First record of beachrock on Black Sea coast of Turkey: Implications for Late Holocene sea-level fluctuations

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A B S T R A C T

We present new data on the diagenetic characteristics, subsurface nature and radiocarbon ages of beachrock from the Thracian Black Sea coast of Turkey, indicative of sea-level changes and climatic conditions favoring lithification of beach sands between 5.4 ka and 3.5 ka cal BP. Micrite coatings and succeeding meniscus cements typify diagenetic history and suggest a two-stage cementation over this timeframe. The early cements are typical of upper intertidal zone when the sea-level was likely similar to that of today. The ensuing intergranular bridges refer to an approximate 2 m decline in sea-level, favoring downward percolation of meteoric waters related to subaerial exposure, marked by a reduction in Mg concentration and dissolution pits on early cement coatings. Formation of beachrock during this bimillennial period could be associated with relatively drier conditions promoting the precipitation of connective cements.

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1. Introduction

As a kind of cemented beach deposit frequently found in the form of blocks or slabs, beachrock offers a record of the morphodynamic, climatic and oceanographic changes that have occurred in coastal areas. Amalgamation of sediments as well as fossil shells and microfossils entombed within cement or intergranular spaces provide a record of the diagenetic history of the beachrock. Since the very earliest studies, attempts have been made to pinpoint the origin, age, distribution and significance of beachrock on various coastal outcrops around the world (see Vouvdoukas et al. (2007) and references therein). Since abiotic cement, i.e., aragonite and high Mg-calcite, is precipitated as a direct result of the evaporation of sea-water, predominantly as a connective carbonate, beachrock has been generally attributed to intertidal cementation and regarded as giving explicit indications of sea-level changes. Nevertheless, contribution of different specific processes regarding to precipitation of binding carbonates have been suggested (Vieira and De Ros, 2006 and references therein). Until recently, however, there was debate on the credibility of beachrock as a key indicator for sea-level changes due to differing viewpoints (Kelletat, 2006; Knight, 2007).

In contrast to authors who have focused on geomorphological data (Kelletat, 2006), many researchers have recently gained benefit from studying cementation characteristics (Kneale and Viles, 2000; Hillgaertner et al., 2001; Calvet et al., 2003; Rey et al., 2004; Vieira and De Ros, 2006) and stable isotope data (Holail and Rashed, 1992; Calvet et al., 2003; Friedman, 2005; Vieira and De Ros, 2006). One of the main problems regarding the solidity of intertidal beachrock in real terms is lack of information on the continuation of beachrock backshore under beach materials, since samples are mostly taken from slabs exposed at the coast. Along the 8333 km-long coastline of Turkey, beachrocks display a wide distribution, from the eastern end of the Mediterranean to the Gulf of Saros, comprising the northern limit of the Aegean Sea (Ayarçan, 1997; Desnuelles et al., 2009).

In this study, results obtained from the first recorded beachrock on the Thracian Black Sea coast of Turkey are discussed (Fig. 1a, b). We considered that the formation of beachrock on the coast of the Black Sea is substantive in that this anoxic sea is presently characterized by low (17–20‰) surface salinity and a nominal amount of evaporation compared to the much greater amount of freshwater input by precipitation and rivers (Beşiktepe et al., 1994; Mertens et al., 2012). Based on diagenetic characteristics in conjunction with radiocarbon ages and
geophysical imaging data, new findings in respect of Late Holocene sea-level fluctuations on the Turkish Black Sea coast are presented.

2. Study area

On the eastern coast of Kıyıköy, Kirkhareli, NW Turkey, the studied deposits constitute the first record of beachrock from the northwestern Thracian Black Sea coast of Turkey (Fig. 1a, b). Comprising the European part of the country, Thrace is bounded by the Sea of Marmara to the south and Black Sea to the north and has a coastline of about 786 km. The Black Sea coast of Thrace starts from the mouth of the River Rezve (Rezovo) at the Bulgarian border and extends in a northwest–southeast direction down to the strait of Istanbul (Bosphorus) (Fig. 1b). The eastern part of Thrace comprises the Çatalca Peninsula and is characterized by a nearly straight coastline. However, in the northwestern section, the Thracian coast is rather indented as the coastal area forms a seaward (northeast) prolongation of the Strandja Mountains, a massif consisting of basement rocks such as gneiss and amphibolite, and cover deposits formed of schist, limestone, sandstone and igneous rocks (Pamir and Baykal, 1947).

