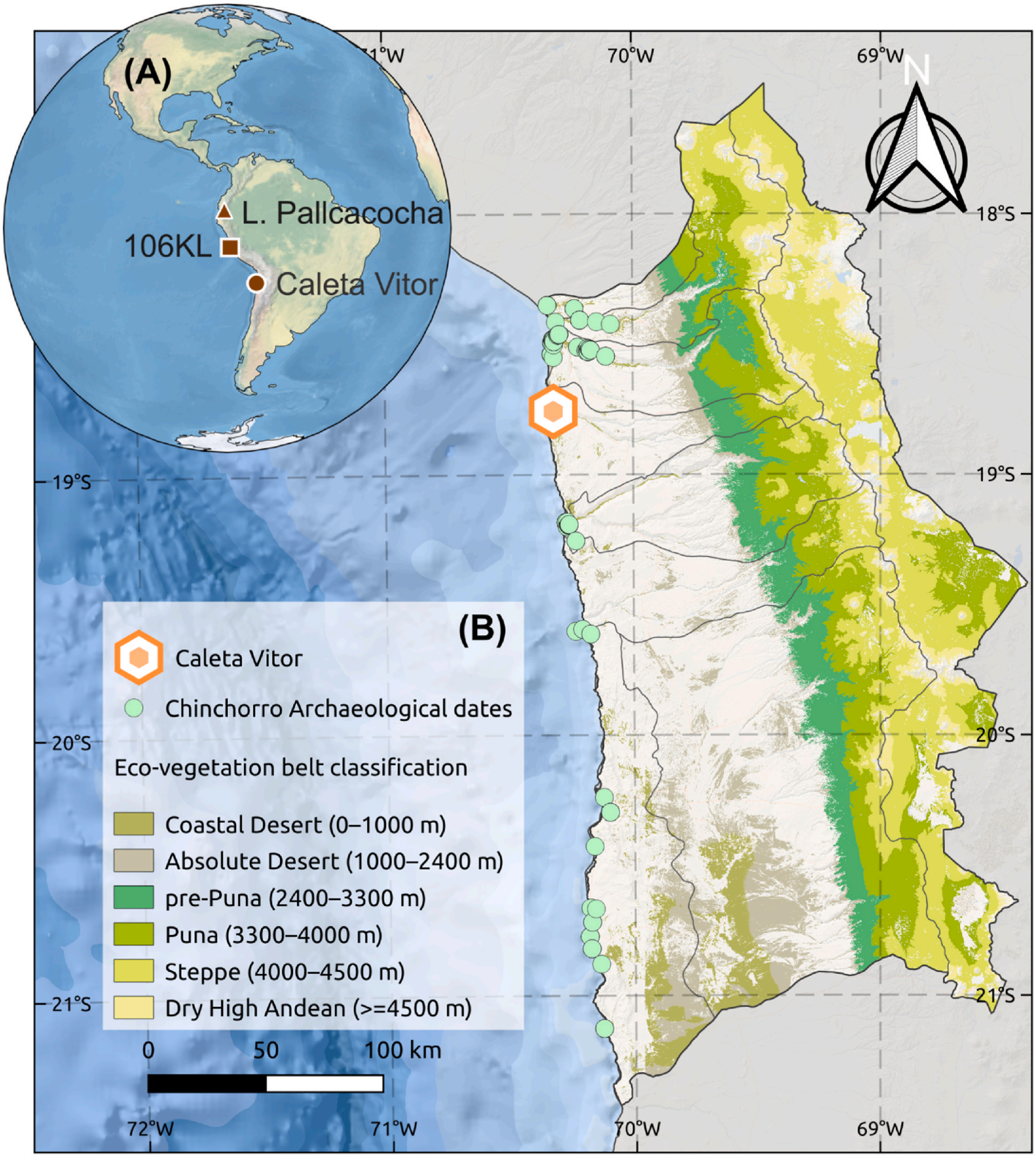

Fig. 1. Local and regional context of dated Chinchorro archaeological sites along the coastal Atacama Desert, Chile, highlighting the location for Caleta Vitor (Bird et al., 2022; Gayo et al., 2015; Latorre et al., 2017). Show the location for paleoenvironmental records considered here, including the 106 KL marine core collected offshore Peru (Rein et al., 2005) and the inland lacustrine record from Laguna Pallcacocha collected at the Ecuadorian Andes (Mark et al., 2022; Moy et al., 2002). Archaeological site of Caleta Vitor and Chinchorro archaeological dates from previously published databases and map shows six elevation zones cross-classified by vegetation presence (SAVI >0.1) as: Coastal Desert (0–1000 m): NV (class 10), V (class 11); Absolute Desert (1000–2400 m); pre-Puna (2400–3300 m); Puna (3300–4000 m); Steppe (4000–4500 m); Dry High Andean Steppes (≥4500 m). Data sources: USGS/SRTM DEM and the Copernicus Sentinel-2 Surface Reflectance products (2020) does not require an explicit citation, since it is standard, openly available satellite imagery. Processed in Google Earth Engine and Python.

summer rainfall patterns in inland areas as well as affecting hydrological systems and coastal upwelling intensity along the southwestern Pacific coast of South America. That is, during La Niña (El Niño) phase, enhanced (reduced) tropical easterlies facilitate (obstruct) moisture influx from the Amazon, leading to increased (decreased) precipitation at elevations above 2000 masl, promoting increased (decreased) runoff in some few semi-perennial and perennial rivers that into the Pacific coast (Houston, 2001, 2006a, 2006b). In marine ecosystems, variations in bioproductivity along the South Eastern Pacific coast are closely linked to coastal upwelling intensity. Between 16° and 25°S, permanent (aseasonal) bursts of cold, oxygen-poor and nutrient-rich waters sustain high primary productivity year-round (Thiel et al., 2007). Still, during the cold (warm) phase of ENSO, the coastal upwelling is increased (subdued), resulting in augmented (subdued) marine bioproductivity, which feeds complex trophic chains through a bottom-up cascading process (Holmgren et al., 2001; Jaksic, 1998, 2001; Thiel et al., 2007).

Most CV archaeological sites (except CV7) are located to the south of the wash from where it is possible to easily access marine resources (Carter, 2016; Carter and Santoro, 2016; Martens et al., 2021). Based on systematic surveys the area was divided in seven large shell midden sites or concentrations of archaeological evidence numbered CV1 to CV7 (Carter, 2016). The sites mostly correspond to dense deposits of shell middens and different types of funerary contexts, although artificial mounds and rock art panels are also found in nearby caves and at the base of the coastal escarpment (Carter and Santoro, 2016). Several excavations have been conducted, comprising 12 trenches of 1 m × 0.5 m, which were placed over profiles previously open due to navy field operations. The selected profile, however, of intact deposits allowed to follow natural stratigraphic layers except for four trenches excavated in artificial layers of 0.1 m or 0.05 m (Carter, 2016). Additionally, other studies have excavated detailed 15 × 10 cm and 5 cm thickness stratigraphic columns on previously exposed profiles of the same archaeological sites, aiming at obtaining biogeochemical records to reconstruct past upwelling dynamics (Latorre et al., 2017).

