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External auditory exostoses in fragmentary remains: Evidence for activity and human-environment interactions at Early Neolithic Bestansur, Iraqi Kurdistan

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ABSTRACT

Objectives: This research assesses external auditory exostoses (EAEs) as markers of aquatic activity in individuals from the Early Neolithic inland site of Bestansur, Iraqi Kurdistan (c.7700–7100 BCE).
Materials: Thirty-four individuals (6 non-adults and 28 adults) represented by 50 external auditory canals (27 left and 23 right), both fragmentary and intact, were included in the study.
Methods: Auditory canals were macroscopically examined for the presence or absence of bone growths, with their location and severity recorded.
Results: Twenty-four individuals (70.6 %) and 31 auditory canals (62 %), 18 left (66.7 %) and 13 right (56.5 %), displayed EAEs. No significant differences in -frequency were found according to biological sex, age-at-death or burial location.
Conclusions: Supported by archaeological evidence, the frequency of EAEs at Bestansur suggests male, female and non-adult engagement in fishing, mollusc harvesting and, possibly, other activities in aquatic environments, shedding light on social participation and the importance of freshwater habitats in Neolithic economies in the Zagros.
Significance: While adding to previous studies of EAEs in fragmentary remains, this research highlights the benefit of contextualised palaeopathological analysis as a means of exploring human behaviour and human-environment interactions. The assessment of EAEs in past populations can offer insights into the variables shaping human behaviour and complex subsistence strategies.
Limitations: Sample size and distribution were affected by poor preservation, requiring interpretative caution.
Suggestions for further research: Future research should acquire regional comparative data and explore correlations between EAE location and severity, and co-occurrences of bone changes in the auditory canal.

1. Introduction

1.1. Research context

Starting from the early 2000s, a resumption of excavations in the Central Zagros has sparked new interest in intersections between biological and cultural spheres during the Neolithic transition in Southwest Asia (*c.* 10,000–6000 BCE) (Matthews et al., 2020a; Zeder, 2024). This phase of prehistory, originally theorised by Childe (1936) as a large-scale revolution in subsistence systems with the emergence of agriculture, was marked by diverse, non-linear shifts from mobile hunting-gathering to farming and sedentism, leading to a redefinition of human agency and the human-environment nexus (Verhoeven, 2011; Svizzero and Tisdell, 2014). The way in which localised, contextual trajectories shaped this change across Southwest Asia, however, is not fully understood. Until recently, and despite their importance to the understanding of early settled life (Zeder, 2024), the Zagros uplands and lowlands of eastern Iraq and western Iran have remained marginal in reconstructions of Neolithic lifeways. In particular, the ways in which people interacted with the landscape as part of habitual activities have rarely been explored through the direct study of human skeletal remains.

In bioarchaeology, traditional methods for behavioural reconstruction rely on the assessment of skeletal activity markers (Villotte, 2008).

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These are acquired bone changes developed in response to a range of stimuli, which researchers have related to repetitive behaviours (Kennedy, 1989; Capasso et al., 1998; Knüsel, 2000). In reality, the contribution of activity to their expression is often challenging to isolate from other variables, including age, biological sex and concomitant pathological processes (Villotte, 2008; Jurmain et al., 2012). Nevertheless, some of these bone changes have a predominant behavioural component that is widely substantiated by the clinical literature, offering more robust grounds for interpretations of activity when combined with contextual data. External auditory exostoses (EAEs) fit in this category.

External auditory exostoses are progressively forming, benign growths of lamellar bone in the tympanic portion of the external auditory canal (Sperling et al., 2013; Larem et al., 2021). Primarily reported in modern groups of water sports participants (e.g. Hurst et al., 2004; Moore et al., 2010; Lennon et al., 2016), they are commonly referred to as 'surfer's ear' in the clinical setting (Seftel, 1977). The pathophysiology of these bone changes is not completely clear. Their formation is, however, associated with sustained irritation of the soft tissues lining the deep meatus, where the lack of a subcutaneous buffer between the skin and the periosteum favours reactive bone formation in response to increased tension (Harrison, 1962; Lobo, 2015). Experimental, clinical and bioarchaeological data concur in identifying water exposure as the main precipitating factor (Lobo, 2015; Villotte and Knüsel, 2016; Trinkaus et al., 2019). Indeed, clinical research indicates that cold water entering the ear canal is responsible for causing hyperaemia and periosteal inflammation, triggering osteoblastic activity in susceptible individuals (Harrison, 1951; 1962). The resulting bone reaction has been suggested as an adaptive mechanism protecting the tympanic membrane and delicate internal ear structures (DiBartolomeo, 1979; Rhys Evans and Cameron, 2017). Simas et al. (2020) have shown that EAEs can occur with extended and repeated exposure to water above 20.6°C. However, lower temperatures may cause enhanced blood flow to the auditory canal for a longer period of time, inducing more severe bone changes at a faster rate (Van Gilse, 1938; Harrison, 1951). Several clinical studies highlight a strong correlation between the prevalence and severity of EAEs, and the frequency and duration of cold-water exposure (Chaplin and Stewart, 1998; Wong et al., 1999; Kroon et al., 2002; Cooper et al., 2010; Nakanishi et al., 2011; Attlmayr and Smith, 2015). Moreover, EAE development can be accelerated by the evaporative cooling effect of wind chill on wet ears (King et al., 2010; Moore et al., 2010; Wegener et al., 2022).

Mild manifestations of EAEs are often asymptomatic (Leonetti and Marzo, 2015). However, progressive size increase can cause partial or complete stenosis of the external auditory canal, leading to a series of complications. These include recurring infections due to cerumen impaction, tinnitus and conductive hearing loss (Goddard and McRackan, 2019; Vallée, 2024).

Bioarchaeological research has supported clinical findings indicating a primary role of environmental and behavioural factors in the onset of EAEs (see Kennedy, 1986; Villotte and Knüsel, 2016). As a result, interpretations of these bone changes as non-metric traits with value for population relatedness studies (e.g. Berry and Berry, 1967; Hauser and DeStefano, 1989; Hanihara and Ishida, 2001) have gradually given way to their use as biocultural markers of activity and human-environment interactions. External auditory exostoses have thus been investigated in archaic and modern humans from different time periods and geographical contexts, offering insights into the exploitation of aquatic environments as part of subsistence-related, occupational and cultural practices (e.g. Manzi et al., 1991; Velasco-Vazquez et al., 2000; Okumura et al., 2007; Kuzminsky et al., 2016; Villotte et al., 2014; Smith-Guzmán and Cooke, 2019). Godde (2010) and Villotte and Knüsel (2016), stressed that isolated cases of EAEs are difficult to link directly to aquatic activity, as aetiopathogenic factors other than cold water may cause repeated irritation and bone reaction in some individuals (e.g. trauma, infection and biochemical alterations; see Hutchinson et al., 1997). On the other hand, when high EAE frequencies are tied into archaeological evidence, they can elucidate aspects of resource procurement, social organisation, habitual behaviour, and their intra- and inter-site variations.

