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First Record of Beachrock in High-Altitude Soda Lakes, Lake Van, Eastern Türkiye

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Abstract This study presents, for the first time, evidence of beachrock formation along the shores of a highly alkaline soda lake. The carbonate cement binding the grains consists of radially grown aragonite, scalenohedral Mg-calcites, and spar calcites filling cavities. Dogtooth cement extending into cavities and meniscus cement textures are also present. These data indicate that the Lake Van beachrock formed through cementation with carbonate polymorphs precipitated from highly saturated lake waters under intense evaporation in extremely arid conditions. There are similarities in the conditions that support the formation of both beachrock and microbialites in the same shoreline zone. The role of high lake alkalinity, bacterial activity, and groundwater supplying Ca to the lake waters is crucial in the precipitation of binding carbonates. The formation of the beachrocks likely occurred between 3.5 ka BP, when the lake began experiencing a pronounced arid trend, and 2 ka BP, when the lake's climate reached a stabilized state. Thus, it can be inferred that the beachrocks predate the microbialites observed on the shelf of the studied shoreline.

Keywords Beachrock · Paleoclimate · Lake Van

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Introduction

High-magnesium calcite and aragonite-cemented beachrock deposits, formed by natural precipitation, are widespread along the world's coastlines between latitudes 0° and 40°, particularly between 20° and 40° (Vousdoukas et al., 2007). Until the 1960s, the widely accepted view regarding the formation environment of these rocks was limited to tropical and subtropical zones (Ginsburg, 1953). However, the discovery of some outcrops in temperate (Rey et al., 2004) and even cold regions (Binkley et al., 1980; Kneale & Viles, 2000) has partly altered this long-standing understanding. In particular, increase in temperature and evaporation are linked to the precipitation of beachrock cement and the subsequent binding of grains (Bathurst, 1972; Calvet et al., 2003; Milliman et al., 1974). Russell and McIntire (1965) stated that, for cementation to occur, pore water temperatures between grains must exceed 20°C for at least half of the year. The common occurrence of beachrock formation on tropical coasts is associated with the presence of warm waters, which emphasizes the importance of water temperature (Bezerra et al., 2003). Similarly, authors such as Beier (1985) and Vieira and De Ros (2006) emphasize that marine carbonate cement hardens more rapidly in warm waters, highlighting the need for elevated temperatures within beach sediments for cementation. These conditions explain the strong relationship between beachrock formation, increased temperature, and high evaporation rates. There is substantial evidence that the pronounced summer droughts and the increased evaporation during these months, under conditions of low tidal range, have led to the formation of late Holocene beachrock along the coasts of Türkiye (For a current reference list, see Tarı et al., 2024).

The detection of incipient $CaCO_3$-cemented beachrock in cold climates (Kneale & Viles, 2000) suggests that such formations could occur in harsh environments. Furthermore, the occurrence of beachrock along lake shores raises the need to revisit hypotheses regarding the cementation processes of these rocks (Vousdoukas et al., 2007). Two well-known examples include the beachrock formed in the freshwater meteoric-vadose diagenetic environment in the southeastern part of Lake Michigan (Binkley et al., 1980) and the beachrock along the shores of Lake Taupo in New Zealand, which results from hot spring waters rich in amorphous silica (Jones et al., 1997). Similarly, beachrock formation is quite common along the shores of Lake Iznik, a freshwater lake in Türkiye (Erginal et al., 2012; Ozturk et al., 2016).

An example of beachrock formation in cold climates is the cemented beach sediments found on the northern shore of Lake Van. Lake Van is located in the Eastern Anatolia region of Türkiye, often referred to as the "Roof of Türkiye." According to the Köppen-Geiger climate classification, the low-lying regions surrounding Lake Van, especially to the west, exhibit characteristics of a Mediterranean climate, designated as Csa. With increasing elevation, the climate transitions first to a continental climate with hot, dry summers (Dsa) and then to a continental climate with warm summers (Dsb) (Taşoğlu et al., 2024).

