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Interactions between beachrock formations and shoreline evolution

Case study: Togo

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Guido Rutten

Universiteitsfonds Delft

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TU Delft

Department of Geotechnology

Delft University of Technology

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Author(s) : Guido L. Rutten

Date : September 2011
Professor(s) : prof. em. S.B. Kroonenberg
prof. M.J.F. Stive
Supervisor(s) : dr. ir. L.A. van Paassen
dr. J.E.A. Storms
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Postal Address : Section for Geo-Engineering
Department of Applied Earth Sciences
Delft University of Technology
P.O. Box 5028
The Netherlands
Telephone : (31) 15 2781328 (secretary)
Telefax : (31) 15 2781189

Preface

Many thanks to my direct supervisors, Leon van Paassen and Joep Storms. They have given me the freedom to carry out this thesis work as I had it in mind, and trusted me in carrying out the field campaign in Togo. Their unconditional enthusiasm has made this thesis work a pleasure for me to conduct. Thanks to professors Salomon Kroonenberg and Marcel Stive for being a part of my committee as they continue to inspire me with their knowledge and stories. A great *merci* for Dominique Ngan-Tillard, who has been a great support during all the time I spent in Delft. And yet another thank you for Bob Hoogendoorn, for his presence and inspiration during my studies.

I have leaned heavily on the knowledge of many experts in the Netherlands, to whom I owe my gratitude: Professor Reijmer at VU Amsterdam, Ad van der Spek of Deltares and Rosh Ranasinghe of UNESCO IHE. Financial support for the field campaign was provided by the Molengraaff fund and the University fund. Thanks also to my colleagues at the Centre de Gestion Integrée du Littoral et de l'Environnement in Togo.

I dedicate this report to those who have been close to me in Togo.

Guido Rutten

September 2011

Summary

Beachrocks are lithified coastal sedimentary formations which form inside the beach body on short time scales, possibly within a year. Beachrocks can play an important role in the evolution of a shoreline as they fix the normally loose sediments. On the other hand, the evolution of a shoreline could play an important role in the genesis of beachrock and their preservation. A better understanding of these interactions will aid their use in science, to understand their genesis and to reconstruct paleo-climates. The knowledge derived is also useful for coastal engineering practice, to evaluate the response of a coastline to beachrock exposure.

This study evaluated the interactions between beachrocks and shoreline evolution both from a theoretical point of view as well as in a practical case study in Togo, West Africa. In the theoretical review, the variability of shore and shoreline has been related to the diagenetic environment of a beachrock. Furthermore, existing literature was reviewed in order to assess the existing knowledge on shoreline response to the exposure of beachrock. A 2-month field campaign was carried out in Togo to gather data on beachrock characteristics and shoreline development. Finally, a synthesis was made of the theoretical findings and the results of the field campaign.

The process of beachrock genesis and the controls on this process are not fully clear. Multiple mechanisms have been proposed but cannot be confirmed for all reported occurrences of beachrock. It is thus likely that no single process is responsible for the formation of beachrock. The availability of carbonate and the temperature of the beach water are likely to be among the controls on beachrock formation. It has been proposed that the stability of a beach is another control, as agitation of beach particles would not allow cementation to develop. This proposition does however not properly consider the variability of shore and shoreline.

The results show that short term variations of shore and shoreline (hours to decades) are likely to be a control on beachrock genesis. The variability of the diagenetic environment related to these variations determines the cementation characteristics of beachrock. Shoreline variations thus determine the diagenetic history of a beachrock, which in turn influences the rock mass properties of the beachrock. Longer term trends in shoreline evolution are probably not linked to the genesis of beachrock, thus limiting its paleo-environmental significance. This theoretically derived conclusion needs to be confirmed by further more detailed investigation in the field. The analysis of shoreline variability related to beachrock genesis can be used to further evaluate the different mechanisms of formation that have been proposed. Analysis of weathering patterns can be the next step in increasing the paleo-environmental significance of beachrock formations.

In the case study of Togo, the impact of a very large outcrop of beachrocks on shoreline evolution was investigated, by defining an approach that could be applied in similar cases. The beachrock in Togo can be divided into two formations: a main formation which shows high continuity and strength, and effectively blocks cross-shore sediment transport along major parts of the coast of Togo. Another less profound formation is found adjacent to the main formation.

