Tarbiat Modares University

The International Journal of Humanities

Received: 2025/12/01
Accepted: 2026/02/29
Published: 2026/03/14

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How to cite this article: Madihi, M. et al. (2026). The Subsistence Economic Shift in the Southeastern of the Caspian Sea during the Early Holocene Period: Resilience or a Conscious Choice? *The International Journal of Humanities* 33(1): 61–94.

RESEARCH ARTICLE

The Subsistence Economic Shift in the Southeastern of the Caspian Sea during the Early Holocene Period: Resilience or a Conscious Choice?

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Abstract

The interaction between humans and the environment in the southeastern Caspian Sea has always been close and reciprocal due to the region's specific environmental features, including its proximity to mountains and the sea, the coexistence of low-lying coastal plains and high-altitude areas, access to freshwater resources, and diverse flora and fauna. Despite the archaeological importance of this region for understanding Neolithic cultural development, the mechanisms through which environmental instability influenced subsistence and technological transformations at Hotu Cave and Komishani sites remain insufficiently clarified. It is unclear whether the observed cultural changes represent passive responses to environmental stress, resilience-based adaptations, or deliberate processes of cultural niche construction. This study investigates the environmental factors that affected human occupation at those sites during the Neolithic period and examines how local communities responded to these challenges. The research focuses on the relationship between climatic and geomorphological events, including earthquakes, floods, the 10.2 ka and 8.2 ka climatic events, and fluctuations in Caspian Sea levels, and major cultural developments such as the emergence of pottery, shifts in subsistence strategies involving domesticated plants and animals (pig, sheep, and goat), and technological innovations in lithic artifacts. Methodologically, the study adopts a qualitative archaeological approach that integrates stratigraphic, technological, and subsistence data from Hotu Cave with comparative evidence from the Komishani open-air site and regional paleoenvironmental studies. The selection of these two sites was motivated by the availability of recent excavation data that provides new and reliable evidence for reconstructing for this period and environmental dynamics in the southeastern Caspian Sea. The archaeological sequence is analyzed within a chronological framework to explore patterns of human–environment interaction during the Early Holocene. The results suggest that the cultural transformations observed after the interruption during the Transitional Neolithic reflect adaptive strategies through which communities reorganized their subsistence systems and technological practices in response to environmental instability. These developments can be interpreted as forms of resilience and cultural niche construction that enabled human groups in the southeastern Caspian region to mitigate environmental stress and maintain long-term occupation of the landscape.

Keywords: Environmental Change, Climate, Resilience, Niche Construction, Neolithic Period, Southeastern Caspian Sea

Introduction

The examination and reconstruction of the transformation from subsistence economies based on foraging to those based on farming, and the systematic exploitation of the environment to meet basic human needs, have rendered the Neolithic period one of the most critical yet ambiguous periods in world prehistory. This transitional phase has raised fundamental questions regarding the emergence of farming communities, as well as the accompanying economic, social, and ideological changes, namely, the shift from millennia-old practices of hunting, seasonal mobility, and foraging toward sedentism, cultivation, and animal husbandry (Matthews et al., 2013; 2022). Furthermore, the interaction between humans and their environments, the impact of climatic fluctuations, and resource management strategies during this period remain central to archaeological inquiry.

To date, most archaeological research on this period in Iran has focused on the Central Zagros (e.g., Riehl et al., 2013; Zeidi et al., 2022; Broushaki et al., 2016). However, fieldwork and discoveries over the archaeological study in northern Iran particularly in the Mazandaran region along the southeastern Caspian Sea have highlighted this region as a pivotal area for studying the transition from foraging to farming (e.g., Fazeli Nashli, 2017, 2021, 2022, 2023; Abbasnejad Seresti et al., 2024; Vahdati Nasab et al., 2020; Shoaee et al., 2021) and for assessing changes in subsistence strategies, such as the replacement of gazelle and seal exploitation with the herding of sheep and goats, potentially linked to climatic change (de Groene et al., 2023, Safari et al, 2024). The Mazandaran ecosystem is divided into three zones: the Caspian lowland plains, forested areas, and the Alborz mountainous region. As argued by Mozhgan Jayez in her studies of lithic industries in the Caspian Sea, the ecological diversity and rich resource base of the southeastern Caspian littoral promoted continuity in lithic technology and mobility strategies even as subsistence gradually shifted toward food production, so that Mesolithic knapping systems and raw-material procurement patterns were largely maintained into the Neolithic, with only gradual adjustments in tool types and reduction techniques rather than abrupt technological replacement (Jayez & Vahdati Nasab, 2016; Jayez et al., 2023). Evidence of Mesolithic and Neolithic occupations in this region, including the well-known sites of Al Tepe (Ali Tepe) Cave (McBurney, 1968), Hotu and Kamarband Caves (Coon, 1951), Komishan Cave (Vahdati Nasab et al., 2011), Komishani Tepe (Fazeli Nashli et al., 2024) and Touq Tepe and Tepe Valiki (Abbasnejad Seresti, 2020; Abbasnejad Seresti et al., 2024; Abbasnejad Seresti et al., 2025; Asadi Ojaei et al., 2024; Asadi Ojaei et al., 2025), attests to the dynamism of this active ecosystem in attracting and sustaining human settlement. These findings have established Northern Iran as a key region for studying Neolithization processes in both Iran and the broader Near East.

In the 1960s, McBurney introduced novel archaeological methods, such as fine-mesh sieving and the application of paleoclimatic theories (McBurney, 1968: plate XXVIII). By analyzing faunal remains from Ali Tepe Cave in relation to climatic sequences, he sought to interpret subsistence strategies and the impact of climate on Mesolithic lifeways. Moreover, his reanalysis of faunal assemblages from Hotu and Kamarband Caves led him to argue, contrary to Coon, that domesticated sheep and goats appeared suddenly in the Ceramic Neolithic, thereby rejecting a gradual model of animal domestication in the region (McBurney,1964;

1968). These contrasting interpretations gave rise to two principal hypotheses for Neolithization and plant/animal domestication in Northern Iran: endogenous (Ramezanpour et al., 2012; 2014; Fazeli Nashli et al., 2013; Leroy et al., 2019) versus exogenous factors (Vahdati Nasab & Nikzad, 2016; Roustaei, 2016; 2018). More recently, Abbasnejad Seresti and Ojaei have proposed a combined exogenous, endogenous framework for the origins of Neolithic life in the region, based on ceramic analysis and interregional comparisons (Asadi Ojaei et al., 2024). Their survey of 53 sites (15 in upland zones and 38 in lowland plains), 41 of which yielded Neolithic cultural materials, demonstrates a strong intra-regional connection between upland and lowland areas, likely reflecting seasonal pastoral mobility. In contrast, evidence of limited extra-regional interaction with the Gorgan Plain is suggested by the presence of ceramics comparable to those of the Sang-e Chakhmaq/Djeitun traditions. Significantly, their findings highlight a marked increase in Ceramic Neolithic sites (41) compared with Transitional Neolithic sites (only 4), which may be attributed to improved climatic conditions during the mid-seventh millennium BCE following the 8.2 ka climatic event (Asadi Ojaei et al., 2024). Zooarchaeological evidence from Hotu Cave further indicates that wild sheep and goats were subject to pre-domestication management during the Transitional Neolithic (PPN) (this period is also known as the Pre-Pottery Neolithic" (PPN) in the Zagros region, and in this article, it is referred to as the Transitional Neolithic period in the Caspian Sea) (Groene et al., 2023). Isotopic analyses of ceramics also reveal the exploitation of secondary products such as milk and fat, corroborating the emergence of localized, endogenous pastoralism in the southeastern Caspian Sea (Asadi Ojaei et al., 2024, as quoted by Gregg and Slater, 2012). Despite these valuable advances, the specific mechanisms through which environmental stressors, particularly Holocene climatic fluctuations such as the 8.2 ka event, shaped adaptive changes in subsistence strategies and settlement dynamics in the southeastern Caspian Sea remain insufficiently understood. This gap highlights the need for a focused reassessment of how environmental instability influenced the development of Neolithic lifeways in northern Iran. Hotu Cave and the Komishani open-air site were selected as case studies because recent excavations at both locations have yielded well-preserved and stratified sequences that directly span the critical foraging-to-farming transition in the southeastern Caspian region. Hotu Cave provides a continuous stratigraphic sequence that captures key shifts in subsistence practices across the Transitional Neolithic, while Komishani offers a complementary open-air context in which evidence of climatic fluctuations is preserved across three distinct phases of the Transitional Neolithic (Fazeli Nashli et al., in press). This combination allows the study to address its central research question regarding how environmental stressors shaped emerging food-producing strategies.

The aim of this article is therefore to examine the role of environmental factors in shaping and expanding food-producing subsistence strategies in this region, and to explore the adaptive strategies and cultural niches developed to ensure resilience and survival. To this end, the study analyzes data from Hotu Cave and the Komishani open-air site within the relevant chronological framework to elucidate the role of environmental conditions in Neolithization processes and the Neolithic period. The reason for selecting these two sites from among the 41 identified sites within these chronological dates is that, in addition to having been excavated recently with the application of modern analytical methods, they contain well-defined cultural-layer sequences, stratigraphic section, and clear evidence of environmental changes alongside cultural transformations. Together, these features significantly enhance our understanding of the developments that occurred during this period.

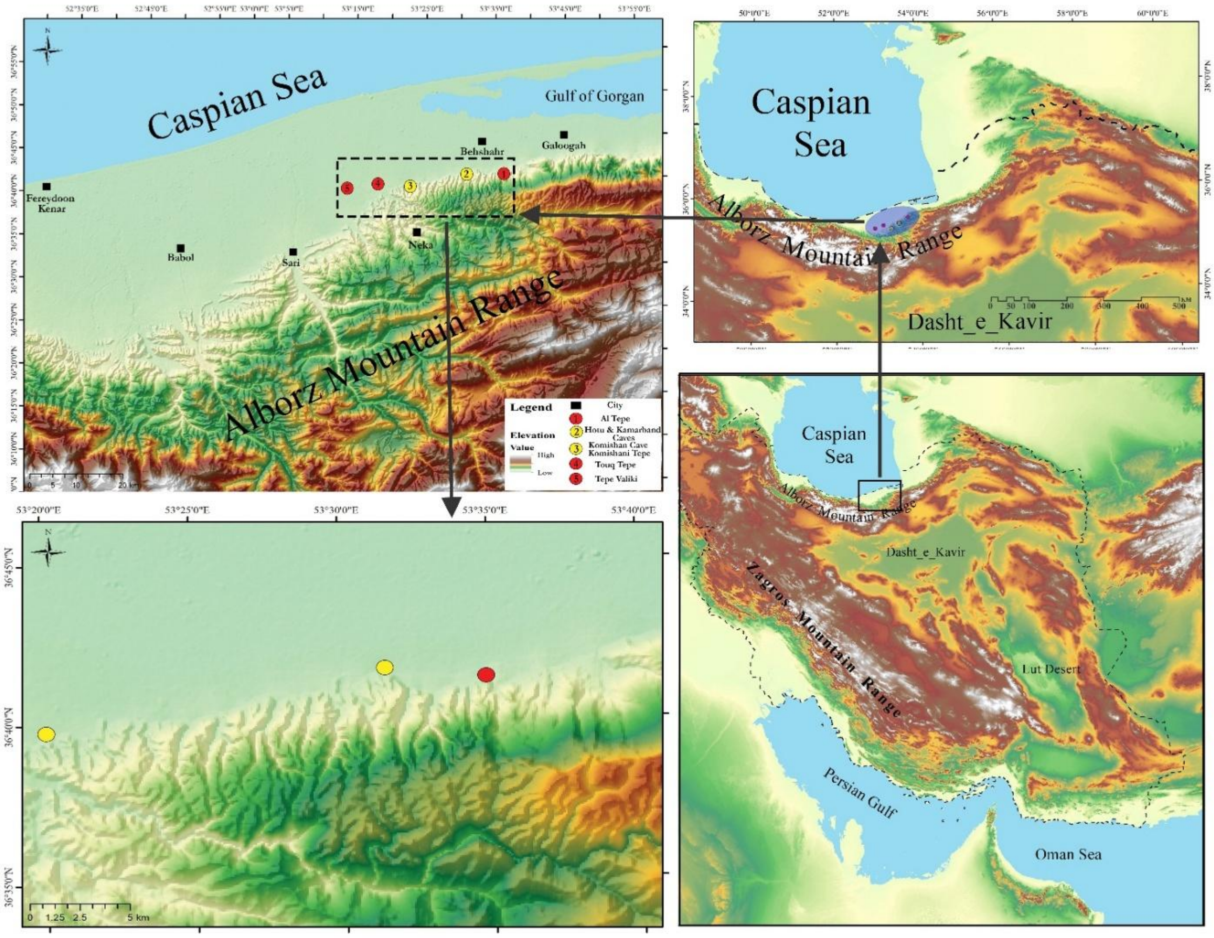
Theoretical Framework

Niche Construction Theory (NCT) offers a valuable framework for understanding the strategies employed by Neolithic communities in the southeastern Caspian region. Unlike traditional models of passive adaptation, NCT emphasizes how humans actively modified their ecological settings, thereby generating new selective pressures and ecological inheritances that shaped subsequent cultural and biological evolution (Odling-Smee et al., 2003; Laland & O'Brien, 2011; Smith, 2011). Within the context of the Transitional Neolithic and Neolithic periods, niche construction operated as a dynamic feedback system in which human groups restructured their ecological surroundings and, in turn, reshaped their own adaptive pathways. One of the most significant mechanisms of niche construction in this region involved the penning and recurrent management of caprines around cave settlements such as Hotu. Concentrated grazing near habitation areas would have intensified localized pressure on vegetation, altering plant community composition and promoting the proliferation of disturbance-tolerant species (Zeder & Hesse, 2000; Zeder, 2012; Fuller et al., 2011). Comparable patterns of early herd management and increasing human control over caprines have been documented across several parts of Southwest Asia, including the Iranian Plateau and the Zagros Mountains (Mashkour, 2002; Arbuckle & Atici, 2013).