Few studies have investigated EAEs in Neolithic communities from Southwest Asia, a research gap that is largely explained by the underrepresentation, often poor preservation and limited accessibility of osteological assemblages from the region. With the exception of a publication on a Proto-Neolithic sample from Shanidar cave, in Iraq (Agelerakis and Serpanos, 2002), and isolated diagnoses in the Levantine area (Hershkovitz et al., 1986; Hershkovitz and Galili, 1990), research on these bone changes remains confined to three inland sites in Anatolia (Özbek, 2012; Koruyucu et al., 2018) and one coastal site in the Eastern Mediterranean (Lorentz, 2020).

Due to the high mineral density of EAEs, a known predisposing factor for increased survival in archaeological settings (Marques, 2019; Thomas, 2019), their occurrence has also been recorded in fragmentary remains. To date, two works have documented these bone changes in incomplete external auditory canals (Trinkaus and Wu, 2017; Lorentz and Casa, 2021), highlighting their value as activity indicators in poorly preserved assemblages.

In this study, the systematic assessment of EAEs in an assemblage of fragmentary remains from Early Neolithic Bestansur (Iraqi Kurdistan) is conducted to investigate habitual water exposure by people who lived in the Central Zagros. The exploitation of aquatic environments and its role in transitional economies have not been widely researched in the region. However, multi-proxy studies focusing on neighbouring Anatolian sites indicate that freshwater habitats may have been important settings for human activities during the Early Holocene (e.g. Özbek, 2012; Itahashi et al., 2017; Koruyucu et al., 2018; Siddiq and Özkaya, 2024). By addressing a considerable geographical gap in bioarchaeological research, the aim is to provide new insights into human-environment interactions, patterns of behaviour and their social dimension at the interface between hunting-gathering and increasing sedentism.

1.2. Archaeological context

The site of Bestansur (35°22'36.7 N, 045°38'44.4 E, *c.* 550 m asl) is an archaeological mound located near the eponymous village in the Sulaymaniyah province of Iraqi Kurdistan, at the western foothills of the Central Zagros. Situated in the Shahrizor plain, a fertile valley shaped by the action of the Tanjaro river and its tributaries (Altaweel et al., 2012), the site benefits from easy access to freshwater sources, including a perennial spring (Matthews et al., 2019) (Fig. 1).

Bestansur bears evidence of a long occupational history, with an Early (Pre-pottery) Neolithic sequence that, according to ^{14}C dating, spans at least 600 years (*c.* 7700–7100 BCE) (Flohr et al., 2020) and may extend into the very early 7th millennium BCE (A. Richardson, personal communication, 20 July, 2025). This longevity probably relates to the site's strategic position in a landscape of rich and diverse ecological niches, including mountainous areas, wetlands and riparian habitats, with watercourses acting as natural attractors for animals (Matthews et al., 2020b). The importance of wild resource exploitation has been confirmed by multi-proxy analyses, which have yielded evidence for limited reliance on plant and animal domesticates (Whitlam et al., 2020; de Groene et al., 2021, 2023).

At Bestansur, hybrid subsistence systems (see Smith, 2001) coexisted with markers of sedentary communities. These include the presence of permanent mud-brick buildings over an area of at least 1 ha (Richardson et al., 2020) and striking diversity in mortuary behaviours. Previous excavations and ongoing archaeothanatological work have brought to light a minimum of 85 individuals from different mortuary contexts, ranging from discrete inhumations to highly commingled deposits reflecting multiple burial events. The former are widely distributed beneath floors and in open spaces across the site, whereas the latter are primarily (though not exclusively) found within Building 5/8, a complex

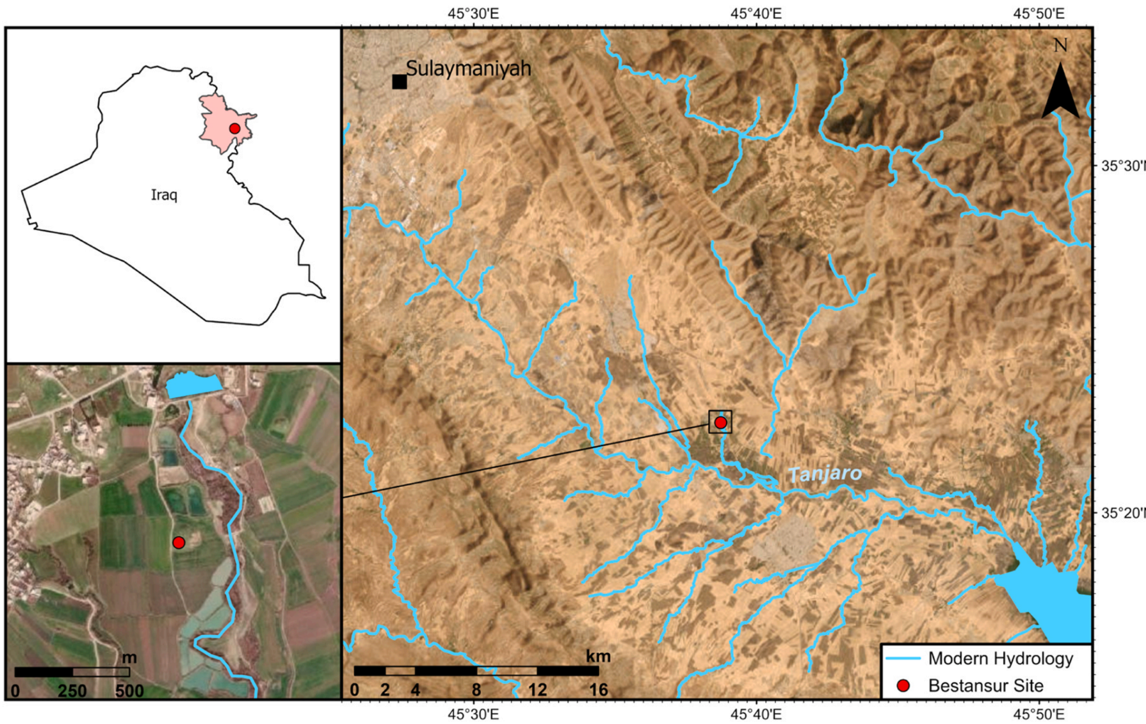

Fig. 1. Map showing modern hydrological features near Bestansur (red circle), with indication of the location (top left panel, Sulaymaniyah province shaded in red) and positioning of the site relative to the Bestansur spring (light blue shape in the bottom left panel). Created using ArcGIS Pro 3.1 with an Earthstar Geographics (2024) basemap and water layers adapted from OpenStreetMap (2021).

of superimposed buildings with communal and mortuary functions (Walsh, 2020). This complex, interpreted as a liminal place where the remains of the dead were curated by the living, is thought to have held great significance in the construction and maintenance of social bonds (Walsh and Matthews, 2018; Matthews et al., 2020b). Its importance is further emphasised by mortuary adornments made with imported materials, otherwise uncommon at the site, found within its boundaries. These comprise marine shells, carnelian and variscite, attesting to engagement in long-distance exchange networks (Richardson, 2020). The representation of different age groups and sexes implies that the selection criteria for burial in Building 5/8 may have been multifactorial and dynamic. Nevertheless, the prominence of this complex hints at possible social differentiation between individuals interred within it and at other locations.