The beachrock in Togo fulfills a role similar to hard engineered structures which are often used in coastal engineering to protect sandy coastlines. The placement of these engineered structures in the nearshore zone triggers a certain response that is adequately understood and can be predicted using modeling software or engineering guidelines. The retreat of a sandy coastline with buried discontinuous beachrock formations poses difficult questions that have not yet been accounted for in science. The complex coupling between sediment transport and hydrodynamic conditions in the nearshore zone is not well understood, and the activation of non-erodible elements inside or as a continuous part of beaches has received only minor attention.

Furthermore, beachrocks differ fundamentally from engineered hard structures as they exhibit a large natural variation in cementation characteristics and thus rock mass properties. Whereas for engineered structures the mechanical properties are known and can be used to calculate the life time of the structure, for beachrock a more thorough understanding of the genesis needs to be developed. The dominant mode of weathering of the main formation appears to be undercutting by scouring around the seaward base of the beachrock.

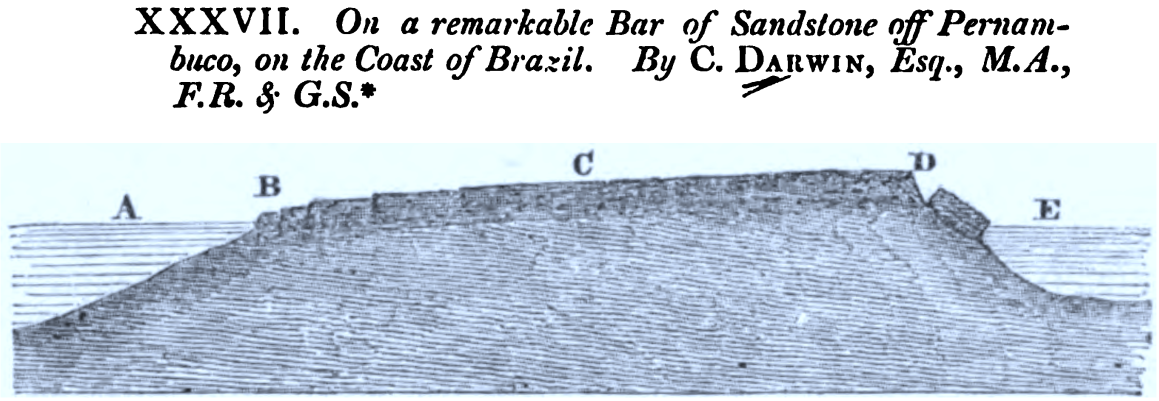
The response of a retreating sandy coast to buried beachrock formations can be qualitatively analyzed using the Phased Retreat Model presented in this study. This model uses equilibrium shoreline profiles to determine different phases in the process of retreat. Longshore processes play a dominant role in the retreat of a coast behind a beachrock barrier. Starting from locations where the beachrock barrier has been breached, erosion landward of the beachrock travels in the opposite direction of the longshore current seaward of the beachrock.

The Phased Retreat Model can be used to further analyze and predict shoreline development along the coast of Togo. Using a more data-driven analysis and by investing in structural solutions. the Togolese government can upgrade their shoreline protection policy to the philosophy of Integrated Coastal Zone Management. Furthermore, the presented model could be used in similar cases elsewhere. Lastly, the Togo case can be used for further generic research on morphodynamic response to barriers in the near-shore zone.

Contents

Chapter 1 Introduction

1.1 Background



XXXVII. *On a remarkable Bar of Sandstone off Pernambuco, on the Coast of Brazil.* By C. Darwin, *Esq., M.A., F.R. & G.S.**

Figure 1 One of the first scientific accounts of lithified beaches (beachrock) made by Darwin (1841).

Lithification of coastal sediments into *beachrocks* is a widespread but poorly understood phenomenon. Beachrocks are often found in tropic to sub-tropic zones, outcropping in the near-shore zone. Meanwhile, research has shown that beachrock formation is in fact a diachronic process which also occurs on higher latitudes. Many questions remain regarding the formation and characteristics of beachrock. Further investigation could yield valuable information both from a scientific point of view as well as in coastal engineering.

> **Scientific understanding** - The process of beachrock genesis is not fully clear. A better understanding of the different mechanisms involved would yield valuable information on the conditions that allow for beachrock formation and the how the rock mass properties relate to their genetic environment. Furthermore, as beachrock formation is thought to occur in the intertidal zone, beachrocks could be indicators of former sea-levels. By dating shell fragments in the beachrock, a paleo-environmental reconstruction of former coastline positions can be made. Beachrock characteristics such as sedimentary structures or weathering patterns may provide more clues for paleo-environmental reconstruction.
>
> **Coastal engineering** - A beach is a very important part of a coastal system in terms of morphodynamics: the coupling between hydrodynamic and sediment transport processes. Increased cohesion of beach particles by cementation (beachrock formation) undoubtedly has a large influence on these processes. Current coastal engineering practice largely neglects this, leaving a considerable hiatus in the predictive capacity of state-of-the-art models. A study into the natural occurrence of beach cementation should be the starting point for future implementation in these models. Furthermore, when a beachrock functions as a shoreline protection, it is important to know the rock mass properties and thus its resistance to weathering. Better understanding of beachrock genesis is necessary to account for and predict the variation in rock mass properties.