Over 70 published radiocarbon dates (Supplementary Data, mmc1) define the occupational sequence of seven archaeological sites from Caleta Vitor (Fig. 2), encompassing nine occupation phases. These phases were determined using the non-parametric estimates for statistically significant occupation periods, calculated with the Bchron Density function of the Bchron package for R (Parnell et al., 2008). The sequence aligns with major cultural periods proposed for the Atacama Desert (Carter, 2016; Santoro et al., 2016), including the Early Archaic (13–7.5 cal ka BP), Middle Archaic (7.5–6.0 cal ka BP), Late Archaic (6.0–4.0 cal ka BP), Formative (4.0–1.5 cal ka BP), Middle Horizon (1.5–0.9 cal ka BP), Late Intermediate Period (LIP, 0.9–0.6 cal ka BP), and Late Period (LP, 0.6–0.5 cal ka BP).

2.2. Testing coastal economy and cultural innovations

To test the hypothesis that a stable coastal economy was maintained while integrating cultural innovations over millennia, we conducted an exhaustive literature review of the available written material of all CV sites. In practice, we surveyed and gathered archaeological data that allow us to trace changes either in the material culture or ecofacts/biofacts (Carter, 2016; Carter and Santoro, 2016; Martens, 2019; Roberts et al., 2013; Santoro et al., 2017a, 2017b; Swift et al., 2015). Specifically, we compiled a dataset in which the presence or absence of three categories of tools (lithics, bone tools and fishhooks) and burials was recorded (Table 1). We focused on the examination of funerary practices, tools and the characteristics of the material culture as these elements reflect not only technological and subsistence adaptations in the Atacama Desert but also the emergence of social complexity driven either from shifts in environmental or demographic conditions (Marquet et al., 2012; Gayo et al., 2024). To maintain chronological control while reconstructing the cultural trajectory, we selected previously dated information. This selection process was guided by the criterion of including only archaeological information that either has absolute dating or is explicitly assigned to cultural periods by the original authors (see Supplementary Data mmc2 and Tables S1–S3 in mmc3, c2).

Table 1
Variables used to assess their continuity and change through the Caleta Vitor cultural sequence.

Category	Descriptor Variable	Sources
Burials	**Type of burial:**	Carter, 2016; Martens, 2019; Roberts et al., 2013; Swift et al., 2015
	1. Scatters human remains	
	2. Skeleton	
	3. Mummy bundle	
	Other attributes:	
	1. Site	
	2. Origin (excavation/ surface collection)	
	3. Phase	
	4. Age	
	5. Position	
	6. Isotopes code analyzes	
	7. Body treatment	
	8. Grave goods	
	9. Diseases	
Bone tool	1. Points for fishing spears	Carter, 2016
	2. Points for composite fish hooks/lures	
	3. Chisels	
	4. Barb shafts	
Lithic tool	1. Bifacially flaked points	Carter, 2016
	2. Unifacially retouched points	
	3. Coarsely denticulated points	
	4. Stemmed points	
	5. Chopping tools	
	6. Possible scrapers	
	7. Sinkers	
	8. Exotic materials	
Fishhooks	1. *C. Chorus* shell fishhook	Carter, 2016
	2. Cactus fishhook	
	3. Copper fishhook	

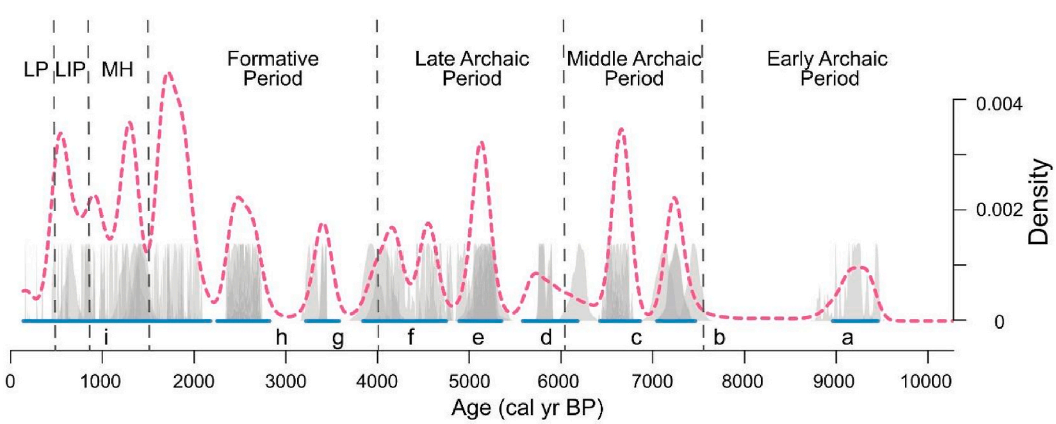

Fig. 2. Chronology of archaeological sites from Caleta Vitor based on the summed probability distribution (SPD, solid magenta curve) of 70 radiocarbon dates (Supplemental Data, mmc1). Horizontal blue bars represent non-parametric estimates of statistically significant occupation phases (at a 0.95 probability level), with letters a-i at the bottom indicating phases at the following intervals: 9.4–8.9, 7.5–7.0, 6.9–6.4, 6.2–5.6, 5.4–4.9, 4.8–3.8, 3.6–3.2, 2.8–2.3, and 2.2–0.1 cal ka BP. Grey curves represent the 95 % highest density for individual radiocarbon dates. Vertical grey dashed lines mark major cultural periods for the northern coast of the Atacama Desert. MH: Middle Horizon, LIP: Late Intermediate Period, LP: Late Period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.3. Proxies for changes in paleodemographic trends and paleoenvironmental conditions

We performed a paleodemographic reconstruction using proxy data to estimate population sizes, in turn based on the 'ages-as-data' method. This approach assumes that the accumulation of archaeological radiocarbon dates over a specific area reflects both the intensity of human activities and the levels of energy consumption and production (e.g., Freeman et al., 2018; Gayo et al., 2015, 2019; Godoy-Aguirre et al., 2024). We reconstructed the Summed Probability Distributions (SPDs) of calibrated radiocarbon dates to track changes in population levels over time. To generate the SPDs, we selected 297 archaeological radiocarbon dates that reflect paleodemographic trajectories in the coastal Atacama Desert, particularly in the area occupied by the Chinchorro groups until the middle Holocene (i.e., 18–21°S/71-70°W; Santoro et al., 2012). These data were extracted from previously published databases (Bird et al., 2022; Gayo et al., 2015; Latorre et al., 2017), comprising 283 terrestrial and 14 marine ^{14}C-dates on terrestrial and marine samples, respectively. The SPDs for archaeological dates was generated in the '*rcarbon*' package v1.5.1 for R (Crema and Bevan, 2021) by using *SHCal20* (Hogg et al., 2020) and *Marine20* (Heaton et al., 2020) calibration curves for dates on terrestrial and marine samples, respectively. We summed unnormalized calibrated radiocarbon dates over the period between 10.0 and 0.5 cal ka BP to avoid the edge effect. We applied a bin size of 100 years to reduce the impact of the overrepresentation of specific chronological phases and/or archaeological sites (Crema and Bevan, 2021).