Material culture, zooarchaeological and heavy-residue analyses suggest that the inhabitants of Bestansur regularly interacted with aquatic environments as part of their resource procurement strategies (Matthews et al., 2020b). These involved sourcing stone and plants from local watercourses and wetland ecosystems for toolmaking and textile production (Mudd, 2020; Matthews et al., 2020b), as well as collecting freshwater shells for decorative purposes (Richardson, 2020). A large ichthyological assemblage, along with the presence of fish bones in coprolites of probable human origin (Matthews, 2020), reflects the contribution of fish to the diet, seasonally supplemented by crabs and river molluscs (Iversen, 2020; Bendrey et al., 2020). While freshwater access was clearly important for the economy of the site, the social aspects of participation in aquatic activities remain obscure. In assessing direct evidence for repetitive engagement with water in human skeletal remains from Bestansur, this study investigates EAEs in relation to biological sex, age-at-death and burial location.

2. Material and methods

2.1. Sample composition

The osteological remains from Bestansur, housed at the Slemani Museum (Sulaymaniyah, Iraqi Kurdistan), were accessed with permission from the Slemani Directorate of Antiquities and Heritage. Contextual information was partly compiled by the author and partly derived from published (Walsh, 2020) and unpublished data. The study sample included fully and partially articulated individuals and isolated crania from discrete and commingled deposits across the site (see Supplementary Information: File A), all dating to the Early Neolithic, with fragmentary, poorly preserved remains forming the bulk of the collection.

Following other EAE studies focusing on Southwest Asia (Özbek, 2012; Koruyucu et al., 2018), a conventional cut-off point for adulthood was set at 15 years. Biological sex was estimated in adults using standard morphological and statistics-based techniques (Ferembach, 1980; Walker, 2008; Klales et al., 2012). Additionally, a single aDNA-based sex estimate was available for a female non-adult (C1228 SK1). Individuals were classified as (probable) males, (probable) females, 'indeterminate-sex', or 'unknown-sex'. To increase representativeness, females and males were pooled with probable females and probable males, respectively. For non-adults, age-at-death was estimated using dental development (AlQahtani et al., 2010) and epiphyseal fusion (Cunningham et al., 2016). Due to poor bone preservation, adult age-at-death assessment relied primarily on dental wear patterns (Lovejoy, 1985), although standard bone-based methods (Brooks and Suchey, 1990; Buckberry and Chamberlain, 2002) were also used wherever possible. The low resolution of adult age-at-death estimates, often reflected in very broad age ranges, did not enable the further organisation of the dataset into smaller age groups.

According to the clinical literature, EAEs can appear as early as one year after regular cold-water exposure in predisposed individuals, but more commonly manifest after 5–10 years (see Villotte and Knüsel, 2016). Likely due to their slow-progressive nature, these bone changes are never noted in infants and rarely diagnosed in older non-adults (Villotte and Knüsel, 2016; Koruyucu et al., 2018), with few bioarchaeological and clinical studies reporting their occurrence in children above 5 years of age and adolescents (Adams, 1951; DiBartolomeo, 1979; Costa-Junqueira et al., 2000; Moore et al., 2010 Koruyucu et al., 2018; Medrano-Enríquez, 2025). Considering the timing for EAE development, the age threshold for inclusion was set at 5 years in this study. Both older children (5.6–10.5 years) and adolescents (10.5–15 years) were represented in the non-adult subsample. Given the small size of the dataset (6 individuals), these age groups were pooled for statistical analysis.

2.2. EAEs assessment, distribution analysis and intra-observer error

Out of 56 individuals meeting the age threshold for inclusion, 46 presented with fragments of at least one external auditory canal. Further inclusion criteria were set to standardise recording, considering the dense structure of EAEs and the possible overrepresentation of affected compared to non-affected canals. In line with the approach proposed by Lorentz and Casa (2021), a minimum observability threshold was set at 25 %. Observable canals were then defined as having at least the anterosuperior, anteroinferior, posterosuperior or posteroinferior quadrant represented (each corresponding to 25 % completeness; Fig. 2). The division of the meatus according to these standardised sections followed a recording system for EAEs used in the clinical setting (Umeda et al., 1989; Wong et al., 1999) and was adopted as easily applicable to fragmentary canals from the site.

Observable external auditory canals were macroscopically assessed for the presence or absence of EAEs. These were recorded as present if appearing as discrete growths, and their position was noted with respect to the meatal walls and quadrants. The most frequent locations for EAEs were then determined from the observation of complete canals. Severity was scored for complete canals using a three-grade ordinal scale describing the extent of meatal occlusion, in line with current bioarchaeological and clinical approaches (see Villotte and Knüsel, 2016; Climstein et al., 2021). Grade 1 corresponded to canal stenosis inferior to 1/3 (<33 %), Grade 2 indicated obstruction between 1/3 and 2/3 (33 %-66 %), and Grade 3 marked loss of patency of more than 2/3 (>66 %) (Standen et al., 1997; Cooper et al., 2010). Since EAEs can simultaneously arise from multiple meatal walls, canal completeness was set as a requirement for severity assessment.

Osteomata were the main lesions considered as a differential diagnosis. These are benign neoplasms, rarer than EAEs and independent from environmental determinants (Montebello et al., 2022). Both

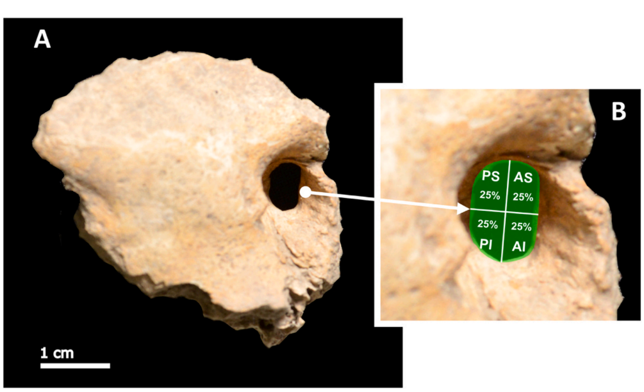

Fig. 2. Visual representation of observability thresholds for EAE assessment adopted in this study. A: Non-affected external auditory canal (right, C2337 SK1). B: canals are observable when ≥ 25 % complete, with minimum representation of the anterosuperior (AS), anteroinferior (AI), posterosuperior (PS) or posteroinferior (PI) quadrant.

conditions appear as growths arising from the external auditory canal and can result in its narrowing. Osteomata present as solitary, unilateral lesions, with a preferential lateral location along the tympanosquamous and tympanomastoid sutures (Goddard and McRackan, 2019). Conversely, EAEs are more medially located, close to the tympanic annular sulcus, and are often multiple and bilateral (White et al., 2012). Additionally, osteomata tend to manifest as pedunculated masses, whereas EAEs are broad-based and sessile (Montebello et al., 2022). Due to the fragmentary nature of the Bestansur sample, differential diagnosis relied primarily on the presentation and location of bone changes, while their number and laterality were only secondarily considered. Criteria followed for EAE assessment are summarised in Table 1.