Under these conditions, the microstructural properties of the cement may preserve records of possible changes in the climate of the lake shores in the past. Cementation of beach sediments of lakes can occur depending on the physicochemical parameters (temperature, salinity, pH, mol% Mg content, etc.) of lake waters (Binkley et al., 1980; Jones et al., 1997; Ozturk et al., 2016). In this study, an example from high-altitude soda lakes is discussed for the first time in the world, to the best knowledge of the authors. The facies environment is examined based on thin section and scanning electron microscopy analyses of the beachrock, and the relationship between beachrock formation and drought is explored alongside the paleoclimatic proxies identified in previous lake research.

Materials and Methods

Study Area

Lake Van, with an area of 3,750 km² and a depth of 451 m, is Türkiye's largest lake, located at an elevation of 1,648 m above sea level in the Eastern Anatolia Region (Figure 1a). The lake has a water volume of 614 km³. The basin, situated in the upper reaches of the Murat River valley, likely became a closed basin as a result of a lava embankment following the Quaternary eruptions of the Nemrut volcano (Maxcon, 1936; Yalçınlar, 1973), leading to a soda-like chemical composition of its waters. In the last 30 years, the lake has again become more popular with the largest known calcareous microbialites in the world (Kempe et al., 1991; Kempe & Kazmierczak, 2007; Kremer et al., 2019; López-García et al., 2005).

Although there is no age data available, beachrock that records climate oscillations, which likely influenced the lake's late Holocene level changes, has been identified along the shores of Adilcevaz. Beachrock layers are exposed at three localities on Bozkirlar Beach, located 6 km east of Adilcevaz, one of the districts of Bitlis, and south of Yolçatı Village. From east to west, the beds range in length from 50 m to 240 m and 500 m, with interruptions and generally slope between 2° to 5° towards the south.

Figure 1. Location of the study area (a) and closer view of the sampling sites (b), generated using Google Earth satellite imagery (image date: November 18, 2023; last accessed: November 10, 2024).

Sampling and Analyses

A total of 12 samples were collected from beachrock beds located 6 km east of Adilcevaz (Figure 1b). Samples were taken from three different levels: underwater, along the shoreline, and above the lake level, to investigate the composition and cementation environment of the beachrock. Thin sections were prepared from each sample for petrographic analysis, and microphotographs of these sections were captured. Scanning electron microscopy (SEM) analyses were conducted on the same samples to examine grain surfaces, voids, and cement textures between grains. Elemental analyses were performed using energy-dispersive X-ray spectrometry (EDX) on the surfaces of carbonate crystals imaged by SEM. Consequently, the deposition and cementation environment during beachrock formation, as well as the climatic conditions influencing cementation, were elucidated.

Results and Discussion

Bedding Characteristics and Composition

In this study, samples were collected from outcrops located 6 km east of Adilcevaz, where the bedding structure provides more representative sections. In the coastal zone known as the Bozkırlar locality, located to the south of Mt. Süphan, beachrocks are present at three sites. The first site, situated along the shores of a small bay in the eastern part of Bozkırlar Beach, features cemented layers that extend parallel to the shoreline, spanning 50 meters in length and 1 meter in width, remaining uninterrupted at and below lake level. These layers were formed through the cementation of coarse-to-medium sands and fine gravels. The beds, with a thickness of 50 cm, dip southward towards the lake (Figure 2).

The beachrock layers in the central part of Bozkırlar Beach consist of discontinuous blocks, 2–3 meters wide, located 5 meters inland from the shoreline in an area primarily composed of coarse-to-medium sand. Beds characterized by a fragile structure were also identified 50–65 cm below the lake's water level along the same beach. The layers along the lake's shoreline are wider and more distinct. These beachrocks, situated within the wave impact zone, lack continuity and form discontinuous sections that measure 90 meters in length and 1–2 meters in width. The cemented layers display a stratigraphic sequence consisting of fine-to-medium sand at the bottom, coarse sand above it, and fine gravel at the top. The entire beachrock series slopes 5° southward towards the lake, with a total thickness of 1.3 meters.