These anthropogenic pressures created new ecological conditions that encouraged continued herding and improved resource predictability and an ecological legacy that could persist across generations (Smith, 2011; Boivin et al., 2016). At the social level, the construction and upkeep of animal enclosures likely required coordinated labor, spatial planning, and task differentiation, signaling an emerging shift toward cooperative organization and planned resource management (Kuijt & Goring-Morris, 2002; Zeder, 2015). Recent excavations at Hotu Cave and Komishani further illuminate these shifts, revealing increasing human engagement with animal resources and gradual transformations in subsistence during the transition from foraging to farming (Mashkour et al., 2013; Safari et al., 2024; Fazeli Nashli et al., in press). Archeozoological evidence from Hotu Cave, including the presence of perinatal caprine remains, suggests that herd management extended beyond opportunistic hunting and reflected a more deliberate strategy of animal husbandry (de Groene et al., 2023). The penning of goats and sheep within or near the cave represents a conscious reengineering of ecological space designed to secure more reliable food resources. Parallel developments such as the transition from wild to domesticated barley (Fazeli Nashli et al., 2024) and the broader use of ceramics for food storage and processing (Abbasnejad Seresti et al., 2024), demonstrate how Neolithic communities actively reshaped ecological niches to buffer against climatic volatility. These practices reflect technological innovation, but also strategic environmental modification aimed at ensuring long-term stability and survival. In archaeological and anthropological theory, resilience is generally understood as the capacity of socio-ecological systems to absorb, reorganize, or recover from environmental stress through largely endogenous and often unconscious processes embedded within subsistence routines, mobility patterns, and technological continuity (Folke 2006; Redman 2005). In contrast, the concept of conscious choice highlights a distinct dimension of human agency, emphasizing deliberate, cognitively mediated decision-making in which groups actively evaluate alternatives, anticipate outcomes, and select adaptive strategies in response to climatic fluctuations or geomorphological disturbances (Lycett 2015; Sterelny 2020). Comparing these two modes of response clarifies that resilience operates primarily through self-regulating mechanisms, such as maintaining established settlement rhythms or preserving familiar technological systems, whereas conscious choice reflects intentional, goal-directed actions, including strategic relocation, deliberate reconfiguration of resources, or innovation in subsistence practices. Juxtaposing these perspectives allows for a more nuanced assessment of how cultural niche construction emerged through the interplay of systemic resilience and purposive decision-making among communities of the southeastern Caspian littoral. Equally central to interpreting the archaeological record of this region is the concept of resilience. Communities in this region were repeatedly challenged by tectonic activity along the Khazar Fault (Rashidi et al., 2022; Nazari et al., 2021), fluctuations in Caspian Sea levels (Kakroodi, 2012; Naderi Beni et al., 2013), and abrupt Holocene climatic events, including the 10.2 ka BP and 8.2 ka BP episodes (Alley et al., 1997; Bond et al., 1997). Rather than leading to societal collapse, these stressors elicited flexible and adaptive responses. For examples, indicators of resilience include the sustained occupation of Hotu despite episodes of roof collapse (Coon, 1951; 1952; 1957; Fazeli Nashli et al., 2024), shifts in subsistence from gazelle and seal hunting to the management of caprines (de Groene et al., 2023), and the diversification of crops during the Pottery Neolithic (Leroy et al., 2019). Importantly, resilience across the southeastern Caspian was not uniform. While some lowland sites, such as Komishani, show evidence of temporary abandonment during flood events (Fazeli Nashli, 2023), upland caves appear to have served as refuge that facilitated long-term continuity. These patterns underscore the capacity of Neolithic groups to transform ecological disturbances into opportunities for innovation, social transformation and reorganization (Folke et al., 2006).

Hotu Cave and Komishani Tepe

Hotu Cave (N 36°41'17.88, E 53°29'47.63) is one of the most famous caves on the Iranian plateau, containing layers dating from the Mesolithic to the historical period (Fazeli Nashli et al., 2024b). The cave has a protected interior area of approximately 142 square meters. It is located about 8 km west of Behshahr, within a limestone formation at an elevation of 38.28 meters above sea level. The coast of the Caspian Sea is 13 km away. Today, the site is located within the boundaries of the village of Shahid Abad (formerly Trojen). The site was first excavated in 1951, and a re-excavation was conducted in 2020 (Coon, 1951, 1957; Fazeli Nashli et al., 2024b). The open-air site of Komishani Tepe containing layers dating from the Transitional Neolithic to the historical period (N 36°40'12.81, E 53°21'55.11) is located on the Neka-Behshahr Road, 28 kilometers west of Behshahr city, on the terrace opposite the Komishan Cave (Mesolithic period) (Vahdati Nasab et al., 2011; Vahdati Nasab et al. 2020), as well as near the Hotu and Kamarband caves (Map 1) (Fazeli Nashli et al.,2024b; 2024c) in Mazandaran province, at an altitude of 35 meters above sea level. The site was first excavated in 2017 and then again in 2023 (Fazeli Nashli et al., 2024a).



Map 1. The study area (location of Hotu and Komishani sites is marked yellow). 1-Al Tepe; 2- Hotu and Kamarband caves; 3- Komishan Cave and Komishani Tepe; 4-Touq Tepe; 5- Tepe Valiki.

Research Method

This study employs a multi-proxy, interdisciplinary framework to reconstruct human–environment interactions at Hotu Cave and Komishani during the Mesolithic–Neolithic transition along the southeastern Caspian Sea. The approach integrates geoarchaeological, sedimentological, geochemical, paleoclimatic, paleotectonic, zooarchaeological, lithic, and archaeobotanical datasets. As analyses from Hotu Cave are still at an early stage, only preliminary results are presented here and should be considered tentative; their purpose is to outline initial patterns and support comparison with Komishani. High-resolution stratigraphic analysis was conducted on excavated trenches at both sites. Cultural and natural layers were systematically documented, measured, and sampled, with detailed recording of sediment texture, structure, Munsell color, and stratigraphic boundaries. Evidence for flooding events and possible tectonic disturbances observed within the sequences was examined and integrated with other datasets. Geomorphological surveys of the surrounding landscape focused on coastal features and tectonic by optically stimulated luminescence techniques, particularly those associated with the Khazar Fault, to contextualize site formation processes. Grain-size analysis was carried out using standard granulometric methods to determine the relative proportions of sand, silt, and clay and to infer depositional conditions. Targeted geochemical analyses were performed on selected samples from Hotu Cave (contexts 63 and 72), chosen due to evidence of environmental change and associated shifts in human subsistence. Given the preliminary nature of the dataset, these analyses are used to identify general trends in sediment sources, moisture conditions, and diagenetic processes rather than to support detailed interpretations.

Stratigraphic data from both sites were correlated with regional records of Caspian Sea-level fluctuations and Holocene climate variability using established chronostratigraphic frameworks. Attention was given to the 10.2 ka and 8.2 ka abrupt climate events. The influence of tectonic activity related to the Khazar Fault was assessed through the identification of soft-sediment deformation structures, micro-faulting, and geomorphological indicators of recent displacement. Additional evidence, such as signs of roof collapse within cave deposits, was also considered. These observations were used to evaluate the role of tectonics in site formation and environmental instability. Faunal remains were identified to the lowest possible taxonomic level and quantified using Number of Identified Specimens (NISP) and Minimum Number of Individuals (MNI). These data were used to reconstruct subsistence strategies and assess shifts in resource exploitation, including the balance between terrestrial and coastal/marine resources. Techonomic evidence, such as cut marks and other anthropogenic modifications, was systematically recorded. Lithic assemblages were analyzed in terms of raw material procurement, reduction sequences, and tool typology. Technological characteristics, including core preparation, blank production, and retouch strategies, were examined to infer patterns of mobility and adaptive behavior. Archaeobotanical remains were analyzed to identify plant taxa, reconstruct local vegetation, and infer land-use practices, providing complementary insights into environmental conditions and human subsistence. All datasets were integrated within a resilience-based framework to explore human responses to environmental and tectonic variability. Comparative analysis between Hotu Cave and Komishani highlights how differing geomorphological settings influenced site formation processes and adaptive strategies. Interpretations related to Hotu Cave remain provisional and will be refined as ongoing analyses progress.

Human Responses to Environmental Pressures in the southeast of the Caspian Sea

Human reactions to their surrounding environment encompass a wide range of economic, subsistence, social, political, environmental, and geographical factors. Any external condition rooted in the environment can place humans under pressure and, in turn, elicit specific responses. Based on archaeological, historical, and contemporary evidence, four major types of human responses to environmental change can be identified (1) collapse/abandonment of settlements, (2) long-distance migration, (3) resilience and adaptation, and (4) negligible or no impact (see Clare & Weninger, 2010; Halstead & O'Shea, 1989; Leppard, 2014; Meze-Hausken, 2000; Weiss & Bradley, 2001).

Collapse of communities (Weiss & Bradley, 2001) in the Paleolithic, Mesolithic, and Neolithic periods is more appropriately interpreted as site abandonment, either temporary or long-term, resulting from hunger, migration, or subsistence-seeking strategies (Weninger et al., 2009). Long-distance migration (Black et al., 2011; Halstead & O'Shea, 1989; Leppard, 2014; Meze-Hausken, 2000) is observable through the abandonment of sites in specific regions and the establishment of new settlements elsewhere. It should be noted, however, that according to a historical-cultural approach, changes in material culture at new settlements may not always be distinct or archaeologically detectable. Adaptation refers to practices that transform threats posed by shocks and pressures into opportunities, thereby enabling persistence in the face of external crises. Such strategies may include subsistence choices such as gathering wild plants, keeping diverse animals, selective hunting, expanding cultivation, increasing short-distance mobility, or pursuing non-agricultural methods (Block and Webb, 2001; Leslie and McCabe, 2013; Meze-Hausken, 2000). Preventive strategies, such as food storage, exchange, and the creation of social and trade networks to secure necessities (Halstead & O'Shea, 1989), also contributed to community resilience. Additionally, the use of ideology and ritual within settlements (Huffman, 2009; Sillitoe, 1993) may signal social mechanisms of adaptation. Studying adaptation within settlements requires examining sites both before and after the onset of climatic changes to assess human responses. This includes investigating shifts in the use of plants and animals (e.g., isotopic studies of mobility, phenotypic and genotypic analyses of flora and fauna), pottery (dietary residues, decoration, and vessel forms), human remains (subsistence and dietary changes), non-local artifacts indicating long-distance exchange networks, and the ideological dimensions of burials and figurines (Twiss, 2008). Such evidence provides valuable insight into community resilience. Nonetheless, it is essential to emphasize that transformations are not linear. Comprehensive understanding the settlement patterns in this area requires examining multiple environmental drivers, most notably tectonic activity along the Khazar Fault, Caspian Sea-level fluctuations, and Holocene paleoclimatic variability. Collectively, these elements shaped the geomorphology, resource distribution, and habitability of the region. By integrating archaeological and environmental data, we specifically investigate whether high-energy events, such as seismic activity on the Khazar Fault or sudden cave collapses triggered “abandonment” and long-term interruptions in the settlement chronology (ca. 8100–6400 cal. BC), or if the evidence reveals a pattern of resilience or NCT through rapid re-occupation and adaptive socio-economic shifts.