Frequencies of EAEs according to biological sex, age-at-death (adult versus non-adult) and burial location (individuals from Building 5/8 versus individuals buried elsewhere) were calculated as crude (affected/observed individuals) and true prevalence rates (affected/observed external auditory canals). For comparative purposes, and in the absence of clear evidence for social stratification, burial location was used as a proxy for social differentiation. Considering expected values (Kim et al., 2017), biological sex-, age- and context-specific frequencies of EAEs were compared using Fisher's exact test with significance at $p < .05$. A Pearson's chi-squared test was used to explore differences in EAE prevalence between left and right auditory canals.

Intra-observer error was tested to evaluate the reproducibility of inclusion and diagnostic criteria. External auditory canals were assessed twice for observability and for presence/absence of EAEs, with an interval of five months between observations. Agreement was calculated using unweighted Cohen's Kappa statistic (Cohen, 1960) and quantified on a scale from 0 to 1 following Landis and Koch (1977) and Viera and Garrett (2005), with a Kappa coefficient (κ) between 0.41 and 0.60 as the mid-point for moderate agreement. All statistical tests were carried out using version 23.0.6 of MedCalc Software Ltd. (2025).

3. Results

Very good intra-observer agreement is reported for the identification of observable external auditory canals (k = 0.91262, standard error =0.04924, 95 % confidence interval =0.81611–1.00000) and for their classification as affected versus non-affected (k = 0.84967, standard error =0.08296, 95 % confidence interval =0.68707–1.00000). The final study sample counted 34 individuals represented by 50 observable canals, 27 left and 23 right (Table 2). Twenty-four individuals (70.6 %) and 31 canals (62 %), 18 left (66.7 %; n = 27) and 13 right (56.5 %; n = 23), demonstrated EAEs. Differences in prevalence between left and right canals were not statistically significant (χ^2 (1) = 0.543; $p = .461$). Frequencies of EAEs according to biological sex, age-at-death and burial location are presented in Table 3, while comprehensive data for each individual can be found in Supplementary Information: File B.

Laterality could only be assessed in 13 of the 24 affected individuals, and bilaterality was slightly more common than unilateral presentations (seven versus six individuals; 53.8 % versus 46.2 %). Five of the six non-adults (83.3 %) displayed EAEs in 25 % of right (n = 4) and 100 % of left canals (n = 4), whereas 19 of the 28 adults (67.9 %) had 63.2 % of right (n = 19) and 60.9 % of left canals affected (n = 23). Except for a single child aged 7.5–8.5 years, the youngest to display EAEs (Fig. 3), observable non-adults were all between 11.5 and 15 years of age, reflecting greater representation bias in the younger age cohort.

In the subsample of individuals with an estimated biological sex (n = 20), eight out of 10 males (80 %) presented EAEs in 50 % of right (n = 8) and 85.7 % of left canals (n = 7). Six out of 10 females (60 %) had 57.1 % of right (n = 7) and 62.5 % of left canals affected (n = 8).

Individuals originating from the Building 5/8 complex (14/19; 73.7 %) demonstrated EAEs in 58.3 % of right (n = 12) and 70.6 % of left canals (n = 17). Individuals buried at other locations (10/15; 66.7 %) had bone changes in 54.5 % of right (n = 11) and 60 % of left canals (n = 10).

Table 1
Summary of criteria for sample selection, observability and severity assessment used in this study. Criteria for differential diagnosis were adapted from Larem et al. (2021) and Montebello et al. (2022).

Sample selection	Observability	Severity assessment	Differential diagnosis		
Individuals aged 5 + years	≥ 25 % of external auditory canal preserved, with minimum representation of:	Complete external auditory canal		**EAE**	**Osteoma**
			Presentation	Broad-based	Pedunculated
At least one external auditory canal observable	Anterosuperior, anteroinferior, posterosuperior or posteroinferior quadrant	Presence of at least one distinct bone growth	**Location**	External auditory canal – medial	External auditory canal – lateral
			Number of lesions	Often multiple	Commonly single
			Lateralisation	Often bilateral	Commonly unilateral

Table 2
Composition of the study sample.

	Non-adults (5–15 years)				Adults (16 + years)				
	Male	**Female**	**ND**	**Pooled sexes**	**Male**	**Female**	**ND**	**Pooled sexes**	**Total sample**
Individuals	0	1	5	6	10	9	9	28	**34**
Left external auditory canals	0	1	3	4	7	7	9	23	**27**
Right external auditory canals	0	1	3	4	8	6	5	19	**23**
Total external auditory canals	0	2	6	8	15	13	14	42	**50**

Notes. Abbreviation: ND, not determined (including indeterminate- and unknown-sex individuals).

Table 3
Prevalence of EAEs according to age-at-death, biological sex and burial location.

		Crude prevalence rates							True prevalence rates					
		Individuals with one external auditory canal		**Individuals with both external auditory canals**		**Total**			**Right external auditory canal**		**Left external auditory canal**		**Total**	
	Subsample	**Affected/ Observed**	**%**	**Affected/ Observed**	**%**	**Affected/ Observed**	**%**	***p* value (FET)**	**Affected/ Observed**	**%**	**Affected/ Observed**	**%**	**Affected/ Observed**	**%**
Age-at-death	Non-adult (5–15 years)	3/4	75	2/2	100	5/6	83.3	.644	1/4	25	4/4	100	5/8	62.5
	Adult (16 + years)	8/14	57.1	11/14	78.6	19/28	67.9		12/19	63.2	14/23	60.9	26/42	61.9
Biological sex	Male	4/5	80	4/5	80	8/10	80	.628	4/8	50	6/7	85.7	10/15	66.7
	Female	2/5	40	4/5	80	6/10	60		4/7	57.1	5/8	62.5	9/15	60
	Indeterminate/ Unknown	5/8	62.5	5/6	83.3	10/14	71.4	-	5/8	62.5	7/12	58.3	12/20	60
Burial location	Building 5/8	6/9	66.7	8/10	80	14/19	73.7	.718	7/12	58.3	12/17	70.6	19/29	65.5
	Other locations	5/9	55.6	5/6	83.3	10/15	66.7		6/11	54.5	6/10	60	12/21	57.1
Total prevalence		**11/18**	**61.1**	**13/16**	**81.3**	**24/34**	**70.6**		**13/23**	**56.5**	**18/27**	**66.7**	**31/50**	**62**

Note. Abbreviation: FET, Fisher's Exact Test.