The geology of the backshore at the southern end of the cemented beach in this study is composed of Middle to Late Eocene fossiliferous limestones with sandstone and claystone intercalations (Fig. 1c). On the northern coast is the mouth of the Kazandere River which flows into the sea from between Kıyıköy port and a coastal spit (Fig. 1c). On the backshore, a low ridge made up of a 5-m thick coastal dune stands between the river mouth and the present sandy beach. Meteorological data (1975–2006) from Kumköy meteorology station 85 km to the southeast indicate that the area receives a yearly precipitation of 831.4 mm. The average annual air and sea-water temperatures were recorded as 13.8 °C and 14.3 °C, respectively. During the hot period between May and September, evaporation values from sea water reach a total of 600 mm, which is lower than the Mediterranean (approximately 2000 mm). Climatically, a humid-temperate Black Sea climate dominates (Türkes, 1996). Tidal range is nominal with an average of 10 cm (Goudie, 2001).

3. Methods

3.1. Analyses of beachrock materials

Five samples of beachrock were collected for analysis and radiocarbon dating. Petrographic analysis was carried out based on thin section interpretations. Energy Dispersive Spectroscopy (EDX-Bruker AXS XFlash) analysis of the beachrock was performed to shed light on elemental composition of connective cements. Using Scanning Electron
Microscopy (SEM–Zeiss EVO 50 EP), the same sub-samples were used for determination of sequential cement fabrics on and around the bond-
ed grains. Analysis was carried out at Izmir Institute of Technology, 
Turkey. To determine foraminiferal contents, samples were treated 
with 10% H$_2$O$_2$ for one day and wet sieved through a 63 μm sieve. The 
residue was then dried in air. In the sediment fraction above the 63 μm 
sieve, foraminiferal fauna was examined under a binocular mi-
roscope. Five bulk samples of beachrock were dated by conventional 
and AMS radiocarbon methods at BETA, Miami, USA.

3.2. Geophysical survey

A geoelectrical survey using electrical resistivity tomography 
(ERT) technique was conducted along 4 coastline-perpendicular lines 
(Fig. 1d), 10 m apart from each other, in order to depict the internal 
structure and contact relationship of the beachrocks and also to monitor 
their landward extent. The ERT measurements were carried out with a 
GF ARES multi-electrode resistivity-meter system using dipole–dipole 
electrode configuration. Apparent resistivity data were collected from 
the beach using 22 electrodes spaced at 1 m for ERT-1 and ERT-2, and 
1.5 m for ERT-3 and ERT-4. The total number of data levels was 11 
for each survey line. Quality enhancement of the measured data was 
carried out by performing 6 stacks (repeated measurements) in each 
data point, and average apparent resistivity values were assigned to 
related datum points. Measured apparent resistivity data were then 
processed by an automatic 2D tomographic inversion scheme based 
on smoothness-constrained least-squares algorithm (Loke and Barker, 
1996), for a more accurate interpretation. There were no topographic 
differences along the survey lines of ERT-1 and ERT-2. However, due 
to the significant topographic relief at the end of the lines of ERT-3 
and ERT-4, elevations of each electrode location were measured and 
the topographical data were incorporated into the 2D inversion proce-
dure in order to carry out more detailed and reliable processing. The cal-
culated apparent resistivity data were obtained using the finite-element 
method with four nodes per unit electrode spacing during the inversion 
process. For final interpretation, geoelectrical resistivity tomograms 
were chosen at the iteration after which RMS error did not change 
significantly.