Paleotectonic: The Khazar Fault, a prominent strike-slip fault extending approximately 600 km along the northern edge of the Alborz Mountains, plays a pivotal role in the region's tectonic evolution (e.g. Jackson et al., 2002; Allen et al., 2003; Ritz et al., 2006; Bakhtiari Zadeh et al., 2019; Nazari et al., 2021). This fault accommodates horizontal motion between the Eurasian and Arabian plates, significantly influencing the area's seismic and geomorphic characteristics (Rashidi et al., 2021). The active tectonics associated with the Khazar Fault have led to the uplift of the Alborz Mountains and the subsidence of the Caspian Sea, creating a dynamic landscape characterized by steep slopes, active fault scarps, and frequent seismic activity (Nazari et al., 2021) (Fig 1). The geomorphic consequences of the Khazar Fault's activity are evident in the formation of terraces, fault scarps, and the segmentation of drainage networks. In addition, the development of extensive and locally coalescing alluvial fans along the northern flank of the Alborz Mountains represents a key depositional response to rapid uplift, steep topographic gradients, and high sediment supply from ephemeral and seasonal streams

(Hollingsworth et al., 2010). These fans typically form where confined mountain catchments debouch onto the low-gradient margins of the Caspian foreland, facilitating rapid sediment transport and accumulation. The interaction between tectonic uplift and episodic high-magnitude discharge events promotes fan progradation, lateral channel migration, and sediment redistribution across the landscape. As a result, these processes not only shape the physical topography but also influence hydrological dynamics, including drainage organization and flood behavior, contributing to the development of flood-prone areas in adjacent lowlands (Javidfakhr, 2018). Furthermore, although alluvial fans often provide relatively level surfaces suitable for agriculture and settlement, they remain highly susceptible to flooding, debris flows, and channel avulsion, thereby playing a significant role in land-use patterns and geomorphic hazards in the northern Alborz region (Ventra & Clarke, 2018; Gillmore et al., 2011). The interplay between tectonic uplift and subsidence has created a complex topography that controls water drainage patterns and sediment deposition, ultimately affecting the frequency and intensity of flooding events. The Alborz Mountains remain a tectonically active region, with long-term uplift rates estimated at 4–6 mm per year, while the Khazar Fault exhibits vertical displacements of 40–70 meters, indicating the persistence of active geodynamic processes. Continuous uplift and episodic seismic events have influenced river catchments, erosion, and deposition patterns, periodically reshaping the landscape. These processes can bury settlements beneath fluvial or colluvial deposits, alter river courses, and disrupt agricultural land (Fazeli et al., 2024a).

Hotu, Kamarband, and Al Tepe (Ali Tepe) Caves, as well as Komishani Tepe, are located at the base of the northern Alborz Mountains in the transitional zone between forested slopes and the Caspian coastal plain, representing a key locus for understanding human–environment interactions in prehistoric Iran. These sites are part of a “Hotu Kesh” of seven closely spaced karstic formations, naturally formed through geological processes, which provided shelter and settlement opportunities throughout the late Quaternary. The region’s subtropical climate, characterized by dry summers and abundant precipitation on the northern slopes of the Alborz, fostered dense vegetation and continuous surface water runoff. These conditions created an ecologically rich environment that was conducive to early human habitation and, later, agricultural development. Additionally, in Hotu Cave, we observe the remains of the cave roof from the Neolithic period in this area, which may be attributed to the presence of this fault and its direct impact on the settlement.

For the first time, Carleton S. Coon, during his excavations at the Hotu Cave, reported the presence of collapsed rock debris within the cave and probably attributed this accumulation of fallen stones to seismic activity associated with a nearby fault system (Coon, 1951, 1957). Based on the removal of these rock fragments from the cave ceiling, he argued that this event coincided with a significant cultural shift, marking the transition from the Mesolithic to the Neolithic subsistence strategies. The recent re-excavations of Hotu Cave in 2020 have provided supporting evidence consistent with Coon’s initial observations. In the archaeological contexts 75 and 76, significant deposits of ceiling collapse were documented (Fig 2). These deposits align with Coon’s findings, as they correspond with notable changes in subsistence practices and, importantly, the earliest appearance of Caspian-type pottery at the site. However, in contrast to Coon's interpretation, the collapsed rock debris appears stratigraphically between two distinct Neolithic phases, the Transitional Neolithic and the Pottery Neolithic (Fig 3). This stratigraphic refinement highlights a more nuanced cultural trajectory, with transformations evident not only in subsistence strategies but also in archaeobotanical and archeozoological data, lithic assemblages, and the adoption of pottery in the region (Fazeli et al., 2024a). Moreover, the interpretation that tectonic activity and seismic events played a crucial role in shaping the cave's occupational history is consistent with broader research linking environmental disturbances to cultural transitions in Southwest Asia (Rosen, 2007; Nur & Cline, 2000). Such findings suggest that the collapse events in Hotu Cave may represent both an ecological disruption and a cultural turning point in the Neolithic process of the southern Caspian Sea.

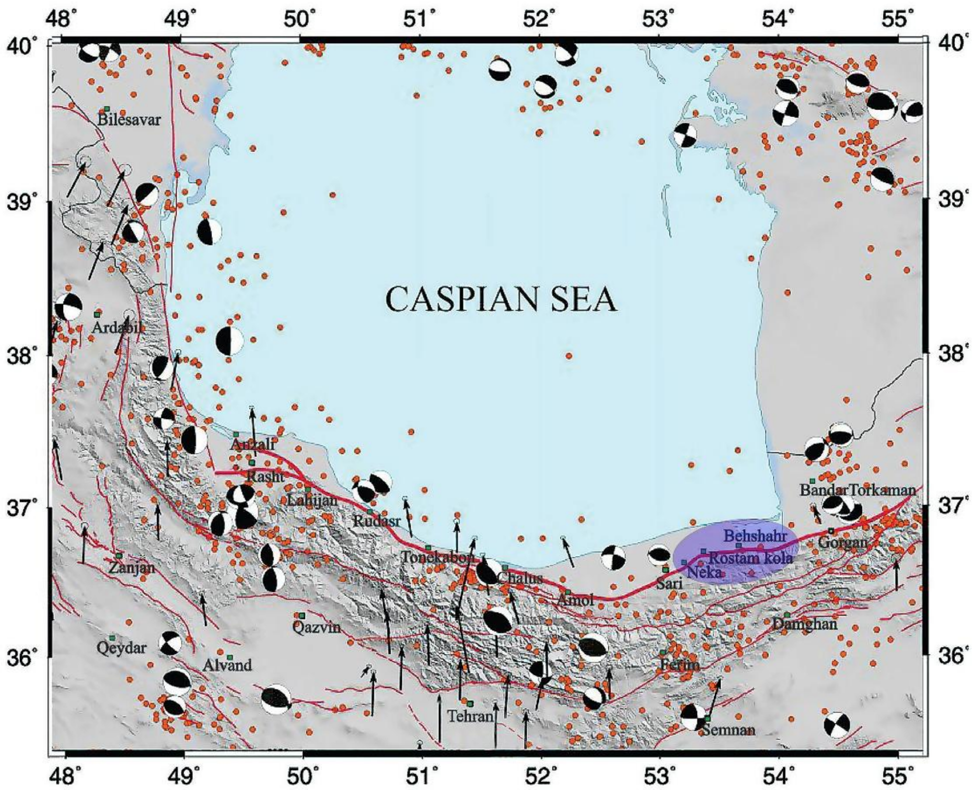


Figure 1. Tectonic and seismic activity of the Alborz Mountains with the location of the study area (Purple oval) (Nazari et al., 2021).

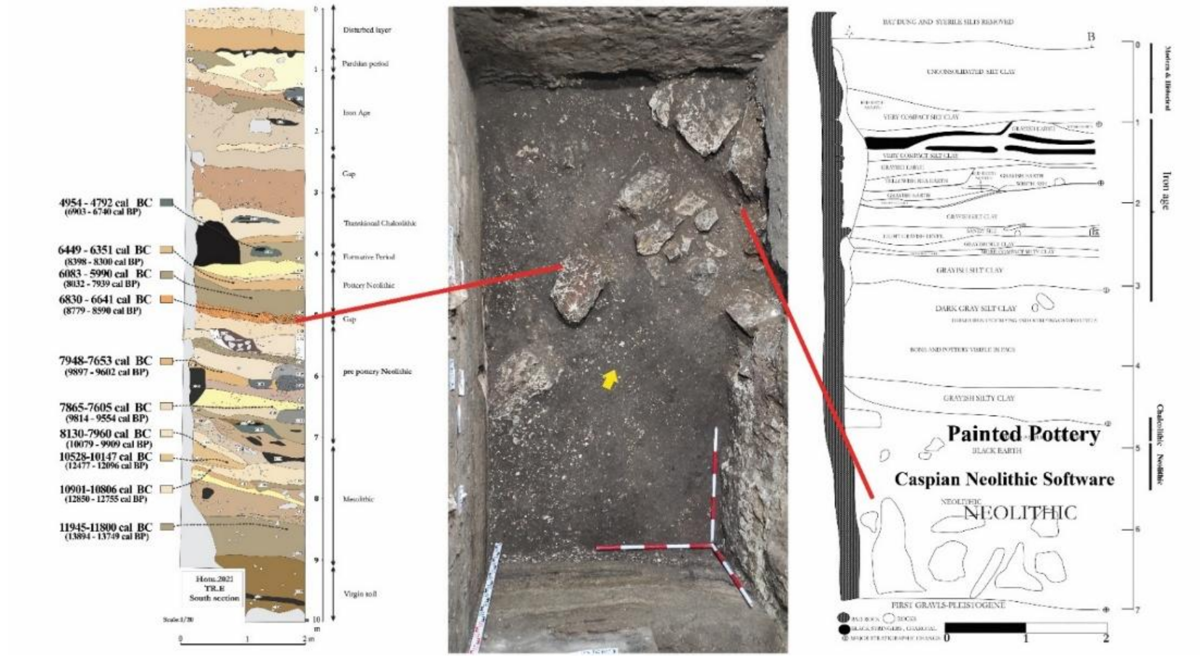


Figure 2. Left: Rock fallen in the south section in 2020 excavation, Tr E; Center: Rock fallen in Hotu Cave, Tr E; Right: Rock fallen in the 1951 Coon excavation in Tr. A and the beginning of the Pottery Neolithic period.

Sedimentological Analysis: in archaeological research, sedimentological and geochemical analyses are increasingly recognized as crucial tools for reconstructing past environmental dynamics and their impact on human settlement. Grain size distribution, geochemical signatures, and depositional structures not only provide insights into natural processes such as floods, earthquakes, and climatic fluctuations, but also allow us to evaluate how these events shaped human adaptation and occupation strategies (Selvaraj et al., 2024; Gallello et al., 2021). In Hotu cave, where cultural and natural deposits are often interlayered, these approaches allow for the identification of disruption events and a detailed reconstruction of paleoenvironmental conditions. Integrating sedimentological and granulometric data in the Neka region, a tectonically active area of the Alborz–Caspian domain, provides insights into how environmental instability influenced the settlement and subsistence strategies of prehistoric communities at sites such as Hotu. Variations in sediment composition, grain size, and geochemical signatures can indicate episodes of floods, shifts in sea level, or tectonic activity, all of which likely impacted human occupation patterns.

