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Article *in* Global and Planetary Change · March 2009

DOI: 10.1016/j.gloplacha.2008.07.009

Global and Planetary Change 66 (2009) 19–33

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Beachrocks and sea level changes since Middle Holocene: Comparison between the insular group of Mykonos–Delos–Rhenia (Cyclades, Greece) and the southern coast of Turkey

Stéphane Desruelles [a,*], Éric Fouache [a], Attila Ciner [b], Rémi Dalongeville [c], Kosmas Pavlopoulos [d], Erdal Kosun [e], Yvan Coquinot [f], Jean-Luc Potdevin [f]

[a] *Université Paris 12-Val de Marne, EA 435 Géonat, F 94010 Créteil Cedex & CNRS, UMR 8591 LGP, F 92195 Meudon Cedex, France*
[b] *Hacettepe University, Department of Geological Engineering, Ankara, Turkey*
[c] *CNRS — Maison de l'Orient et de la Méditerranée, UMR 5133 Archéorient, F 69365 Lyon Cedex 07, France*
[d] *Harokopio University, Department of Geography, 17671 Athens, Greece*
[e] *Akdeniz University, Department of Geology, 07058 Campus Antalya, Turkey*
[f] *Université des Sciences et Technologies — CNRS, UMR 8157 Géosystèmes , F 59655 Villeneuve d'Ascq Cedex, France*

ARTICLE INFO

Article history:
Received 9 April 2008
Accepted 31 July 2008
Available online 30 November 2008

Keywords:
sea level changes
beachrocks
early diagenesis
Holocene
Turkey
Greece
Mediterranean

ABSTRACT

The small insular group of Mykonos–Delos–Rhenia in Cyclades, Greece, and the southern coast of Turkey from Andriake to Arsuz show three bands of beachrocks, emerged up to +0.35 m and submerged sometimes down to −4.3 m. Because beachrocks are formed within the intertidal zone by carbonate cementation of the beach deposits during stages of shoreline stabilisation (both eustatic and tectonic), they correspond to different generations indicating different sea level stands.

11 sites on the southern coast of Turkey and 7 bays on the insular group of Mykonos–Delos–Rhenia were studied. 52 beachrock samples were analysed by polarizing microscope, cathodoluminescence and SEM. This study indicated that carbonate elements that constitute most of the samples were at least partly incorporated within the intertidal zone. The adequate method for radiocarbon dating (total sample or cement) was decided according to these observations. Because diagenetic cements seemed difficult to extract manually and the sources of carbonate pollution are limited in Mykonos–Delos–Rhenia, we performed ^{14}C AMS dating on total samples. On the southern coast of Turkey, due to the abundance of micrite in between the limestone pebbles that often constitute the beachrocks, available cements had to be manually extracted for ^{14}C AMS dating.

The dates obtained from Mykonos–Delos–Rhenia beachrocks indicate 3 separate sea level stands: the first one at about −3.6 m (±0.5 m) around 2000 BC, the second one at about −2.5 m (±0.5 m) around 400 BC and finally the third sea level at about −1 m (±0.5 m) around 1000 AD. On the southern coast of Turkey, several relative sea level positions in 4 areas (I to IV) are recognised. From Finike Bay to the west (area I), a post-Roman relative sea level rise is observed after a period of coastline stabilisation. The area from the east of Finike Peninsula to Çimtur (area II) witnessed relative sea level rise since mid-Holocene interrupted by 3 phases of stability corresponding to beachrock bands. Two levels have been dated. The first one is between 0 m and −0.8 m and dates from 5th to 7th century AD. The second one is between −1.5 m and −2.2 m and dates around 7th to 6th century BC. From Incekum to Karataş–Osmaniye Fault Zone to the south of Adana (area III), the shoreline was raised around +0.5 m after 19 BC–200 AD and later becomes stable at least since the 12th century AD as can be interpreted from archaeological remains. To the east, beachrocks in Gözcüler (area IV) indicate a relative sea level rise interrupted by a phase of coastline stabilisation between 0 m and −0.5 m from the 4th to the 7th century AD. Our southern Turkish coastline observations reveal a very dynamic tectonic regime – mainly subsidence to the west and uplift to the east – since at least mid-Holocene.

The comparison of the results obtained from Greece and Turkey indicates a tectonic subsidence during the last 6000 years in the centre of Cyclades.

1. Introduction

The eastern Mediterranean has been the focus of numerous studies on relative Holocene sea level variations (Négris, 1903; Cayeux, 1914; Flemming, 1969; Kelletat, 1975; Blackman, 1982a, b). Although the absolute timing of sea level changes is often qualitative there are

* Corresponding author.
E-mail addresses: sdesruelles@free.fr (S. Desruelles), eric.G.Fouache@wanadoo.fr (É. Fouache), aciner@hacettepe.edu.tr (A. Ciner), kpavlop@hua.gr (K. Pavlopoulos), kosun@akdeniz.edu.tr (E. Kosun), yvan.coquinot@hotmail.fr (Y. Coquinot), Jean-Luc.Potdevin@univ-lille1.fr (J.-L. Potdevin).

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doi:10.1016/j.gloplacha.2008.07.009

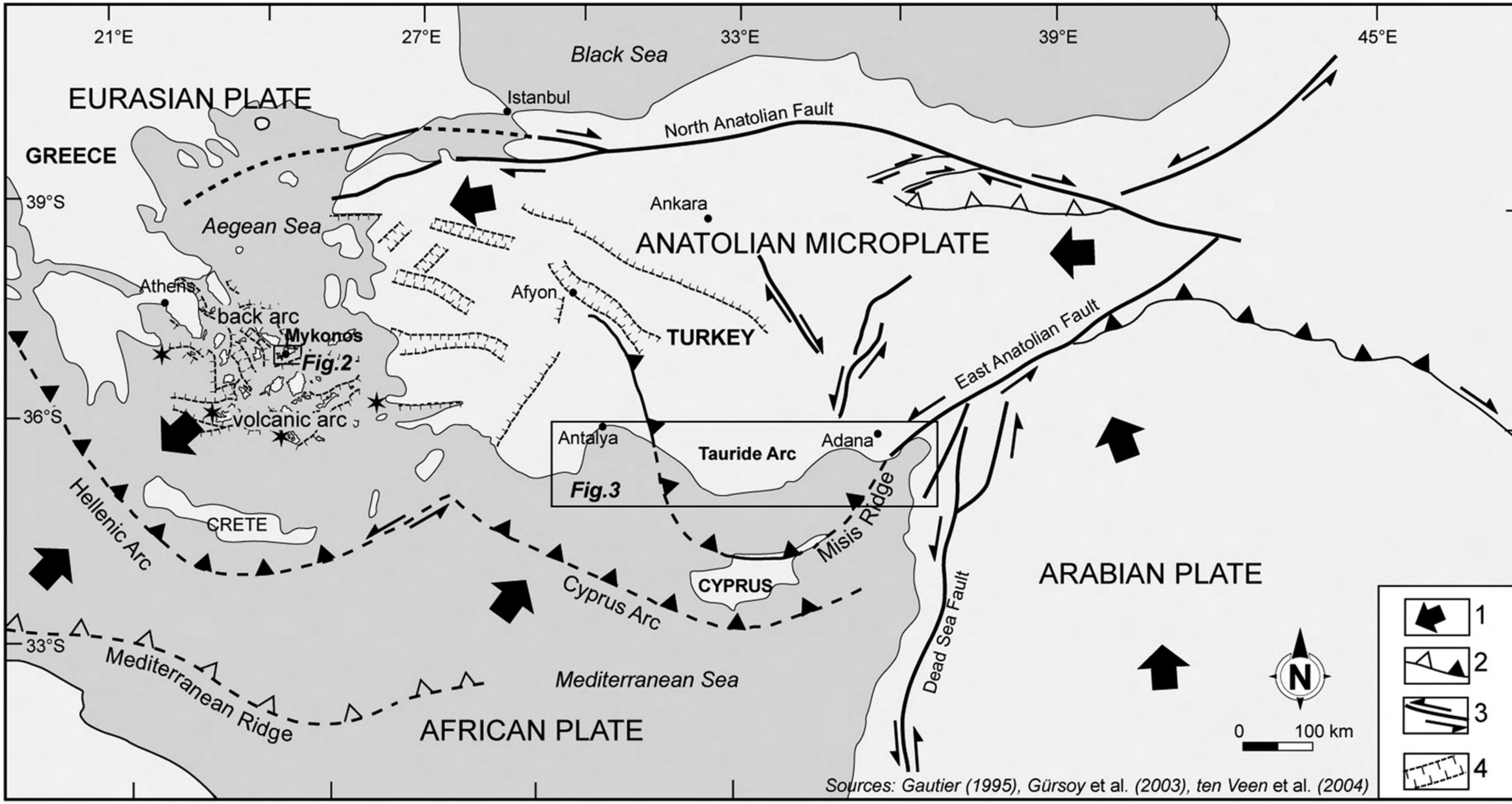


Fig. 1. Geodynamic setting of the eastern Mediterranean and location of study areas 1: strike-slip fault; 2: overthrust and thrust faults; 3: tectonic plate relative movement; 4: horst and graben system. (Gautier, 1995; Gürsoy et al., 2003; ten Veen et al., 2004).

nevertheless few studies with quantitative proxy data obtained from vermetids developed on notches (Pirazzoli, 2005; Morhange et al., 2006). In order to present new reconstructions, we studied beachrocks in 2 areas where archeological remains are numerous: Mykonos–Delos–Rhenia in Cyclades, Greece, and southern Turkey from Andriake to Arsuz (Fig. 1).

Beachrock is an early cemented sedimentary body composed of aragonite or high-magnesium calcite (HMC), within the intertidal zone. Its formation requires vertical stability of the shoreline, probably for several centuries (Dalongeville and Sanlaville, 1984; Neumeier, 1998; Vousdoukas et al., 2007), associated with the progradation of the beach in which the beachrock is formed. The exhumation of beachrock is the result of seashore erosion due to a negative sediment budget or as a consequence of a sea level rise. Parts of the beachrock that have resisted erosion represent the original intertidal zone. This marker horizon can be dated thanks to the early cement which is developed between sediments. Although beachrocks are less precise than other markers such as fauna associated to bio-constructions, forms of bio-corrosion and notches at the foot of limestone cliffs, they are often the only markers permitting sea level reconstructions.

This paper aims to establish the chronology of the relative sea level variations that occurred since Middle Holocene in areas studied in Greece and in Turkey by using the ^{14}C dating obtained from the beachrocks.

