

Electrical resistivity tomography mapping of beachrocks: application to the island of Thassos (N. Greece)

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Abstract Electrical resistivity tomography (ERT) technique is widely used in mapping subsurface electrical properties. In this study, ERT was used to map a beachrock outcrop, extended both inland, under beach sediments, and seawards, on and under seafloor sediments. Mapping of beachrock is considered important because it can help evaluate the lateral and vertical extend of the formation. Fast and reliable mapping of beachrocks may contribute in several applications like engineering and construction, coastal management, recreational reformation as well as scientific approaches like coastal evolution research, and palaeo-environmental studies. The outcome of the survey was the mapping of the formation with centimeter precision, especially towards the sea. Special processing was applied to the data in order to constrain the inversion procedure to include the known sea water layer.

Keywords Beachrock · ERT · Greece · Mapping · Geophysics

Introduction

The rapid cementation of beach sediments in the intertidal zone leads to the formation of characteristic syndimentary lithified structures termed as beachrocks (Rey et al. 2004). Beachrock is a hard, rocky, coastal formation, lithified in the intertidal zone by carbonate cements. The importance of beachrocks can be rendered in three main topics: their impacts on coastal evolution (Cooper 1991), their role as sea-level indicators (Hopley 1986; Caldas et al. 2006) and the information they contain regarding the coastal processes of cementation and palaeo-environmental evolution (Longman 1980; Vieira and De Ros 2006).

Several impacts on coastal evolution result from the presence of beachrocks. These include the reduction of littoral sediment volume, the change in coastal morphology and the change in preservation potential of shoreline facies (Cooper 1991).

On retreating coasts, outcrops of beachrock may be evident offshore where they may act as a barrier against coastal erosion. Beachrock presence can also induce sediment deficiency in a beach and out-synch its wave regime.

Because beachrock is lithified within the intertidal zone and because it commonly forms in a few years, its potential as an indicator of past sea level is important (Turner 1999). A considerable amount of studies have taken place in order to examine the setting of the beachrocks' formation and the reliability of the information from the cement, like dating, stable isotope analysis, etc. (Friedman 2004). Today, significant development in this subject has been achieved and the numerous outcrops of beachrocks around the world can be used for scientific purposes.

A further important issue which is related to the formation of beachrocks has to do with the coastal management and the outcrops' impact on tourist industry.

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Although beachrock can prevent extended beach erosion and recession, its exposure causes several socioeconomic impacts, as a result of the alteration of a beach from sandy to rocky. This problem is multiplied along the Mediterranean coastline, where tourist industry is the main financial source. The recorded sea-level rise of recent years may cause further exposure of buried beachrock outcrops, which in turn could lead to a decline of many coastal areas.

Mapping of beachrock is considered important because it can help evaluate the lateral and vertical extend of the formation, help better understand its formation mechanism and aid subsequent modeling. Furthermore, mapping can be used directly to plan engineering works related to removing beachrock, founding in coastal areas or beach reform for recreational use.

Given the need for beachrock mapping, geophysical techniques can be considered an option. The different degree of cementation and thus porosity of the beachrock compared with that of the typical coastal unconsolidated sediments suggest that beachrock is potentially distinguishable to other sedimentary formations producing higher resistivity signatures.

The electrical resistivity tomography (ERT) technique (Dahlin 1996, 2001) is widely used in mapping subsurface resistivity in both two and three dimensions. The advent of automated resistivity meters combined with the developments of advanced interpretation (inversion) algorithms (Loke and Barker 1995, 1996) allow the rapid acquisition of accurate images of the subsurface resistivity and render ERT one of the most important near surface geophysical techniques. Simple modification of instrumentation allow the application of ERT into addressing environmental and engineering problems related to marine environments as several recent applications suggest (Zhou et al. 2000; Drahor et al. 2006; Yang et al. 2002; De Souza and Sampaio 2001).

In this paper, a case study is presented; where the ERT technique was used successfully, for the first time in literature, to map the beachrock extend in a coast of the island of Thassos (N. Greece). Given that beachrock extends both inland, under beach sediments and seawards, on sea-bottom sediments, part of the individual ERT measured lines was placed on land using standard spike electrodes. Special processing was applied to the data in order to constrain the inversion procedure to include the known sea water layer.