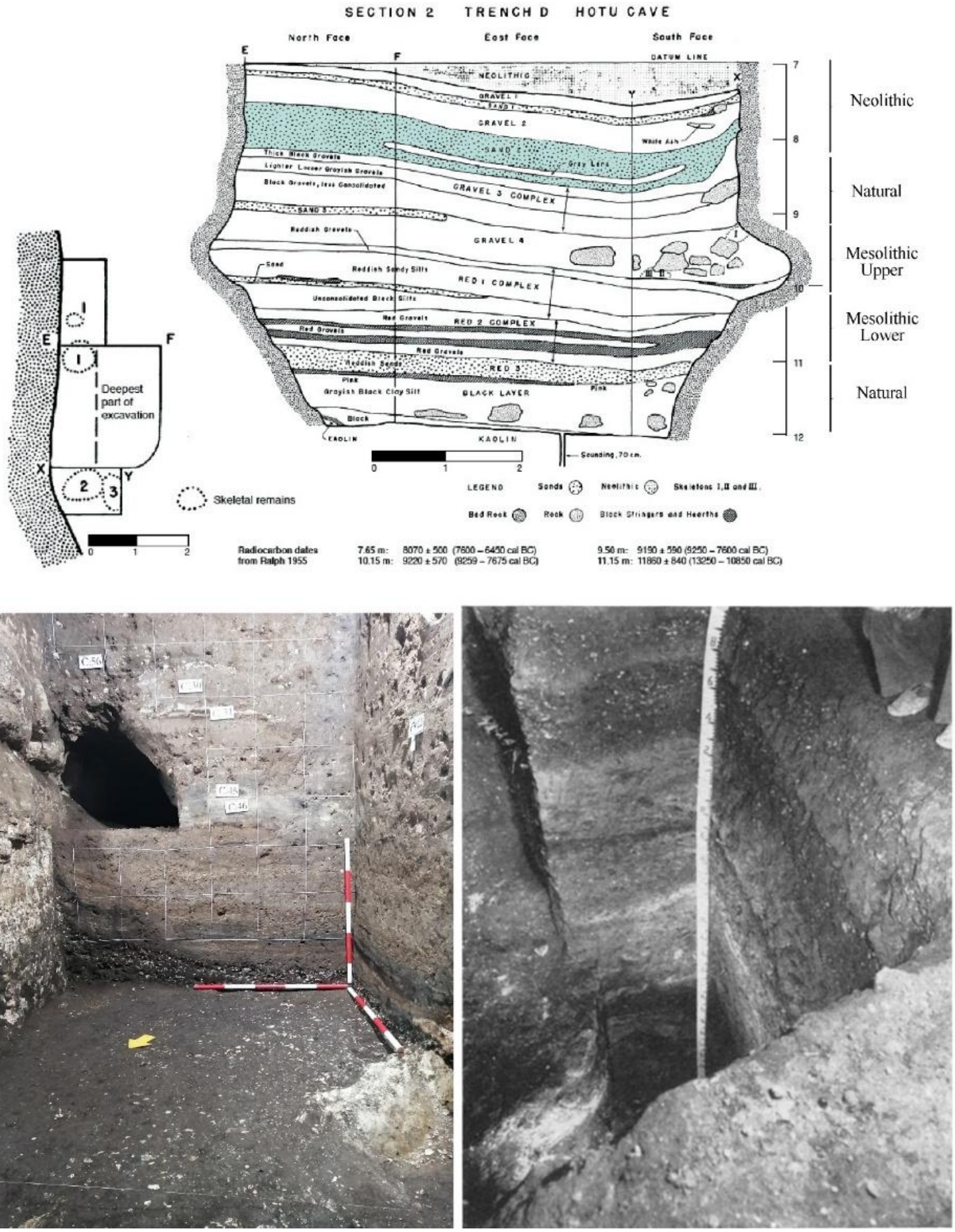


Figure 3. Top: Stratigraphic section of the 1951 Trench D Hotu cave and the gravel layer resulting from the crushing of gravel from the ceiling collapse; Bottom right: Trench D Hotu in the 1951 excavation; Bottom left: Gravel layer in the stratigraphic section of Hotu in 2020.

Context 63

The granulometric analysis (grain size analysis was undertaken using dry mechanical sieving and laser granulometry of fines. Detailed results of this analysis are forthcoming, but a summary is provided here of selected key samples) of Context 63 reveals a heterogeneous sedimentary composition, ranging from very fine clays and silts to coarse sands. Approximately 66% of the sediment is finer than 63 µm, with the mean (25.9 µm) and median (28.9 µm) values falling within the medium silt range, while the mode (31.5 µm) indicates coarse silt dominance. This overall distribution suggests primarily low-energy depositional conditions, interrupted by higher-energy episodes. Sorting values are consistently poor (SD = 2.61 phi), pointing to a highly mixed sedimentary environment. Skewness is near symmetrical, while kurtosis values are platykurtic, reflecting a flattened, poorly peaked distribution typical of heterogeneous sedimentary inputs. The particle size distribution (PSD) is clearly multimodal, with five distinct peaks. The early peaks fall within fine to coarse silt, representing calm depositional phases, whereas the final peak in the coarse sand range reflects a high-energy depositional event, most plausibly a flood episode. The presence of such multimodal signals indicates the interplay of steady background sedimentation and episodic, high-energy influxes, likely tied to flash flood activity in the region (Fig. 4).

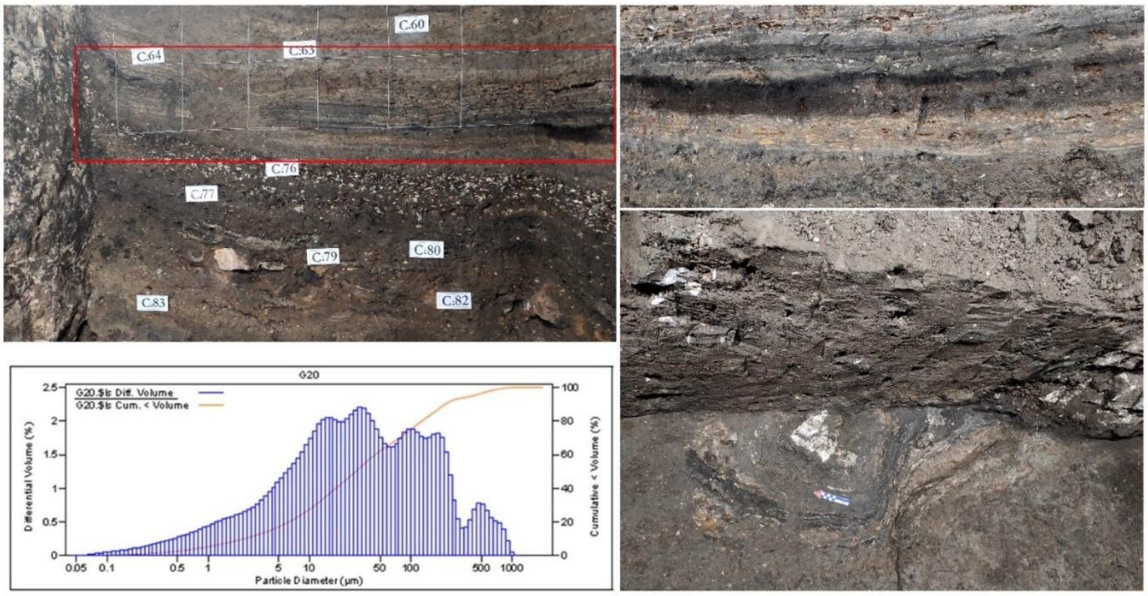


Figure 4. Granulometric chart and elemental analysis of Context 63.

Context 72

Context 72 also contains a mixture of grain sizes from fine clays and silts to coarser sands. More than 70% of the particles are finer than 63 µm, with mean (21.9 µm) and median (26.6 µm) values within the medium silt range, and a modal value of 34.5 µm (coarse silt). These statistics suggest a predominantly low-energy depositional environment similar to Context 63, though with subtle differences in depositional dynamics. Sorting is poor (SD = 2.39 phi), with a positive skewness reflecting an excess of fine-grained material. The kurtosis values fluctuate between leptokurtic and mesokurtic, indicating a somewhat peaked but still dispersed distribution. This complexity reflects the influence of multiple depositional episodes. The PSD is polymodal, with four main peaks; the initial peaks in the silt range reflect flocculation and gradual deposition under calm conditions, while the final peak in the coarse sand range marks a distinct high-energy depositional pulse. These fluctuations imply alternating low- and high-energy episodes, plausibly linked to flood events or abrupt hydrological shifts (Fig 5).

The analyses of Contexts 63 and 72 highlight the dynamic depositional environment of the Behshahr region in the Neolithic period, where predominantly low-energy sedimentation was repeatedly interrupted by episodic, high-energy flood events. For prehistoric communities occupying the nearby sites, such as Hotu Cave, these environmental oscillations would have posed challenges in terms of settlement stability, resource availability, and site preservation. By integrating sedimentological and granulometric analyses, archaeologists can better distinguish between anthropogenic and natural layers, thereby refining the reconstruction of both environmental history and human responses to ecological stress.

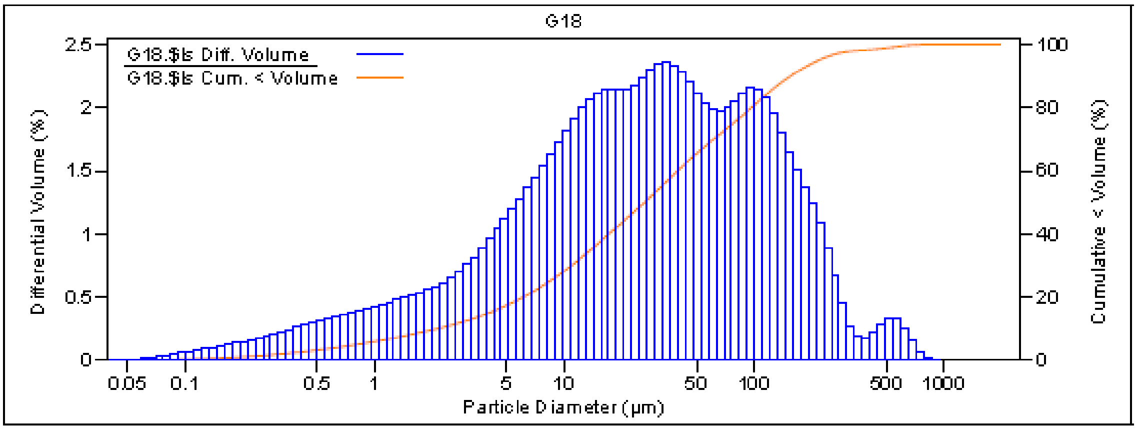


Figure 5. Granulometric data and elemental analysis of Context 72.

Caspian Sea-Level Fluctuations: The southern Caspian lowlands, including the Hotu region, are situated just a few decimeters above the present Caspian Sea level (-28 m a.s.l.) (Figs 6 & 7). During the Late Quaternary, the Caspian Sea underwent multiple transgressions and regressions driven by glacial meltwater, river inflow, particularly from the Volga, and climatic oscillations. These sea-level changes periodically inundated low-lying coastal plains during transgressions, while regressions exposed fertile alluvial surfaces suitable for human occupation. Notably, at least four major Holocene transgressions, commonly classified as the Khazarin, Khvalynian, and Neo-Caspian events, occurred interspersed with regression phases (Mamedov, 1997; Arsalanov et al., 2015).

Such oscillations had a direct influence on human settlement patterns. Rising sea levels likely forced communities from low-lying coastal plains into higher elevations, including cave sites such as Hotu, while periods of regression created arable land that facilitated the establishment of Neolithic agricultural settlements. Over the past 25,000 years, Caspian Sea level fluctuations ranged from -95 m to +35 m a.s.l., with particularly notable historical levels around 2400 BC and 9700 BC at approximately -40 m a.s.l., and 4500 BC, 8000 BC, and 9000 BC at approximately -20 m a.s.l. During the maximum Holocene transgression around 7 ka BP, sea level reached -20 m a.s.l., flooding extensive areas of the coastal plain and extending the shoreline up to 1,500 m from Hotu Cave (Fig 8). These fluctuating sea levels had profound impacts on settlement areas. High water levels not only flooded and destroyed habitation zones and agricultural fields but also caused salinization, which likely impeded agricultural recovery even after the waters receded. Alongside these sea-level changes, variations in the local erosion base, similar to tectonically induced processes, altered patterns of sediment erosion and accumulation, further shaping the landscape available for human settlements (Ghamari Fatideh et al., 2015; Heydari et al., 2022; Fazeli Nashli et al., 2024b) (Figs. 9 and 10).

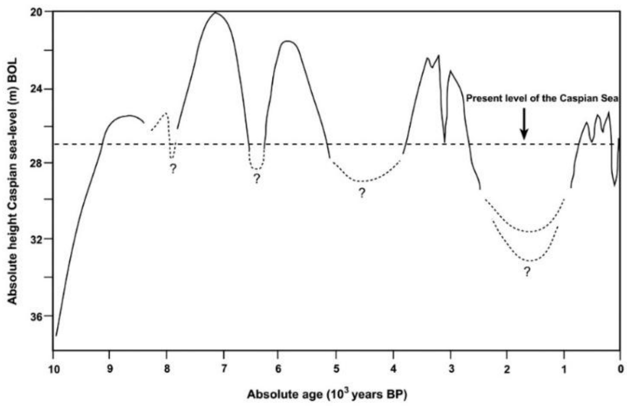


Figure 6. Sea level Fluctuation during the Holocene period (Kakroodi et al., 2015; Fazeli Nashli et al., 2024b).