Available paleoclimate reconstructions on the impact of ENSO-driven shifts in paleoenvironmental conditions in the Atacama are characterized by temporal discontinuity and poor resolution, providing qualitative and comparative insights into the direction of past changes in hydroclimate and coastal upwelling dynamics. The lack of data on the absolute magnitude or intensity of paleoclimate conditions complicates the integration of these reconstructions into models of human-environment interactions in the Atacama Desert (Gayo et al., 2024). Therefore, our work draws on high-resolution Holocene paleoclimate records available for other areas of the Pacific coast of South America. Specifically, we selected the annually resolved relative concentrations of photosynthetic pigments in the marine sediment core SO147-106 KL retrieved offshore Peru at 12°S (Rein et al., 2005). Variations in the relative concentrations of carotenoid in this record serve as a proxy for shifts in marine bioproductivity resulting from changes in the coastal upwelling intensity. While changes in the accumulation of terrestrial clasts provides insights into variations in runoff discharge to the Peruvian shelf, driven by fluctuations in the intensity/magnitude of coastal rainfall. Additionally, we considered statistical data derived from a principal component analysis of elemental compositions of different laminated sediment cores collected in Laguna Pallcacocha to reconstruct the ENSO-driven flood history in the Ecuadorian Andes (9°S) (Mark et al., 2022). The relationship between hydroclimate patterns and ENSO along the western Andean slope north of 18°S, however, differs from that observed at the latitude of the CV. In this region, La Niña (El Niño) events correlate with reduced (increased) rainfall, leading to diminished (amplified) discharge of runoff into the Pacific Ocean (Rein et al., 2005; Mark et al., 2022). So, an antiphase relationship is expected between the proxy record for changes in the coastal upwelling dynamic and hydroclimate conditions inferred either from marine or terrestrial sediment cores.

To assess significant shifts in paleoclimate conditions and gain a deeper understanding of how these environmental changes influence human adaptive strategies at CV, we implemented a change detection analysis. Specifically, we applied independent change-point analysis to standardized and detrended time series for relative concentrations of carotenoids in the SO147-106 KL marine sediment core, as well as to data derived from the principal component analysis of elemental compositions of sediments from Laguna Pallcacocha. The Empirical Mode Decomposition (EMD) method was employed to detrend each time series, and the data were standardized by subtracting the mean and dividing by the standard deviation. Subsequently, change-point analyses were conducted using the R package strucchange v1.5-1 (Zeileis et al., 2002, 2003). Additionally, we employed statistical techniques of spectral analysis and wavelet transforms, to examine the relationship between the ENSO-driven paleoclimate signals captured in the flood record from Laguna Pallcacocha and in the marine bioproductivity off the coast of Peru. The Cross-Wavelet Transform (XWT) method was employed to evaluate how the signature of changes in hydroclimate and coastal upwelling exhibit significant covariance across both time and frequency domains during the Holocene. Building on the results from the XWT, we applied the Wavelet Transform Coherency (WTC) method to quantify the strength and examine the phase relationship between the two selected time series. The WTC method is particularly useful for identifying regions in time-frequency space where the two signals are significantly coherent, allowing us to assess the degree of synchronization and determine whether their variations occur in-phase or with a time lag. All wavelet analyses were conducted on each detrended and filtered time series, utilizing the weighted wavelet Z-transform for unevenly spaced datasets in the *Pyleoclim* package v1.0.0 for Python (Khider et al., 2022). This approach was selected due to its ability to handle unevenly spaced datasets, which are common in paleoenvironmental records, allowing for accurate time-frequency analysis while maintaining the integrity of the temporal resolution (Khider et al., 2022).

3. Results

3.1. Trajectory of funerary patterns

Thirty-eight human burials were individualized from the published literature by correlating their origin (site/layer) with other available individual data, such as burial position, age, and offerings (see Supplementary Data, mmc2). Of these, twenty-nine burials come from looted remains collected from the surface, while nine were retrieved from excavations. Twenty-seven burials were assigned to a cultural period based on either direct dating or stratigraphic association. All periods are represented, except for the Early Archaic. Within the Archaic Period, there is clear stratigraphic evidence that three burials specifically belong to the Middle-Late Archaic. However, seven additional burials could only be broadly assigned within the Archaic period, lacking definitive determination regarding their chrono-cultural position within the Archaic period (i.e., Early, Middle, or Late).

Three main funerary patterns are observed throughout the cultural sequence (Fig. 3a). The Archaic burials are characterized by scattered human remains and skeletons buried in extended positions, with offerings that include feathers, reed matting and lithic tools. Notably, the only documented body treatment involves bird skin attached to a human mandible. From the Formative Period onward, funerary patterns involve burial chambers (Fig. 3). Specifically, Formative burials feature scattered human remains and skeletons in a side-flexed position. Offerings comprise reed and woven mats, baskets, pottery, bone tools and shell beads, with burial forms that include mounds, timber posts and underneath boulders. The third funerary pattern, spanning the Middle Period to Late Period, is represented by exposed skeletons, scattered human remains and mummy bundles in a seated position. Funerary offerings include feathers, bird skin, reed, woven matting, textiles, ceramics and unique items such as a bow and arrow burial.

3.2. Distribution of archaeological tools through occupational sequence

A diverse array of artifacts, including bone tools, lithic typologies, and fishhooks, provides a comprehensive understanding of the technological adaptations and cultural practices of CV inhabitants during the past 10,000 years (Fig. 3). Four categories of bone artifacts, all related to