In the following sections, some general introductory material concerning the beachrock as well as the particular setting in the area of study are presented. Further details regarding the ERT data collection and data processing procedure that was followed in this work are given. The obtained resistivity images were subsequently interpreted and the results are compared with the existing information regarding the mapped beachrock.

Beachrock formation and position

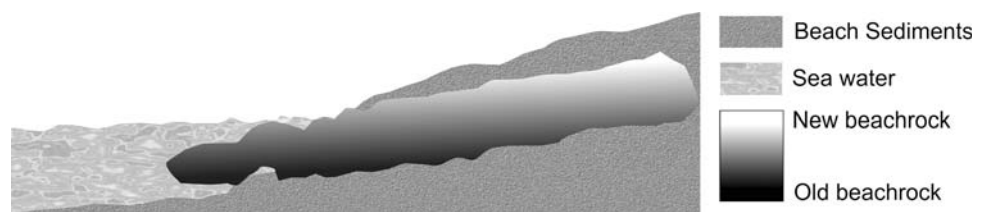
Beachrock units form under a thin cover of sediment and generally overlie unconsolidated sand. They typically consist of multiple units, representing multiple episodes of cementation and exposure. The mineralogy of beachrocks is mainly high-magnesium calcite or aragonite (Stoddart and Cann 1965). The main processes involved in the cementation are: supersaturation with CaCO_3 through direct evaporation of seawater (Ginsburg 1953; Stoddart and Cann 1965), groundwater CO_2 degassing in the vadose zone (Hanor 1978), mixing of marine and meteoric water fluxes (Schmalz 1971) and precipitation of micritic calcium carbonate as a byproduct of microbiological activity (Neumeier 1999; Taylor and Illing 1969).

Beachrocks are located along the coastline in a parallel term and they are usually inside the swash zone (Amieux et al. 1989). They are generally separated in several levels that may correspond to different generations of beachrock cementation. Thus, the older zones are located in the outer part of the formation when the younger ones are on the side of the beach, possibly under unconsolidated sand. They also seem to have a general inclination to the sea ($5\text{--}15^\circ$). There are several appearances of beachrock formations which are characterized by multiple cracks and gaps. The result of this fact is an interruptible formation of separated blocks of beachrock, which may be of the same formation (Turner 1999).

The length of beachrocks varies from meters to kilometers, its width can reach up to 300 m and its height starts from 30 cm and reaches 3 m, depending on the tidal range.

Following the process of coastal erosion, beachrock formation may be uncovered (Fig. 1). Coastal erosion may be the result of sea level rise or deficit in sedimentary equilibrium. One way or another, unconsolidated sand that

Fig. 1 Typical position of exposed beachrock. Different colors of the formation indicate different phases