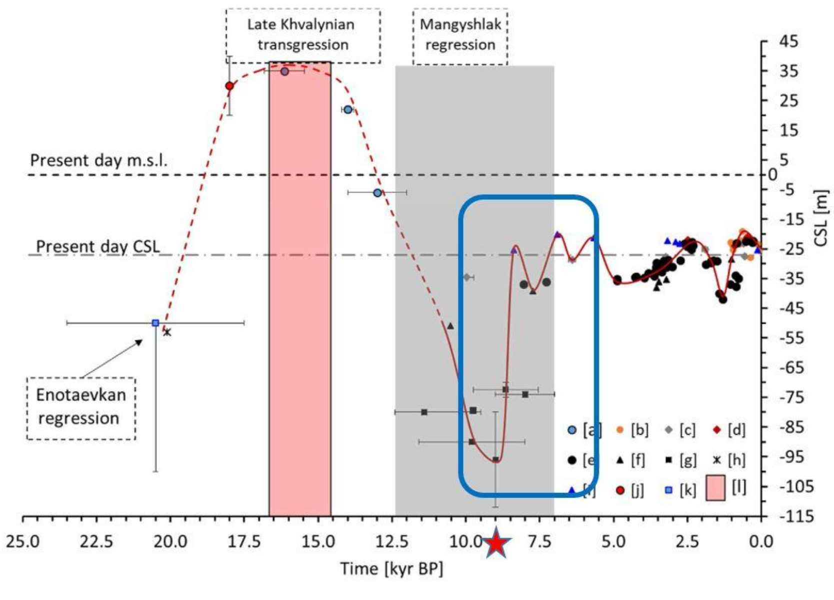


Figure 7. Sea level changes of the Caspian Sea with the timeframe of the cave sequences (blue rectangle) and the 8.2 ka BP (6.2 ka BC) event (red star) (Koriche et al., 2022; Fazeli Nashli et al., 2024b).

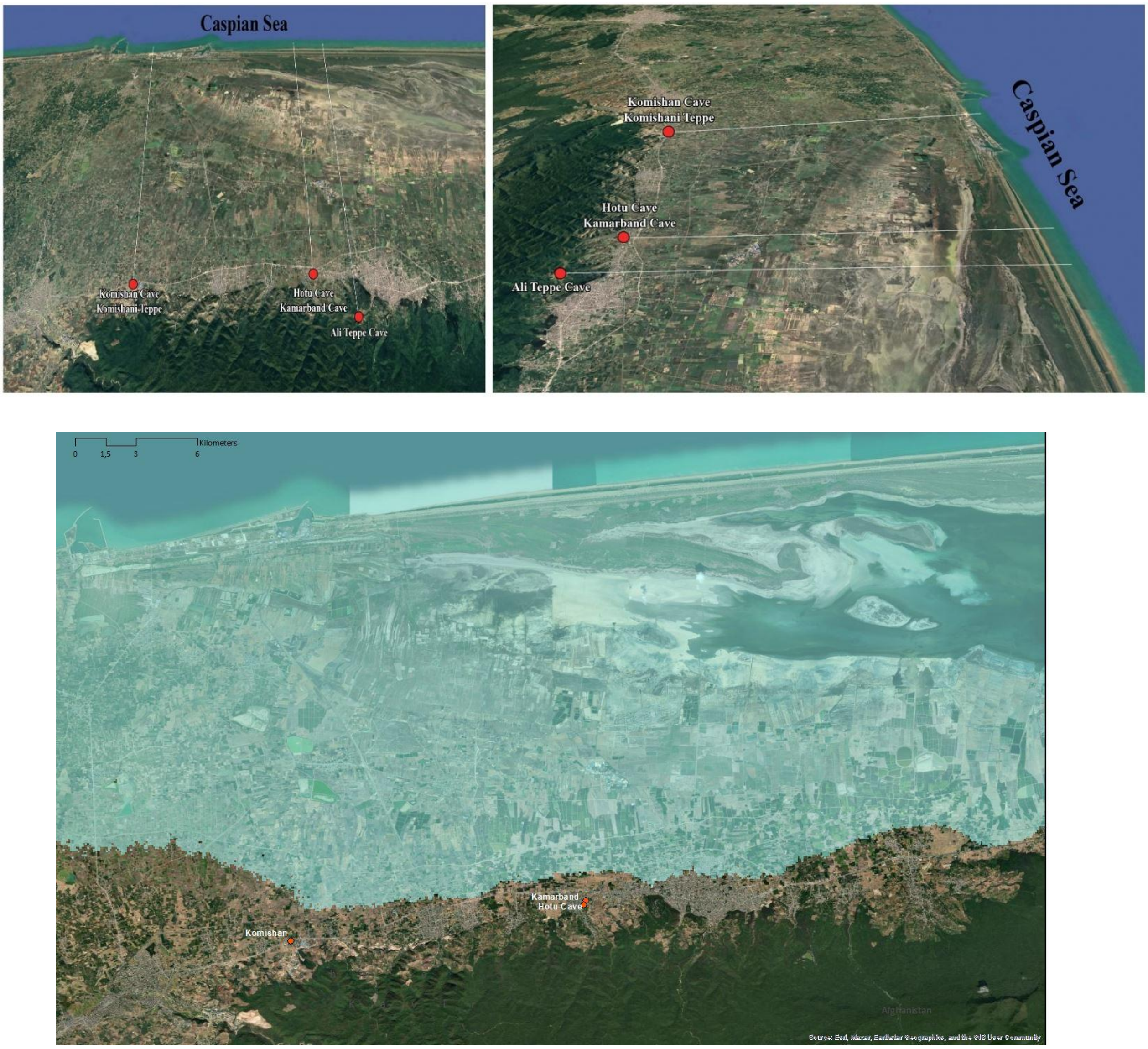


Figure 8. Above: The distance between the study site and the coastline; below: Illustration of the maximum transgression of the Caspian Sea during the Holocene around 7 ka BP (-20 m.a.s.l.) with flooded areas and location of Hotu, Kamarband, and Komishan caves and Komishani Tepe (Fazeli Nashli et al., 2024b).

Climate Event & Time (BP)	The Caspian Sea Level Changes			Archaeological Period			
	Time (BP)	Water Level	Transgression/ Regressive	Time (BP)	Period		
Middle Holocene 8.2 ky BP	8400 BP	-	Water level drop related to 8200 BP	Belt Cave 8640-7640 (Thornton, 2013)	Pottery Neolithic	Holocene	Quaternary
Early Holocene 9.3/9.2 kyBP 10.2 ky BP	10590-8400 (kakaroodi et al., 2015)	-34 M	The Neocaspian transgression	Belt Cave 9500-8050 (Thornton, 2013)	Pre-Pottery Neolithic		
				Belt Cave 11155-9570 (Gregg & Thornton, 2012)	Upper Mesolithic (Gazelle)		
Younger Dryas 12800-11550	11900-10500 (Bezerodnykh, 2016)	-53 to 80 M	The Mangyshlak regressive			Pleistocene	
Allerød Old Dryas Bøling	18000-12000 (Bezerodnykh, 2016)	0 to -2 (-12) M	The Khvalynian transgression	Belt Cave (11740 ± 825) Hotu Cave (12215 ± 865) (Gregg & Thornton, 2012)	lower Mesolithic (Seal)		

Figure 9. Archaeological period, the Caspian Sea level, and climate change events in this region.

Paleoclimate Change of the Southern Caspian Sea and Holocene Climatic Events

The southern Caspian lowlands, including the Hotu region, are located just a few decimeters above present sea level (−28 m a.s.l.). The unique geomorphological setting of this region, bordered by the Caspian Sea to the north and the Alborz Mountains to the south, has historically rendered it highly sensitive to both global and regional climatic fluctuations. Factors such as altitude, slope orientation, proximity to the sea, local and regional wind patterns, northern and western air mass movements, and the dense Hyrcanian Forest cover have collectively influenced the climatic conditions of the area (Faraji, 1987). As early as 1968, McBurney highlighted the ecological uniqueness of the Caspian coastal zone based on faunal remains from the Hotu, Kamarband, and Ali Tepe caves, emphasizing that the interplay between coastal proximity and mountain barriers shaped human subsistence and settlement patterns (Leroy et al., 2019).

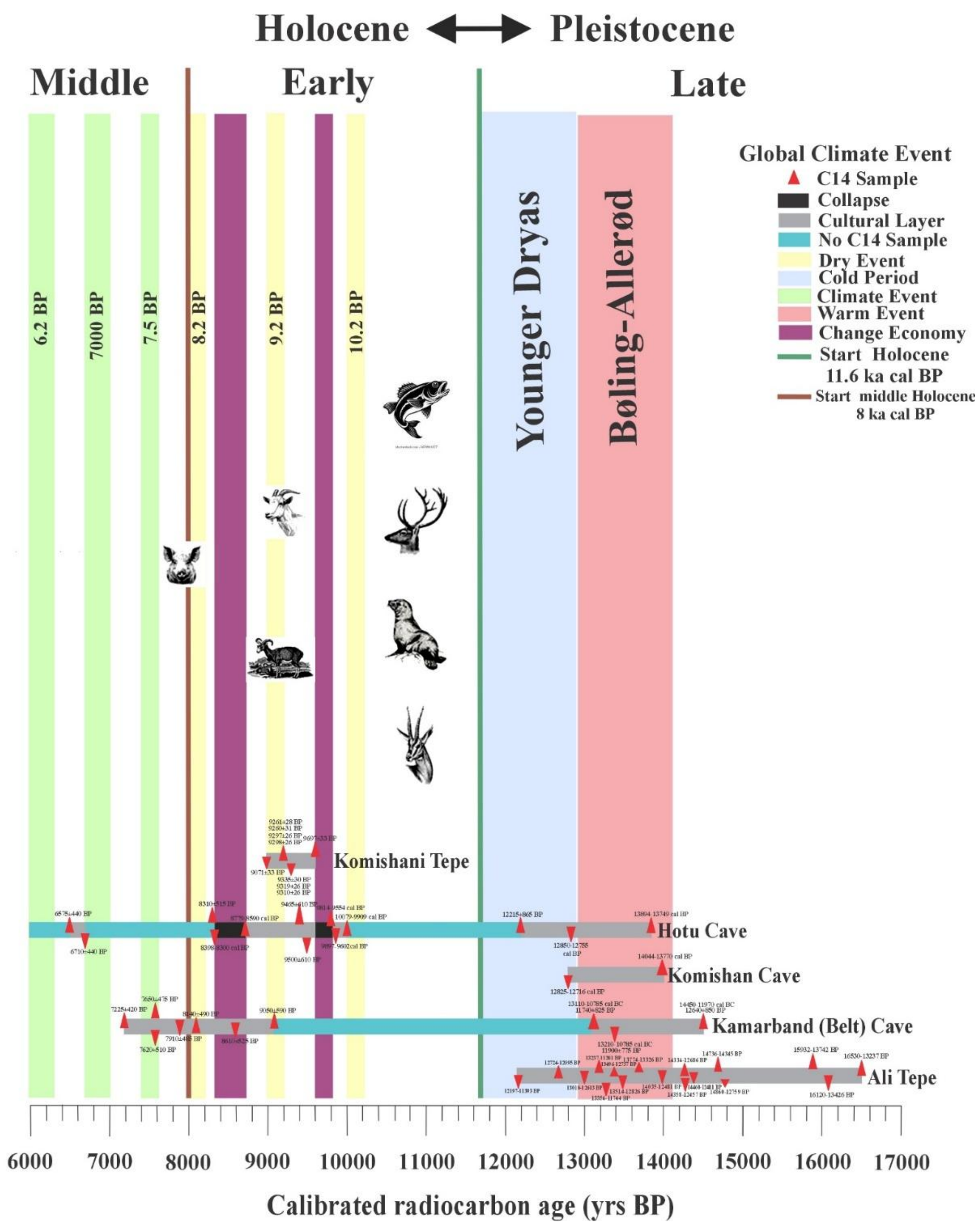


Figure 10. Climate change and adaptation to absolute dating in the region.

Holocene Climatic Events: 10.2, 9.2, and 8.2 ka BP

The early Holocene was punctuated by multiple abrupt climatic events, most notably the 10.2, 9.2, and 8.2 ka BP events, characterized by rapid cooling and increased aridity (Weninger et al., 2009; Yu et al., 2010; Fleitman et al., 2008; Fernandez-Lopez & Jochim, 2010; Jones et al., 2019). The 10.2 BP climatic event that occurred in the period 8200 BC coincided with the settlement of the Hotu Cave and the Komishani. At the Hotu site, we see flood flows/landslide and abandonment of the site, and at the Komishani, a major flood caused a break and abandonment of the site. In Context 5008 at the Komishani site, a rocky texture full of river stones was found (Fig 11), which, based on carbon-14 studies, probably caused a short break in the site in the period 8295-8470 BC.