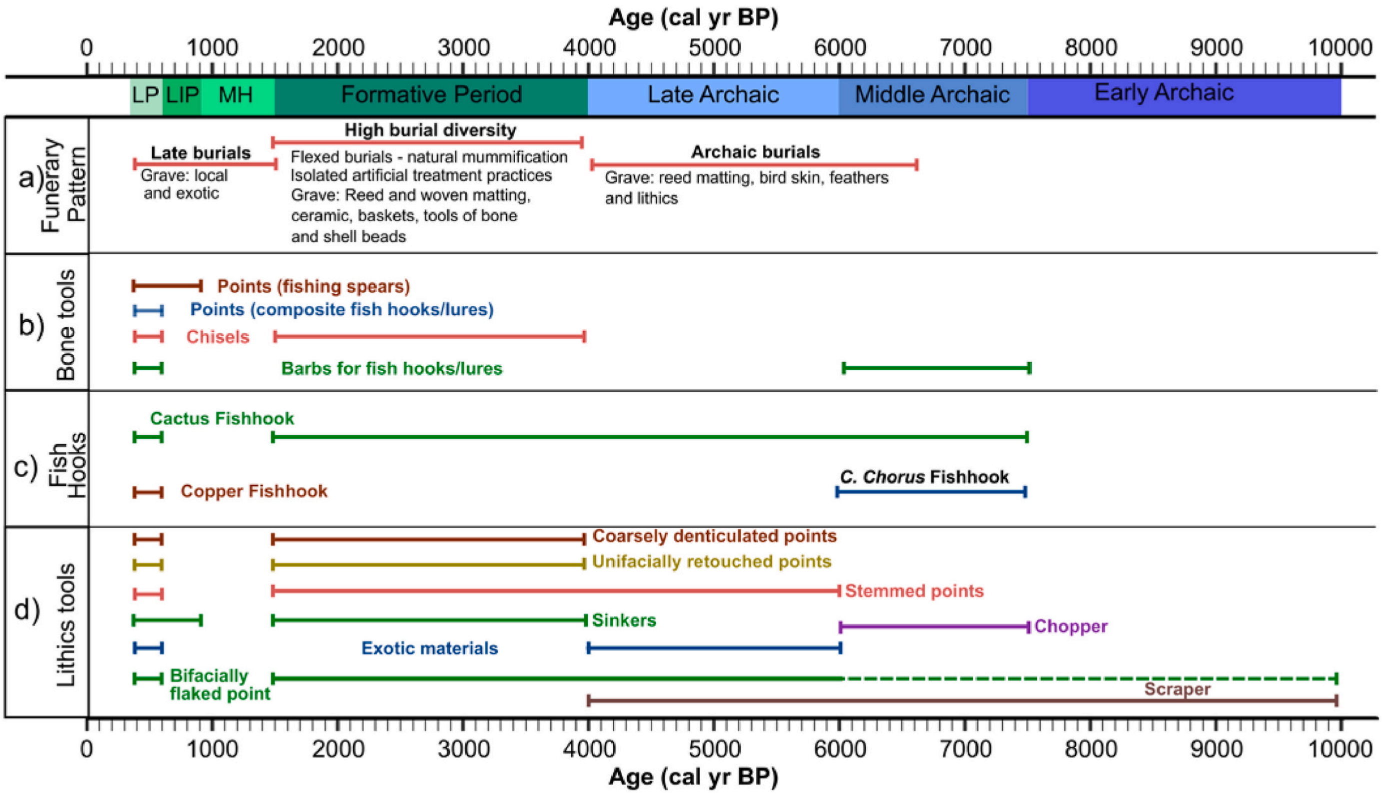

Fig. 3. Temporal distribution of funerary patterns and technological tools along the occupational sequence of Caleta Vitor archaeological sites.

fishing practices, have been documented in the literature (Fig. 3b). These include fishing spear points (n = 6), composite fishing hook or hook points (n = 3), chisels (n = 3), and shafts for fishhooks or lures (n = 3). Overall, barbs are scarce in the archaeological record of CV but are present throughout much of the Middle Archaic and Late Periods, suggesting a potential shift in fishing techniques or preferences over time. Chisels are primarily found during the Formative and Late Periods, suggesting that these tools were more prominent in specific cultural phases. Fishing spear points appear later in the archaeological sequence, emerging during the Middle Horizon, while composite fishing hooks and lure points are predominantly found in the Late Period (Supplementary Data, Table S1).

Our review reveals that at CV three categories of fishhooks are clearly identified, such as a *Choromytilus chorus* fishhook (n = 1), cactus fishhooks (n = 7) and copper fishhook (n = 1) (Fig. 3c) (Supplementary Data, Table S3). Cactus and *C. chorus* hooks first appear during the Middle Archaic. Shell hooks, which are specific to this cultural period, were not recorded in any subsequent periods at CV archaeological sites. In contrast, cactus fishhooks display a broader temporal distribution, appearing in stratigraphic layers associated with the Late Archaic, Formative, and Late Periods. This suggests that cactus hooks remained an important fishing tool across multiple cultural phases. The single copper fishhook is chronologically linked to the Late Period.

The diversity of lithic tools in the archaeological record is greater than that of bone tools and fishhooks; in fact, eight distinct lithic types have been identified and assigned to specific cultural periods (Fig. 3d; Table S2). These types include coarsely denticulated points (n = 3), stemmed points (n = 7), sinkers or lures (n = 8), bifacially flaked points (n = 33), unifacially retouched points (n = 6), scrapers (n = 4), chopping tool (n = 1), and lithic exotic material (n = 3). Throughout the temporal sequence, a considerable number of flaked pieces and core fragments are recorded; however, a clear temporal distribution for these categories could not be established (Carter, 2016). While non-local or exotic lithic materials are relatively scarce, they are present in both the Late Archaic and Late Period levels, suggesting that trade or exchange networks may have existed during these times. In contrast, scrapers are consistently observed from the Early to Late Archaic, highlighting their enduring utility in the subsistence strategies of these populations. The only chopping tool in the entire sequence dates to the Middle Archaic, underscoring the significance of this period for unique tool-making techniques. Bifacially flaked points emerge as the most prevalent lithic artifacts in the sequence, with a continuous distribution from the Archaic Period -although without precise chronology-extending into the Formative Period. Still, these points are absent in subsequent periods until their reappearance in the Late Period. Denticulated and unifacially retouched points first appear late in the sequence during the Formative Period, followed by a hiatus until the Late Period. Stemmed points are documented from the Late Archaic to the Formative Period, after which there is a gap until their reemergence in the Late Period. Similarly, sinkers or lures are also found late in the Formative Period, with a slightly shorter gap before they reappear during the Late Intermediate and Late Periods.

3.3. Paleodemographic reconstruction for coastal northern Chile

The unnormalized SPD curve for calibrated ^{14}C-dates (Fig. 4), suggests that population levels in the Coastal Atacama Desert where CV sites remained low at the beginning of the sequence until approximately 7.0 cal ka BP. Thereafter, a rapid increase is observed, with a notable decline around 5.5 cal ka BP, followed by a peak at approximately 4.2 cal ka BP. Population levels decline until around 3.7 cal ka BP, after which another upward trend is evident between 3.7 and 2.2 cal ka BP. This is followed by a brief decline, with a rapid recovery starting around 2.0 cal ka BP. After this time, a relatively continuous growth pattern is observed, with the highest population level in the sequence occurring between the Late Intermediate Period (LIP) and the Late Period (LP), approximately 1.2 and 0.6 cal ka BP.

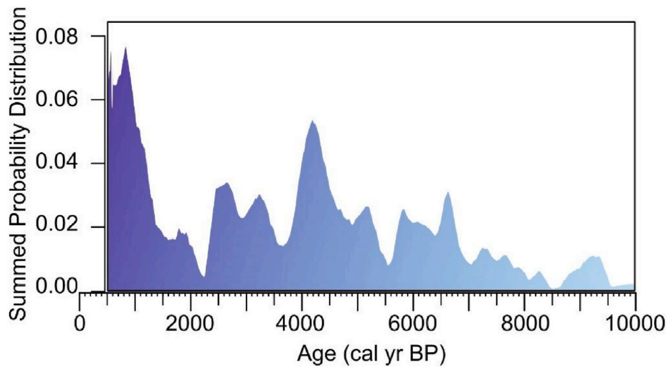

Fig. 4. Time series for population levels inferred from the unnormalized Summed Probability Distribution of calibrated radiocarbon dates from coastal archaeological sites in the Atacama Desert.

3.4. Paleoenvironmental trends

Major changes are observed at ca. 8.5, 6.9, 5.4, 3.9 and during the last 1.5 cal ka BP (Fig. S3a). The 106 KL marine sedimentary sequence time series analysis has seven optimal break dates, corresponding to ca. 8.5, 7.0, 5.5, 3.9 and 2.4 cal ka BP (Fig. S3b). The first statistically significant frequency changes, spanning approximately 10 to 9.0 cal ka BP, are characterized by increased pigment values. However, we do not observe any significant change in the XRF frequency from the Laguna Pallcacocha record (Fig. 4, S1 and S2). During these intervals, wavelet analysis shows significant variability along the coast of Peru in both lithic and carotenoid fluxes. The XWT analysis reveals a periodicity centered between 10 and 50 years, particularly during the interval between ~10.0 and 8.0 cal ka BP (Fig. 5, S1 and S2). A decrease in frequency in both records is observed after ca. 9.0 and 8.0 cal ka BP (Fig. 5, S2 and S4). Between 5.5 and 5.0 cal ka BP, a significant shift takes place for pigment concentration (Fig. S4). From 4.5 cal ka BP onwards, wavelet analysis begins to detect significant changes in the frequency of lithics and pigment concentration. This change lasted until ca. 2.0-2.5 cal ka BP for both the coast of Peru and the PC1-XRF Pallcacocha lacustrine sequence. Subsequently, from 2.5 cal ka BP to the present (calibrated to 1950), the wavelet analyses show increased variability in both datasets.