Figure 2. A view of the exposed beachrocks along the shores of Lake Van.

Cementation and paleoclimatic implications

Thin section analyses reveal a similar facies environment across all samples, indicating that the deposition and subsequent cementation processes have not varied significantly. All samples contain high amounts of metamorphic rock fragments, including quartz-mica schist, volcanic rock fragments such as andesite and basalt, as well as quartz, plagioclase, and to a lesser extent, pyroxene, augite, and opaque minerals. Ooids and pisoliths are also quite common non-skeletal components (Figure 3).

Closer examination of the samples using SEM reveals the presence of highly specific cement textures in detail. No aragonitic cement was found in samples taken from about 50 cm above the lake level. Calcite crystals exhibiting scalenohedral habits formed micritic crystals encrustations on grain surfaces, while larger spar calcites filled the voids, forming radial aggregates with radiating orientation in all directions within the voids, and meniscus bridges between grains (Figure 4a,b).

The calcite crystals with scalenohedral terminations are likely suggestive for the upper beach environment (Mauz et al., 2015). The calcitic coatings are relatively thin, indicating not only accelerated carbonate saturation in the lake waters but also representing an initial phase of the cementation process (Scoffin, 1987; Beier 1985; Neumeier 1999). Additionally, bacterial mats are commonly observed in the outer layers of nucleus-free ooids (Figure 4c), suggesting that bacterial activity contributes to the precipitation of binding carbonates (Krumbein, 1979). In areas where these mats are present, carbonate precipitation is very intense, and crystal sizes are observed to be large. Micritic pore-filling cement is also typical of microbial activity and/or rapid precipitation (Webb