One of the most pronounced Holocene climatic episodes in the region is the 8.2 ka BP event, a rapid and severe cooling associated with abrupt hydrological and ecological changes. Globally, this event is linked to a sudden release of meltwater from North American glacial lakes, causing disruptions in the Atlantic Meridional Overturning Circulation (AMOC) (Alley et al., 1997; Bond et al., 1997). In the Caspian Sea, the 8.2 ka BP event coincided with a significant sea-level decline, estimated to reach −42 m a.s.l. by 7,710 cal BP, and resulted in the deposition of alternating layers of dark silt and clay in coastal sediments (Kakroodi et al., 2015; Kakroodi, 2012).

This abrupt climatic deterioration directly impacted Neolithic populations: settlements in low-lying coastal areas, such as Komishan, were likely abandoned, agricultural lands were temporarily lost or salinized, and human communities were forced to adapt both subsistence strategies and settlement locations. Paleoenvironmental proxies, including pollen and sediment analyses, indicate reductions in vegetation cover and shifts in species composition during this interval, highlighting the ecological stress imposed by rapid cooling (Leroy et al., 2013a; Kakroodi et al., 2015).

The 8.2 ka BP event exemplifies the role of abrupt Holocene climatic events in shaping human-environment interactions. Within the framework of environmental determinism, this cooling episode constrained human activity by reducing resource availability, compelling settlement relocation, and promoting the diversification of subsistence strategies. Communities responded by adjusting agricultural practices, exploiting upland and forested zones, and modifying social and economic organization. Consequently, the 8.2 ka BP event is a critical marker for understanding both environmental pressures and adaptive responses in early Holocene societies of the southern Caspian Sea (Salque et al., 2018).

The shift in subsistence strategies during the Neolithic cannot be understood in isolation from climatic transformations, particularly the increased climatic stability of the Holocene, which facilitated sedentism and the development of agriculture (Richerson et al., 2001; Roberts, 2014; Bellwood, 2005). Within the framework of Cultural Ecology, climate acted as both a constraint and a catalyst, shaping the trajectory of human adaptation. The warming and ecological diversification of the early Holocene created conditions that made farming and herding viable, ultimately redefining human–environment relations. This perspective underscores the interdependence between environmental change and cultural evolution, offering a critical lens through which archaeological evidence, particularly in environmentally dynamic regions such as the southeastern Caspian Sea, can be interpreted.

Subsistence changes, as traced through plant and animal remains and stone artifacts, can help us understand how the transition from the Transitional Neolithic to the pottery Neolithic occurred. Samples recovered from the Transitional Neolithic at Hotu include grassy and wild barleys, with grassy/wall barley (Hordeum glaucum), wild barley (Hordeum spontaneous), and a significant proportion of the much larger and apparently "domesticated" barley Hordeum vulgare L (Fig 12).

Figure 11. Flood layer in the Komishani Tepe and coincidence with the climatic event 10.2 BP (Fazeli Nashli, 2023).

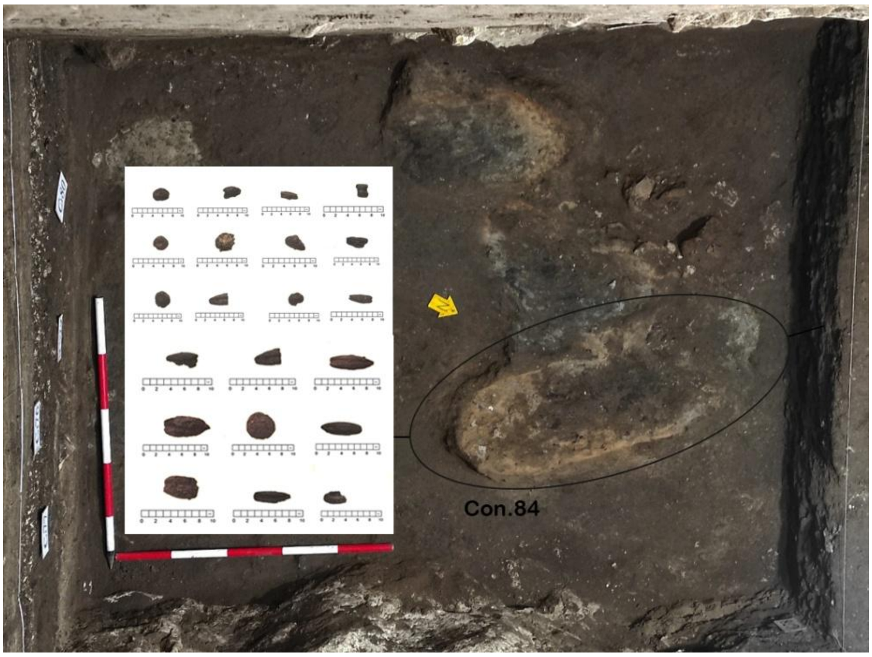


Figure 12. Plant remains from the Transitional Neolithic period include barley (weedy and wild).

The plant remains of the Pottery Neolithic period are clearly different from those of the previous period. In this period, we see domesticated species of plants, which indicates that after a period of hiatus and with the return of people to the cave, they were familiar with the methods of domestication, resource management, and food production. These samples are being studied, and the results will be published in the future (Fig. 13).

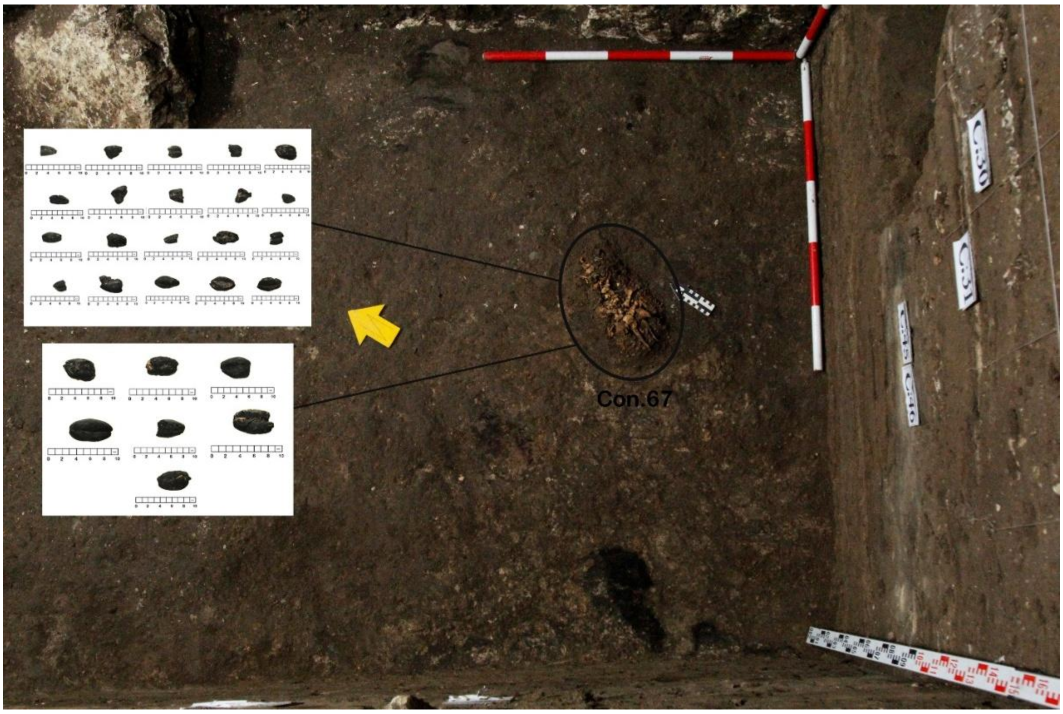


Figure 13. Plant remains from the Pottery Neolithic period include glume wheat and barley.

Animal Remains at Hotu Cave

Early Neolithic: At Hotu Cave, a fundamental shift in faunal composition is observed compared to the Mesolithic. Formerly dominant species such as gazelles and seals have almost disappeared, being replaced by goats and sheep (Fig 14). This marks a significant turning point in the subsistence of the cave's inhabitants. At this stage, goats are far more numerous than sheep (approximately twice as many), suggesting that goats played a more central role in subsistence and herd management strategies. One of the most important findings is the discovery of numerous perinatal remains of sheep and goats. Such evidence cannot be explained solely by hunting, since hunting typically targets adult animals. This strongly indicates that these animals were kept in or near the cave, and that the cave may have served as a pen for pregnant or recently born animals. The mortality profile also differs from that expected in hunting. Most goats and sheep died at a young age, whereas in hunted wild populations, one would expect a predominance of prime adults. This clearly reflects human control over the life cycle of animals. Osteometric analysis (LSI) shows that Early Neolithic goats display two distinct peaks, which may reflect sexual dimorphism (male and female). This suggests the presence of a managed population. It remains uncertain whether the animals were fully domesticated or subjected to an early form of proto-management of semi-wild herds.

Nevertheless, the abundance of perinatal remains strongly implies that at least part of the flocks was kept and bred locally. From a socio-cultural perspective, this evidence suggests that the inhabitants of Hotu Cave were likely to experiment with or tentatively practicing animal management. This may represent the onset of local domestication processes or the introduction of domesticates and herding practices from western regions such as the Zagros.

Late Neolithic / Pottery Neolithic: In this phase, sheep and goats remain the dominant species, but their exploitation patterns differ from those in the Early Neolithic. First, the abundance of perinatal remains, which was very high in the Early Neolithic, decreases sharply. This suggests that the cave was no longer primarily used to keep pregnant animals or newborns, and that herd management had become more structured and organized. The mortality profile reflects a classic herding strategy, most young males were culled before 18 months of age, while females were retained for reproduction and herd maintenance. This conforms closely to the economic strategies of established pastoral systems and indicates the full consolidation of herding practices in the region. Morphological evidence indicates that body size in sheep and goats has decreased compared with the Early Neolithic. Several factors may explain this reduction 1. The arrival of new groups introducing smaller animals from other regions. 2. Changes in breeding strategies leading to reduced sexual dimorphism. 3. Environmental or nutritional factors.

This size reduction parallels trends observed in the Zagros during the Pottery Neolithic and is most likely linked to more advanced domestication processes and genetic changes in the herds. In addition, evidence of domestic pigs has recovered from this phase, indicating greater diversification of domesticated species. Overall, the Late Neolithic can be characterized as the period when animal husbandry moved beyond its experimental stage and developed into a stable, efficient, and economically integrated system (deGrone et al., 2023) (Tab 1; Fig 15).
This evidence indicates increasing human control over animal life cycles, while archaeobotanical data demonstrates a shift toward domesticated cereals. These developments are niche construction processes, whereby humans actively reshaped both biotic and abiotic components of their environment to ensure more predictable resource flows. At the same time, the gradual and non-linear nature of these changes highlights resilience as an adaptive capacity, enabling communities to experiment, reorganize, and ultimately stabilize their subsistence systems under fluctuating environmental conditions.

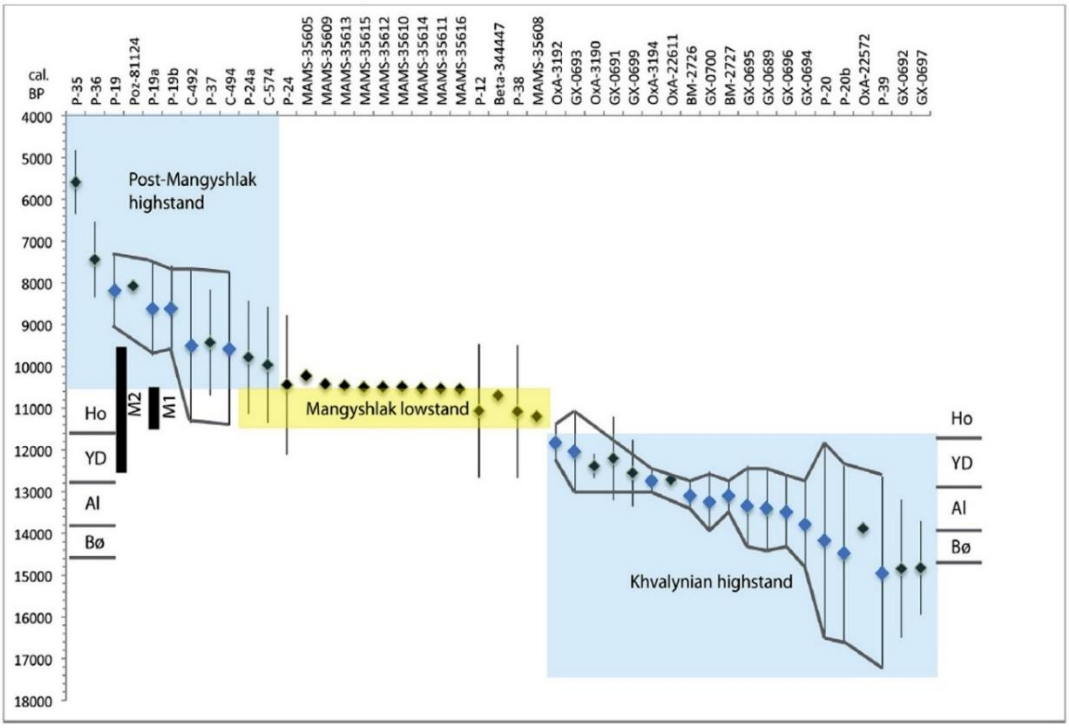


Figure 14. Seal hunting in blue and gazelle and steppe animals in black and their relationship with the water level of the Caspian Sea (Leroy et al, 2019).