4. Results and discussion

4.1. Morphology and subsurface nature of beachrock

Similar to the orientation of the present beach, the beachrock beds 
extend in a northwest–southeast direction to the south of a coastal 
spit stretching toward Kıyıköy Port (Fig. 2a). Visible thickness of the 
exposed beds ranges between 10 cm and 75 cm. The length and 
width of the beds are 250 m and 20 m, respectively. Dipping toward 
the sea at angles between 5° and 10°, the beds are composed of 
hard-bonded coarse sands with sizes ranging between 0.5 mm and 
1 mm, very fine gravels smaller than 3 cm and bivalvia fragments 
(Fig. 2b). Having a maximum visible thickness of 75 cm, many of 
the beds emerge from the 20-m wide sandy beach and are backed 
by iron-oxidized dune deposits with abundant fossil shells of Donax 
trunculus. Throughout the cemented zone, the surface of the beachrock 
and fractures enlarged by sea waves is substantially colonized by 
Enteromorpha sp. At the southeast end of the beach, the beachrock 
beds terminate in front of cliffs cut in Middle–Upper Eocene lime-
stones mostly composed of overlapping broken blocks due to violent 
sea-wave erosion. These blocks, up to 3 m in size, appear to have dis-
sected along fracture sets of orthogonal and polygonal joints. Given 
that the studied coast is tectonically dormant, these fractures may 
be supposed to be of syndepositional origin, showing a lack of any 
tectonically-induced displacement along the studied coast.

Even though the visible thickness of the emerged beachrock is about 
75 cm, the seaward margin of the submerged beachrock at a 
depth of — 2 m extends up to 20 m offshore. Following the assump-
tion that beachrock is suggestive of intertidal cementation, and its 
potential for highlighting sea-level changes, knowledge of the total 
thickness of beds, including buried slabs, is of importance. For this 
purpose, ERT images (Fig. 3) were obtained from the beach. Taken 
perpendicular to the coastline (Fig. 1d), resistivity tomograms pro-
duced by the 2D tomographic inversion process displayed a depth 
range of about 2.7 m for ERT-1 and ERT-2 and about 4 m for ERT-3 
and ERT-4 (Fig. 3). The resistivity values in the survey area vary 
between about 1 and 550 ohm.m. Thus, the tomographic images clearly 
show a sharp resistivity contrast between the high-resistivity beachrocks 
and high-conductivity beach material. The abnormal decrease in the 
resistivity values of the beach material might have resulted from an in-
crease in salinity due to seawater intrusion. These images also show 
that the buried slabs of beachrock are about 1 m thick, showing a 
sharp termination at this depth. Additionally, a high-resistivity zone 
is observed at the end of ERT-3 and ERT-4 lines. This high-resistivity zone 
is thought to be associated with fossil dunes located on the backshore. 
According to ERT images, the buried beds are followed up to about 
23 m at the backshore. At the beginning of the ERT lines, traces of the 
beachrocks are not observed probably due to erosion.

Geophysical imaging data provided two important insights into 
the beach environment cemented to form this beachrock; i.e., (1) a 
maximum thickness of beds of 1.75 m, exceeding the inconsiderable 
tidal amplitude of the Black Sea (Goudie, 2001), when exposed and 
buried slabs are taken into consideration, and (2) the total width of the 
cemented zone (about 40 m), including the submerged parts off-
shore and buried onshore parts.