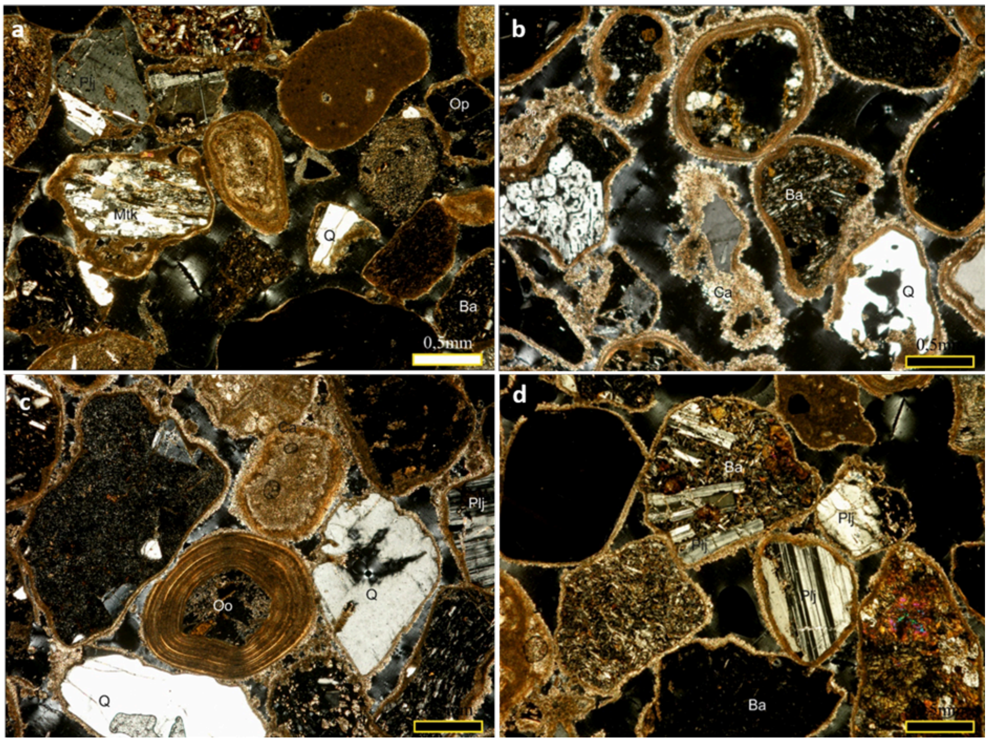

Figure 3. Thin section images of beachrock samples; (a) rock and mineral fragments in coarse-grained sandstone are enclosed by calcitic envelopes; (b) drusy calcite texture, where calcite crystals grow into pore spaces; (c), basalt, andesite, and quartz fragments surrounded by calcitic cement and oolitic and pisolitic coatings;(d) fibrous calcite envelopes around volcanic rock fragments (Mtk: metamorphic rock fragment; Ca: calcite; Plj: plagioclase; Q: quartz;, Vk: volcanic rock fragment; Ba: basalt.

et al., 1999; Kneale and Viles, 2000; Calvet et al., 2003). Other commonly observed cement textures include gravitational dog-tooth cement directed into cavities and meniscus bridges, suggestive of carbonate-rich meteoric water flux (Figure 4a-c). This is supported by mol% $MgCO_3$ values obtained from the calcite surfaces, which range from 0.43 to 2.24, with an average value of 1.09 (Table 1). The low Mg-calcite along low Mg/Ca values also support vadose beachrock cementation similar to that in Michigan Marl Lake rich-in algal pisoliths (Binkley et al., 1982). The following elements were identified on the crystal surfaces analyzed by EDX (Table 1): O (42.6%), Ca (41.3%), C (12.6%), Si (1.9%), Mg (1.2%), Fe (0.6%), Al (0.5%), and Na (0.4%).