2. Geological setting

The study areas are both located in the eastern Mediterranean, and exhibit different geological and tectonic characteristics.

2.1. Mykonos–Delos–Rhenia group

The islands of Mykonos, Delos and Rhenia are located on a Miocene metamorphic dome (Lucas, 1999), essentially made of granite and to a lesser extent, of gneiss (Fig. 2). Meta-volcanic and meta-sedimentary rocks outcrop in the northeast of Mykonos. This insular group is located in the centre of the Aegean back-arc extensional basin, to the north of the subduction of the African plate under the Eurasian plate (Fig. 1). This N–S extension initiated during the Early Miocene probably causing the subsidence of the Cyclades Plateau and consequently of Mykonos–Delos–Rhenia (Piper and Perissoratis, 2003). The major N–S faults that cut the insular group may have been active until the Pliocene (Anastasakis and Dermitzakis, 1990). There has probably not been any significant tectonic activity since then (Hejl et al., 2002).

2.2. Southern coast of Turkey

This area is located in the eastern extension of the Aegean arc, on the southern piedmont of the Taurus Mountains chain (Fig. 1 and 3). Mainly limestones and to a lesser extent ophiolitic rocks make up the dominant lithologies in these mountains. Roughly N–S extending faults that were active during the Quaternary, especially on the eastern and western fringes of the Köprüçay and Aksu Basins (Glover and Robertson, 1998; Deynoux et al., 2005) and to the south of Adana town (Karataş–Osmaniye Fault Zone) (Fig. 3) indicate the complex nature of tectonics along the coastline.

The westernmost part of our study area (north of Finike Bay) is composed of the Bey Dağları carbonate platform of Late Cretaceous to Palaeogene age (Poisson, 1977). The southerly-derived Antalya Complex, made up of allochtonous Mesozoic rocks (mostly carbonates) occupies the southeastern part of Antalya town (Robertson, 2000).

In the Antalya area and towards the east, small Miocene sedimentary basins (Aksu, Köprüçay and Manavgat Basins) filled with coarse clastics and reefal limestones are observed (Akay et al., 1985; Flecker et al., 2005; Karabıyıkoğlu et al., 2000; Çiner et al., 2008). These basins are unconformably overlain by Pliocene shallow marine to fluvial sediments (Poisson et al., 2003) and Quaternary tufas especially in and near the Antalya town (Bürger, 1990; Glover and Robertson, 2003). The Metamorphic Alanya Massif composed of 3 thrust sheets (Okay and Özgül, 1984) bounds the eastern part of the Miocene Manavgat Basin. To the northeast of Anamur town, the Miocene Mut and Adana Basins are mainly made up of shallow to deep water clastics and reefal carbonates (Şafak et al., 2005; Yetiş et al., 1995).

To the east of İçel lies the delta of the Seyhan and the Ceyhan Rivers, essentially made up of alluvium which fill in the Çukurova delta plain. This area is defined by a SW–NE strike-slip fault zone (Karataş–Osmaniye Fault Zone) located in the extension of the Misis Rift (Fig. 1). Cretaceous ophiolitic and calcareous rocks (Boulton and Robertson, 2007) dominate the area south of İskenderun.

3. Materials and methods

3.1. Selection of sample sites

Field prospecting in Mykonos–Delos–Rhenia using previous works by Bernier et al. (1987) and Bernier and Dalongeville (1996) enabled us to select 7 sites (Fig. 2). In southern Turkey, beachrocks from 11 sites have been collected following previous studies by Dalongeville and Sanlaville (1977, 1979) (Fig. 3). We focused on sites containing multiple generations of beachrocks, submerged and/or emerged, stratified and located in different geologic and tectonic settings. In Mykonos–Delos–Rhenia, all 7 sites were selected within the same tectonic group, subjected to a slow subsidence. In Mykonos, sites A (Kalafati), B (Aghios Ioannis) and C (Aghios Sostis) are on granites (Fig. 2). However, locally sandstones (essentially eolianites) can be observed. In Delos, site D (Fourni) is surrounded by granite, locally covered by eolianites. In Rhenia, sites E (Kormou Ammos), F (Steni) and G (Lazaret) are found on gneissic outcrops.

In southern Turkey (Fig. 3), site 1 (Finike), the westernmost studied area, is located in a large bay with a thick Quaternary alluvium surrounded by calcareous rocks in general. Sites 2 (Adrasan), 3 (Kemer) and 4 (Kargacık) are bound by an ophiolitic complex and limestones of Bey Dağları. Site 5 (Belek) is located between the mouths of the Aksu and Köprü Rivers. Çimtur Bay (site 6) lies on the eastern border of the Manavgat sedimentary coastal plain, just south of the Alanya Metamorphic Complex. The latter frames sites 10 (east of Alanya) and 11 (west of Kahyalar). North–South vertical faults cut this coastal section. Site 13 (east of Aydıncık) is located within an environment of sedimentary rocks. In the coastal area from Aydıncık to İskenderun, there are few markers of ancient shorelines. A few marine abrasion platforms, correlating with the present sea level, have been observed in the cliff area stretching from Aydıncık to Viranşehir (site 14) (Fig. 3). Besides, in places (such as Viranşehir and İçel) there are a few beachrocks, located at elevations comparable to the outcrop described by Taillefer (1964). In addition, the sediments of Seyhan and Ceyhan Rivers that create the Çukurova delta plain might cover some existing beachrocks. Sites 15 (Gözcüler) and 16 (Arsuz) are in Hatay, a region mainly made of ophiolitic and calcareous rocks.

3.2. Topographic and bathymetric surveys

Each site has been studied according to its geomorphic and hydrologic environments (Figs. 4 and 5). The readings are based on the present mean sea level, established from consulting tide gauge records and recording the altitude of the closest biological markers (such as vermetid reefs). The seashores of the studied areas have a low average tidal range (±0.2 m to ±0.3 m; Dalongeville, 1997), but annual variations caused by barometric fluctuations can reach as much as ±0.5 m.

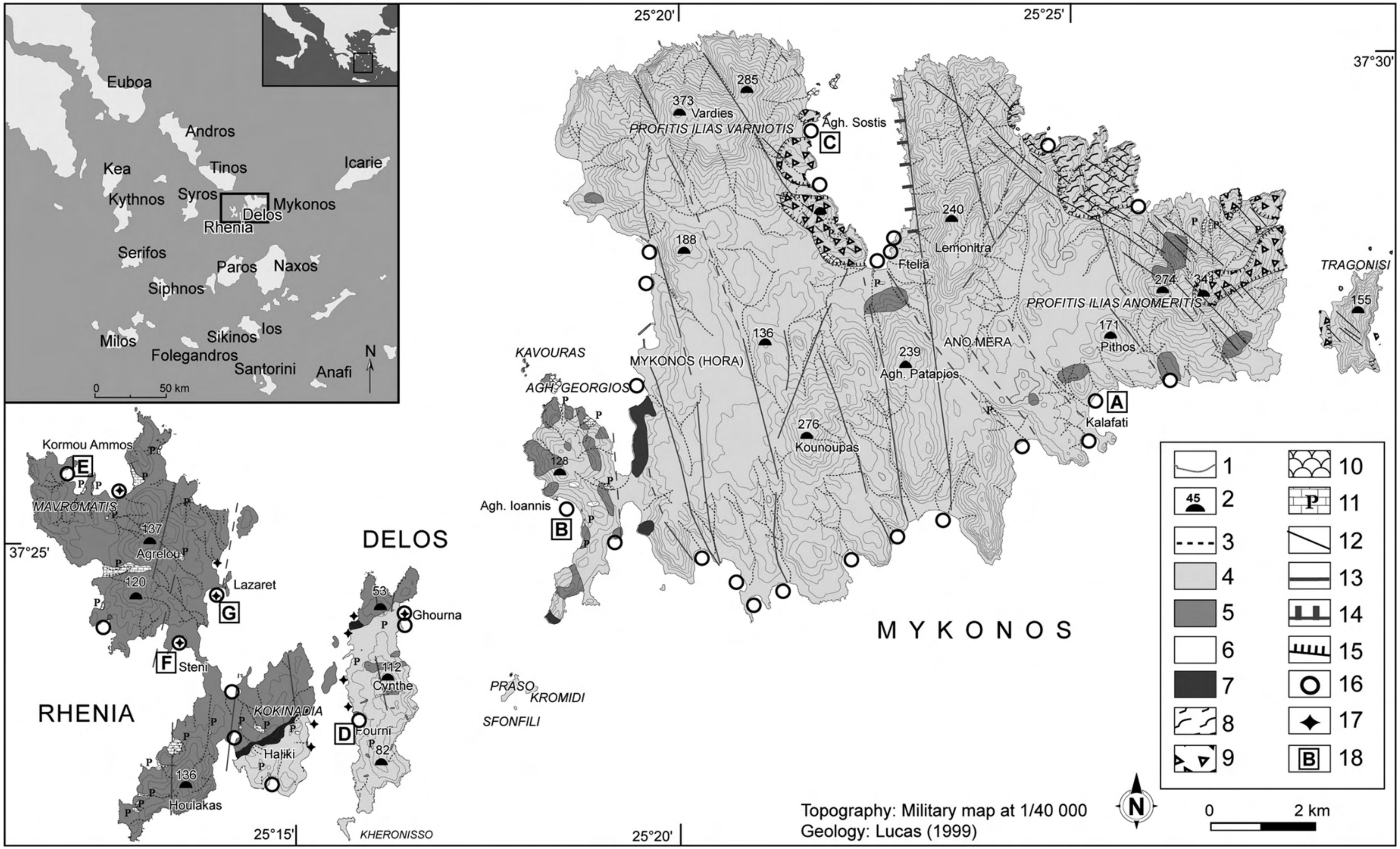


Fig. 2. Geology and location of the sample sites of Mykonos, Delos and Rhenia islands 1: elevation contours, 20 masl; 2: spot height in m; 3: ephemeral flow; 4: granites; 5: gneiss; 6: marbles; 7: micaschists; 8: metavolcanics; 9: Miocene conglomerates; 10: Permo-triassic carbonates; 11: sandstones (eolianites); 12: barite veins; 13: faults, joints and hidden faults, hidden joints; 14: normal faults; 15: low-angle normal faults; 16: beachrocks, cemented pebble bars; 17: submerged archaeological vestiges; 18: sample site.

Within each bay, the sampling sites were chosen after a careful observation of the beachrocks outcrops. We selected areas where the erosion and removal of beachrock slabs were limited.