Much of the existing research on beachrocks is highly case-specific. Earlier researchers such as Russell and McIntire (1965) undertook extensive field campaigns, covering a wide variety of geographic locations, and tried to understand the key processes responsible for beachrock formation from observations in the field. Many of the generic inductive conclusions drawn in these documents have later been proven false in other case examples.

More recently, laboratory research has provided proof for cementation under microbial action (Neumeier, 1999). Current developments, amongst others at Delft University of Technology, are oriented towards using these biologically induced cements for ground enhancement in civil engineering. Studying the natural analogue might yield valuable information for further improvement of this method.

1.2 Research Objective

The following main research objective and associated research questions have been defined:

Main research objective:

To determine the relationship between the evolution of the shoreline profile in Togo and the exposure and characteristics of beachrock along this shoreline, and to determine how we can use this knowledge to predict the impact of beachrock on the shoreline evolution in the future.

Research questions:

- What is the provenance of beachrock along the coast of Togo, what are its characteristics in terms of geometry, cementation type/degree and discontinuities and how can these be related to its degradation?
- What is the influence of shore and shoreline variation on the formation of beachrock, and how can this knowledge be used in paleo-environmental reconstruction?
- What is the morphodynamic response of a retreating sandy coast to a buried beachrock formation, and how can this knowledge be used to better predict future shoreline evolution?

1.3 Approach

This study combines a thorough theoretical review and a case study. The theoretical review provides an analysis of the literature on beachrock. Herein, the basic concepts and principal uncertainties in the existing knowledge on beachrock have been investigated. After definition of the research topic (the role of beachrock formations in shoreline evolution), a study into the principles of shoreline dynamics was made.

Upon selection of the location for a case study, an in-depth investigation of documents related to this case was performed. Initial appraisal and pre-selection of research sites was carried out using the existing literature study and satellite imagery. During a 2-month field campaign in Togo, geological investigation was done on site and local experts were interviewed. Upon return, samples were investigated and a synthesis was made of the theoretical review and the findings from the field campaign.

1.4 Outline of this report

This report comprises of three parts; the theoretical review (Part I), the case study (Part II) and a synthesis of the theoretical and practical findings (Part III). In Part I, first the definition and characteristics of beachrocks are discussed (Chapter 2), after which in Chapter 3 the principles of shoreline dynamics are dealt with. The interaction between beachrock and shoreline dynamics is split into two categories: morphodynamic controls on beachrock genesis and occurrence (Chapter 4), and the impact of beachrock on coastal morphodynamics (Chapter 5).

Part II describes the results from the case study. First, the case is introduced and the geological setting is given (Chapter 6). Subsequently, an overview of available data is given and the methodology of the fieldwork is described (Chapter 7). Finally, Chapter 8 puts forward the results of the field campaign. These results are compared with the findings from the theoretical review in Part III. Here, hypotheses are validated and implications are discussed (Chapter 9). In Chapter 10, the final conclusions are drawn and suggestions are made for further research.

Part I: Theoretical review

Chapter 2 Definition and characteristics of beachrock

2.1 Introduction

Beachrocks are lithified coastal sedimentary formations consisting of various beach sediments. Lithification occurs through the precipitation of (mainly) carbonate cements (Vousdoukas et al., 2007). The beach may consist of any type of sediments, both of clastic and biogenic origin (Russell, 1962), while the cements typically consist of High-Magnesian Calcite (HMC) or Aragonite (Ar) (Bricker and Mackenzie, 1971).

The first scientific mention of these cemented beach deposits has been made by Chamisso in 1815 (Gischler, 2007) who described the Radak and Ralik Islands in the Pacific. Many famous 19th century scholars have later reported beachrock occurrences, including Sir Francis Beauford in 1817 (Goudie, 1969), Lyell who discovered human skeletons cemented into an 'indurated beach' on the island of Guadeloupe (Lyell, 1837) and Darwin (Darwin, 1841).