4.2. Composition and diagenetic stages

A coastal conglomerate predominated by small pebbles and coarse 
sands in grain size distribution, the studied beachrock contained 
calcium carbonate of between 34 and 45%. The amalgamated compo-
nents were poorly sorted, containing pebbles (48%) and sands (52%), 
the latter of which were composed mainly of very coarse sand (81%) 
and finer grains. Pebbles smaller in size than 3 mm were predomi-
nant, implying that the cemented beds arose from a higher-energy 
shingle beach. Broken shell fragments dominated by D. trunculus, 
Venus gallina and Patella sp. were observed to be tightly embedded 
solely on the case-hardened surface of beds. Petrographic analyses 
from thin sectioned images of the finer parts indicate that the beachrock 
was composed of quartz arenite to sublitharenite based on Folk’s (1974) 
classification, containing various rock fragments derived from granite, 
micaschist and quartzite as well as some algae (Fig. 2c–g). This composi-
tion is indicative of derivation from the Strandja massif in the northwest 
which holds the basement rocks of Thrace. Thin section images showed 
that grains are, to a large extent, composed of weakly-bonded sands 
of sub-rounded polycrystalline quartz typical of short-distance drift by 
longshore coastal currents.

The benthic foraminiferal fauna within the samples consisted of 
number of species (Table 1) at varied amounts, the majority of which 
were recently reported from a cemented coquina to the east of the 
study area (Erginal et al., 2012). Predominance of Rosalina vilardeboana 
and Ammonia tepida within the samples indicates shallow water in re-
spect of the depositional environment.

SEM analyses in conjunction with EDX undertaken to highlight the 
origin and diagenetic history of the beachrock indicated the presence 
of different cement fabrics (Fig. 4). These cements are composed, in 
order of priority, of micrite coatings and meniscus bridges formed 
exceptionally of radial aggregates and scalenohedral calcite rims. In 
decreasing order of abundance, cements measured by EDX (Table 2) 
contain, on average, O (49.64%), Ca (25.76%), C (12.98%), Si (5.15%), 
Mg (1.27%), Al (0.98%), Fe (0.31%) and Na (0.29%). Albeit at low 
concentrations, the presence of Al, Si and Fe in cements is likely related 
to involvement from the mineral fragments. These cements are composed
exclusively of low-Mg calcite (0.52–1.7 mol% MgCO₃), suggesting the influence of freshwaters. Such fabrics are known to dominate not only in beachrocks from temperate coasts (Kneale and Viles, 2000) but also ascribed to freshwater diagenesis (Binkley et al., 1980). In this respect, it is essential to establish whether this cement was either low-Mg calcite, originally transported by downward-percolating carbonate-rich groundwaters from Eocene limestones at the backshore, or is associated with transformation from aragonite or high-Mg calcite to low-Mg calcite with the lapse of time (Siesser, 1974; Guerra et al., 2005). EDX analysis of the bedrock samples displayed a lack of Mg in their elemental concentration, being composed of C (18.6%), O (60%), Ca (20.3%), and Si (0.6%) (Table 2). Thus, neomorphic replacement from early cement to low-Mg calcite is not likely.

Containing 1.29 mol% MgCO₃, micritic envelopes with a maximum thickness of 20 μm were very common in all the analyzed samples, with a high void ratio (Fig. 4a, b). These cements were attached to siliciclastic grains (Fig. 4c, d), lithoclasts and, to a lesser extent, shell fragments. Constituting different orientations on their substrates, micrites are composed of equal-sized crystals with an average length of 4 μm. Closer views of these coatings display the presence of micritic aggregates of low-Mg calcite (Fig. 4e). This fabric may be attributed to precipitation in the backshore by meteoric groundwater in the upper intertidal zone (Guerra et al., 2005).

These thin coatings are followed by bridging cements, i.e., meniscus fills connecting grains and lithic fragments (Fig. 4f). Lower than the former, the low percentage of Mg calcite, with an average of 0.52 mol%, is indicative of precipitation from the mixing of sea water and meteoric waters or solely from the latter (Scoffin and Stoddart, 1983; Spurgeon et al., 2003; Rey et al., 2004). Rey et al. (2004) suggest that the mixing of marine and meteoric waters results in an increase in the concentration of dissolved carbonates, in that increased pH makes carbonate precipitation easier. The existence of carbonates formed by Eocene limestones might have been a landward source of cement.