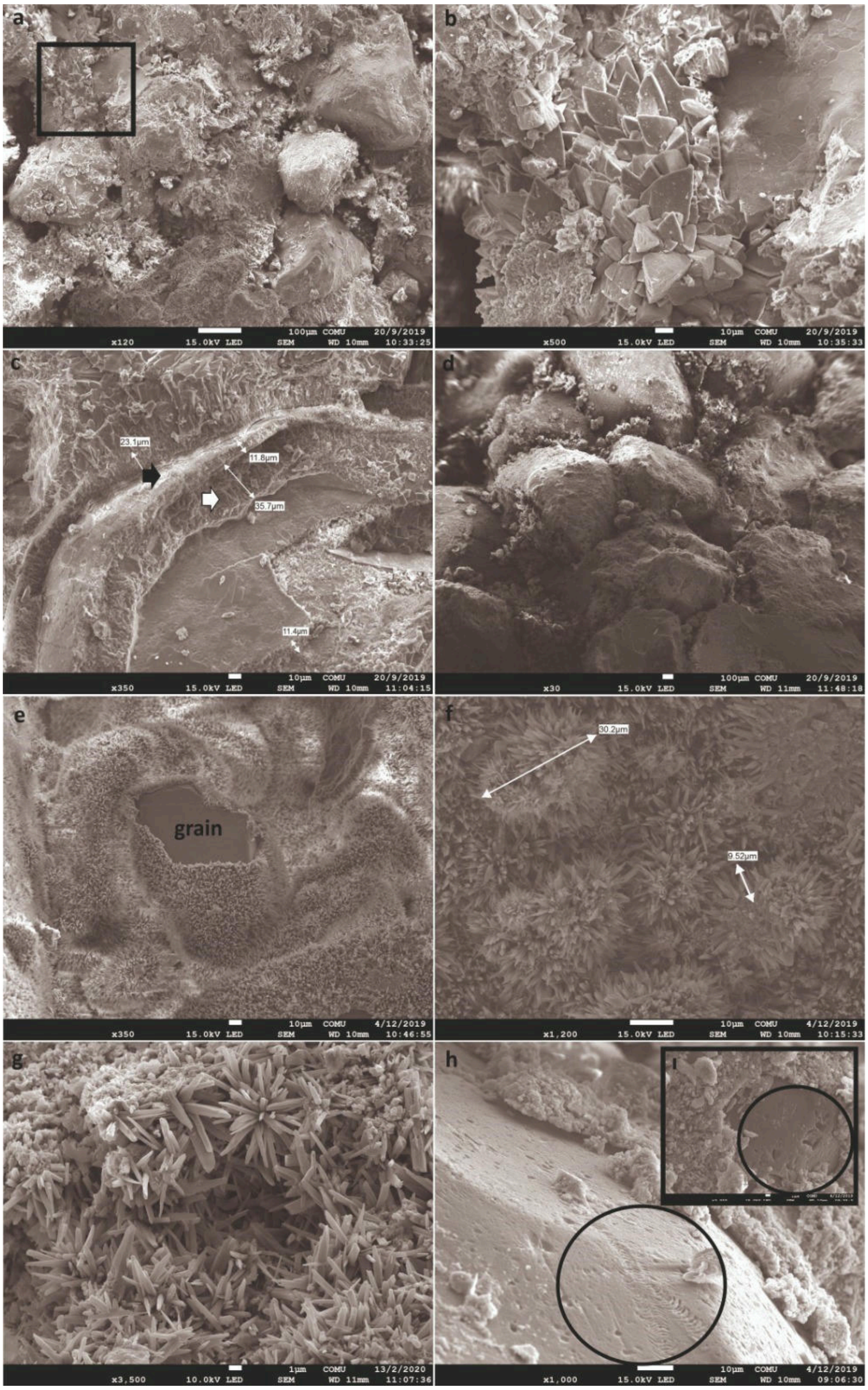

Figure 4. SEM images of beachrocks along the shores of Lake Van, exposed above lake level (a-c), at lake level (d-gf), and submerged below the lake surface (g-h).

Table 1. EDX analysis results of beachrocks.

Sampling site	*Sample no*	*Analysis surface*	*Fabric*	**Elements (Wt%)**										
				C	*O*	*Na*	*Mg*	*Al*	*Cl*	*Si*	*Sr*	*Ca*	*Fe*	*Mol % $MgCO_3$;*
Above lake level	1.1	Calcite	Radial aggregate	19.6	52.3	-	0.7	-	-	-	-	27.3	-	0.5
	1.2	Calcite	Radial aggregate	12.2	54.7	0.8	3	0.9	-	3.4		24.6	0.5	2.24
	1.3	Calcite	Dog-tooth	11.7	40.8	0.6	1.9	0.6	-	2.1	-	42.3	-	1.65
	1.4	Calcite	Dog-tooth	7	30.2	0.3	1	0.5	-	2.6	-	57.5	0.9	1.02
	1.5	Calcite	Dog-tooth	11.5	41.4	0.6	1.6	0.3	-	1.5	-	43.1	-	1.39
	1.6	Bacterial math	Bacterial math	22.8	54.8	0.2	1.1	0.3	-	1	-	19.9	-	0.77
	1.7	Calcite	Coating	12.4	41.1	0.2	0.5	-	-		-	45.9	-	0.43
		Calcite	Coating	12.3	40.9	0.4	0.8	-	-	1.8	-	43.4	0.5	0.69
	1.8	Calcite	Coating	5.2	26.3	-	0.5	-	-	-	-	68	-	0.86
	1.9	Bacterial math	Bacterial math	11.5	44.2	0.5	1	-	-	1.3	-	41.5	-	0.85
Lake level	2.1	Aragonite	Coating	20.8	53.9	1.3	3.6	1	0.5	4.9	-	13.6	0.4	2.55
	2.2	Aragonite	Meniscus bridge	18	52.1	1.2	2.5	0.8	-	3.2	-	21.8	0.5	1.85
	2.3	Aragonite	Radial aggregate	6.6	30.5	0.7	0.9	-	-	-	5.4	56	-	0.95
	2.4	Aragonite	Radial aggregate	15.5	46.9	-	-	-	-	-	3.7	33.9	-	-
	2.5	Aragonite	Radial aggregate	17.6	49.7	0.6	0.5	-	-	-	1.6	30	-	0.38
	2.6	Aragonite	Coating	20.8	51.8	0.6	0.6	-	-	-	1.9	24.3	-	-
Submerged	3.1	Calcite	Bacterial math	10.7	37	-	1.7	0.7	-	2.2	-	47.8	-	1.54
	3.2	Calcite	Bacterial math	5.5	30.8	0.7	-	-	-	1.8	-	61.1	-	-
	3.3	Calcite	Bacterial math	9.4	41.2	0.7	4.1	0.9	-	3.8	-	38.4	1.4	3.62
	3.4	Aragonite	Ooid cortex	22.7	51.2	0.9	0.3	-	-	-	1.4	23.5	-	0.21