3.3. Beachrocks sampling

In order to date the sea level corresponding to each beachrock, we have dated the beachrock end slabs. In fact, the back-end slab (landward) is theoretically the oldest, and the front-end slab (seaward) is the youngest. However, sampling was not possible at all extremities, particularly for the ones buried under the sand, and some samples could not be dated. In Mykonos–Delos–Rhenia, 30 samples were collected by diving. In southern Turkey, 38 beachrock samples were collected in and out of the water, often by diving.

3.4. Microscopic study and radiocarbon dating

After preliminary observations under a binocular magnifier, 16 samples were removed from our study because their composition did not permit to make thin sections. Thin sections were made from 20 beachrock samples from Mykonos–Delos–Rhenia and from 32 samples collected from southern Turkey. They were examined under a polarizing and a scanning electron microscope and in cathodoluminescence. These observations permitted to characterize the nature of the constituents and organic elements, the morphology and the geochemistry of the cements. This analysis allowed us to select samples where dating could be carried out. It also permitted to choose the most adequate method for the extraction of cement. Although the cement can be contaminated by carbonate particles other than the calcite cement, the radiocarbon ^{14}C dating is still the most appropriate method for the Mediterranean beachrocks.

All Mykonos–Delos–Rhenia samples were dated by the “Centre de datation par le Radiocarbone” (in Lyons, France) and the ones from Turkey were dated by the “Poznan Radiocarbon Laboratory” in Poland. The dates were calibrated using the curve of Hughen et al. (2004), according to the $^{13}C/^{12}C$ isotopic ratios. The marine reservoir effects, assessed in Ftelia (Mykonos) (Fig. 2) by Facorellis and Maniatis (2002), do not bring about significant differences in relation to the calibrated dating of the Mykonos–Delos–Rhenia samples. In southern Turkey, the $^{13}C/^{12}C$ ratios of the samples dated with ^{14}C indicate an insignificant influence of fresh water (Fig. 10). In addition, seawater samples were collected and dated. They indicate a negligible ageing of seawater by carbonates of the surrounding rocks.

3.5. Precision of the reconstructions carried out using the beachrocks dating

Sedimentary structures within the beachrock such as keystone vugs (rounded vacuoles which form in the intertidal top segment as the swash floods the beach sediment from the top and traps air bubbles, Beaudoin, 1954; Dunham, 1970) permit a precise reconstruction of sea levels (to ±0.25 m). In the case of submerged beachrock (numerous in the studied areas) where the sedimentary structures are difficult to identify, this range is increased to ±0.5 m.

From the field measurements carried out on the beachrocks, the ancient intertidal zones are reconstructed in the following manner:

- the average summit altitude from both beachrocks ends (“front” and “back”) (Figs. 4 and 5) represents the central axis of the reconstructed intertidal zone. For example, the central axis for the first beachrock line in Kemer is reconstructed at −0.4 m (average from 0 m and −0.8 m) (Fig. 5B).
- the entire reconstructed intertidal zone corresponds to a theoretical altitude ranging ±0.5 m from this axis (Fig. 9). In the case of the beachrock in Kemer, this former intertidal zone is located between +0.2 m and −0.9 m.

This method aims to harmonize the data and compare beachrocks from different sites and regions. It allows for the reconstructions of intertidal zones of constant extent (1 m in height) as some beachrocks have been partially dismantled since their formation. If we had based the study solely on present altitudes of some of those beachrocks, the corresponding intertidal zone would not be completely recreated (case of site 1 (Finike) beachrock of which the summits of the two ends are at the same height) (Fig. 5A).

4. Results

On all 7 sites selected in Mykonos–Delos–Rhenia, the beachrock bands, separated by sandy stretches, are located between 0 m and −3.8 m (Fig. 4). In southern Turkey, the submerged beachrock bands might go down to −4.3 m, as in Finike (Fig. 5). The beachrocks are best exposed between Alanya and Kahyalar (Bener, 1974; Avşarcan, 1997). Our observations confirm the existence of several beachrocks tens of kms long at about 0 m and +0.35 m height.

4.1. Types of cements

The bounding materials observed between the grains are early intertidal cements, sparitic and micro sparitic cements, peloidal HMC and micrite (Desruelles et al., 2004; Fouache et al., 2005a) (Figs. 6–8). Most of the material was set in when the beachrock was formed within the intertidal zone.

4.1.1. Early intertidal cements

The early diagenetic cements are characterized by a high proportion of magnesium calcite (HMC) or aragonite in their composition. Their genesis is contemporary to the beachrocks and they originate from sea or brackish water (Heckel, 1983; Longman, 1980; Neumeier, 1998).

The cements are a few tens of mm thick and often envelop the grains as a thin film. When they have a micritic texture (as observed in Mykonos–Delos–Rhenia), they form thin isopach fringes (sample A11) or clusters and bridges between the grains (sample G12). The HMC cement coating is often characteristic of the marine phreatic zone: non-jointed limpid crystal fringes (calcite), jointed limpid crystal fringes with a palissadic texture (Fig. 8B) and/or thicker radiaxial fibrous calcite cements (RFC) (Fig. 8A, C and D).

Among the beachrock samples from southern Turkey (Fig. 7), two other types of diagenetic cements were observed:

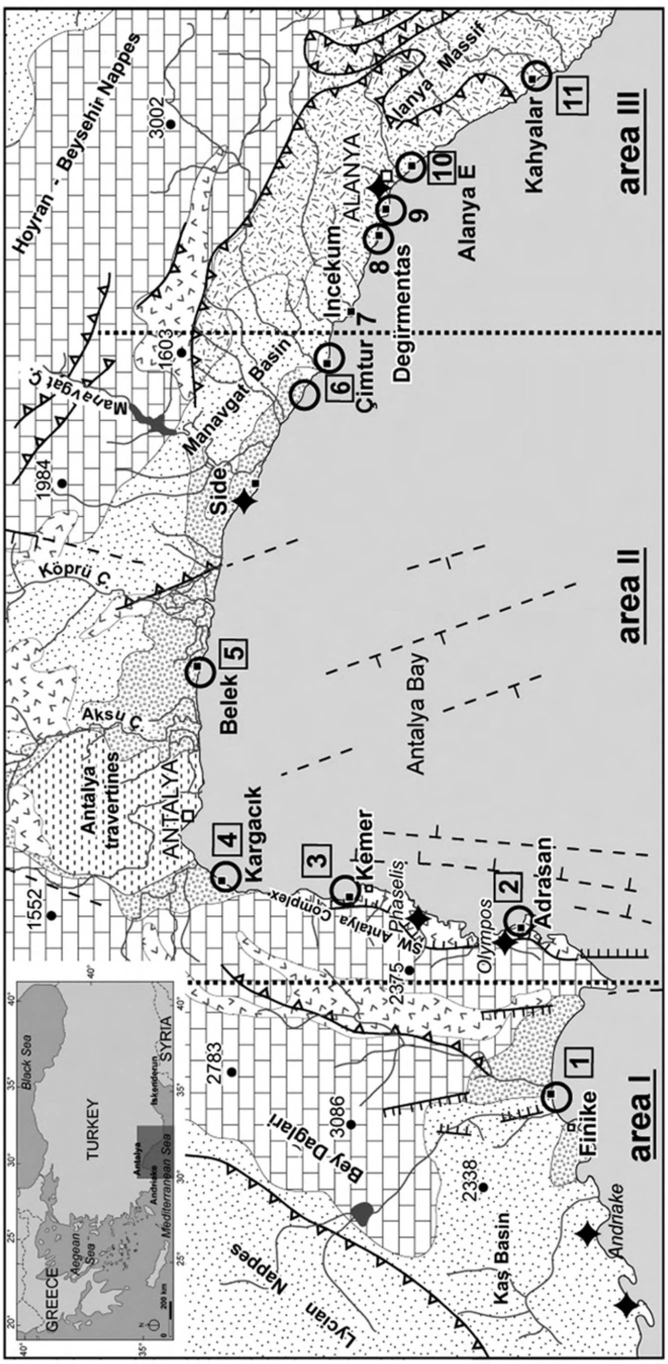
- fan and needle-shaped aragonitic cement characteristic of the marine phreatic zone (samples Ke2 and Ke4) (Fig. 8B),
- HMC sparitic cements in stalactic disposition characteristic of the marine vadose zone (sample Kah3).

4.1.2. Peloidal high-magnesium calcite (HMC)

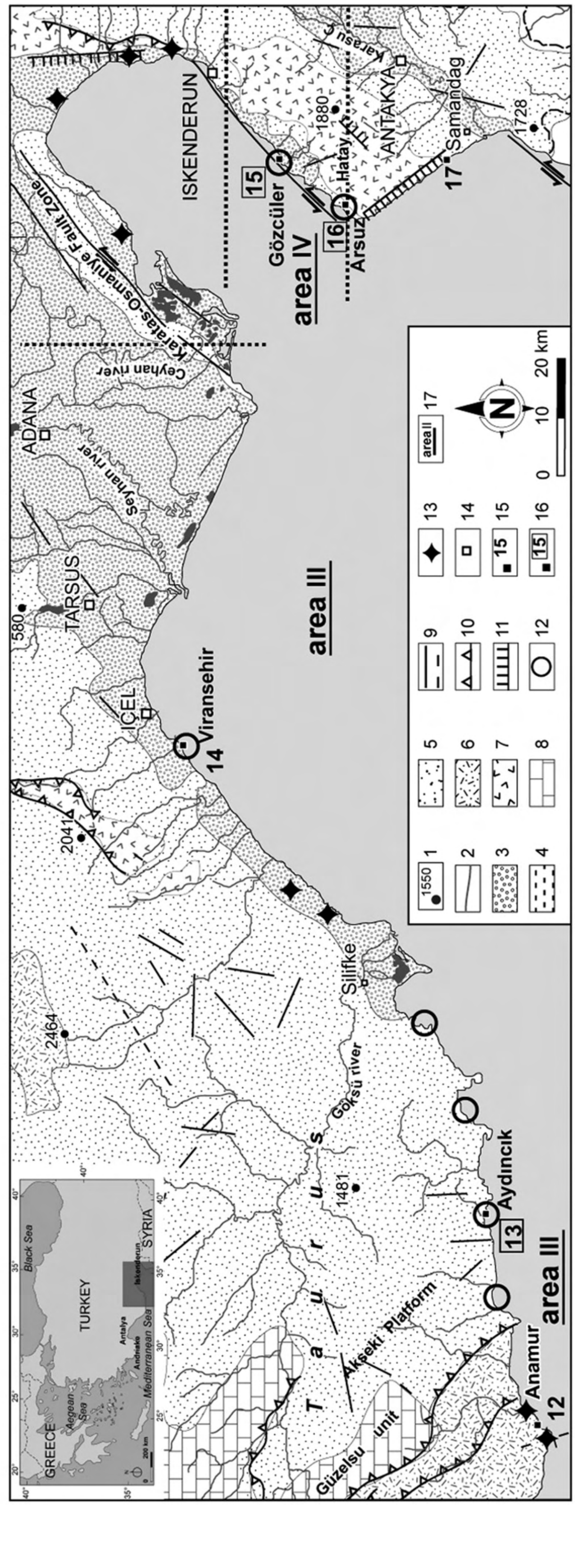
Peloidal HMC is a micrite partially replaced by coalescent pellet clusters. These pellets are agglomerates of particles whose size ranges from 10 µm to 100 µm (Fig. 8C). They form during the diagenesis inside the pore space within the intertidal zone. They are probably associated to a precipitate of HMC caused by bacterial action (Amieux et al., 1989; Chafetz, 1986; Kerans et al., 1986; Meyers, 1987; Pickard, 1992; Strasser et al., 1992) and by interstitial water circulation (Neumeier, 1998). Consequently, the peloidal HMC can be considered as true cement contributing to the strengthening of the beachrock (Neumeier, 1998). However, it is often “polluted” by later cements (LMC micro sparitic cements). The peloidal HMC contains cements that were not completely formed in the intertidal zone.