The width of the connecting bridges may reach 200 μm. Closer examination of meniscus cements displayed the presence of aggregates of calcite (1.45 mol% MgCO₃) subjected to dissolution under subaerial exposure conditions (Fig. 4g). Albeit rare, the third form of cement binding siliciclastic grains is composed of low-Mg calcite rims consisting of clumps of reciprocal-oriented calcites having scalenohedral terminations (Fig. 4h, i). Contributing to building intergranular bridges, these rims are thinner than 50 μm and follow 5-μm thick micritic envelopes.

4.3. Implications for Late Holocene sea-level changes

Radiocarbon dating of the bulk carbonates obtained from the five samples was undertaken to date the formation of the beachrock samples collected from three different sections; namely, the middle, backmost and leading edges. Results presented in Table 3 yielded ages 5460 cal BP and 3500 cal BP for the oldest and the youngest beds, respectively. Extracted from a depth of 15 cm, the oldest sample (KK1) represents the middle section of the cemented beds, dated to 5460–5260 cal BP. Samples from the leading edges and backmost parts of beds are represented by the youngest calibrated ages of 3830–3570 cal BP (KK3) and 3760–3500 cal BP (KK4), respectively. This indicates that beds lying on the seaward side and outer (a few meters offshore) parts of beds are concurrent units in the sense of
deposition, as opposed to the belief that outer units manifest older generations of beachrock (Psomiadis et al., 2009). Two samples taken from the landward and seaward edges of slabs yielded very similar values of 4270–3970 cal BP (KK5) and 4210–3920 cal BP (KK2), respectively.

In view of middle to Late Holocene sea-level changes in the Black Sea, the ages obtained are of particular importance for the period spanning the last 5 ka. It is known that the Black Sea has been in equilibrium with the Mediterranean sea-level since their last reconnection at 7500 cal BP (Fouache et al., 2012). Since then, several authors have dealt with the sea-level history of the Black Sea (Brückner et al., 2010 and references therein).

Superimposed curves illustrative of Holocene sea-level fluctuations during the Holocene infer a rising sea-level trend with important fluctuations up to near 5 ka BP, then rises and falls thereafter in reference to the present-day (Martin and Yanko-Hombach, 2011). Regarding this timeframe, the curves represent different magnitudes of fluctuations before and after 5 ka BP from the perspective of ages acquired from beachrocks. For instance, the curves by Ostrovsky et al. (1977), Tchepalyga (1984), Voskoboinikov et al. (1982), Filipova-Marinova (2007) and Balabanov (2007) all agree on a decline varying between − 2 m and − 8 m at 5.5 ka BP, as against Nevessky’s (1970) curve which demonstrates a remarkable descent near − 25 m (Fig. 5). For the period when early marine-phreatic cements were precipitated at 5.4 ka, the Filipova-Marinova (2007) and Balabanov (2007) curves appear to be the most plausible as they show a sea-level between 0 m and − 2 m, which does not conflict with those proposed for the Eastern Mediterranean (Fouache et al., 2012). This is confirmed by data from the offshore delta lobes of the Danube (Giosan et al., 2006). On the basis of the optical age of beach ridge sands and 14C ages of bivalves within them, Giosan et al. (2006) suggested that the sea-level in the past 5 ka was between +1.5 m and − 2 m.

From 5 ka BP to the present, the level of the Black Sea followed a more regular trend with lower-magnitude fluctuations. With regard to the time span between 4.2 ka and 3.5 ka when many of the beachrock slabs developed, the proposed curves display apparent contradiction. For example, variations of a few meters in proportion to the present sea-level illustrated by Tchepalyga (1984) and Voskoboinikov et al. (1982) as well as the calibrated and uncalibrated curves of Filipova-Marinova (2007) are at variance with the relatively regular regressive stage depicted in Ostrovsky et al. (1977) and Balabanov (2007). Furthermore, a remarkable short time regression around 500 BC is marked by a fall up to −10 m on all curves, which has been attributed to the postulated Phanagorian regression by Fedorov (1963), criticized by Fouache et al. (2012) based on archeological, historical and hydrodynamic arguments.