4. Discussion

Fishing and shellfishing appear to have been the primary subsistence activities throughout the cultural occupation of CV (Carter, 2016). Although lithic and bone tool assemblages associated with fishing from the Archaic period are scarce, making it challenging to identify specific changes across subperiods (Fig. 3), alternative sources of evidence may provide insight into subsistence strategies. A comprehensive review of regional paleoenvironmental data, along with marine resource assemblages from CV archaeological sites, offers valuable clues about fishing and collecting practices as part of human strategies to cope with maritime fluctuations throughout the Holocene.

Rein et al. (2005) and Kaiser et al. (2008) documented that SST off the coast of Peru and north-central Chile were approximately 2°C warmer than present during the Early Holocene. Rein et al. (2005) also observed a high frequency of ENSO events during this period, which were associated with severe El Niño-driven floods (Fig. 5 and Fig. S4), which is supported by the SST anomaly record from shells at archaeological sites from Peruvian sites (Carré et al., 2005). In contrast, SST records based on archaeological mollusk shells from central-southern Peru and northern Chile indicate cooler-than-present coastal temperatures during the Early Archaic, suggesting higher nutrient levels likely driven by enhanced coastal upwelling (Carré et al., 2014; Flores and Broitman, 2021; Ortlieb et al., 2011; Vargas et al., 2006). Differences between offshore and inshore SST, may be interpreted as a proxy for oceanographic dynamics linked to the coastal transition zone (Hormazabal et al., 2004). Warm offshore and cold inshore SST, may indicate a transition zone close from shore and a strong seaward temperature gradient influencing coastal ecosystems in terms of abundance and distribution of available resources (Broitman et al., 2001; Flores and Broitman, 2021; Salvatteci et al., 2019). Despite these dynamics, the sedimentary ENSO record from Laguna Pallcacocha (Fig. 5, Fig. S2) shows no significant changes in interdecadal variability during this period (Mark et al., 2022; Moy et al., 2002).

In addition, flood deposits overlying late Pleistocene archaeological sites suggest ENSO-like events along coastal southern Peru (Sandweiss, 2003). These apparent discrepancies —such as the increase in carotenoid concentration, the El Niño-induced floods along the coast of Peru, with no significant changes in the frequency of El Niño flood events in the southern Ecuadorian Andes (Fig. 5c)— may be attributed to the varying spatial effects of different ENSO-like phases (ENSO 'flavors'; e.g., Central Pacific ENSO/Modoki). These phases likely generated differential impacts on coastal precipitation patterns, upwelling, and glacial activity on the western slope of the Andes at millennial and centennial timescales, which cannot be attributed to orbital changes (Ashok et al., 2007; Houston and Latorre, 2022; Kaiser et al., 2008, 2024; Karamperidou and DiNezio, 2022; Yu and Kim, 2013). The decreased frequency of warming events in the eastern Pacific, due to La Niña-like states, can promote coastal warming by reducing atmospheric stability and destabilizing the ITCZ through atmospheric teleconnections (Wu, 2023). During a coastal El Niño event, the ecosystemic effects can generate substantial losses in biodiversity, especially north of 12°S, with the southern region serving as an eco-refuge for fisheries. This may have favored shore fishing strategies and increased resource selectivity with relatively small human population sizes (Sandweiss et al., 2020).

Although in situ SST and ENSO data are unavailable for the CV area, the lower diversity and greater selectivity of shellfish found at the sites (Fig. 6c) align with the productive oceanographic conditions of the Early Holocene. The abundance of resources likely allowed for a strategy focused on selecting larger, more profitable species, such as *Concholepas concholepas* (Santoro et al., 2017b). Evidence of formalized tools from this period is scarce. Besides scrapers, there are no records of harpoons or specialized instruments, apart from bifacially flaked points found in Archaic period trenches (Fig. 3b), possibly linked to hunting or fishing (Carter, 2016). However, there are no stratigraphically associated dates for these points to assign them a specific temporal distribution within the Archaic period. While there is ongoing debate regarding the use of nets during the Early Holocene on the northern coast of Chile (Martens, 2019; Rebolledo et al., 2021; Disspain et al., 2016), it has been suggested that the abundance of smaller fish at Caleta Vitor, especially during the Early Archaic, may indicate they were caught using nets (Carter, 2016; Rebolledo et al., 2021). Indirect evidence includes a cord fiber holding a shell bead, dated to 8662–9487 cal ka BP, suggesting early fiber work for net-making (Carter, 2016; Martens, 2019). Additionally, the absence of Early Archaic tool kits and burials at Caleta Vitor supports the idea of a small, highly mobile population with few territorial markers during this period (Marquet et al., 2012).

One of the earliest and most marked environmental changes in the time sequence corresponds to a loss of ENSO-like variability at the time of transition between the Early and Middle Archaic (ca. 8.5 and 5.5 cal ka BP, see Fig. 5) (Mark et al., 2022; Marquet et al., 2012; Moy et al., 2002; Rein et al., 2005). At 25°S, the SST record shows a peak in warm temperatures during the early Middle Holocene (7.6–7.0 cal ka BP), indicating a period of reduced coastal upwelling activity (Carré et al., 2014; Flores and Broitman, 2021; Ortlieb et al., 2011; Vargas et al., 2006). These conditions of reduced ENSO-like variability remained relatively stable across the region until ca. 5.5–4.0 cal ka BP and coincided with arid conditions in the Chilean Andean Altiplano (Giralt et al., 2007; Grosjean et al., 2001; Moreno et al., 2007; Rein et al., 2005;