Table 1. Comparison of faunal findings obtained in two phases of the Neolithic period in Hotu Cave.

Early Neolithic/ Transitional Neolithic	**Late Neolithic / Pottery Neolithic**
Dominant species: shift from gazelle and seal goat and sheep (goats twice as numerous as sheep).	**Dominant species: sheep and goats remain dominant; evidence of domestic pigs.**
Perinatal remains: high frequency of foetal and neonatal sheep/goat bones animals penned in or near the cave.	**Perinatal remains: Sharp decline in foetal and neonatal remains structured herd management.**
Mortality profile: predominantly young animals; not consistent with hunting evidence of human control.	**Mortality profile: Classical pastoral strategy, culling of young males (<18 months), females retained for reproduction.**
Body size trends: larger body size overall; two distinct peaks in goat LSI, possible sexual dimorphism.	**Body size trends: Reduction in body size of sheep and goats linked to advanced domestication, new stock, or reduced dimorphism.**
Economic: experimental/proto-management; subsistence economy transitioning from hunting to herding.	**Economic: Consolidated pastoral economy; efficient and integrated system.**

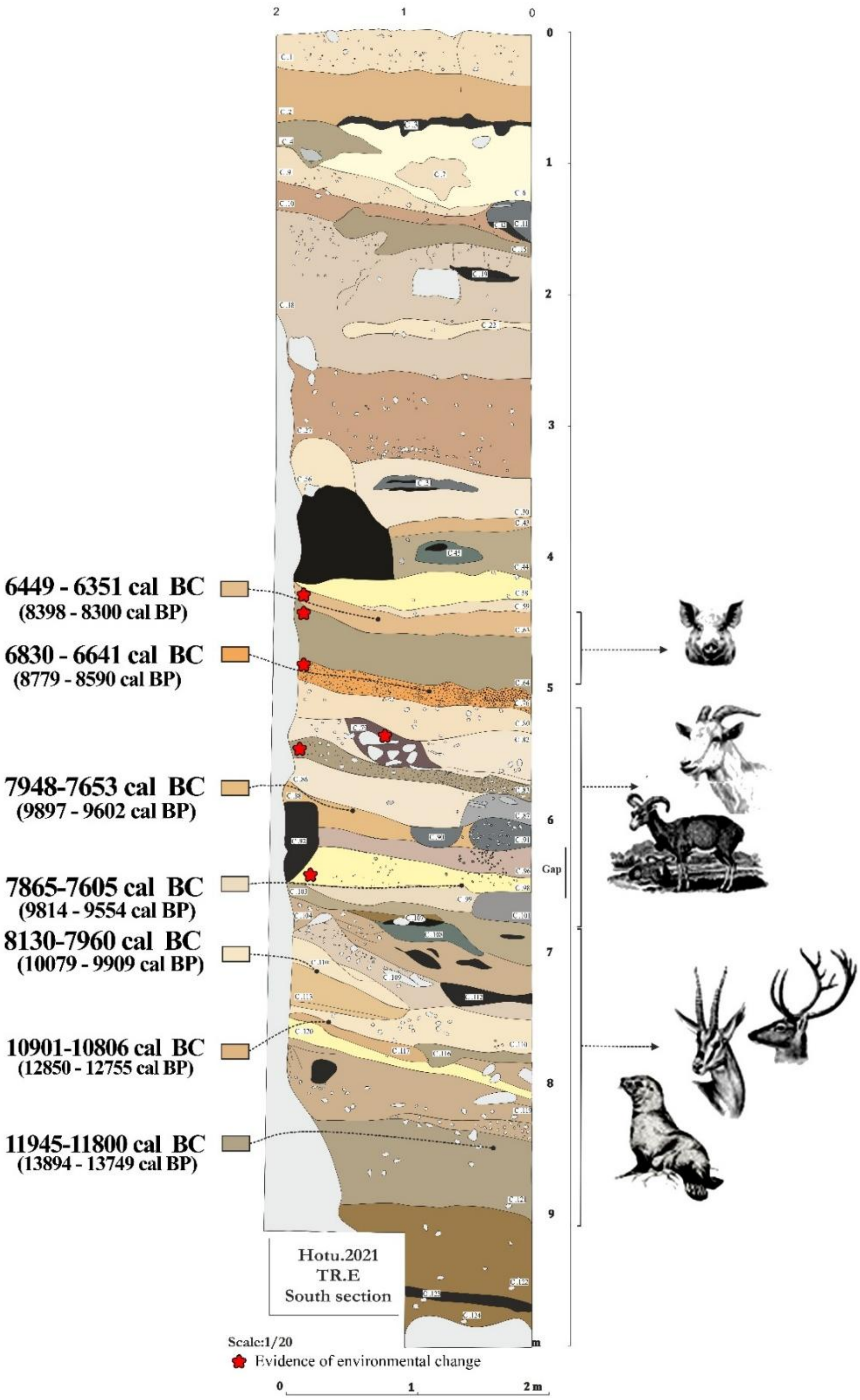


Figure 15. Animal remain profile at Hotu Cave.

Stone Artifacts: The lithic assemblages recovered from Hotu Cave, spanning the Mesolithic to the Chalcolithic, were recently studied and classified (Jayez et al., 2024). Within the Pottery Neolithic levels, sickle blades dominate the toolkit. The Hotu sickles can be classified into two main categories. The first group consists of implements manufactured from small blade segments and hafted parallel to the cutting edge, as evidenced by the presence of characteristic sickle gloss. The second, more distinctive group comprises trapezoidal elements that indicate oblique hafting within the handle. Some specimens were manufactured using pressure flaking techniques, while others, though evidently made by pressure, bear no traces of use or gloss. Additional blade tools include finely retouched (nibbled) forms, denticulate, and notched pieces. The flake tools of the Pottery Neolithic comprise retouched and denticulated specimens, scrapers, and sickles.

In contrast, the largest number of tools derives from the Transitional Neolithic layers, more than half of which were manufactured on flakes. The most abundant categories are denticulated or notched flakes and blades, followed by finely retouched specimens. Among microliths, retouched forms predominate, often with direct retouch along one or both edges; in some cases, the retouch created delicate denticulations. Denticulation was usually achieved by a series of small adjacent retouches on one or both edges. Most retouches are direct, although inverse and alternating patterns are also observed. Scrapers occur in various forms, including lateral, double, terminal, combined lateral/terminal, circular, and boat shaped. Several of these exhibit features diagnostic of the Caspian lithic tradition, notably the denticulated retouch applied to scrapers. Together, retouched microliths, denticulates, and scrapers account for nearly 80% of Transitional Neolithic stone tools, with the remainder consisting of chisels, scraper–chisel hybrids, notched pieces, and sickle elements. Sickle implements appear in two general forms throughout the Neolithic sequence. The first group consists of unmodified blades and microblades inserted directly into handles, typically in parallel alignment. These are the only sickle-type attested in the Pottery Neolithic. The second group comprises geometric microliths, generally trapezoidal in form. In Transitional Neolithic, both categories are well represented, showing greater variability in hafting techniques. Of the ten sickles identified from this phase, three were blade fragments hafted either parallel or oblique to the handle, as revealed by gloss patterns. The remaining seven were trapezoidal or indeterminate broken pieces, all showing gloss consistent with oblique hafting. Notably, not all notched or trapezoidal tools were sickles; some may have functioned as composite hunting implements. A unique break pattern on one denticulated specimen may suggest a specific knapping technique for producing geometrical microliths, though the evidence is too limited for firm conclusions. Due to chronological gaps between occupational phases at Hotu, it is not possible to trace the full technological transformation from Mesolithic foragers to Neolithic and post-Neolithic communities. Nonetheless, two major shifts are evident (1) the introduction of pressure flaking in microblade production, and (2) the replacement of notched tools by larger geometric microliths as sickle elements. A shared feature across all phases is the exclusive use of high-quality local raw materials. No exotic lithic materials were identified, suggesting strong local technological continuity. This reliance on local sources mirrors patterns at nearby Komishan Cave, where industries are characterized by coherent technological organization, large tool dimensions, and scarcity of cores (Jayez & Vahdati Nasab, 2016). The Hotu assemblages also display distinctive features of the Caspian lithic tradition, dominance of denticulated tools and notched forms, presence of diagnostic notched tools, absence of geometrical microliths in the Mesolithic but their appearance in the Neolithic, narrow-platform microblade cores, and a wide variety of scraper forms, particularly terminal scrapers. These features highlight technological homogeneity across the southeastern Caspian region, while also reflecting local adaptations. The exclusive reliance on local raw materials shaped the technological profile of the Hotu industries. All stages of procurement, knapping, and tool use occurred on-site, suggesting a household-based production system within self-sufficient communities. Measures of lithic diversity further indicate that Hotu functioned as a base camp with a wide range of domestic activities. Faunal studies reinforce technological evidence, just as gazelle remains dominate the Mesolithic but are replaced by sheep/goat in the Neolithic, lithic industries likewise shift from backed Mesolithic implements to Neolithic geometric sickle elements. Despite the occupational hiatus, it remains unresolved whether Neolithic subsistence strategies in the southeastern Caspian were developed locally or introduced from the Zagros. Addressing this question requires integrating Hotu with other nearby sites, such as Kamarband, Al Tepe, and Komishani, that preserve more continuous stratigraphic sequences (see Jayez et al., 2024) (Fig 16).

Also, evidence from ground stone tools at Komishani further complements this technological picture (Fig 17). At that site, the earliest ground stone assemblages are dominated by pestles and mortars, which in later phases gradually give way to hand stones and grinding slabs. This shift likely reflects an increasing emphasis on cereal processing and the growing role of plant resources in subsistence practices. Many of these implements were produced from foraminifera-bearing stones probably collected from the nearby seashore, demonstrating deliberate raw material selection and skilled manufacture. Their relatively light and portable character suggests that such tools could have been used within mobile or semi-mobile lifeways. At the same time, the abundance of fish and bird remains indicates that these communities maintained a broad-spectrum subsistence strategy. Taken together, these patterns suggest a transitional phase in which hunter-gatherer groups employing diversified subsistence strategies gradually moved toward more agriculture-oriented economies, a process likely shaped by changing environmental conditions and shifting subsistence needs (Mahmoudabadi et al., 2025).