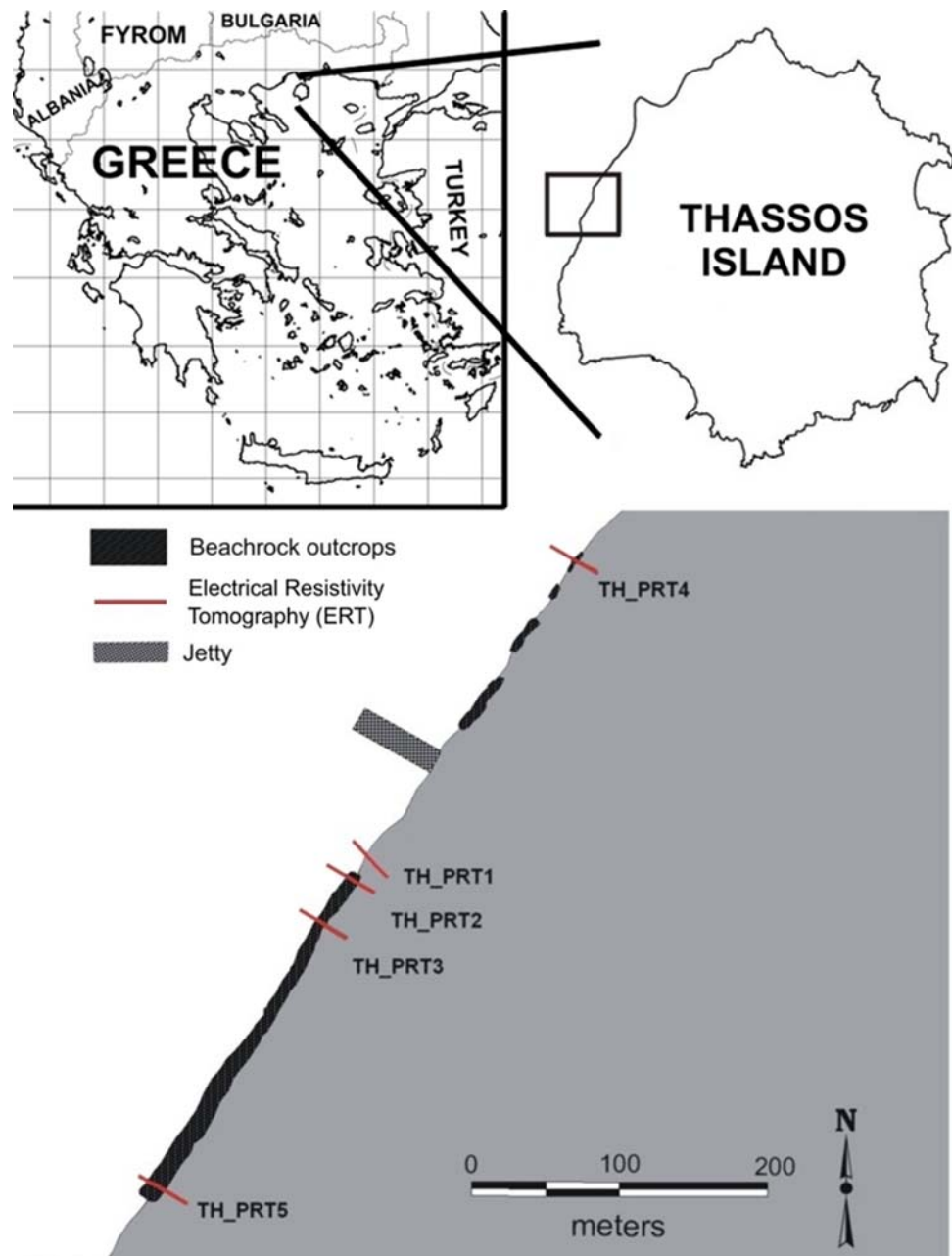


covers the beachrock draws away and the formation is revealed. If the process of cementation continues, new beachrock would be formed in a new position in the intertidal zone. Successive phases of sea level change may result in sequential zones of beachrock.

As beachrock outcrops may be uncovered in different locations inside the coastal zone (e.g., in the surf-zone, inland, offshore), it has been usually impossible to map the outcrops with geographical accuracy and especially in a three-dimensional aspect. Moreover, it has not been possible to evaluate the depth of the beachrock formation when it is covered by the coastal sediments or when it dips under the sea-bottom sediments.

The resistivity values of the beachrock are related to the material and the pore-water of the formation. Beachrock is composed of beach sand, skeletal debris and some pebbles, similar to the materials of the beach where it is located. Clay and mud materials scarcely take part in the formation. The pore-percentage of the beachrock is conditioned by the amount of CO_3^{2-} precipitation. Thus, the age of the formation and intensity of CO_3^{2-} precipitation determines the pore volume, which is directly connected with the amount of pore-water of the beachrock. Pore-water may be a mix of sea and fresh water with different participation each, depending on the conditions during the formation of the beachrock (Stoddart and Cann 1965).

Fig. 2 Study area and position of tomographies



Area of study

The case study presented in this work was conducted in Thassos Island (N. Greece), which is located in Northern Aegean sea. The study area is located at the west coast of the island, between Skala Sotira and Skala Kallirachis villages (Fig. 2). The area is characterized by the oil drilling industry, the commercial port of Prinos and the extended forest fires during the two last decades.

The prevalent rocks in the area are gneiss and marbles. The basins that end up to the study area include Holocene sediments, Miocene marbles, marbles and gneiss alternations and Maries gneiss (Mountrakis 1985).

Two local seasonal streams end up to the study beach, with a total length of 26.48 km, which cross carbonate rocks and transfer similar sediments to the coast.

The area of Thassos is characterized by coastal—marine climatic type, transitional to continental climate (high summer temperature, storms), due to the slight distance of the island from the coasts of Macedonia at the north. The average annual temperature is approx. 15.8°C, the average annual precipitation is approximately 770 mm and the prevalent wind direction is NW for the western part of the island (study area).