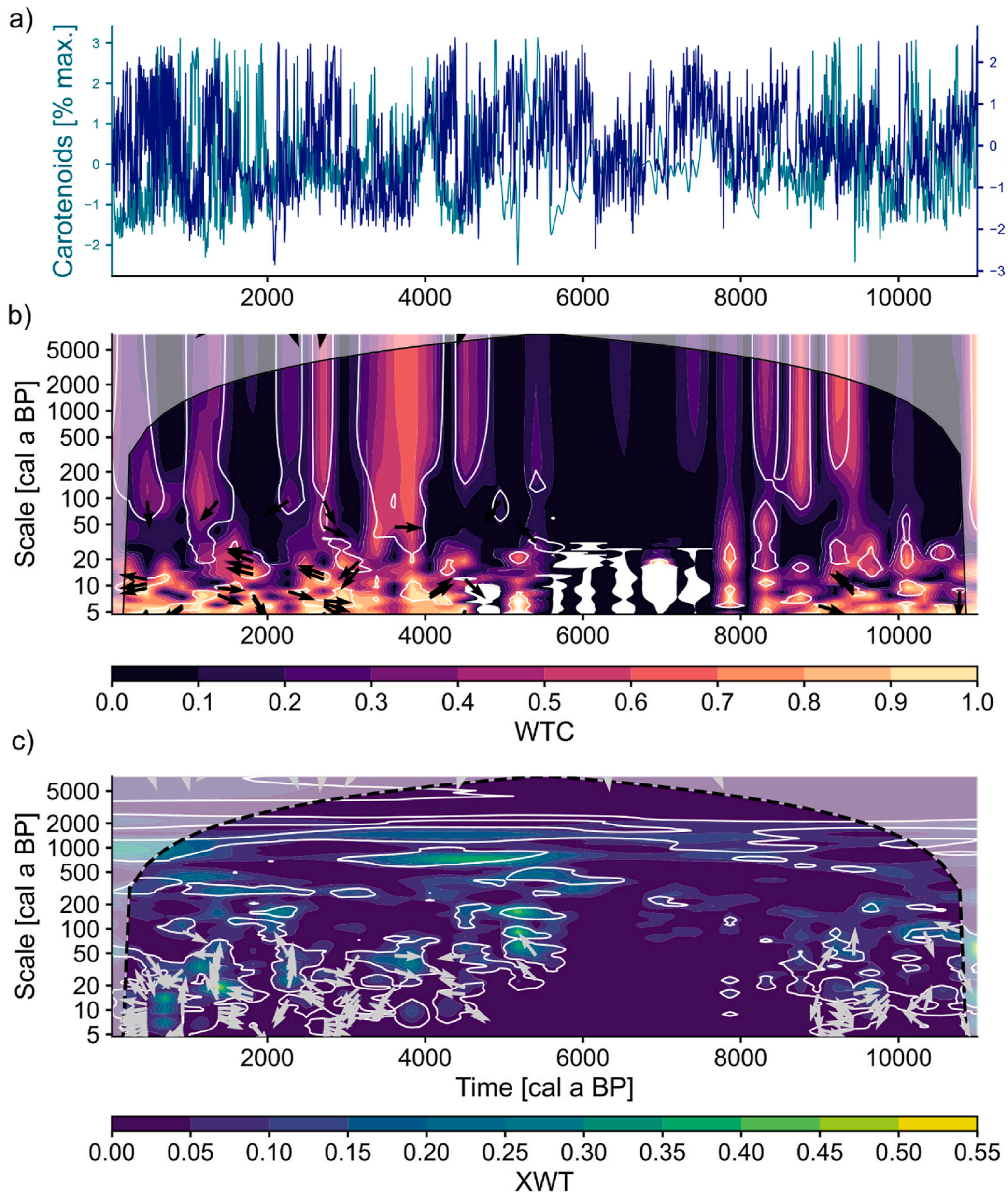

Fig. 5. Time series and Wavelet Transform Coherency (WTC) analysis using Weighted Wavelet Z-transform applied to data on carotenoid from the 106 KL marine sedimentary record off the Peruvian coast (Rein et al., 2005), and the XRF PC1 from the Pallcacocha lacustrine record from the Ecuadorian Andes; spanning the last 10,000 years (Mark et al., 2022; Moy et al., 2002). (a) Time series of carotenoids [% max] and XRF PC1 data, showing fluctuations over the last 10,000 years. (b) Wavelet Transform Coherency (WTC) analysis illustrating the strength of coherence between the carotenoid [% max] series and the XRF PC1 series (c) Cross-Wavelet Transform (XWT) analysis showing common power between the two-time series, with regions of significant coherence indicated by contour lines.

Valero-Garcés et al., 1996). Compared to the Early Archaic shellfish assemblage, people inhabiting the CV area during the Middle Archaic appear to have targeted a greater variety of mollusk species (Fig. 6c. Santoro et al., 2017b). The presence of fishhooks made of cactus, shell, and bone barbs for fish hook or lures, as well as the maintenance and addition of new lithic categories (scrapers and chopping tools) indicates also the development of technologies associated with new activities (Fig. 3). Despite this marked increase in artifacts diversity, fish data maintains the Early Archaic pattern with higher abundance of very small fish (Clupeidae and Engraulidae), and low amounts of fish of major sizes. In addition, the presence of threads begins to be ubiquitously mentioned in the trenches with dates associated to this period (Carter, 2016), with a preponderance of undetermined plant fibers and to a lesser extent, camelid fibers and cotton (Martens, 2019) (Fig. 6e). This entire body of broadened artifactual evidence can be related to the exploration of new habitats and the expansion of selected species in response to a decline in productivity in the area, but it also reinforces the idea of a population increase at the CV sites. These results highlight that drastic environmental changes after the Early Archaic did not end up in population "collapses" on the coast, but stimulated adaptation changes in technology, activities and a slight increase in human occupation beginning around c. 7000 to c. 4000 cal ka BP (Fig. 6j). This in agreement with previous analyses based on smaller data sets from the area (Gayo et al., 2015; Marquet et al., 2012). Although territoriality may have intensified during periods of higher population size, previous studies have noted that intergroup violence did not significantly increase at this time (Standen et al., 2020). However, some territorial practices were exercised through the marked presence of mortuary rituals (Marquet et al., 2012). Indeed, the first burials in CV sites characterized by scattered human remains and skeletons in extended position, is coincident with an