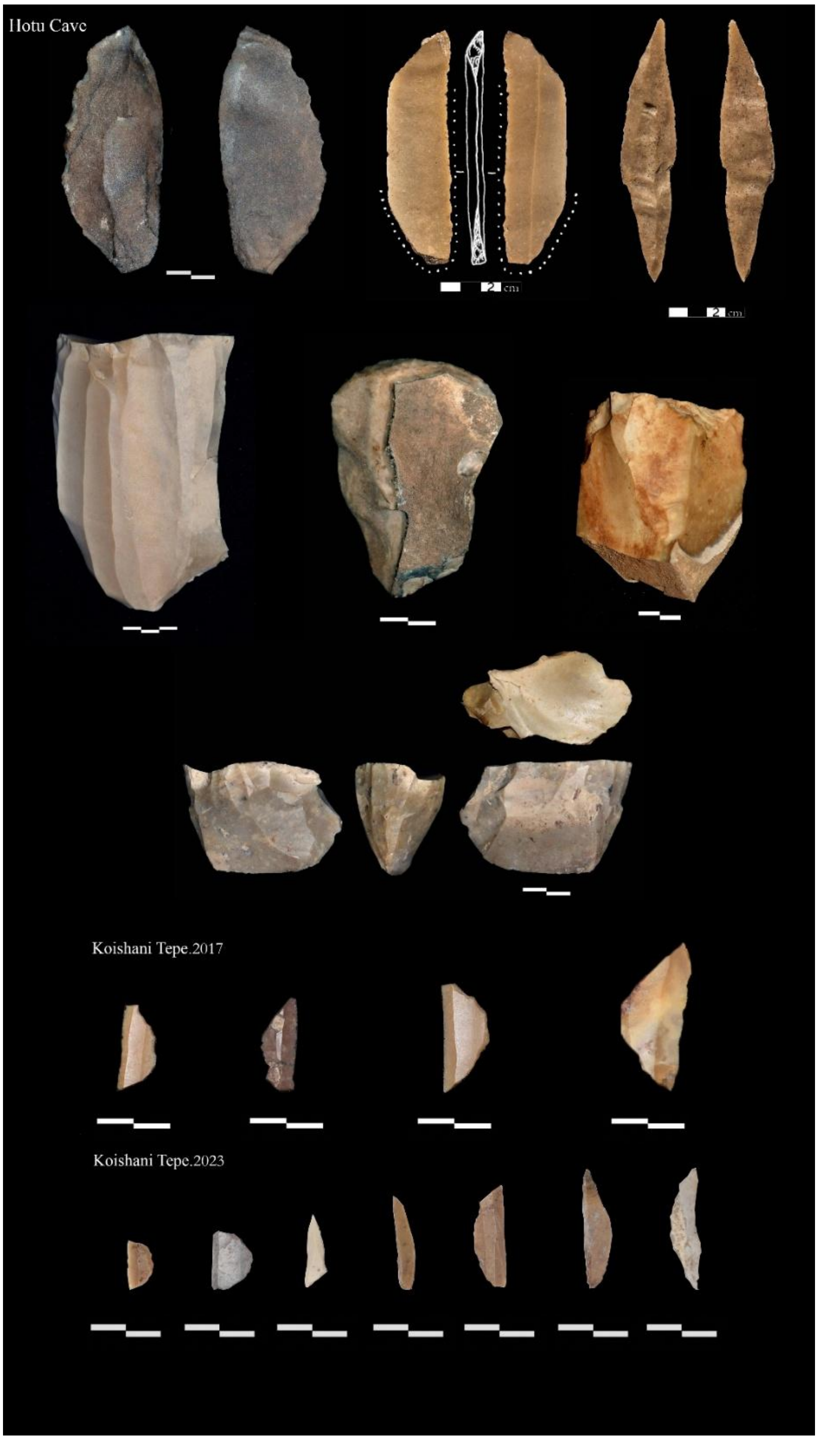


Figure 16. Lithic artifacts recovered from Hotu Cave and the Komishani site, including core, blades, microblade, backed and geometric pieces.

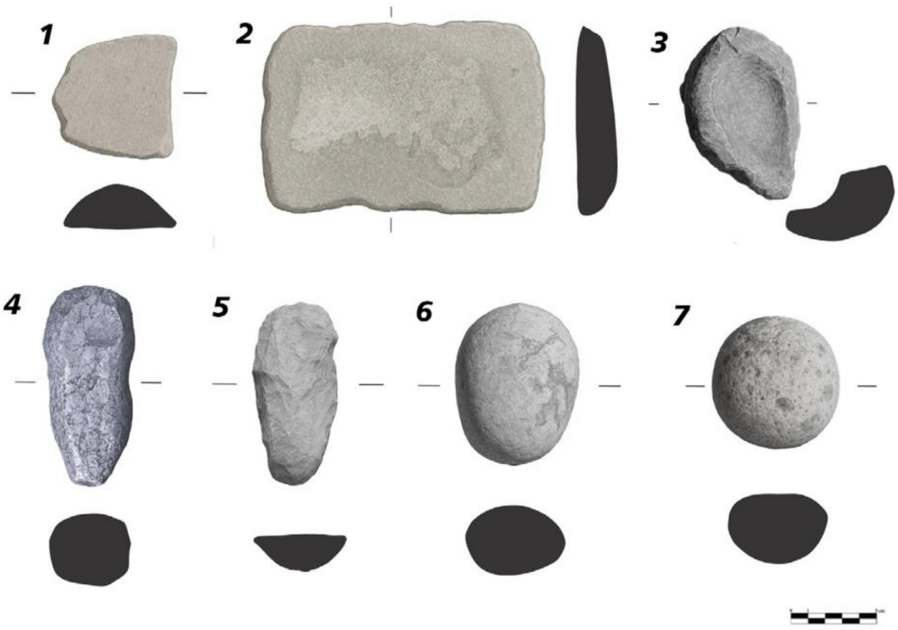


Figure 17. Some ground stone specimens from Komishani; 1. Upper grinding stone; 2. Grinding slab; 3. Mortar; 4-5. Pestle; 6-7. Hand stone (Mahmoudabadi et al., 2025).

Discussion

The Neolithic record of the southeastern Caspian Sea highlights the reciprocal relationship between environmental pressures and cultural strategies. While tectonic instability, sea-level fluctuations, and abrupt Holocene climatic events repeatedly disrupted settlement stability, these challenges did not lead to collapse in the sense of cultural disappearance. Instead, the evidence from Hotu and Komishani demonstrates that communities employed a spectrum of adaptive responses consistent with the concepts of resilience and niche construction. An inference from this study is that occupational hiatuses should not be interpreted simply as indicators of collapse or cultural discontinuity. Instead, they represent critical phases within broader adaptive cycles. Periods of abandonment of settlements, maybe happen by flood events, seismic activity, or climatic events such as the 8.2 ka BP event, created conditions for social and economic reorganization. The reoccupation of sites, accompanied by the appearance of pottery, domesticated plants, and more structured herding systems, suggests that these interruptions functioned for innovation rather than endpoints of cultural change.

Archaeobotanical evidence indicates a gradual shift from wild cereals to domesticated varieties, suggesting that plant cultivation may have been reintroduced after occupational hiatuses, possibly with prior knowledge of domestication practices already in place. This pattern may reflect deliberate ecological management, implying that communities were not solely dependent on naturally available resources but likely engaged in practices that reshaped local environments in ways that helped stabilize food supplies. Similarly, zooarchaeological evidence, particularly the transition from hunting gazelle and seal to the management of sheep and goats, suggests that animal herding strategies may have developed as a local response to environmental instability and subsistence risk. The relatively high frequency of perinatal remains in the Early Neolithic layers at Hotu may indicate early forms of herd management and penning practices, while the more structured mortality profiles of the Pottery Neolithic likely reflect the progressive consolidation of pastoral lifeways. Taken together, these patterns point to a gradual yet increasingly intentional intensification of human influence over plant and animal resources, broadly consistent with the expectations of Niche Construction Theory.

Lithic and ceramic technologies reinforce this picture. The introduction of sickle blades and ceramic storage vessels signals an investment in cultivation and long-term resource management. In the framework of Niche Construction Theory, these innovations can be seen as cultural modifications of the local ecosystem, creating new conditions for survival and transmitting ecological knowledge across generations. Importantly, the southeastern Caspian evidence suggests a non-linear and regionally distinct pathway to Neolithization. Unlike the gradual domestication trajectories of the Central Zagros or the exogenous influences observed in Anatolia, the Caspian evidence points to a mosaic process, shaped by local ecological conditions and punctuated by selective external contacts. Ceramic parallels with the Gorgan Plain and Central Asia indicate occasional interaction, but the dominance of local raw materials in lithic industries and the prevalence of endogenous pastoral practices highlight the primarily local foundations of Neolithization in this region.

The integration of environmental and archaeological data suggests that subsistence changes were neither linear nor uniform. Instead, they followed an iterative pattern, environmental disruptions, such as tectonic events or sea regressions, created crises, which were met with adaptive strategies that, in turn, generated cultural innovations. This cycle of disruption and response reveals how resilience functioned not only as survival but also as a driver of transformation. In this sense, the southeastern Caspian should be regarded as a distinctive laboratory of Neolithic adaptation. Its communities demonstrate that human–environment interaction during the early Holocene was not a story of environmental determinism alone, but of active ecological negotiation, cultural creativity, and long-term resilience.

The dynamics of subsistence change in the southeastern Caspian Sea can be conceptualized within an adaptive cycle framework (Fig 18). Each phase, from initial exploitation to conservation, collapse, and reorganization, reflects how Neolithic communities negotiated environmental pressures while actively constructing cultural niches.

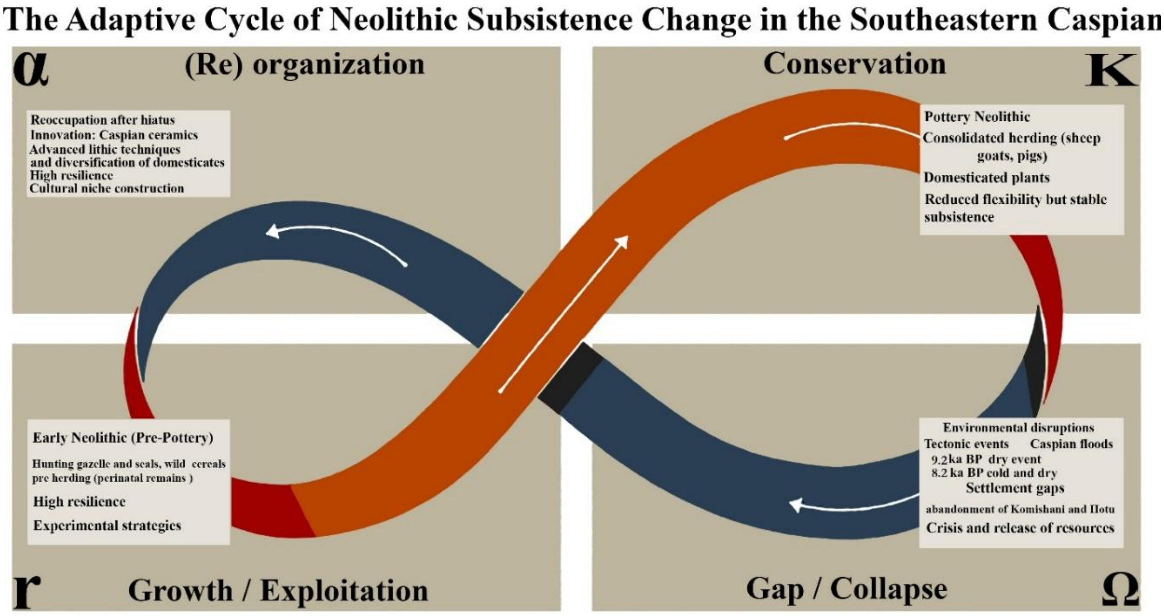


Figure 18. Adaptive cycle of subsistence changes in the Southeastern Caspian Sea: Growth / Exploitation (r-phase) Early Neolithic (Transitional Neolithic). Hunting gazelle and seals, wild cereals to pre-herding (perinatal remains at Hotu). High resilience, experimental strategies. Conservation (K-phase) Pottery Neolithic, consolidated herding (sheep, goats, pigs), domesticated cereals. Reduced flexibility but stable subsistence. Collapse / Gap (Ω-phase) Environmental disruptions: tectonic events, Caspian floods, 8.2 ka BP cold and dry period, settlement gaps, abandonment of Komishani, crisis, and release of resources. Reorganization (α-phase) reoccupation after hiatus. Innovation: Caspian ceramics, advanced lithic techniques, and diversification of domesticates. High resilience, cultural niche construction.

Conclusion

The Neolithic process of the southeastern Caspian illustrates a dynamic interplay between environmental volatility and human agency. Far from a linear transition from foraging to farming, subsistence change in this region was characterized by iterative experimentation, marked by cycles of disruption, adaptation, and innovation. Tectonic instability, fluctuations in Caspian Sea levels, and abrupt Holocene climatic events provided both constraints and opportunities, forcing communities to reorganize their lifeways while stimulating resilience and creativity. Archaeobotanical and zooarchaeological evidence from Hotu Cave and Komishani Tepe demonstrates that these groups did not merely react to ecological stress but actively reshaped their environments through plant domestication, animal management, and the adoption of ceramic technologies. This process reflects a deliberate construction of new cultural niches, enabling sustainable subsistence strategies that buffer against environmental shocks. The reduction in gazelle and seal exploitation, the emergence of caprine herding and pig domestication, and the gradual shift from wild cereals to cultivated varieties collectively underscore the mosaic character of Neolithization in the Caspian Sea. The southeastern Caspian thus emerges as a distinctive laboratory of Neolithic development, in which local innovation was interwoven with selective external influences. By framing these dynamics within the concepts of resilience and niche construction, this study highlights the capacity of prehistoric communities not only to endure environmental upheavals but also to convert them into avenues of cultural transformation. These findings underscore the need to situate Caspian evidence within broader comparative frameworks, offering insights into the diversity of pathways by which human societies across the Near East and beyond negotiated the challenges of the early Holocene.

Acknowledgments
The authors would like to express sincere gratitude to all members of the excavation team of the Hotu and Komishani archaeological sites for their invaluable collaboration, dedication, and field support throughout the course of this research. Their commitment, expertise, and teamwork during the fieldwork seasons played a crucial role in the successful completion of this study. This project was supported by the Iran National Science Foundation with the reference number of 40405443.

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