4.1.3. Micritic fillings, including internal sediments

These micritic fillings are not diagenetic cements, but result from infiltrations within the pore space of the newly formed beachrocks.



Geology map modified from Robertson (2000)



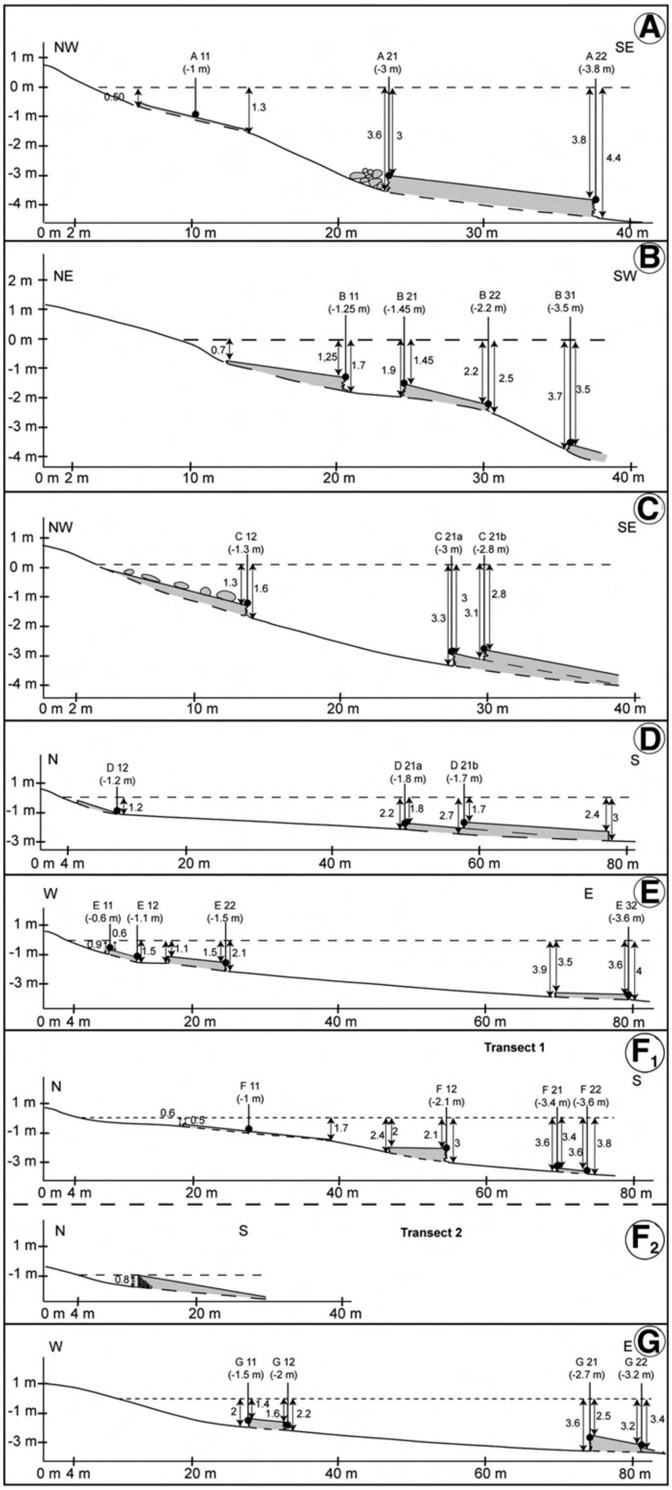


Fig. 4. Profiles of the dated beachrock outcrops in Mykonos–Delos–Rhenia A: Kalafati (37°26′N; 25°25′E); B: Aghios Ioannis (37°25′N; 25°18′E); C: Aghios Sostis (37°29′N; 25°21′E); D: Fourni (37°23′N; 25°16′N); E: Bay to the west of Kormou Ammos (37°26′N; 25°12′E); F1: Steni (37°24′N; 25°13′E), transect 1; F2: Steni, transect 2; G: Lazaret (37°24′N; 25°14′E).

They are composed of a fine matrix containing microclasts, mainly siliceous in Mykonos–Delos–Rhenia and generally carbonate in southern Turkey, and some bioclasts. These calcareous constituents are likely to influence the radiocarbon dating by producing apparently older dates. The micrite infiltrations are contemporary or posterior to the beachrock formation in the intertidal zone. They are often geotropic deposits resulting from gravity in the beachrock pore space (Fig. 8D). These internal geotropic sediments may come from the percolation of fine particles originating from the water/sediment interface, in the intertidal zone.

In 4 beachrock samples from Turkey (Ke3, DA3, DA4, Kah3), we often observe laminated micrite, partially filling the pore spaces (Fig. 8E). These micritic fillings can be considered as internal sediments with a centrifugal disposition. Because of their layout mode, conditioned by the presence of a gaseous phase, these sediments are interpreted to be characteristic of marine vadose environments (Purser, 1980).

20 beachrock samples, 17 of which come from the Turkish coast, contain interstitial micrite (Fig. 8F). This non-diagenetic micrite seems to have been incorporated to the sediments during the beachrock cementation in the intertidal zone and/or later, in a quieter environment, in the upper subtidal zone. Among the calcareous constituents identified in the observed beachrocks of both study areas, the most reliable for radiocarbon dating are the diagenetic intertidal cements.

4.2. Cement composition and mineralogy of the dated beachrock samples

Most of the collected samples contain at least one of the calcareous constituents deposited within the intertidal zone. The microscopic analysis, together with the field observations, provides evidence that these samples come from beachrocks.

4.2.1. Samples collected in Mykonos–Delos–Rhenia

These samples are mainly made of siliceous clasts. They also contain some bioclasts and limestone lithoclasts, particularly when limestones and eolianites outcrops are located near the sites (sites B, C and E) (Fig. 2).

Diagenetic intertidal cements are absent in three samples (Fig. 6). However, two of them (D21b and A22) contain internal sediments which can be considered as peloidal HMC contemporary to the lithification in the intertidal zone. Although field evidence indicates that sample D12 is taken from a beachrock, it does not contain any cement characteristic of the intertidal zone.

Diagenetic intertidal zone cements are usually thin (less than 100 µm). For all samples except C12, they are associated to detritic constituents (bioclasts, micritic fillings, internal sediments), sometimes to micritic cement and to peloidal HMC (Fig. 8).

Considering the thinness of the cements, the dominance of siliceous clasts and the low proportion of bioclasts and non-recrystallized micritic fillings, the beachrock dating was carried out on "total sample". As observed under the microscope, the cements are often less than 100 µm thick and therefore the carbonate fraction below this size was collected after the crushing of the sample. This allowed the elimination of most of the clasts before the radiocarbon dating.

4.2.2. Samples collected in southern Turkey

Except in Hatay area to the east where samples also contain siliceous clasts derived from the ophiolites outcropping nearby, all samples are essentially made up of carbonate clasts and contain bioclasts as well as micritic fillings (Fig. 7).

The diagenetic intertidal cements, observed in 24 out of 32 samples, are finer than the Mykonos–Delos–Rhenia beachrocks.

Fig. 3. Geology and location of the sample sites in southern Turkey 1: spot height in m; 2: main river; 3: Holocene alluvium; 4: Pliocene–Quaternary sediments; 5: Miocene sediments; 6: Mesozoic–Early Tertiary metamorphic complex; 7: Mesozoic–Early Tertiary allochtonous margin and oceanic derived units; 8: Mesozoic–Early Tertiary carbonate platform; 9: main faults, hidden faults; 10: overthrust and thrust faults; 11: normal faults; 12: beachrock; 13: coastal archaeological sites; 14: main town; 15: study site; 16: sample site; 17: area established according to our study.