The exposed beachrock in the area has been studied by both underwater and ground observation. It is located in the swash zone and dips gently seawards (mean 5°), following the arrangement of the beach. The main body of the formation has a total length of 700 m and exposure width 2–10 m. The height of the beachrock at its underwater face reaches up to 70 cm (Fig. 3). This face is quite steep and has been undercut in many places, resulting in cracking, collapsing, even in displacement of blocks of the formation.

A quite interesting fact in the study area is the breaking and depleting of a part of the beachrock a decade ago by

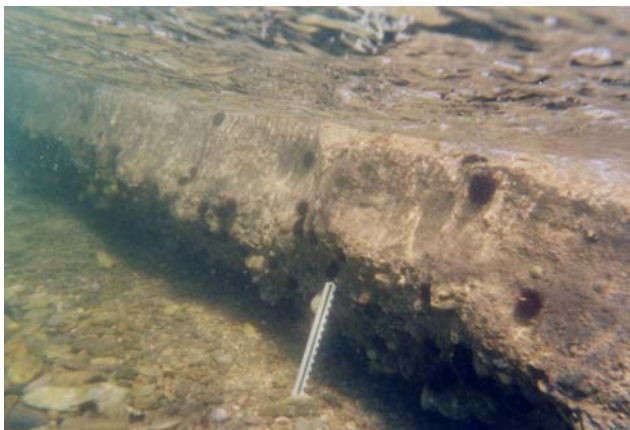


Fig. 3 Underwater image of beachrock front. Scalebars 30 cm

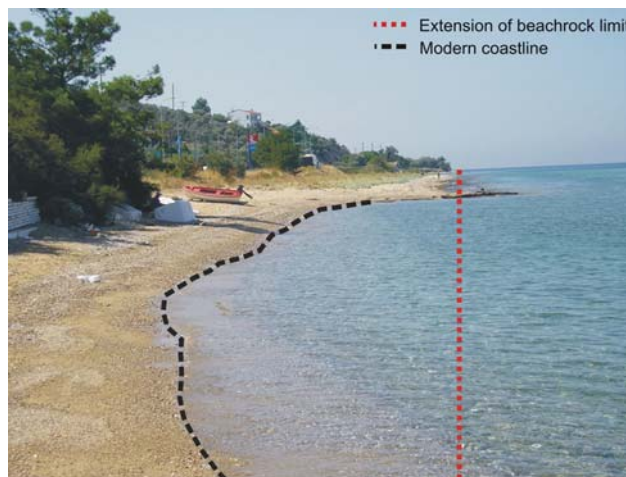


Fig. 4 Coastal erosion due to beachrock removal

local citizens. This act had an immediate impact on the coastal equilibrium. Beach sand in the specific part of the coast drew away rapidly (Fig. 4), while the rest of the coast remained in balance state, behind the protection of the beachrock body.

Methods

Electrical resistivity tomography

The application of the ERT technique aims to determine the electrical properties of the ground (Dahlin 2001). ERT can be considered as the development of the standard geoelectrical method. The advent of fully automated measuring instruments with electrode multiplexing ability in combination to the development of advanced interpretation algorithms (Loke and Barker 1996), allows the collection of a large amount of data and the production of electrical resistivity images of the subsurface.

Electrical resistivity tomography technique is increasingly used to map underwater formations (Kwon et al. 2005; Nyquist et al. 2008) as an aid in solving environmental and engineering problems. When compared with other geophysical techniques used in water surveys (seismic, GPR) resistivity is a relatively low resolution technique but on the other hand it is robust, low-cost, can operate in highly conductive areas and most importantly the interpreted images are a realistic representation of the subsurface resistivity, easily understood by other geoscientists. The advent of multichannel resistivity meters allows the rapid resistivity measurement collection using towed arrays either floating or placed at the bottom of the sea.

Data collection and interpretation

The main purpose of this study is to apply electrical resistivity geophysical method for mapping beachrock outcrops. The present study employed fixed ERT lines in a mixed environment, i.e., using both land and water electrodes. Part of the measured ERT lines was laid on the seaside using standard stainless steel spike electrodes while the remaining part of the array consisted of floating electrodes (Fig. 5a). In every case, the sea segment of the cable was anchored to a fixed point to keep it relatively steady and render measurements less noisy due to sea waves. Further, special care was given to collect measurements at times when sea was relatively calm (typically early morning or late afternoon hours).