2.2 Temporal and Spatial Distribution

2.2.1 Occurrence and Setting

Beachrock exposures are quite conspicuous where they can be found as pseudo-linear, elongated features in the intertidal or nearshore zone (Gischler, 2007). Given their origin on the beach and relatively recent age, these exposures are often found parallel to the present shoreline. This alignment might be preserved by beach locking, which is described in §2.6.2. Older beachrock exposures, in the form of isolated ridges, are thought to represent ancient shorelines and are often used in sea-level studies (see §2.6.1). Beachrock exposures commonly show layering or sequences of bands, which may be associated with textural laminations. The bands mostly dip gently seaward following the beach slope (Russel, 1959). However, some beachrock exposures have been found showing markedly different orientations than those of the hosting beaches (e.g. Beier, 1985), which might in turn be caused by diagenetic processes after cementation. Inherent to the location of origin, beachrock exposures are usually subjected to continuous destruction by fracturing and mechanical erosion caused by abrasion or corrasion (e.g. McLean, 1967). During erosion-accretion cycles, older broken-off fragments of beachrock might be incorporated into younger beachrock (Strasser and Davaud, 1986).

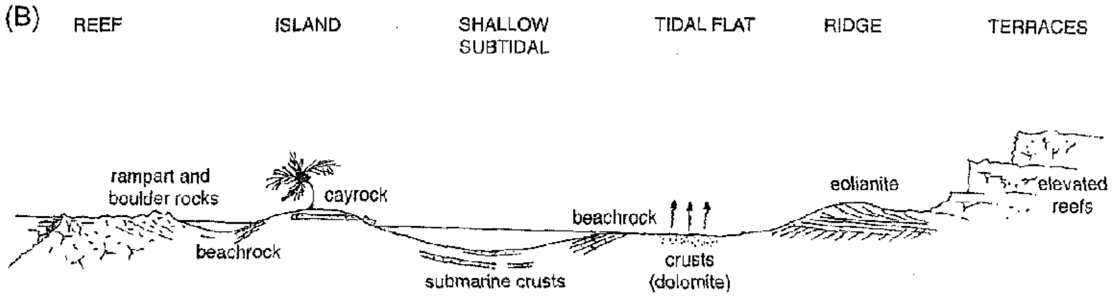


Figure 2 Cementation phenomena in beach settings. From Gischler (2007)

The distinction between beachrock and other coastal cemented deposits can be difficult. The term 'cay sandstone' was coined for supratidal cemented deposits on reef islands (Kuenen, 1950). This cay sandstone (or *cayrock*) may be distinguished from beachrock based on its horizontal bedding, very good sorting and the predominance of meteoric calcite cements (Gischler, 2007). Another cemented deposit likely to be found close to beaches is aeolianite (Ward, 1975). Similar to cayrock, cementation in this sediment is dominated by meteoric calcite. Aeolinite can be distinguished from cayrock and beachrock by sedimentary structures resulting from wind transport, such as cross-stratification (Gischler, 2007). However, very little research exists on the sedimentary structures of beachrocks (Kelletat, 2009b).

Other intertidal and subtidal cementation phenomena may prove more difficult to distinguish from beachrock. Rampart and boulder rocks, consisting of cemented coral branches and fragments larger than 10cm, sometimes show inclined bedding similar to beachrock (Scoffin and McLean, 1978). Elevated reefs and reef terraces can also be confused with beachrock (Hopley, 1986). Cemented layers of sediment formed on tidal flats, on the shallow seafloor and along lake coastlines show identical diagenetic marine-phreatic cement characteristics to beachrock. However, they cannot, probably be regarded as beachrocks *stricto sensu* (Vousdoukas et al., 2007).

2.2.2 Global Distribution

A first inventory of all documented beachrock occurrences was made by Vousdoukas et al. (2007). This section discusses the inventory and conclusions drawn by the authors in this article.

Vousdoukas et al. (2007) listed all documented occurrences with the associated location, cement type, age, climate, tidal range and proposed formation process. This overview was used to induce information regarding the controlling factors of beachrock occurrence and thus of its formation. Debatably, the authors used "occurrences" as the *N*-factor in their analyses without explicitly stating the spatial definition of an "occurrence". A sandy coast of 100 km in length is counted as one occurrence, while on a small island every beach is counted as a separate occurrence. Thus, no spatial definition is used that considers the variation in parameters of the environment.