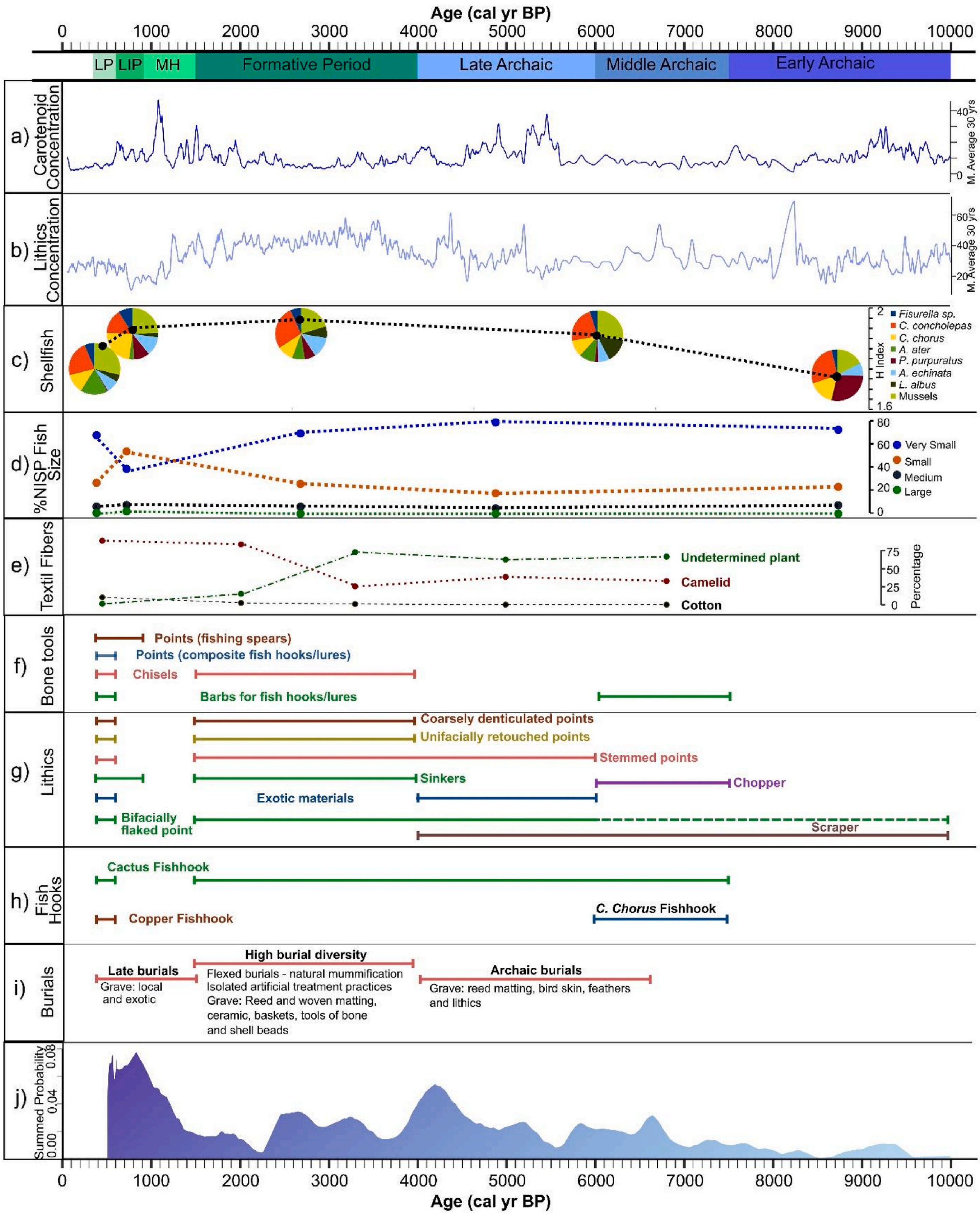

Fig. 6. (a) Carotenoid concentration from a marine core taken offshore of Lima (Rein et al., 2005). (b) Lithic concentration from the same area as a proxy of ENSO (Rein et al., 2005). (c) Shellfish assemblage from CV (Santoro et al., 2017b). (d) Number of identified specimens (%) of CV fish assemblage by prey size (Santoro et al., 2017b). (e) Textile fibers percentage from CV through the cultural sequence (Martens, 2019). (f) Presence-absence of bone tools categories in the CV cultural sequence. (g) Presence-absence of lithic tools categories in the CV cultural sequence. (h) Presence-absence of fishhooks types in the CV cultural sequence. (i) Types of burials identified through the occupational sequence of CV. j) Distribution of summed probabilities as a proxy for coastal occupation (18-21°S/71-70°W) over the last 10,000 years.

SPD that shows a growing population in the region (Fig. 6i and j).

During the Late Archaic (6.0–4.0 cal ka BP), some characteristics observed at the beginning of the Middle Archaic seem to be maintained, such as high shellfish diversity, the rank abundance of fish size types, and the composition of the different textile fibers. Some of the differences with the previous period are the disappearance of bone tools and shell fishhooks, and the appearance of stemmed points and exotic lithic materials, together with an increased but highly fluctuating population density (Fig. 6j). This may be interpreted as changes in the tools used in the acquisition and process of resources but without modifying what is being acquired, and probably linked with the higher number of people participating in the tasks of resource acquisition and use. The funerary patterns also continue from the previous period, with offerings made of reed matting arrangements, feathers and lithic artifacts. The only case of body treatment shows an individual with bird skin attached to his jaw, which is a typical pattern for the so-called "black" or "red" mummies (Arriaza et al., 2008). In addition to burial as territorial markers, the larger population size could also be related to the occurrence of the first no local materials (i.e. different kinds of quartzite), suggesting augmented contacts or more circulation networks during this time of increased regional coastal human occupation (Fig. 4).

A new major change in environmental conditions is detected around 4.0 cal ka BP, relatively synchronous with the transition between the Late Archaic and Formative Period (Fig. 6a–b). A downward trend in marine productivity begins around this time, reaching its lowest point during the Formative Period (c. 3.0 cal ka BP) (Fig. 6a–b). A shift in interdecadal climatic variability began around 4.0 cal ka BP, with a gradual recovery of cyclicity observed in the sedimentary records of the Peruvian coast (Fig. 5) (Mark et al., 2022; Moy et al., 2002; Rein et al., 2005) and other regions of north-central Chile (Frugone-Álvarez et al., 2017, 2020, 2025; Grosjean et al., 2001; Jenny et al., 2002; Moreno et al., 2007; Valero-Garcés et al., 1996; Villa-Martínez et al., 2003). Around 3800 years ago, a major earthquake and tsunami impacted 1000 km of coastline (18–25°S), likely causing significant social disruptions among prehistoric hunter-gatherer-fisher communities (Salazar et al., 2022). Cultural changes at this time occurred in the CV archaeological area in several ways. There is a change in funerary patterns with different types of body treatments and offerings. Although a wide diversity of funerary patterns suggests an increased number of people occupying the sites, a greater population load is not observed in the SPDs (Fig. 6j). On the contrary, a population decline on the coast of the region is evident during the Archaic-Formative transition, along with the decline in coastal productivity (c. 4.0 cal ka BP).

In comparison to the present conditions of decreased marine productivity and greater variability of ENSO cycles, the Formative Period in the CV record shows changes that could shed light on adaptation strategies toward a broader set of subsistence strategies. A wide set of tools was added to the lithic assemblage, where fishing weights and different types of points are found, such as unifacially retouched and coarsely denticulated points (Fig. 6g). Chisels are the only bone tools, but are relevant to mention, considering the gap of bone tools during the Late Archaic. The shellfish assemblage is the most diverse of the entire temporal sequence, which has been proposed as a strategy of greater flexibility in a more complex environmental setting (Fig. 6c) (Santoro et al., 2017b). There is a slight decrease in very small fish and an increase in the representation of larger fish, with a preference for Sciaenids, such as *corvinas* and *ayanque* (Carter, 2016). Selected terrestrial resources also show variation during this cultural and environmental transition, with a marked increase in camelid fibers and decrease in plant ones (Martens, 2019). Some debate exists considering the implications of this change in raw materials, as some regional studies propose that this pattern responds to an increase in exchange networks with highlands (Grogan, 2023; Rothhammer et al., 2009). Stable isotope studies on these fibers show that animals used throughout the whole sequence of Caleta Vitor, from the Archaic to the Formative Period, grazed preferentially on woody mixed vegetation from coastal ecosystems, arguing that people at CV used technologies probably introduced from other localities but using local resources (Gayo et al. 2020). Likewise, supporting the preference of local resources, syntheses of archaeobotanical evidence and isotopic studies on human remains have shown that crops from other localities (Núñez and Santoro, 2011; Ugalde et al., 2021) were not strongly adopted in Caleta Vitor and other coastal areas during the Formative period as was the case in other coastal hunter-gatherer groups (Carter, 2016; Roberts et al., 2013).

Thus, throughout the entire marine hunter-gatherer lifeway recorded in CV archaeological sites, marine productivity predominated despite major changes in and overall conditions. To cope with these fluctuations people flexibilized their pattern of subsistence consumption by diversifying the targeted fish and shellfish resources (Santoro et al., 2017b). In other parts of the world, multiple examples have been observed of how marine hunter-gatherers formulated diverse responses to environmental changes during the Holocene, including the intensification of fishing and shellfish harvesting, as well as the generation of new trade networks (García-Escárzaga et al., 2022; Kennett et al., 2007).

From 2.5–1.2 cal ka BP years onward, the paleoenvironmental record shows a trend towards increased interannual variability in all the analyzed proxy records, together with an upward trend in marine productivity (Fig. 5). These changes are synchronous to the Late Formative Period (ca 2.5–1.5 cal ka BP). Although CV sites have several well-represented occupations in this phase, reviewed literature does not provide precise chronological resolution to establish fine changes in technology, fish abundance and mollusk diversity along Formative sub-periods. Despite better environmental conditions during the Late Formative Period, there still appear to be low population numbers on the coast regionally (Fig. 6j) and funerary patterns are conspicuous in mounds, timber posts and underneath boulders. How do we interpret the relationship between favorable marine conditions-productivity, high technological diversity, changes in fibers raw material, burials as territorial markers but low population?