No statistically significant differences in EAE frequencies were detected between males and females ($p = .628$), adults and non-adults ($p = .644$), and individuals buried within and outside of Building 5/8 ($p = .718$) (Table 3). It must be noted, however, that small sample sizes may have affected statistical power.

The most common location and severity of EAEs were determined from the observation of nine complete affected canals belonging to nine different individuals. These consistently displayed posterior growths (100 %), which were associated with anterior changes in five cases (55.6 %). Superior wall involvement was only observed once (11.1 %), in combination with posterior and anterior EAEs. Bone changes were more frequently located posteroinferiorly (8/9; 88.9 %) than anterosuperiorly (4/9; 44.4 %), anteroinferiorly (2/9; 22.2 %) or posterosuperiorly (2/9; 22.2 %).

Seven of nine cases of EAEs were scored as mild (Grade 1; 77.8 %) and two as moderate (Grade 2; 22.2 %,) (Figs. 4–5). Grade-1 bone changes were observed in two non-adults and five adults of both sexes, whereas the Grade-2 cases were recorded in two probable male adults (Table 4). Given the small number of scorable canals, no attempt was made to explore statistical correlations between severity and sex or age. In two canals, one complete and exhibiting Grade-2 EAEs and one fragmentary, bone growths were associated with pitting of the meatal floor.

4. Discussion

Clinical and bioarchaeological studies comparing the prevalence of EAEs across groups with differential aquatic engagement support the primary role of environmental and behavioural factors in the occurrence of these bone changes (e.g. Kennedy, 1986; Standen et al., 1997; Trinkaus et al., 2019; Hecht-López et al., 2022), highlighting their value as biocultural markers. So far, most studies have concentrated on complete external auditory canals, whereas few works have recorded EAEs in poorly preserved temporal bones (Trinkaus and Wu, 2017; Lorentz and Casa, 2021). At Bestansur, where fragmentation is high, assessing EAEs on fragmentary remains provided the only opportunity to explore social participation in aquatic activities at an important transitional site.

External auditory exostoses could be assessed in 34 individuals, offering the first insights into the occurrence of these bone changes in an Early Neolithic community of the Central Zagros. All observed growths were broad-based and medially located, and, where laterality could be assessed, bilateral occurrences were slightly more common than

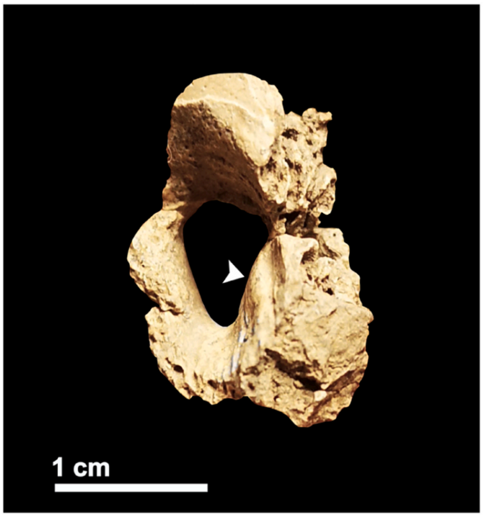

Fig. 3. Left external auditory canal of non-adult individual displaying a Grade-1 EAE on the posterior wall (posteroinferior quadrant; C2979 SK1); lateral view.

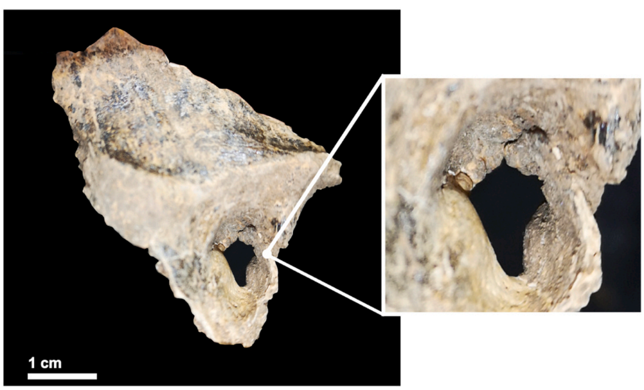

Fig. 4. Right external auditory canal of a probable male individual displaying Grade-2 EAEs on the anterior, posterior and superior walls (all quadrants; C1868 SK5); lateral view.

unilateral presentations. Due to the fragmentary nature of the sample, additional cases of bilateral EAEs may have been obscured by intra-individual differences in representation between the left and the right side. Clinical studies have suggested a correlation between asymmetrical EAE development and environmental factors, such as differential ear exposure to the prevailing wind, in water sports participants (e.g. Hurst et al. 2004; King et al., 2010; Nakanishi et al., 2011). At Bestansur, no significant differences were detected in EAE occurrence between the left and right auditory canals. Nevertheless, poor preservation hindered severity comparisons between the two sides, limiting meaningful interpretations.

In agreement with previous studies (Gregg and Bass, 1970; Turetsky et al., 1990; Manzi et al., 1991; Standen et al., 1997; Günay and Akpolat, 2009; Koruyucu et al., 2018; Delgado-Darias et al., 2023), EAEs were mainly observed on the posterior walls, followed by the anterior walls of complete affected canals. Overall, posteroinferior bone changes were more common. DiBartolomeo (1979) proposed that a selective anterior and posterior location of EAEs could relate to the embryology of the tympanic ring, with areas corresponding to the ends of the annulus being more prone to irritation and osteogenic activity. Umeda et al. (1989) later postulated that their position may be dictated by a specific growth pattern beginning in the anterosuperior quadrant, which they identified as the most frequently affected site. This was not confirmed by Wong et al. (1999), who reported a similar involvement of all quadrants in affected surfers' ear canals (n = 441). However, their study did not explore correlations between the location and severity of EAEs, leaving it unclear whether quadrant-based distribution varies with progression. Bioarchaeological studies examining this relationship in large, well-preserved samples may contribute to testing the existence of underlying developmental patterns, shedding further light on factors influencing EAE expression.

4.1. External auditory exostoses, activity and human-environment interactions

With a recorded prevalence of 70.6 % for the whole sample and 67.9 % for the adult subsample, Bestansur exhibits similar frequencies of EAEs to modern groups of water sport participants (e.g. Umeda et al., 1989; Wong et al., 1999; Attlmayr and Smith, 2015; Simas et al., 2020; Wegener et al., 2022). Prevalence rates are higher than those reported for other inland sites in Southwest Asia, except for Proto-Neolithic Shanidar Cave, in the same region (Table 5). However, differences in sample size require caution when drawing comparisons, and it must be stressed that only complete external auditory canals were assessed in these assemblages.