The cement fabrics of samples collected from the lake level differ from those taken from the upper beach. The elements identified on the crystal surfaces analyzed by EDX are as follows: O (47.4%), Ca (29.9%), C (16.5%), Si (4%), Sr (3.1%), Mg (1.6%), Al (0.9%), Na (0.8%), and Fe (0.4%). Notably, calcitic cement with atypical scalenohedral terminations is rarely observed in these samples. The cementing carbonate polymorph primarily consists of aragonite needles. This aragonite forms a thin coating, generally less than 10 µm thick, nearly covering grain surfaces entirely and creating a dense radial aggregate texture within the voids. These aggregates are so dense that the intricate aragonite needles extend to lengths of up to 30 µm. SEM images clearly show that the porosity between the grains is high (Figure 4d). In samples with intense aragonite precipitation, aragonite forms radially grown aggregates extending from the center to the periphery (Figure 4e-f). This cement indicates the supersaturation of $CaCO_3$ due to the evaporation of lake waters, similar to those reported from ocean coasts (Vieira & De Ros, 2006).

Beachrocks submerged under lake waters contain cement structures that are quite similar to the layers extending at lake level. Well-developed, self-shaped radial aragonite needles have filled both the grain surfaces and the voids (Figure 4g). In addition, scratching/burrowing traces, a few micrometers in size, created by microorganisms living in the shallow water environment, are observed on the grain surfaces (Figure 4h). EDX showed the elements on the crystal surfaces analyzed, such as: Ca (42.7%), O (40%), C (12%), Si (2.6%), Mg (2%), Sr=Fe (1.4%), Al (0.8%), and Na (0.7%).

Microbialites and Beachrock: Links to the Origin

In beachrocks, as observed on grain surfaces and especially in ooid cortices, bacteriogenic nanocrystals of aragonite, along with globule aggregates and pore-filling dog-tooth prismatic calcite crystals, are commonly found in microbialites in Adilcevaz shelf (Çağatay et al., 2024). Firstly, the pH level of the lake waters has likely played an important role in carbonate sedimentation and lithification in Lake Van with a very high alkalinity, with a pH value of 9.7 (Degens et al., 1978; Kremer et al., 2019). The elevated pH and intense carbonate precipitation have facilitated the formation of such organosedimentary structures and beachrock cementation. For example, it has been stated that the mineralization of the modern calcified microbialites of Lake Van also began with in vivo aragonite precipitation within microbial mats (Kremer et al., 2019). As a result of the mixing of calcium-rich groundwater with alkaline lake water at the lake floor, Çağatay et al. (2024) revealed that these microbialite chimneys likely formed during the warm and humid Medieval Climate Anomaly (circa AD 800–1300).

The presence of microbialites in the shallow waters of the lake, formed in a shelf environment in close proximity to beachrock formations, should serve as an analogue for the lithification processes of beachrock beds. Since the formation of dense calcareous microbialites is explained by bacterial processes, similar to the relationship between photolithotropic and chemoorganotrophic bacterial activity in beachrock formation (Krumbein, 1979), bacterial processes may also have contributed to the precipitation of connective carbonates in Lake Van beachrock, as confirmed by SEM-captured bacteriogenic nanocrystals of aragonite. In other words, as observed in marine environments (Belkhedim et al., 2024; Diaz & Eberli, 2022), microbial cements can also play a fundamental role in crystal growth in lacustrine beachrock, with microbial processes mediating sediment stabilization and contributing to the formation of firm grounds and surfaces (Diaz & Eberli, 2022; Hillgärtner et al., 2001).