With regard to the questions raised above, the bimillennial period spanning 5.5 ka BP and 3.5 ka BP matches the formation of the studied

![Fig. 3. Interpreted inverse model resistivity tomograms taken perpendicular to the coastline.](image-url)

**Table 1**

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Foraminifera</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK1</td>
<td>Ammonia tepida</td>
<td>35</td>
</tr>
<tr>
<td>KK3</td>
<td>Ammodiscus planorbis</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Patellina corrugata</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Quinqueloculina sp.</td>
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</tr>
<tr>
<td></td>
<td>Pseudotrioculina sp.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Rosalina vilardeboana</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Rosalina sp.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Cibicides sp.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Ammonia sp.</td>
<td>1</td>
</tr>
<tr>
<td>KUM1</td>
<td>Ammonia parkinsoniana</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Ammonia sp.</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Elphidium macellum</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Elphidium sp.</td>
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beachrock based on limiting age values. The aforementioned characteristics of cement fabrics in samples are suggestive of the initially precipitation of low-Mg calcite to form micritic coatings from meteoric groundwaters in the backshore, followed by meniscus bridges and, to a lesser extent, rims of low-Mg calcite. This consecutive pattern is typical of the precipitation in upper intertidal and vadose zones. Observed

Table 2
EDX analysis results obtained from beachrock cements.

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<tr>
<th>Sample code</th>
<th>Analyzed surface</th>
<th>C</th>
<th>O</th>
<th>Na</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Ca</th>
<th>Fe</th>
<th>MgCO_3 (mol%)</th>
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<td>50.34</td>
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<td>3.92</td>
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<td>1.5</td>
<td>1.4</td>
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<td>Micritic coating</td>
<td>12.5</td>
<td>51.1</td>
<td>0.56</td>
<td>1.47</td>
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<td>3.08</td>
<td>29.2</td>
<td>0.7</td>
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<td>11.09</td>
<td>49.37</td>
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<td>3.77</td>
<td>30.5</td>
<td>1.1</td>
<td>1.33</td>
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<td>Micritic coating</td>
<td>11.93</td>
<td>51.28</td>
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<td>2</td>
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<td>18.9</td>
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<td>1.77</td>
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<td>4.83</td>
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<td>0.82</td>
<td></td>
</tr>
<tr>
<td>KK5</td>
<td>Micritic coating</td>
<td>13.45</td>
<td>51.92</td>
<td>-</td>
<td>2.16</td>
<td>2.33</td>
<td>30.1</td>
<td>1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bedrock</td>
<td>Bulk sample</td>
<td>18.6</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>20.3</td>
<td></td>
<td>1.7</td>
</tr>
</tbody>
</table>

Fig. 4. SEM images from beachrock samples. (a–e) Thick micrite coatings. These coatings are typical in all samples; (f) all samples have high void ratio; (g) close-up view of white square in (a), showing that calcite surfaces are mostly marked by solution pits due possibly to percolated freshwaters during subaerial exposure of beachrock slabs; (c–e) another views of such envelopes; (g) closer view of the square in (d) demonstrating micritic aggregates with thickness of about 20 μm; (f) typical image of meniscus cement; (g) closer view of bridge marked in square showing aggregates of calcite subjected to dissolution, as in (b); (h) low-Mg calcite rims; (j) rims binding juxtaposed siliciclastic grains are thinner than 50 μm and composed of clumps of reciprocal-oriented calcite crystals with scalenohedral terminations.
widely in all samples, the coexistence of dissolution on early micritic cements and minute concentrations of MgCO₃ within both cements are likely suggestive of diagenetic alteration by deeply percolated freshwaters.

In the present case, climatic conditions might have played an important role with respect to the precipitation of calcium carbonates during the evaporation-prone stages and thereby beachrock cementation. During the abovementioned timeframe, precipitation of amalgamating carbonates into loose beach sand prior to 3.5 ka would have been promoted by increased evaporation under drier conditions. Hence, based on recent data from the Sofular Cave records, the wet period of Holocene Climatic Optimum starting from 9.6 ka changed into a drier climate after 5.4 ka BP (Göktürk et al., 2011). Although no record is available for the evaporation-prone stages and thereby beachrock cementation.