Bestansur is located at a latitude of 35°22'N and in proximity to water sources, including the Tanjaro river, less than 3 km to the south, and a nearby perennial karst spring, which is a key source of drinking and irrigation water to this day. Mean water temperatures of 20°C to 22°C (Seeyan et al., 2021; Rasheed and Moradi, 2024) and 17.3°C (Al-Manmi and Saleh, 2019) are reported for the river and the spring, respectively, with local inhabitants confirming that the latter is cool throughout the year. Today, seasonal river fluctuations between 8°C and 33.1°C (Aziz et al., 2022) match average atmospheric temperatures between 6.5°C in winter and 33°C in summer (Bosomworth et al., 2020). Palaeoclimatic reconstructions indicate greater moisture availability in the Central Zagros during the Early Holocene (Regattieri et al., 2023; Rostami et al., 2024), with predominantly wet and warm periods punctuated by cold, dry events on a multicentennial scale (Regattieri et al., 2023). Increased water abundance and general climatic amelioration following the Pleistocene (Zeder, 2024) would have created favourable conditions for the exploitation of aquatic environments at Bestansur. The high prevalence of EAEs recorded at the site is suggestive of regular contact with (cold) water and the concomitant exposure to wind chill, particularly during the colder season (see Kroon et al., 2002; Sheard and Doherty, 2008; Moore et al., 2010). According to the classifications proposed by Kennedy (1986) and Trinkaus et al. (2019), Bestansur can be identified as a middle-latitude 'wet' site, (i.e. a site located at 30°-45°N and characterised by water proximity and exposure). This site typology has been associated with high frequencies of EAEs (Trinkaus et al. 2019).

Contextual evidence reveals that water access for food and raw material procurement played a central role in the life of the Bestansur community. Net and trap fishing is indicated by abundant fish remains, primarily cyprinids (Bendrey et al., 2020), and their association with perforated net sinkers bearing freshwater *Polychaeta* worm casings (Mudd, 2020; Richardson et al., 2020). Compared to hook-and-line fishing, the use of nets and traps is more likely to involve cephalic immersion and expose the ears to water splashes and wind-enhanced evaporative cooling (Villotte et al., 2014; Koruyucu et al., 2018), which are key factors in EAE development. Along with fishing, the harvesting of freshwater resources from the local spring and river is evidenced by river clams of the *Unio Tigridis* type (Iversen, 2015; 2020) and crabs of the *Potamon* species, whose claws were also used for bead production (Richardson, 2020). Most striking is the presence of hundreds of decorative beads made from *Theodoxus Jordani* nerite snails (Richardson, 2025). These snails, which inhabit submerged rocks in fast-flowing water (Amr et al., 2014), were likely collected alive, as suggested by the excellent preservation of their shells.

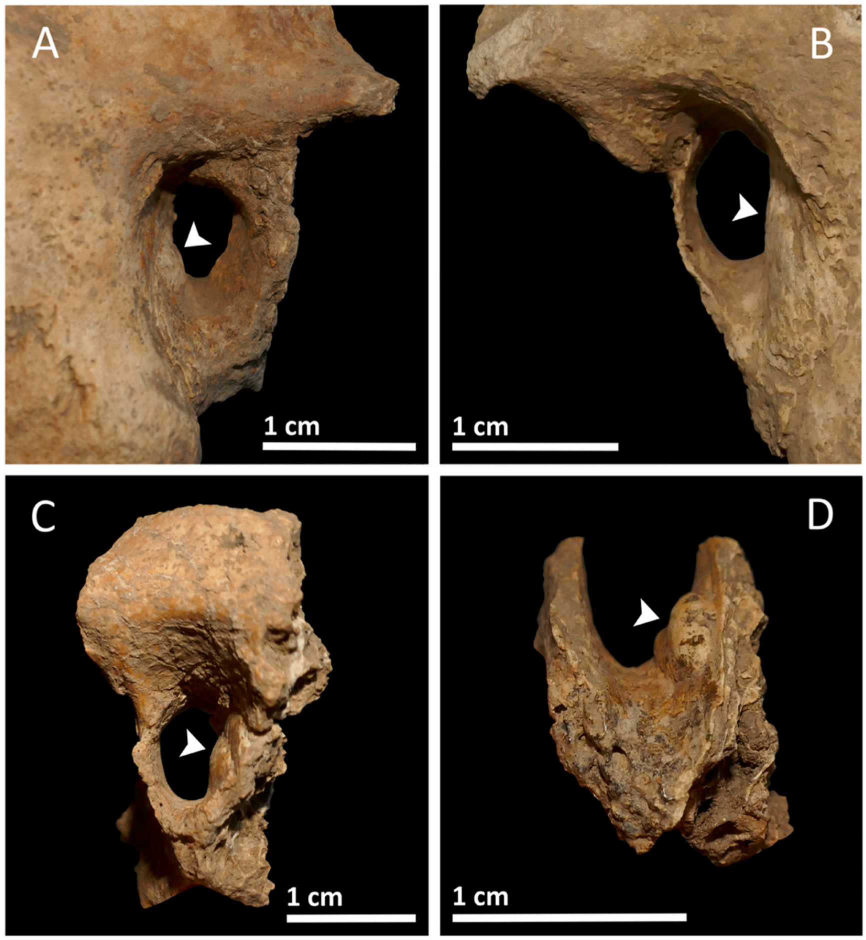

Fig. 5. Examples of EAEs located on the posterior wall (posteroinferior quadrant) of complete and fragmentary external auditory canals; lateral views. A: Grade-1 EAE (right, C2725 SK1); B: Grade-1 EAE (left, C2387 SK2); C: Grade-1 EAE (left, C1228 SK1); D: EAE in canal with > 50 % completeness (left; C2909 SK4).

Table 4
Severity of EAEs in complete affected canals by age-at-death and biological sex.

	Adults (5–15 years)				Non-adults (16 + years)				
Severity	**Male**	**Female**	**ND**	**Pooled sexes**	**Male**	**Female**	**ND**	**Pooled sexes**	**Total**
Grade 1	3	2	0	5	-	1	1	2	**7**
Grade 2	2	0	0	2	-	0	0	0	**2**
Grade 3	0	0	0	0	-	0	0	0	**0**
Total	**5**	**2**	**0**	**7**	**-**	**1**	**1**	**2**	**9**

Note. Abbreviation: ND, not determined (including indeterminate- and unknown-sex individuals).

Despite a lack of emphasis in previous research on Neolithic fish assemblages (see Van Neer et al., 2005), aquatic resource procurement is attested at other landlocked sites in the Central Zagros. Fish remains from M'lefaat and Shimshara, for example, reflect the consumption of mostly analogous taxa to those represented at Bestansur, which may have been procured through similar fishing practices (Bendrey et al., 2020). Numerous crab remains were identified at the recently excavated site of Zawi Chemi Rezan, near the Chemi Tabin river (CZAP, 2023). Additionally, edible freshwater bivalves are documented in the Iranian Zagros, at Tepe Asiab (Reed, 1962), Sheikh-e-Abad and Jani (Shillito et al., 2013), and in Iraq, at Nemrik 9, where they were also used to craft adornments (Kozlowski, 1989). While some of these sites have produced assemblages of human remains, no information is available on the occurrence of EAEs.