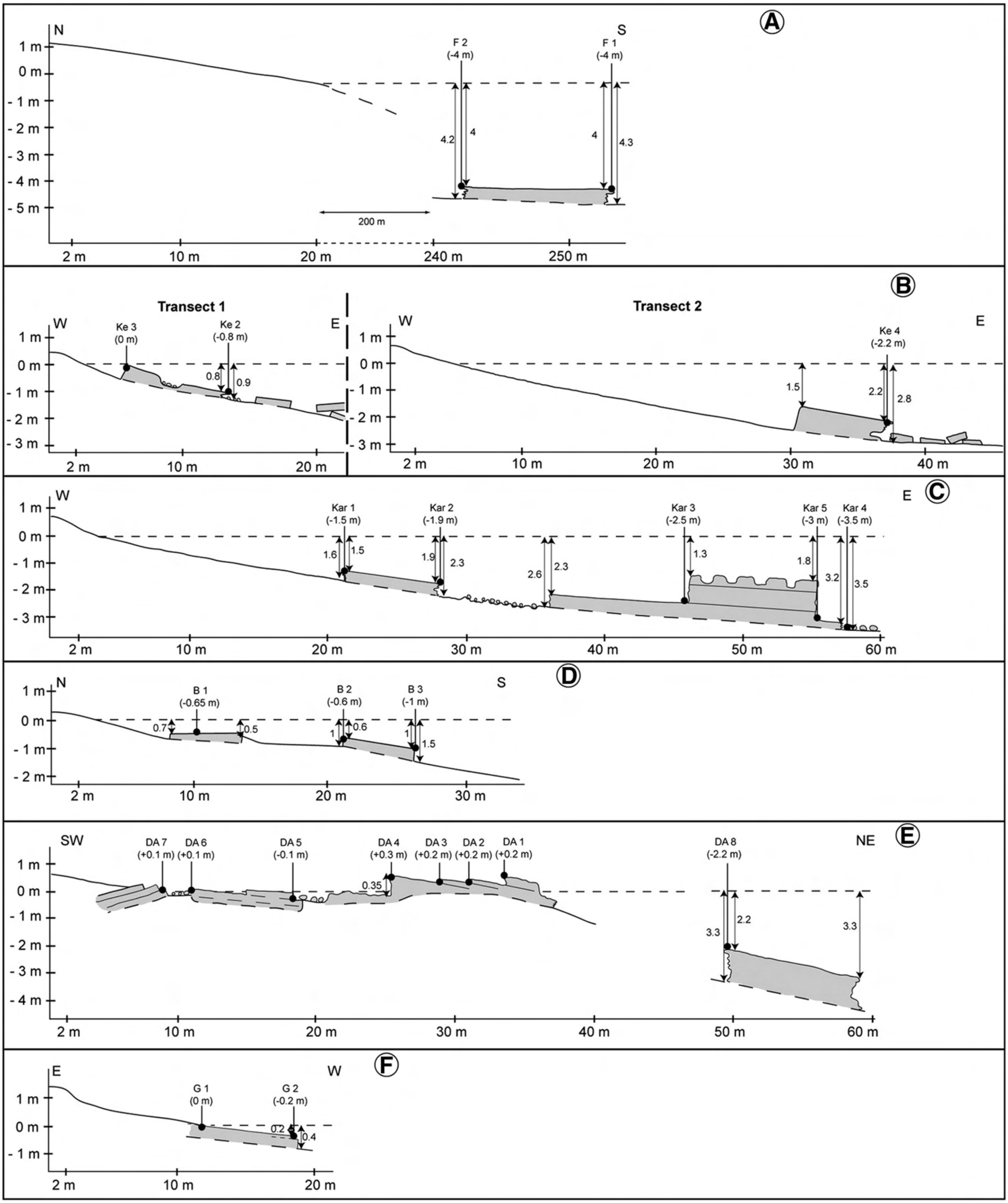


Fig. 5. Profiles of the dated beachrock outcrops in southern Turkey A: Finike (36°20′N; 30°15′E); B: Kemer (36°38′N; 30°33′E); C: Kargacık (36°45′N; 30°34′E); D: Belek (36°51′N; 31°03′E); E: east of Alanya (36°32′N; 32°02′E); F: Gözcüler (36°26′N; 35°54′E).

Only one sample (B2) contains diagenetic intertidal cements, nevertheless associated to bioclasts and numerous carbonate clasts. Samples deprived of early intertidal cements come nonetheless from beachrocks because their pore spaces are partially filled with internal sediments with geotropic or centrifugal dispositions.

Considering the thinness of the diagenetic intertidal cements and the important proportion of carbonate clasts, bioclasts, and micritic fillings in most samples, we have chosen to date the cement and, in addition, to manually extract and date non-pelleted internal sediments which are poor in carbonate microclasts. Due to technical difficulties, limited amount of material could be extracted under the binocular microscope. Besides, our aim to date several beachrock bands from a single site reduced the number of datable samples.

Besides, to obtain complete transects, we aim to date several generations of beachrocks located in the same site. This method required to eliminate samples: there are only 2 sites (Kemer, site 3, and Gözcüler, site 15) (Figs. 3 and 5) where beachrock bands belonging to several generations can be dated. For the former site, dating was carried out on centrifugal internal sediments (sample Ke3) or on intertidal aragonitic cement (samples Ke2 and Ke4). For the latter site, dating was done on intertidal HMC cements (G1 and G2).

4.3. Beachrocks morphology and dating

At the scale of the Mykonos–Delos–Rhenia insular group, 3 beachrock bands have been distinguished (Desruelles et al., 2004; Fouache et al., 2005a). They permitted to reconstruct 3 successive intertidal zones that indicate phases of relative sea level stability:

- the first one, closest to the shoreline, is generally located between 0 m and −1.7 m,
- the second, intermediate and less widespread, is developed between −1.1 m and −2.5 m,
- the third, farthest from the shoreline, is generally found between −2.7 m and −5 m.

Radiocarbon dating on the “total sample” is generally satisfying (Fig. 10). In most cases, the oldest dates correspond to the deepest

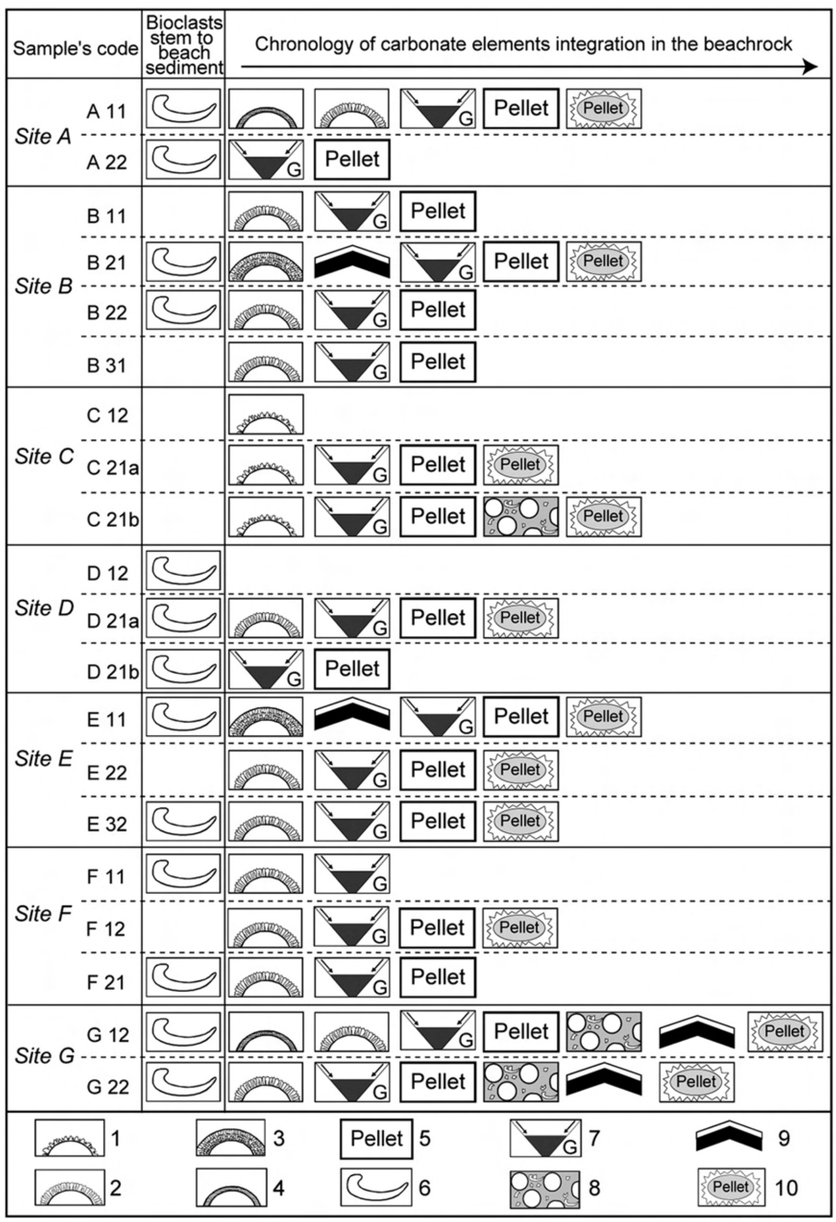


Fig. 6. Carbonate fabrics observed in the samples collected in Mykonos–Delos–Rhenia 1: small isopachous fringe of limpid and non contiguous HMC crystals; 2: small bladed isopachous fringe of limpid and contiguous HMC crystals; 3: isopachous cement of radiaxial fibrous calcite (RFC); 4: isopachous micritic cement; 5: peloidal HMC cement; 6: bioclasts; 7: geotropic deposit of internal sediments; 8: micrite infiltration; 9: early zoned spar cement; 10: marine cementation of magnesium calcite around pellets (probably caused by bacterial actions) and/or recrystallization.