As emphasized by Kremer et al. (2019), the mix of alkaline lake water and Ca-Mg-rich groundwater resulted in the deposition of cyanobacterially precipitated aragonite. This situation clearly explains the reason for the aragonite precipitation, where the varve chronology from the last 15,000 years clearly shows the sawtooth pattern of aragonite and calcite precipitation (Landmann et al., 1996).

Another notable point here is why beachrocks and microbialites have coexisted and only formed in this specific part of the Lake Van shores. The cemented shore was formed in the coastal area in front of Lake Aygır, a freshwater maar lake situated on the slope of Mount Süphan. The snow on Mount Süphan melts particularly in spring, and the released freshwater accumulates in Lake Aygır. This freshwater then reaches Lake Van through an outflow channel. This condition suggests the influence of calcium- and magnesium-rich waters reaching the cemented beach from both the surface and underground. Additionally, the freshwater inflow must have also contributed to the formation of the microbialites in this coastal area. As observed in microbialite formations (Çağatay et al., 2024), the high Ca ion content in the spring waters originating from the Adilcevaz Limestone aquifer along the northern shore of the lake must have also supported carbonate precipitation (Reimer et al., 2009).

What is important here is the drought process that has led to the rapid evaporation of lake waters, causing the water to become supersaturated with carbonates, and subsequently resulting in the cementation of beach materials. Albeit the lack of absolute age data, the fragile structure of the studied beachrock suggests that cementation did not occur far back in time. The onset of cementation in the lake is supported by the varve chronology of the lake over the last 3,500 years, which shows that the last regression occurred during this period, as well as by a decrease in Quercus concentration, sedimentological evidence, and pollen distributions (Landmann et al., 1996; Reimer et al., 2009). The shift towards a more continental climate in the lake began between 4200 and 4000 BP, as indicated by the Mg/Ca ratio and oxygen isotopes, showing a decrease in humidity and a transition to drier conditions, and by 2000 BP, a climate regime similar to today's was established (Wick et al., 2003).

Moreover, high-resolution multi-proxy climate and environmental records by Şimşek and Çağatay (2018) indicate that Lake Van experienced 16 alternating cold/dry and warm/wet periods, each lasting between 100 and 350 years over the last 3.5 ka, with the period between 3.5 and 1.6 ka cal BP being marked by drier conditions. The conditions characterized as the 3rd millennium crisis, with dry conditions prevailing around 3000 cal BP, have also been reported from Lake Hazar in Eastern Anatolia (Eriş, 2013). It can be suggested that the warm and arid climate that supported the formation of beachrock was followed by warm and humid conditions, during which increased inflow of Ca-rich freshwater from rivers into the lake likely facilitated the formation of microbialites between AD 800 and 1300 (Çağatay et al., 2024).

Since no beachrock formation is observed at the lake shore under present climate conditions, the necessary conditions for cementation must have occurred between 3500 BP and 2000 BP. The exposed layers extending above the lake level have likely formed earlier. The absence of Sr in these layers, compared to the near-shore and submerged beds, can be attributed to submerged exposure followed by leaching by meteoric waters, which likely removed the Sr. Considering the submerged beds, there might have been at least a 1-meter rise in the lake level since the last cementation stage.

Conclusion

This study provides the first evidence of beachrock formation along the shores of a highly alkaline soda lake. The beachrocks are cemented by aragonite, scalenohedral Mg-calcites, spar calcites, dogtooth and meniscus cement textures. These findings suggest that the beachrocks formed from carbonate polymorphs precipitated in super-saturated waters under intense evaporation and arid conditions. The interaction of the high alkalinity of lake waters, Ca-Mg–rich groundwater from volcanic surroundings, and intense bacterial activity, as evidenced by bacterial mats and gouging traces, contributes to the formation of beachrock, similar to the process that forms microbialites along the same shoreline. The beachrocks formed between 3.5 ka BP and 2 ka BP, prior to the formation of Late Holocene microbialites on the shelf plain off the coast of this littoral zone.

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