At Bestansur, the majority of ichthyofaunal, malacological and crustacean remains linked with food preparation and consumption come from occupational and discard areas (Bendrey et al., 2020; Iversen, 2020). Conversely, most crab and shell beads were uncovered in mortuary contexts. These objects, interpreted as bodily adornments (Richardson, 2020), were mainly found with non-adult remains (Walsh, 2020). While some freshwater specimens were also excavated near the isolated crania of three adults included in this study, two of whom exhibit EAEs (one probable male and one of unknown sex), these individuals originated from commingled deposits, making associations uncertain. The placement of an unworked crab claw with the partially articulated remains of a non-adult with EAEs is more secure. However, no direct relationship can be detected in the mortuary display of water-derived materials (or other accompaniments) between affected and non-affected individuals.

Fishing and mollusc harvesting involve repetitive exposure to water and wind chill and are therefore frequently associated with EAE development in archaeological settings (e.g. Crowe et al., 2010; Villotte et al., 2014; Kuzminsky et al., 2016; Lorentz, 2020; Lorentz and Casa, 2021). This connection is supported by clinical research reporting high EAE

Table 5
Crude prevalence rates of EAEs at Neolithic and Proto-Neolithic inland sites in Southwest Asia.

Site	Period	Sample size	Total %	Adult %	Non-adult %	Reference
Bestansur, Iraq	Early (Pre-pottery) Neolithic	34 (28 adults, 6 non-adults)	70.6 %	67.9 %	83.3 %	Present study
Körtik Tepe, Türkiye	Late Epipalaeolithic - Early (Pre-pottery) Neolithic	128 (81 adults, 47 non-adults†)	35.2 %	47.6 %	12.8 %	Koruyucu et al., 2018
Çayönü, Türkiye	Early (Pre-pottery) Neolithic	114 (97 adults, 17 non-adults)	17.5 %	17.5 %	0 %	Özbek, 2012
Aşıklı Höyük, Türkiye	Early (Pre-pottery) Neolithic	40 (28 adults, 12 non-adults)	3.6 %	3.6 %	0 %	Özbek, 2012
Shanidar, Iraq	Proto-Neolithic	7 (5 adults, 2 non-adults)	80 %	80 %	0 %	Agelerakis and Serpanos, 2002

† Unlike Bestansur, the non-adult subsample from Körtik Tepe includes individuals below 5 years of age.

prevalence among fishermen and surface seafarers from northern Chile (Hecht-López et al., 2022). In Early Neolithic Southwest Asian samples, EAEs appear linked to zooarchaeological evidence of aquatic resource procurement. Specifically, at middle-latitude inland sites comparable to Bestansur, high and low EAE frequencies respectively correlate with the presence (Özbek, 2012; Koruyucu et al., 2018) or absence (Özbek, 2012) of ichthyofaunal remains. Studies focusing on historical periods have also shown that EAEs can be associated with cultural practices, including the use of thermal and ritual baths (Ascenzi and Balistreri, 1975; Manzi et al., 1991; Günay and Akpolat; 2009; Charlier et al., 2025). In the absence of documentary evidence, similar activities remain archaeologically invisible. Nevertheless, water access as part of cultural practices, such as bathing and swimming, can at least be postulated at Bestansur. A glimpse into the past may be sought in current recreational uses of the nearby spring, whose cool waters welcome locals of all ages during the hot summer months.

In addition to environmental and behavioural factors, genetic susceptibility may play a role in EAE prevalence. Early research hinted that some individuals could be more prone to developing EAEs in response to triggering stimuli (Harrison, 1962; DiBartolomeo, 1979). Today, the role of inherited predisposition remains unclear, but a predominance of external determinants in their expression is widely recognised (Villotte and Knüsel, 2016). At Bestansur, EAE frequencies are provisionally read within a feedback system in which environment, biology and behaviour influence each other. Posited a component of genetic liability, contextual evidence supports the contribution of habitual activities in conducive environments to the development of EAEs (Fig. 6). The distribution of these bone changes thus provides a human-derived glimpse into how social participation was defined at the site.

4.2. Aquatic engagement and social participation

Frequencies of EAEs in the sample are consistent with habitual exposure of all segments of society to aquatic environments. No correlation was found between burial location and the occurrence of these bone changes. Therefore, whether interment inside or beyond the boundaries of Building 5/8 is reflective of social differentiation, this cannot be inferred from the prevalence of EAEs. The lack of differential mortuary treatment for non-affected individuals may indicate that participation in aquatic activities was not perceived as an element of

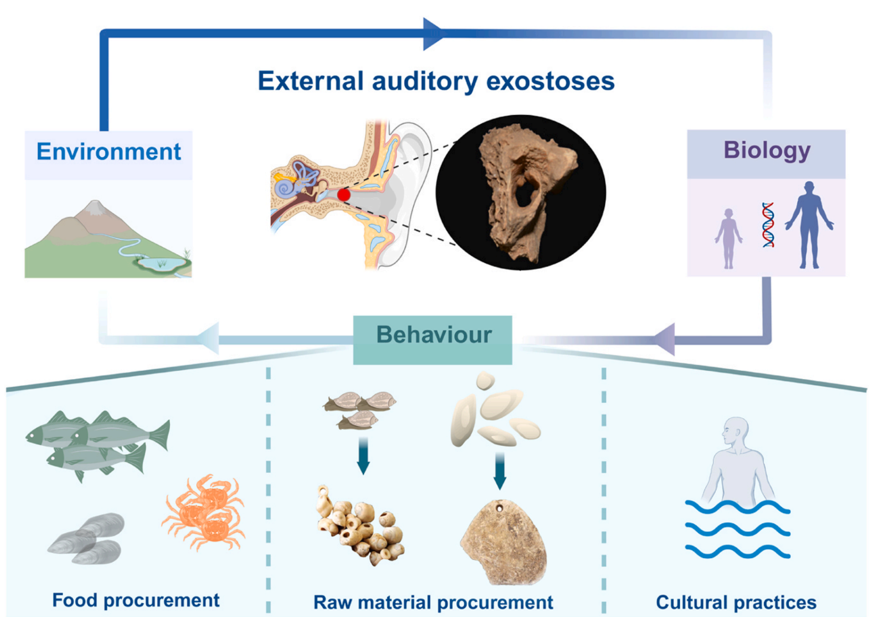

Fig. 6. Interplay of different factors in EAE development at Bestansur. A case of Grade-1 EAEs (right external auditory canal, C2139 SK2) is illustrated at the centre of the figure, and nerite shell beads and an incomplete net sinker are included in the 'raw material procurement' panel as examples of objects made with source materials from aquatic environments (i.e. snails and river pebbles). Created in BioRender (Ragazzon, 2025); pebble icons from Integration and Application Network (Saxby, 2010).

distinction. It is also possible, however, that some individuals simply did not develop EAEs due to lower susceptibility and/or more infrequent exposure.