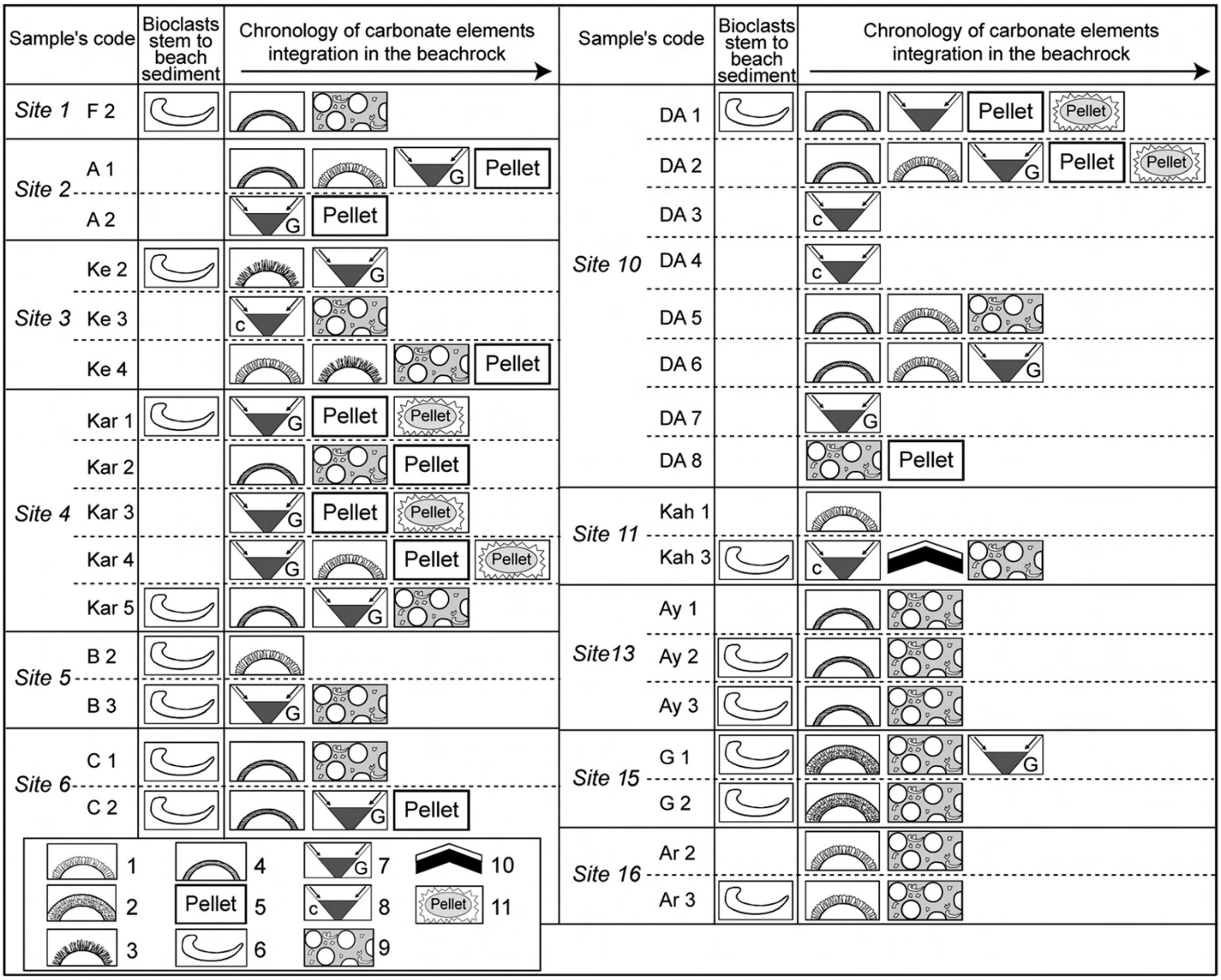


Fig. 7. Carbonate fabrics observed in the samples collected in southern Turkey 1: small isopachous fringe of limpid and non contiguous HMC crystals; 2: isopachous cement of radiaxial fibrous calcite (RFC); 3: fan and needle-shaped aragonitic cement coatings; 4: isopachous micritic cement; 5: peloidal HMC cement; 6: bioclasts; 7: geotropic deposit of internal sediments; 8: centrifugal internal sediments; 9: micrite infiltration; 10: early zoned spar cement; 11: marine cementation of magnesium calcite around pellets (probably caused by bacterial actions) and/or recrystallization.

beachrocks. A few exceptions must be noted. Samples for site F (Figs. 2 and 4) are too recent in comparison to the overall tendency. This is probably related to the presence of submerged archeological remains (Desruelles et al., 2004). Samples C21a, C21b and D21a, from sites C and D, look too old compared to their depth. This could be related to an ageing of the dating by some detritics (particularly carbonate clasts and micritic fillings — Desruelles, 2004; Desruelles et al., 2004).

However, when the two end-slabs of a beachrock are dated, the front-end slab is younger than the back-end one. This chronology is in compliance with the model of beachrock formation.

Over the entire Turkish coastline 3 beachrock bands are observed, whose layout sometimes varies significantly from site to site (Fig. 9). 4 areas can be distinguished (Fig. 3):

- the area I corresponds to the Finike Bay. Only one generation can be observed; it corresponds to a fossil intertidal zone between −3.5 m and −4.5 m.
- the area II stretches east of the Finike peninsula to Çimtur. It comprises sites 2, 3, 4, 5 and 6. In this area, 2 to 3 former submerged intertidal zones are reconstructed: the first one between 0 m and −1 m, the second between −1.2 m and −2.3 m and the third between −2.2 m and −3.2 m.
- the area III stretches from Incekum to Karataş–Osmaniye Fault Zone. It comprises sites 10, 11 and 13. It is the only area where the central axes of the reconstructed intertidal zones are emerged. This layer can be compared to the first intertidal zone reconstructed in areas II and IV. On site 10, this level is added to another fossil intertidal zone, reconstructed between −2.2 m and −3.3 m.
- the area IV covers İskenderun Bay down to Arsuz and comprises sites 15 and 16. Two generations, corresponding to two fossil intertidal zones are distinguished: the first one between +0.3 m and −0.8 m and the second one between −0.7 m and −1.7 m. No beachrocks are observed south of Arsuz till the Syrian border.

In Turkey, only 2 sites could be dated (3 and 16). They show ages coherent with the oldest ages obtained from the deepest beachrocks (Fig. 10). In Kemer (Figs. 3 and 5B), the sample collected at −2.2 m on the beachrock located between −1.4 m and −2.8 m is dated at 659–502 BC. As for the beachrock closest to the surface

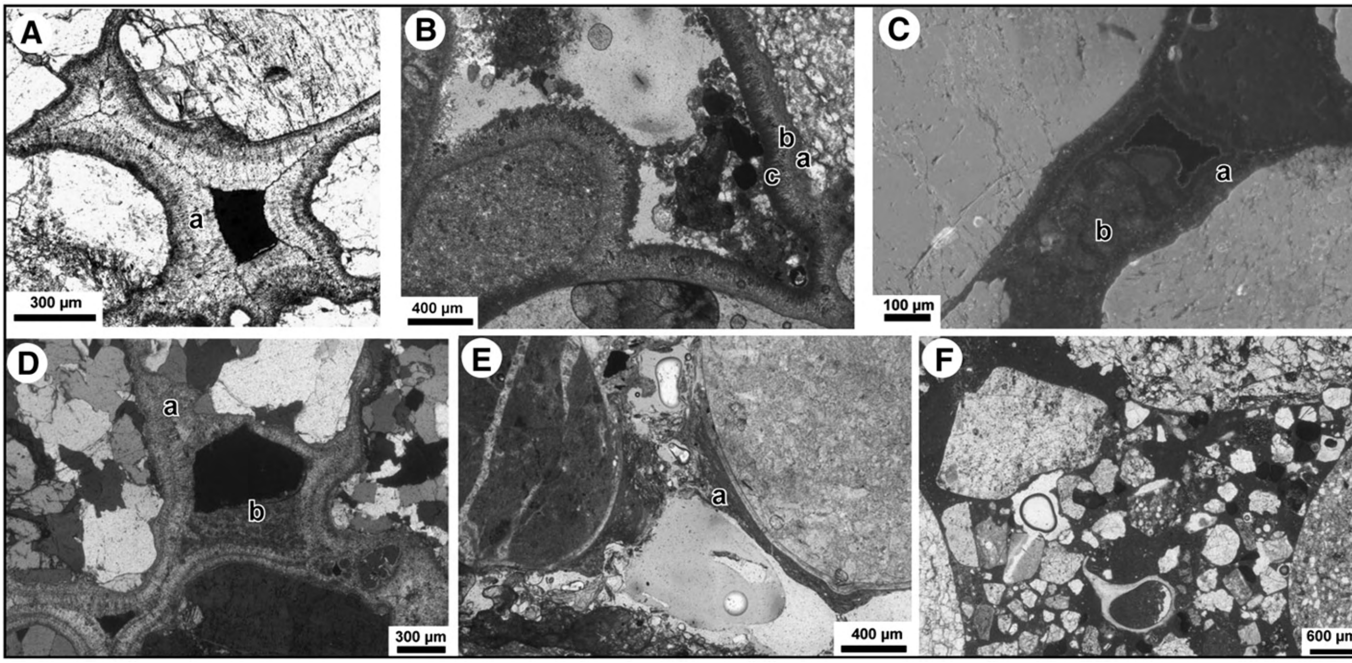


Fig. 8. Cements and detrical elements identified in the beachrock samples A: thin section B21 seen with plane-polarized light. Isopachous cement of radiaxial fibrous HMC (a); B: thin section Ke4 seen with cross-polarized light. Small isopachous fringe of calcite cement (a), aragonite cement (b) and micritic mud (c); C: thin section B 21 seen with cathodoluminescence. Isopachous cement of radiaxial fibrous calcite (a) and peloidal HMC cement (b); D: thin section B21 seen with cross-polarized light. Isopachous cement of radiaxial fibrous calcite (a) and geotropic deposit of internal sediment containing pellets (b); E: thin section DA4 seen with plane-polarized light. Centrifugal internal sediment (a) containing sometimes microclasts; F: thin section S6 seen with cross-polarized light. Micritic mud rich in carbonate microclasts and bioclasts.

(between 0 m and −0.8 m), the obtained dating on the back-end extremity (435–534 AD) is older than the one obtained at the other end (669–733 AD). In Gözcüler, the sample G1, collected on the back-end extremity (439–537 AD) (Fig. 5F) is older than G2 collected at the other end (606–667 AD).

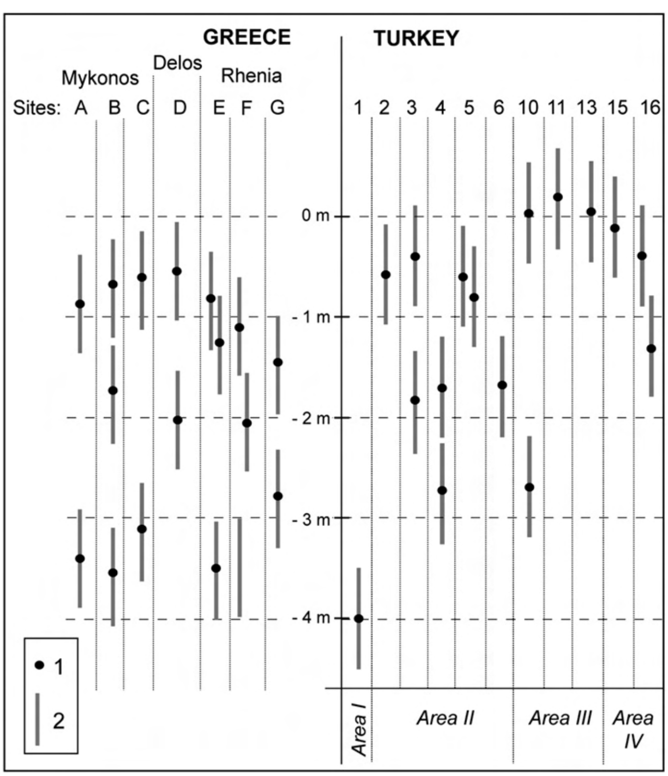


Fig. 9. Depth of intertidal zones reconstructed in Mykonos–Delos–Rhenia and in southern Turkey using the beachrocks 1: depth of the reconstructed intertidal zone; 2: middle of the intertidal zone reconstructed using the lower and the upper limits of the beachrock line.