Inter-electrode spacing was set to 1 m and every measured line had various lengths depending on the available land space, yet all sea cable segments had a length of 23 m (24 electrodes). Five practically parallel ERT sections were applied, focusing in positions where beachrocks occurred with morphological variations. The position of the cable was identical in all five tomographies, i.e., 24 electrodes

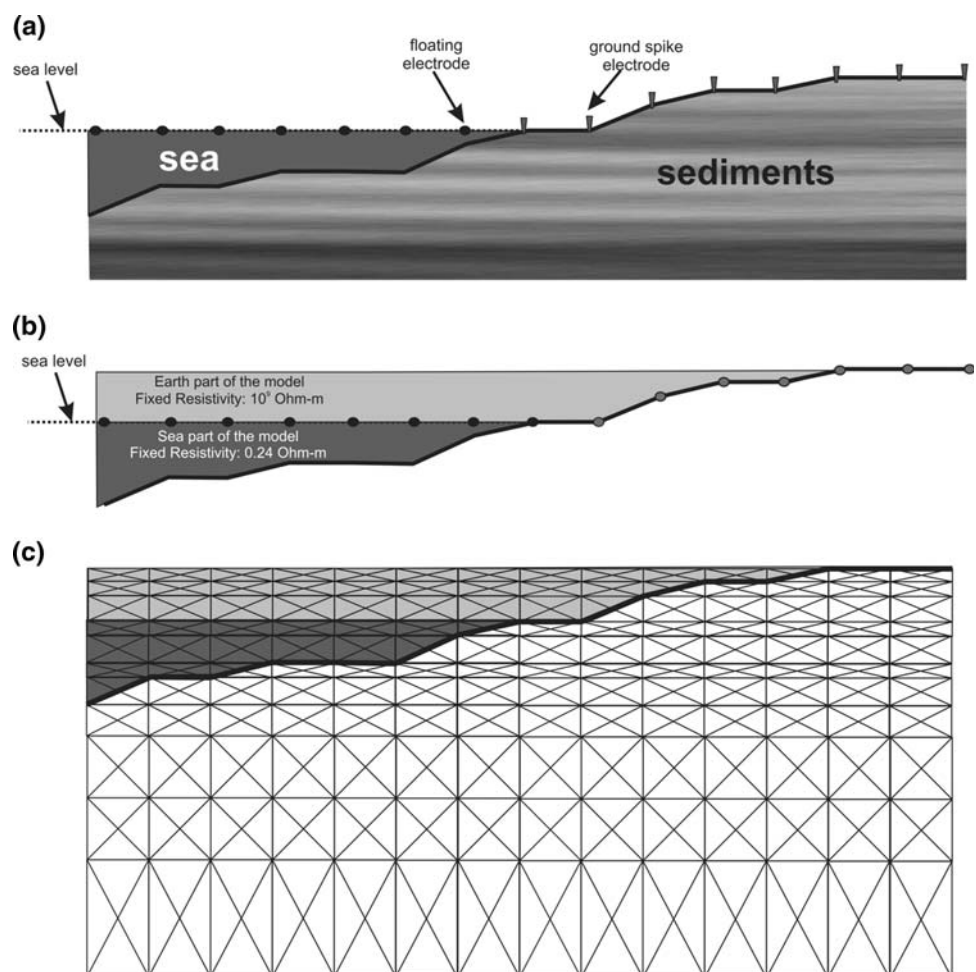
were floating on the sea surface (with floaters) and the rest were on the surface of the coastal sediments.

Data were collected using the Wenner–Schlumberger array since this array has adequate signal/noise ratio, an important parameter in low resistivity environments, while it provides adequate resolution (Ward 1989). Given that the maximum water depth in the measured lines did not exceed the 1.6 m, the Iris Instruments Syscal-Junior resistivity meter was used, with a 48-channel multiplexing unit. The inserted current of 1.2 A, which is the maximum that the instrument can produce, proved adequate and provided data of good repeatability having a mean standard deviation of less than 1%.

Further, given the mixed (land, sea) nature of the measuring mode and the fact that the seaside had a topography relief; both water depth and elevation were recorded for sea and land electrodes, respectively.

All measured ERT sections were inverted using a 2-D inversion scheme which performs iterative optimization based on a smoothness constrained inversion (Tsourlos 1995). The inversion algorithm uses a 2.5D finite element method (FEM) scheme as the platform for the forward

Fig. 5 **a** ERT measuring mode used in this work, **b** fixed resistivity air and sea part of the model, **c** triangular element FEM mesh consistent to the sea bottom and seaside relief with fixed resistivities



resistivity calculations that uses crossed triangular elements for the FEM grid (Tsourlos et al. 1999).