The lack of Emiliania huxleyi, recently documented from slightly younger-aged carbonate-cemented coquina on the southeastern Thracian Black Sea coast of Turkey (Erginal et al., 2012), also permits forecasting the cementation environment. This calcareous nanoplankton is notably abundant in surface waters of the Black Sea (Lancelot et al., 2002) and first appeared in this body of water about 3000 years ago when salinity prone to its adaptation reached 11‰ (Bukry, 1974). The absence of the coccolith E. huxleyi within all samples could be indicative of the fact that cementation took place prior to 3500 BP and did not continue thereafter. During the precipitation of connective carbonates just before the invasion of the Black Sea by E. huxleyi, on the lower boundary of ecozone 1 at 3300 BP (Giunta et al., 2007), water-salinity was below the tolerance limit of this coccolith.

Another argument associated with coastal processes matching the formation of beachrock arises from a relict coastal dune sequence on the backshore at the Kıyıköy location. The sandy beach is backed by a 3-m thick dune deposit consisting of polycrystalline quartz, epidote and plagioclase with coloration of opaque iron oxide rings. The sequence also includes fragments of ferro-magnesium minerals as well as poorly rounded metamorphic rock fragments derived from quartz-epidotite-schist and marble. The bottom and middle levels of the sequence contain fossil shells of D. trunculus and V. gallina, the latter of which is present only in the middle level. The sequence is almost absent of foraminifera with the exception of the bottom level which incorporates Elphidium macellum, broken fragments of Elphidium sp., Ammonia parkinsoniana and other Ammonia sp.

From bottom to top, the total amount of CaCO₃ in this relict dune, decreases from 14% to 2%. Coarse and medium sands are predominant (95%). The rest of the dune deposit comprises very fine sand and silt. All these components are weakly bonded by meniscus cement formed by iron-oxides. Besides being of similar composition to the beachrock, two shells of D. trunculus collected from the bottom and middle levels yielded AMS radiocarbon ages of 5440–5230 cal BP and 3230–2940 cal BP, respectively (Table 2). These ages, as well as the compositional attributes specified, are virtually identical to those of beachrock, suggesting that both occurrences are coeval. Nevertheless, this consolidated, well-drained and iron-oxidized dune deposit requires further study owing to its paleosoil-like characteristics.

**5. Conclusions**

The beachrock exposures in this study were observed on the northwest coast of East Thrace, Turkey. Albeit with a limited exposure,
the studied beachrock is the first record from the Black Sea coast. The ages range between about 5.5 ka BP and 3.5 ka BP, a controversial period with regard to the Middle to Late Holocene sea-level history of the Black Sea. Predominating coarse grains and small pebbles in the cemented beds are indicative of the fact that the pre-cementation environment was a high-energy shingle beach backed by coastal dunes. These dunes are preserved as a relict dune sequence at the backshore and form a contemporaneous unit based on the AMS radiocarbon age of its bioclasts.

Our results revealed that the thickness of the beds, based on the geophysical imaging survey, exceeded the tidal range, implying that the cemented beach could not be simple of intertidal origin. Besides the existence of low-Mg calcite, the secondary cement-producing meniscus bridges on early micritic cements and dissolution pits on micrite coatings are likely connected with freshwater penetration due to subaerial exposure of slabs when the sea-level was slightly lower than it is today. We assume that the cements were precipitated when Black Sea’s salt content was lower than present, based on the absence of E. huxleyi. We suggest that the cements were first precipitated in the upper intertidal zone when the sea-level was close to the present. Beachrock formation continued during exposure of the whole sequence when the sea-level declined slightly (about 2 m), inasmuch as early cements have etched surfaces in consequence of downward-percolating meteoric waters.

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References