5. Discussion

5.1. Relative sea level variations in Mykonos–Delos–Rhenia

The location of beachrock bands indicates 3 generations, corresponding to 3 phases of relative sea level stability with unknown durations separated by periods of acceleration in the rise of sea level (Fig. 11):

- the first phase of relative stability, around 1000 AD, corresponds to a sea level at −1 m (±0.5 m),
- the second phase of relative stability, around 400 BC, has a sea level at −2.5 m (±0.5 m),
- the third phase of relative stability, around 2000 BC, has a sea level at −3.6 m (±0.5 m) compared to present sea level.

For the first and third phases, the mean height values and ages of the reconstructed intertidal zones have been retained. For the second phase, this mean value was obtained from information on the archeological remains of Delos and Rhenia (Dalongeville et al., 2007; Desruelles et al., 2004; Desruelles et al., 2007).

Our datings, although probably slightly “over-estimated”, indicate an evolution different from the Lambeck and Purcell's (2005) model: the range of the relative Holocene sea level rise (about 3.6 m since 4000 years) is higher than the value proposed by this glacio-hydro-isostatic model (Fig. 12), which does not take into account the effects of local tectonics. The model indicates sea levels at −1 m in 2000 BP whereas our results show that it took 1000 years for such a rise to occur. The difference between those results is caused by the influence of the regional subsidence over the relative sea level variations in Mykonos–Delos–Rhenia. On the other hand, our results are in agreement with the ones provided by Flemming et al., (1971) established from the inventory of submerged archeological markers in the Aegean Sea.

		Sample's code	Laboratory code	Depth of beachrock (lower limit-upper limit)	Depth of sample	^{14}C Yr BP	Calibrated age	δ13C (‰)
MYKONOS (Greece)	Site A: Kalafati	A11 (total sample)	Lyon-2050 (OxA)	0.5 m - 1.3 m	1 m	1330 ± 35	**1032-1122 AD**	+ 3.67
		A 22 (total sample)	Lyon-2051(OxA)	3 m - 3.8 m	3.8 m	3185 ± 45	**1112-964 BC**	+ 3.7
	Site B: Agh. Ioannis	B 11 (total sample)	Lyon-2052(OxA)	0.7 m - 1.25 m	1.25 m	1775 ± 40	**596-672 AD**	+ 3.51
		B 21 (total sample	Lyon-2053(OxA)	1.45 m - 2.2 m	1.45 m	2465 ± 45	**235-82 BC**	+ 3.15
		B 22 (total sample)	Lyon-2058(OxA)	1.45 m - 2.2 m	2.2 m	2265 ± 30	**36-123 AD**	+ 2.76
		B 31 (total sample)	Lyon-2059(OxA)	3.5 m - 3.7 m	3.5 m	4860 ± 35	**3309-3165 BC**	+ 3.42
	Site C: Agh. Sostis	C 12 (total sample)	Lyon-2074 (Poz)	0 m - 1.3 m	1.3 m	970 ± 35	**1349-1423 AD**	+ 3.35
		C 21a (total sample)	Lyon-2075 (Poz)	2.8 m - 3.3 m	3 m	1750 ± 25	**628-680 AD**	+ 3.06
		C 21b (total sample)	Lyon-2076 (Poz)	2.8 m - 3.3 m	2.8 m	3745 ± 30	**1770-1665 BC**	+ 2.72
DELOS (Greece)	Site D: Fourni	D 12 (total sample)	Lyon-2079 (Poz)	0 m - 1.2 m	1.2 m	440 ± 25		+ 2.33
		D 21a (total sample)	Lyon-2080 (Poz)	1.7 m - 2.4 m	1.8 m	1700 ± 30	**661-720 AD**	+ 2.91
		D 21b (total sample)	Lyon-2081 (Poz)	1.7 m - 2.4 m	1.7 m	2545 ± 25	**330-228 BC**	+ 1.71
RHENIA (Greece)	Site E: Kormou Ammos	E 11 (total sample)	Lyon-2082 (Poz)	0.6 m - 1.1 m	0.6 m	1300 ± 25	**1058-1140 AD**	+ 2.8
		E 22 (total sample)	Lyon-2083 (Poz)	1.1 m - 1.5 m	1.5 m	2175 ± 30	**137-229 AD**	+ 3.02
		E 32 (total sample)	Lyon-2084 (Poz)	3.5 m - 3.6 m	3.6 m	3815 ± 30	**1867-1764 BC**	+ 2.65
	Site F: Steni	F 11 (total sample)	Lyon-2085 (Poz)	0.5 m - 1.7 m	1 m	1610 ± 30	**723-811 AD**	+ 3.2
		F 12 (total sample)	Lyon-2086 (Poz)	2 m - 2.1 m	2.1 m	1380 ± 30	**991-1055 AD**	+ 2.82
		F 21 (total sample)	Lyon-2087 (Poz)	3.4 m - 3.6 m	3.4 m	2595 ± 30	**380-294 BC**	+ 2.94
	Site G: Lazaret	G 12 (total sample)	Lyon-2088 (Poz)	1.4 m - 1.6 m	2 m	1635 ± 25	**710-780 AD**	+ 4.77
		G 22 (total sample)	Lyon-2089 (Poz)	2.6 m - 3.2 m	3.2 m	2775 ± 30	**650-487 BC**	+ 1.66
TURKEY	Site 1: Kemer	Ke 2 (cement)	Poz-14349	0 m - 0.8 m	0.8 m	1685 ± 30 BP	**669-733 AD**	- 4.1
		Ke 3 (internal sediment)	Poz-14351	0 m - 0.8 m	0 m	1925 ± 35 BP	**435-534 AD**	+ 4.2
		Ke 4 (cement)	Poz-14356	1.5 m - 2.2 m	2.2 m	2785 ± 30 BP	**659-502 BC**	+ 11.1
	Site 15: Gözcüler	G 1 (cement)	Poz-17927	0 m - 0.2 m	0 m	1774 ± 29 BP	**606-667 AD**	+ 2.5
		G 2 (cement)	Poz-17929	0 m - 0.2 m	0.2 m	1920 ± 35 BP	**439-537 AD**	+ 0.4

Fig. 10. ^{14}C ages of beachrock samples collected in Mykonos–Delos–Rhenia and in southern Turkey.

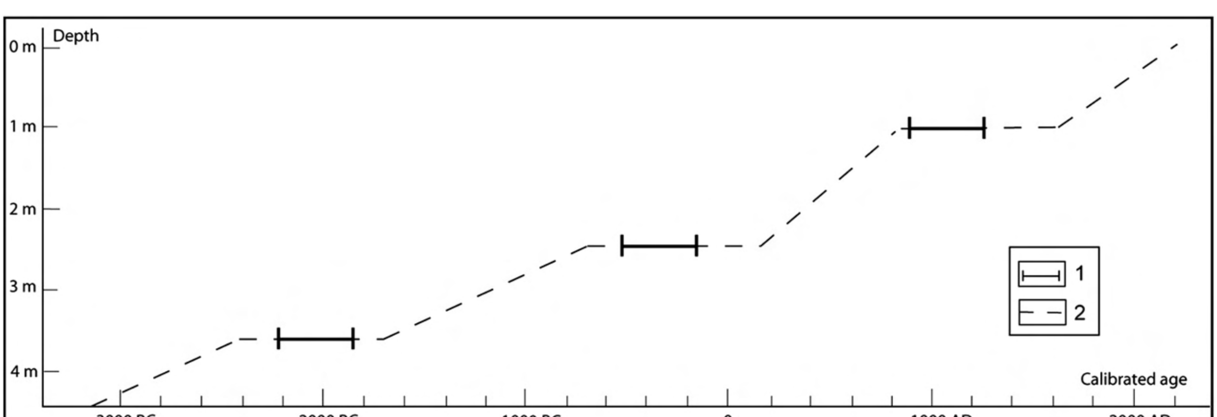


Fig. 11. Periods of relative sea level stabilisation and elevation in Mykonos–Delos–Rhenia since 5000 BP 1: period of relative sea level stabilisation attested by the beachrocks outcrops; 2: probable evolution of the relative sea level.

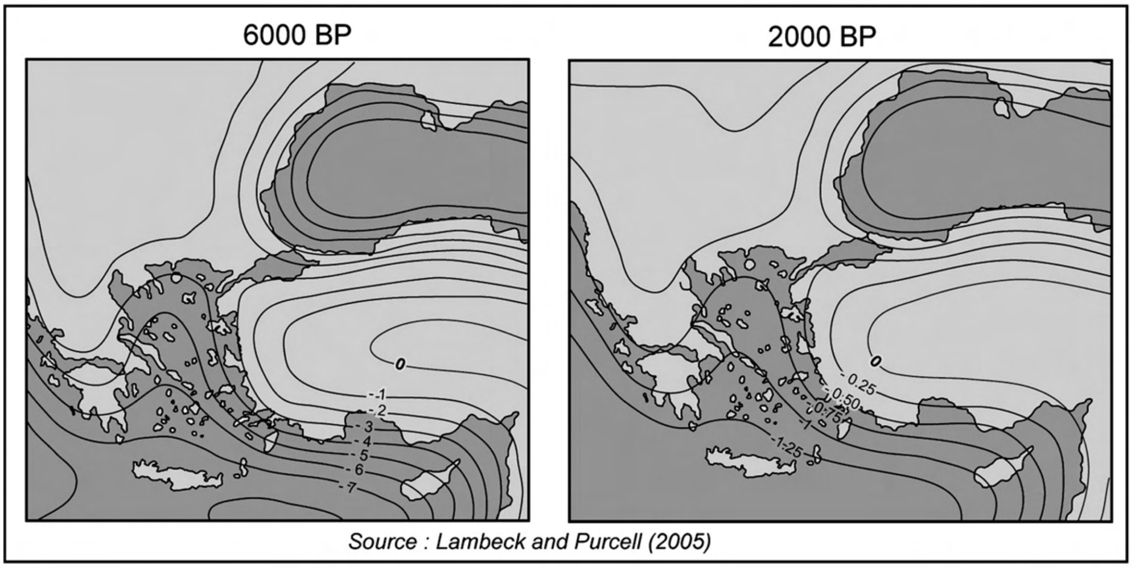


Fig. 12. Predicted sea level changes according to Lambeck and Purcell's (2005) model.