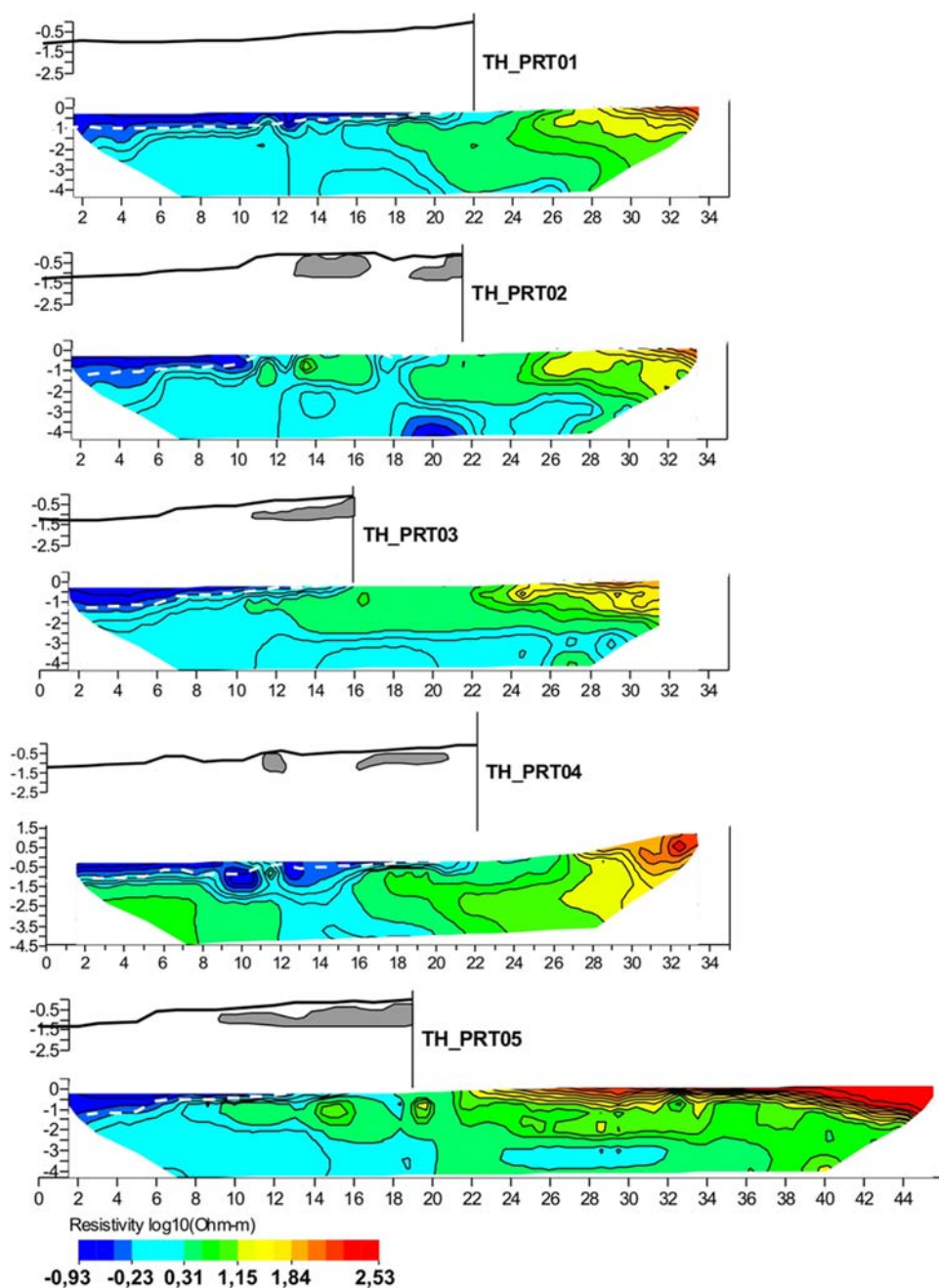
To cope with the particularities of the measured ERT data, the inversion scheme required certain modifications. The air part of the model was introduced by fixing the resistivity to $10^9 \Omega \text{ m}$ to simulate the topographic effect of the land electrodes, while to incorporate the known water layer, a fixed resistivity of $0.24 \Omega \text{ m}$ was assigned to the sea part of the model (Fig. 5b). This involved producing a finite element mesh which is consistent to both the sea bottom and ground relief and on fixing the resistivity of the triangular elements accordingly (Fig. 5c). The inversion

parameters were extended only at the non-fixed resistivity part of the model. Inversions results were produced typically after five to six iterations having average inversion RMS errors of about 2%.