For the Middle Horizon period (1.5–0.9 cal ka BP), there are yet no reported radiocarbon dates from the excavated sites at CV. Nevertheless, several human bones scattered on the surface were directly dated to this time (Swift et al., 2015), showing that the site was occupied. The lack of shell midden data prevents the characterization of resource use strategies and the artifactual assemblages employed to face environmental conditions of the epoch.

A significant decline in flooding events off the Peruvian coast is observed between approximately 1.2 and 0.8 cal ka BP (Rein, 2004). This reduction is likely attributed to a weakening of ENSO-like conditions, which may have influenced marine productivity in the CV region from around 0.8 cal ka BP to the present. Following this event, ENSO-like variability recovers, maintaining conditions similar to those at present. There has been a declining trend in marine productivity over the last 1.2 cal ka BP, which becomes more prominent over the last 600 years (Fig. 6a, Fig. S3). On the other hand, the cyclicity in the records known so far is not clear, as they show slightly different trends in terms of maintaining interdecadal variability along the coasts of Peru and Ecuador (Fig. S2–S4).

The archaeological periods contemporaneous to this time frame are LIP and LP, which in CV show significant changes in a very short period. New tools focused on fishing activities, such as bone fishing spear points, bone points, and copper fishhooks, together with the reappearance of bone barbs for fishhooks (after a gap since the Middle Archaic), expanded the artifactual assemblage. Fish of slightly larger size than those recorded throughout the entire sequence were favored as never before (Fig. 6d). Mollusk diversity remained high, showing continuity in a broad species selection strategy (Fig. 6c). Coastal population size increased from 1.0 cal ka BP, reaching its peak at 0.7 cal ka BP onwards (Fig. 6j). Other studies have also described a general population increase in the Atacama Desert since 1.0 cal ka BP, which has been explained by the consolidation of coast-interior networks (Mendez-Quiros et al., 2023). Indeed, CV funerary patterns differ from those recorded during the Formative Period, showing evidence of a mixture of local and foreign offerings that would account for greater coastal-interior integration (Fig. 6i).

As suggested by various ethnographic and archaeological studies in the Andes, these funerary practices can be understood as collective acts, actively involving the community and grounded in relational worldviews that attribute animacy to all beings and materials (Brosseder, 2014; Brown Vega, 2016; Fernández Juárez, 1995; Bray, 2009). Although our current data -based on both artifact and ecofact evidence (Fig. 6)-, alongside stable isotope characterizations of human diets (Roberts et al., 2013; Alfonso-Durruty et al., 2019; King et al., 2018), suggest a continuity in the primary reliance on marine resources, the funerary pattern aligns with broader trends observed across the Atacama Desert. Proximity to the coast remains the most significant factor influencing the extent of marine resource consumption, although such resources are present at all sites regardless of period or cultural affiliation (King et al., 2018). The increasing importance of introduced crops, cultivated in inland settlements in the Arica region, especially maize, from the Middle Period (Ugalde et al., 2021) onwards is also reflected isotopically (King et al., 2018). Nevertheless, the persistence of marine resource use over time -even as other cultural practices were adopted-highlights a dietary continuity that cannot be easily disrupted or fully captured through stable isotope analysis alone (King et al., 2018). We emphasize that this continuity should not be interpreted as cultural stasis. On the contrary, it reflects adaptive strategies that allowed people to live in an extreme desert with very limited terrestrial resources, as they dynamically managed the contrasting richness and variability of coastal marine resources —demonstrating resilience rather than stagnation over time.

Despite this maintenance of the traditional way of life, from the Late Period onwards new external cultural influences seem to have strengthened the extraction of coastal resources, adding new fishing technologies to the tool-kit, such as some fishing artifacts that had never been present throughout the entire cultural sequence (bone points for fishhooks/lures), copper fishhooks, and an increase in the use of cotton fibers (Fig. 6). The latter element has proven a key factor in the development of different fishermen societies in the coast of Peru (Beresford-Jones et al., 2018). The decisions to gather and fish a wide range of species, with new technologies for their extraction, may have been encouraged by the relevance of marine and coastal resources at the regional level, both as goods for exchange with the highlands and as fertilization material for inland agricultural fields, which were in great demand during these later periods (Ballester and Gallardo, 2011; 2018; Carter, 2016; Santana-Sagredo et al., 2021). It is notable that the greatest population increase occurred at a time when coastal productivity conditions began a significant decline (from the LIP onward). This could suggest the growing importance of complementarity and cooperation between coastal communities and those from other areas as a key strategy for addressing the challenges posed by the decrease in marine resources.

5. Conclusions

Environmental proxies used in this study show variation in marine productivity on the northern coast of Chile throughout the Holocene (10,000 years to present). Major bioproductive drops are inferred to have brought periods of increased environmental stress, which occurred in the transitions from the Early Archaic to the Middle Archaic (first transition; 13–7.5 cal ka BP), then from the Late Archaic to the Formative Period (second transition; 6.0–4.0 cal ka BP), and more recently, approximately within the last 1000 years (third transition). The archaeological record from CV sites shows diverse adaptation strategies for these transition periods, which involved both economic, social reorganization, and network of interactions.

During the first transition (13–7.5 cal ka BP), linked to the beginning of human occupation along coastal environments, the archaeological record exhibits low coastal population density, and a notable diversification in shellfish species selection, and a wide variety of small fish prey; easy captured from shore, possibly using small nets.

During the second transition (6.0–4.0 cal ka BP) higher environmental stress –lower marine productivity–coincided with a decrease in population density but communities did not abandon coastal settlements. New exchange networks were established to possibly handle harder coastal environments. There was also increased diversity in both shellfish assemblage and tool-kit artifacts (i.e., fishhooks made of cactus, shell, and bone barbs for composed fishhook) that we interpreted as a deliberate shift toward broad subsistence strategies to secure alternative food, with emphasis in small fish prey as in the Early Archaic. This is also an expansion over the capture and consumption of larger fish species. Additionally, the increased use of terrestrial resources, such as plant and camelid fibers, demonstrates complementary multifaceted strategies.

The third transition (last 1000 years), coincides with a period of significant fluctuation towards a decline in marine productivity and increased interaction between coastal and inland social groups. Coastal communities further adopted new technologies to maximize marine resource exploitation, such as the introduction of copper fishhooks and specialized bone tools. This period also saw an increase in the diversity in the captures of shellfish and fished species, and guano mining, which reflect flexible socio-economic strategies to cope with both the possible growing demand of resources for local consumption and for exchange with inland populations, including guano only needed as fertilizer in agricultural fields in lowland valleys and oases. In sum, the entire archaeological record shows that marine hunter-gatherers managed remarkable abilities to adapt to persistent environmental variability and to socially keep going with their traditional habitats, without fully abandoning them, and their way of life.

Author contributions

Conceptualization: EMG, CF,
Methodology: CGA, MFA, EMG, CF.
Validation: CGA, MFA, EMG, CF, CMS, CL.
Formal analysis: CGA, MFA.
Data curation: CGA, MFA, EMG, CF.
Writing – original draft preparation: CGA, MFA, EMG, CF, CMS, CL.
Funding acquisition: EMG, CF
Writing – review and editing, CGA, MFA, EMG, CF, CMS, CL.
Investigation and project administration: EMG, CF.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2025.109580.

Data availability

All data and codes are available at the GitHub repository: https://github.com/mat1506/GodoyCV2024.git. Raw data are also provided as Supplementary Data (mmc 1-2).

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