5.2. Relative sea level variations in southern Turkey

In area I the beachrock between −3.5 m and −4.5 m is deeper than the Roman archeological remains located at −1.5 m (Fouache et al., 1999, 2005b) in Andriake (Fig. 3). That beachrock may result from a phase of relative sea level stability older than the Roman period. As an alternative hypothesis we relate the formation of these beachrocks to the same period. Their actual depth might be related to the rapid submersion of the Finike Bay that is mainly covered by unconsolidated sediments contrary to the Roman foundations built on hard rocks.

The placement of the reconstructed intertidal zones in area II is comparable to the one in Mykonos–Delos–Rhenia. These two areas have gone through 2 or 3 sea level stability phases. In Kemer, sample Ke4's dating (Fig. 10) permits the reconstruction of a mean sea level located between −1.5 m and −2.2 m during the 6th and 7th centuries BC. The dating of samples Ke2 and Ke3's permits the reconstruction of another sea level between 0 m and 0.8 m during the 5th and 7th centuries AD. In this area, Lambeck and Purcell's (2005) glacio-hydro-isostatic model indicates a smaller amount of sea level rise (Fig. 12). It predicts a sea level between −0.25 m and −0.5 m 2000 years ago. A sea level rise of about 0.37 m can be deducted over 2000 years, whereas our results show that a similar amount of rise (ca. 0.4 m) has taken place over 1400 years. The comparison of our results, even though slightly “over-estimated”, with this model brings forth the influence of tectonics in the vertical displacements in this coastal region. This influence appears more important on the submersion of the deepest beachrocks.

In area III, the present sea level appears unchanged since the 12th century AD. In fact, the Seldjoukid boatsheds in Alanya (Fouache et al., 1999, 2005b) (Fig. 3) are at the same level as the notch that is developing at the foot of the cliff. Their utilization appears to be adapted to a sea level comparable to the present one.

We have also identified a corrosion bench emerged at +0.5 m above the present mean sea level in Incekum (Fig. 3). Fossil vermetid tubes collected at this height and their radiocarbon dating has permitted the reconstruction of an ancient sea level at 19 BC–200 AD (sample Lyon-2801Poz). This sea level has shaped the corrosion bench that has later been uplifted by at least +0.5 m, probably before the 12th century AD. Kelletat and Kayan (1983) also reported similar vermetids (*Dendropoma petraeum*) at +0.5 m, developed on bio-erosional benches in Fığla Burnu 1 km to the east of Incekum. They presented several ^{14}C dates obtained from stomatolitic algaes (*Neogoniolithon notarisii*) ranging between 1815±35 years BP and 1545±45 years BP. Our result from Incekum is in accordance with their dates.

The presence of emerged beachrocks at similar heights on sites 10, 11, 13 and 14 (Taillefer, 1964) permits to infer that this uplift has affected most of the area III. Before this tectonic coastal uplift, tectonic in origin, relative sea level stability has provoked the formation of a band of beachrock located today between −2.2 m and −3.3 m. This former sea level could not be dated, because of the lack of suitable cement in the beachrock.

The area IV has gone through at least 2 relative sea level stability phases. The study of samples from site 15, collected on the line closest to the surface, permits the reconstruction of a sea level between 0 m and −0.5 m during the 4th to 7th century AD. This result is very similar to the proposed reconstruction in area II. As for area I, the proposed sea level rise is higher than the one indicated by the Lambeck and Purcell's (2005) model. From this model, the sea level 2000 years ago was similar to the present one. Area IV then appears to have been affected by a slight subsidence, tectonic in origin.

5.3. Regional synthesis

The reconstructed relative sea levels in areas II and IV of the Turkish coast can be compared to the ones reconstructed in Mykonos–Delos–Rhenia:

- area II has seen a phase of relative sea level stability between −1.5 m and −2.2 m coeval to the 6th and 7th centuries BC, whereas a deeper sea level (−2.5 m) was restored for a more recent age (around the 4th century BC) in the Cyclades.
- areas II and IV have seen a phase of relative sea level stability between 0 m and −0.8 m coeval to the 4th to 7th century AD. A deeper sea level (−1 m) is also restored for a more recent age (around the 10th century AD) in the Cyclades.

This comparison indicates that subsidence is greater in Mykonos–Delos–Rhenia than in areas II and IV of the Turkish coast, at least since 2800 years. This corresponds to the comparative results of Lambeck and Purcell's (2005) model. In Mykonos–Delos–Rhenia, a relative sea level rise of 1 m was observed in 1000 years instead of 2000 years as predicted by the model. In areas II and IV, a rise of about 0.4 m occurred over 1400 years instead of 2000 years as indicated by the model.

The influence of tectonics is greater in the other areas studied in southern Turkey. Area I has undergone an important subsidence, probably before the Roman period. The sea level reconstructed at about −1.5 m for this period (2nd century BC–6th century AD) corresponds well to sea levels reconstructed in area II. Areas I and II would then have seen a comparable evolution, at least since the Roman period. The presence of deeper Roman foundations, down to −3 m to −4 m, west of Andriake (in Demre and in Kale, particularly) permits to bring the limit of area I to the west, near Andriake (Fig. 3).

Especially the eastern part of area III was uplifted by about +0.5 m, probably before the 12th century AD. The Incekum corrosion bench can be compared to corrosion benches frequently observed, at about +0.6 m, in Syria and Lebanon (Morhange et al., 2006), where they were dated to 1900–2000 BP (Sanlaville, 1977). It can also be related to the visible +0.8 m notch south of area IV (around the Orontes delta, Samandağ), dated to 1700–2800 BP (Pirazzoli, 2005). These corrosion forms may have been shaped before a co-seismic uplift, during the “Early Byzantine Paroxysm” (Pirazzoli et al., 1996; Pirazzoli, 2005), dated to 1750–2000 BP. Several studies indeed indicate a clustering of earthquakes in the eastern Mediterranean between 4th and 6th century AD (Stiros, 2001).

Such regional comparisons show that tectonics played a determining role in the Holocene relative sea level evolution in our study areas. Subsidence, with amplitude varying in time and space, accounts for the presence of submerged beachrock bands in all studied areas. This amplitude explains the difference in beachrock depths (the case of area I in Turkey) between these regions. Uplifts are the cause of the partial emersion of the beachrocks in area III in Turkey. Their formation probably correlates to the first generations of areas II and IV.

Part of these differential movements appears to have been caused by a tectonic event of regional extent, the “Early Byzantine Paroxysm”. Numerous studies of the emerged corrosion forms in the eastern Mediterranean tend to prove it (Pirazzoli, 2005). Rapid rises of relative sea level, as in the subsiding regions on the Turkish coast (area II) and the centre of the Cyclades, might be related to this regional event.

6. Conclusions

The comparative study of beachrocks from Mykonos–Delos–Rhenia and southern Turkey has confirmed the difficulty to date the markers of ancient sea levels in geological contexts where calcareous rocks dominate. Because of the dominance of this lithology intertidal diagenetic cements had to be manually extracted from the beachrocks and unfortunately with a limited success. Therefore only 2 areas could be dated from numerous samples collected along the Turkish coast. This study has permitted, by cross-comparing the positioning of several beachrock bands with dates and indications obtained from archeological remains and corrosion benches, to bring forth the role of tectonics in relative sea level variations in eastern Mediterranean.

This study establishes similar points in the evolution of these shorelines, points which have been submerged for at least 4000 years. Periods of slower rise or relative stability of sea level have followed one another. They have shaped corrosion forms at the foot of cliffs and, when they were associated to sufficient sedimentary inputs, allowed the formation of beachrocks in sandy shores. These periods have been interrupted by phases of acceleration of the relative sea level rise, often caused by vertical tectonic movements. These movements have also displaced existing beachrock bands. This explains the differences in the height of beachrock positions observed between four areas in the southern Turkish coast.

The chronological comparison of the phases of relative stability and acceleration of the sea level rise brings forth the role of local tectonics, in relation to the regional geodynamics. On the Turkish coast from Andriake to Arsuz, a first phase of relative sea level stability may have permitted the formation of the beachrock band located about −3 m (±0.5 m). A tectonic subsidence, before the Roman period, may have displaced the beachrocks at depth in area I. A second phase of relative sea level stability at about 2.5 m (±0.5 m) around the 4th century BC may have favored the formation of another generation of beachrock. Later, these beachrocks do not appear to have been strongly displaced by vertical movements in areas II and III. On the contrary, one may wonder if such movements might have obstructed their formation in area I. A third phase of relative sea level stability at about −0.4 m (±0.5 m) around the 6th century AD may be the origin of corrosion forms and of a beachrock generation. In area III, as in other eastern Mediterranean regions, the “Early-Byzantine Paroxysm” (Pirazzoli, 2005) may have caused uplift, of about +0.5 m, of former sea level markers. The sea level would be stable or in slight rise since the 12th century AD.

In Mykonos–Delos–Rhenia, where the altitudinal placement of beachrock resembles the one in areas II and IV of the Turkish coast, tectonic subsidence has intensified the rise of relative sea level of eustatic or glacio-hydro-isostatic origin. In fact, the total range of the rise of relative sea level is greater there than in the first 2 areas in Turkey.

Although the tectonic context is different between the study areas in Greece and Turkey, strong similarities have been observed in the Holocene relative sea level evolution. Local tectonic movements of variable intensity might explain the observed differences between these areas. Therefore the use of the beachrocks as a potential paleo-sea level indicator might be an important tool in the understanding of the tectonic development of the region since mid-Holocene.

Acknowledgements

This study was carried out in Mykonos–Delos–Rhenia thanks to the financial support of the French School of Athens (*Water in Delos* program directed by M. Brunet) and in southern Turkey thanks to the support of the French Ministry of Foreign Affairs (*MALRHO* program directed by R. Dalongeville and E. Fouache) and of *TÜBITAK*, the Scientific and Technological Research Council of Turkey (Project n 104Y261). Thin sections and microscopic studies were made in the laboratory UMR 8157 *Géosystèmes* (Université des Sciences et Technologies — CNRS, Villeneuve d'Ascq, France). The authors warmly thank Dr. Marc Massault (Université Paris-Sud, UMR 8148 *IDES*, Orsay, France), for analysis and dating of fresh and marine waters from southern Turkey, Dr. Cecile Fouache-Loire, Dr. Nikos Palyvos and Prof. Dr. Morgan De Dapper for the English improvement. We also thank the anonymous reviewers for their comments and suggestions to improve this paper.

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