Results

The final inversion results of the ERT sections have been analyzed and interpreted in combination with the field observation of beachrock. In general, all tomographies recorded the formation well, in term of depth and lateral

Fig. 6 Electrical resistivity tomographies after inversion



extend (Fig. 6). This fact is based on the well-known geometry of beachrock formation, which is actually imprinted by the tomographies. On the backshore, the limits of the beachrock are not well defined, as resistivity of the formation is similar to that of the unsaturated coastal sediments. On the other hand, the limit of the beachrock underwater is recorded with precision, both in width and in depth. The method monitors cracks, gaps or anomaly on the surface of the formation, along the measured section. It also shows the limits of the beachrock under the sea bottom and beach sediments.

The graphic scale renders the resistivity of sea water saturated sediments (0.25–1.5 Ω m) dark blue, the beachrock formation and the unsaturated sediments (2–15 Ω m) green–red, respectively. In Fig. 6, every tomography is accompanied by a sketch of the observed form of the beachrock (gray colored) in each position.

In particular, tomographies TH_PRT5 and TH_PRT3 show the beachrock sequent, compact and without any morphological gaps along the sections. Tomography TH_PRT2 depicts the beachrock with a major discontinuity. The depiction agrees totally with the field observation and moreover imprints the discontinuity further deeper in the sea-bottom sediments. In tomography TH_PRT1 the formation seems to be cut off in the swash zone, which is actually a fact as this tomography took place at the position of beachrock removal (Fig. 4). Finally, in tomography TH_PRT4 beachrock is presented broken with a block deposited remotely from the main formation (Fig. 6). In this tomography, a large block of an unknown formation is depicted approximately 12 m from the shoreline. This formation seems to have similar resistivity values with the beachrock. The underwater study of the seafloor could not confirm the presence of such a formation as it seems to be more than 50 cm under seafloor sediments. However, the size and the shape of this block, in addition to its continuance in depth, lead to the speculation that it does not seem to be a beachrock.

Conclusions

Mapping exposed or buried beachrocks can be a handful tool in integrated coastal management, especially in regions with extended and developed coastline. Data of beachrock mapping can be taken into account in coastal engineering projects which aim to upgrade coastal areas and recreational beaches, or like harbor construction, building founding, drilling, etc. Moreover, this kind of data can improve the efficiency of palaeo-environmental studies that refer to coastal environments, such as past sea-level changes, palaeo-environmental and palaeo-climatic conditions (oxygen, temperature, salinity) of coastal areas and

coastline displacements. Finally, beachrock outcrops have been subject of interest in geoarchaeological studies, cave exploration, geomorphological research etc. Hence, the development of a fully-functional method for fast and reliable beachrock mapping could lead to a source of data for thorough coastal research and management.

The applied geophysical survey of ERT in this study mapped the targeted beachrocks with good accuracy in term of depth, width and length. The resulted images of the mapped beachrock agreed with the in situ observation of the formation. Beachrock is represented between resistivity values 2–15 Ω m, lower than the dry terrestrial and coastal sediments and higher than sea water and seafloor sediments. The RMS error was about 2%, with maximum values at wavy sea surface. The survey depicted the beachrock's limits very well in sea water and in seafloor sediments but not clear towards the land, in dry beach sediments. The data retrieved by the tomographies provided useful information about the continuity, the solidity and the extension to depth of the beachrock formation.