The lack of sex-specific prevalence patterns is in contrast with findings at Neolithic Çayönü, where Özbek (2012) reported a marked preponderance of affected males, but is consistent with EAE distribution at Shanidar (Agelerakis and Serpanos, 2002) and Körtik Tepe (Koruyucu et al., 2018), and can provisionally be interpreted as absence of evidence for sex-based task differentiation.

Non-adult cases of EAEs are noteworthy, as they add to a small body of bioarchaeological research recording their manifestation in children. This includes reports of bone changes in two non-adults aged 6 and 12 years from a coastal hill site in Northern Chile (Costa-Junqueira et al., 2000) and a lake site in Mexico (Medrano-Enríquez, 2025), respectively. Within Southwest Asia, Bestansur is comparable to Körtik Tepe, where the youngest affected individuals are also aged at around 7 years (Koruyucu et al., 2018). Interestingly, most bioarchaeological cases of EAEs in children have been documented in landlocked contexts. However, it is uncertain whether this datum is meaningful, as prevalence studies do not consistently include non-adult individuals. More systematic reporting of juvenile EAE cases from both coastal and inland sites will be key to exploring how different aquatic environments may have shaped non-adult activities in the past. At Bestansur, EAE distribution points to repeated engagement with water from an early age and, if considered in relation to task allocation, suggests that non-adults held active social roles within the community. The involvement of children in river fishing, for example, has modern parallels. In an ethnographic note (Bendrey et al., 2017), an informant from the Bestansur village described how, until the 1960s, groups of mixed-age males would participate in weekly river-fishing practices using hand-made willow baskets. Interestingly, fishing parties would be most active in the colder and windier autumn and winter months, when fish were deemed to be tastier compared to the summer catch. The concept of non-adult participation in occupational tasks is not foreign at Early Neolithic Bestansur, where the use of teeth as tools has been detected in individuals as young as five years of age (Walsh, 2022). It is still possible that aquatic activities differed according to age, gender or group affiliation; this, however, cannot be established bioarchaeologically.

Considerations on the health impacts of EAEs are restricted to the few external auditory canals for which severity could be scored. Grade-1 EAEs were noted in two non-adults and five adults of both sexes, whereas Grade-2 cases were only observed in two probable male adults. While factors influencing the severity of EAEs are difficult to isolate, these two individuals may have been exposed to stimuli triggering bone responses more frequently/intensely or over longer periods of time.

All observed EAEs fit with asymptomatic or mildly symptomatic presentations (Lobo, 2015). In two affected canals, one complete and with Grade-2 EAEs, porosity was noted on the meatal floor. As the association of EAEs and floor porosity is generally not discussed in the literature, its implications are unclear. It is possible to hypothesise a connection with chronic inflammation and infection, as consistent with recurrent otitis externa, a common co-occurrence of EAEs (Leonetti and Marzo, 2015). However, further research is needed to clarify the relationship between hyperostotic and porous bone changes in the external auditory canal.

Despite the location of most Early Neolithic sites near water bodies, the exploitation of aquatic environments is understudied in the Zagros region. The case of Bestansur suggests that freshwater habitats may have played an important role in local communities. Favoured by proximity to water, naturally abundant aquatic resources could have indeed complemented and/or supported active resource management (Zeder, 2024), reflecting the persistence of hybrid economies at a time where experiments with domestication and sedentism were well under way (Watkins, 2023). As rigid dichotomies between hunter-gatherer and farmers are increasingly challenged in current research, this evidence contributes to a nuanced picture of human-environment interactions during the Neolithic. From a human perspective, contextual and, possibly, diachronic variability in aquatic engagement is indicated by comparisons with Anatolian sites, calling for more research on a regional scale. Currently, the distribution of EAEs at Bestansur does not offer clear evidence for social differentiation or task specialisation. However, as excavations progress, interpretations presented in this study may need to be revisited in the light of new findings. Ongoing palaeodietary and palaeomobility analyses will also contribute to a more comprehensive understanding of the site, providing additional interpretative bases for the characterisation of subsistence, activity and social structures.

5. Limitations of the study and future directions

Working with fragmentary remains is a rewarding challenge but is not without limitations. Firstly, the effects of representation bias could not be eliminated in the sample and may have contributed to the high frequencies of EAEs observed. Secondly, subtle generational shifts in prevalence may have been masked by low temporal resolution. While rarely acknowledged, this is a common issue with Neolithic samples, which often span several centuries. Lastly, the analysis of EAE severity and distribution was constrained by small sample size and preservation, which may have obscured patterns related to age-at-death, biological sex and burial location.

Overall, more work can be done to improve EAE recording in poorly preserved remains. Due to the limited accessibility of the Bestansur assemblage, only intra-observer error tests could be carried out to evaluate the reproducibility of assessment criteria used in this study. However, measures of inter-observer agreement offer greater objectivity, and wider criteria applicability would benefit from further testing. Future research should also explore correlations between EAE severity and location to investigate the existence of specific developmental patterns. Finally, co-occurrences of EAEs and other bone changes in the auditory canal deserve attention. Indeed, their joint assessment may reveal hidden cause-effect relationships, shedding new light on EAE experiences and their correlates in the past.

6. Conclusion

This study presents the first systematic assessment of EAEs at an Early Neolithic site in the Central Zagros. The case of Bestansur adds to previous reports of EAE occurrences and prevalence in fragmentary remains, confirming their informative potential in poorly preserved assemblages. While acknowledging limitations imposed by sample size and preservation, frequencies of EAEs recorded at the site are provisionally explained within a model of intersecting environmental, biological and behavioural determinants. Bioarchaeological and contextual data point to similar male, female and non-adult engagement with freshwater landscapes as part of procurement activities and, perhaps, other cultural practices, reflecting deep integration in the environment and community-wide participation. The presence of EAEs in children is of particular significance, as these bone changes are rarely reported in young individuals and contribute to delineating active social roles for non-adults at the site.

The picture emerging at Bestansur suggests that freshwater environment exploitation may have played an important role in Zagros economies well into the 8th millennium BCE. Yet, comparisons with Early Neolithic Anatolian sites demonstrate contextual variability in aquatic engagement and its social dimension, highlighting the need for further work in the region. Additional research on EAEs and the acquisition of comparative data for the Zagros and beyond will help tie the results of this study into broader reconstructions, offering new perspectives on life, human-environment interactions and behavioural diversity during the foraging-to-farming transition.

CRediT authorship contribution statement

Giulia Ragazzon: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ijpp.2025.09.003.

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