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References

- Amieux P, Bernier P, Dalongeville R, Medwecki V (1989) Cathodoluminescence of carbonate-cemented Holocene beachrock from the Togo coastline (West Africa): an approach to early diagenesis. *Sediment Geol* 65:261–272
- Caldas LHO, Statterger K, Vital H (2006) Holocene sea-level history: evidence from coastal sediments of the northern Rio Grande do Norte coast, NE Brazil. *Mar Geol* 228:39–53
- Cooper GA (1991) Beachrock formation in low latitudes: implications for coastal evolutionary models. *Mar Geol* 98:145–154
- Dahlin T (1996) 2D resistivity surveying for environmental and engineering applications. *First Break* 14:275–284
- Dahlin T (2001) The development of DC resistivity imaging techniques. *Comput Geosci* 27(9):1019–1029
- De Souza H, Sampaio E (2001) Apparent resistivity and spectral induced polarization in the submarine environment. *An Acad Bras Cienc* 73(3):429–444
- Drahor GM, Gokturkler G, Berge AM, Kurtulmus TO (2006) Application of electrical resistivity tomography technique for investigation of landslides: a case study from Turkey. *Environ Geol* 50:147–155
- Friedman G (2004) Holocene chronostratigraphic beachrocks and their geologic climatic significance. *Geochem Investig Earth Space Sci* 9:125–142
- Ginsburg RN (1953) Beach rock in South Florida. *J Sediment Petrol* 23:85–92
- Hanor JS (1978) Precipitation of beachrock cements: mixing of marine and meteoric waters vs. CO₂ degassing. *J Sediment Petrol* 48:489–501
- Hopley D (1986) Beachrock as a sea-level indicator. In: Van de Plassche O (ed) *Sea-level research*. Galliard Printers, Great Yarmouth, pp 157–173

- Kwon H-S, Kim J-H, Ahn H-Y, Yoon J-S, Kim K-S, Jung C-K, Lee S-B, Uchida T (2005) Delineation of a fault zone beneath a riverbed by an electrical resistivity survey using a floating streamer cable. *Explor Geophys* 36:50–58
- Loke MH, Barker R (1995) Least-squares deconvolution of apparent resistivity pseudosections. *Geophysics* 60:1682–1690
- Loke MH, Barker R (1996) Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophys Prospect* 44:131–152
- Longman MW (1980) Carbonate diagenetic textures from near surface diagenetic environments. *AAPG Bull* 64(4):461–487
- Mountrakis D (1985) *Geology of Greece*. University Studio Press, Thessaloniki, pp 27–35
- Neumeier U (1999) Experimental modeling of beachrock cementation under microbial influence. *Sediment Geol* 126:35–46
- Nyquist JE, Freyer PA, Toran L (2008) Stream bottom resistivity tomography to map ground water discharge. *Ground Water* 46:561–569
- Rey D, Rubio B, Bernabeu AM, Vilas F (2004) Formation, exposure, and evolution of a high-latitude beachrock in the intertidal zone of the Corrubedo complex. *Sediment Geol* 169:93–105
- Schmalz RF (1971) Formation of beachrock at Eniwetok Atoll. In: Bricker P (ed) *Carbonate cements*. Johns Hopkins Press, Baltimore, pp 17–24
- Stoddart DR, Cann JR (1965) Nature and origin of beach rock. *J Sediment Petrol* 56:422–428
- Taylor JCM, Illing LV (1969) Holocene intertidal calcium carbonate cementation, Qatar, Persian Gulf. *Sedimentology* 12:69–107
- Tsourlos P (1995) Modelling interpretation and inversion of multi-electrode resistivity survey data. PhD, University of York, UK
- Tsourlos P, Szymanski J, Tsokas G (1999) The effect of terrain topography on commonly used resistivity arrays. *Geophysics* 64(5):1357–1363
- Turner R (1999) The evolution of beachrock morphology and its influence on beach morphodynamics. The non-steady-state of the inner shelf and shoreline: coastal change on the time scale of decades to millennia the late quaternary. Abstract with Prog. IGCP Project 437: coastal environmental change during sea level highstands, pp 249–254
- Vieira MM, De Ros LF (2006) Cementation patterns and genetic implications of Holocene beachrocks from northeastern Brazil. *Sediment Geol* 192:207–230
- Ward S (1989) Resistivity and induced polarization methods. In: Ward S (ed) *Investigations in geophysics 5, geotechnical and environmental geophysics 1*, SEG, Tulsa, pp 147–189
- Yang C-H, You J-I, Lin C-P (2002) Delineating lake bottom structure by resistivity image profiling on water surface. *TAO* 13(1): 39–52
- Zhou W, Beck BF, Stephenson JB (2000) Reliability of dipole-dipole electrical resistivity tomography for defining depth to bedrock in covered karst terranes. *Environ Geol* 39(7):760–766