Further analyses based upon the number of occurrences are highly sensitive to variation in this definition. For a proper inductive analysis of controlling factors in beachrock formation, a more advanced systematic approach is indispensable. As the authors already stated, the abundance of recent beachrock is likely to be underestimated, since they are often buried under a thin wedge of unconsolidated sediments. Older beachrocks are likely to be either hidden from view by overlying sediments, or eroded. Table 1 shows a list of documented beachrock occurrences, after Vousdoukas et al., updated with occurrences not previously listed.

Re-evaluating the analyses made by Vousdoukas et al. using a better definition of "occurrence" and adding the non-listed occurrences might yield interesting results. With the existing definition, the number of occurrences in the Mediterranean Sea is very high. As a result, the statistical analyses show a peak in occurrences at temperate latitude and for micro-tidal coasts. This leads Vousdoukas et al. to suggest that "large tidal ranges may not allow sufficient time for the beach sediment consolidation to develop". Many of the non-reported beachrocks and the beachrocks of larger extent seem to occur in mesotidal coasts. A more thorough investigation is thus indispensible to induce useful conclusions from the global list of occurrences.

Table 1 Overview of reported beachrock occurrences, updated from (Vousdoukas et al., 2007). Occurrences printed in bold are not previously listed, for which the full reference is given at the end of this report. For other full references, the reader is referred to (Vousdoukas et al., 2007).

Location		Reference
Atlantic	Spain	Rey et al. (2004); Knox (1973)
	Scotland	Kneale and Viles (2000)
	Togo, Benin	Bernier and Dalongeville (1996); Amieux et al. (1989)
	Ivory Coast	Martin (1972)
	Canary Islands	Tietz and Muller (1971); Calvet et al. (2003)
	Morocco	Russell (1962)
	USA, South Carolina	Russell (1962)
	Brasil	Caldas et al. (2006); Tatumi et al. (2003); Vieira and Ros (2007); Bezerra et al. (2004)

Location		Reference
	Argentina	**(Aliotta et al., 2009)**
Australia	Australia	Scoffin and Stoddart (1983); Webb et al. (1999); Davies and Kinsey (1973); …
Carribean	Bahamas	Shapiro et al. (1995); Strasser and Davaud (1986); Kindler and Bain (1993); …
	Belize	Gischler and Lomando (1997)
	GB, Honduras	Stoddart and Cann (1965)
	USA, Florida	Multer (1971); Stockman et al. (1967); Spurgeon et al. (2003)
	GB, Grand Cayman	Moore, (1973); Moore and Billings (1971)
	Jamaica	Pigott and Trumbly (1985)
	USA, Florida	Ginsburg (1953)
	St George	Russell (1962)
	USA, Virgin Island	Moore (1977); Hanor (1978)
	Venezuela	**Daniel (1976)**
N. America	Michigan (lake)	Binkley et al. (1980)
Indian	Bangladesh	Chowdhury et al. (1997)
	Ceylon	Cooray (1968)
	Keeling Islands	Russell and McIntire (1965)
	Maharastra	Badve et al. (1997)
	Mauritius	Russell and McIntire (1965)
	Godavari Delta	Ramkumar et al. (2000)
	Mozambique	Siesser (1974)
	South Africa	Siesser (1974)
	Seychelles	Badyukova and Svitoch (1986); Russel and McIntire (1965)
	India	**Kumar et al. (2001) and Wagle (1990)**
	Maldives	**Moresby (1835)**
	Tanzania and Madagascar	**Battistini (1966)**
Persian Gulf	Qatar	Taylor and Illing (1969)
	United Arab Emirates	Evamy (1973); Kendall et al. (1994)
Black Sea	Bulgaria	Georgiev (1989)
Mediterranean	Egypt	Holail and Rashed (1992);
	Cyprus	Alexandersson (1972a and 1972b)
	Greece	Bernier and Dalongeville (1996); Alexandersson (1969); Desruelles et al (2004); ...
	Israel	Gavish and Friedman (1969); Magaritz et al. (1979)
	Italy	Alexandersson (1969); **Bloch and Trichet (1966)**
	Corsica	Bernier et al. (1997)
	Spain	Russell (1962); Alexandersson (1969)
	Syria	Bernier and Dalongeville (1996)
	Tunisia	Strasser et al. (1989)
	Turkey	Yaltirak et al. (2002)
	France	**Masurel (1953)**
Red Sea	Egypt	Mansour (1993); El-Sayed (1988)
	Jordan	Lazar et al. (2004); Nesteroff, (1955); Krumbein (1979)
	Saudi Arabia	Neumeier (1998); El-Sated and Abou Auf (1995)
South China Sea	Hong Kong	Hsi-lin (1962)
	Borneo	**Andriesse (1970)**
	Malaysia and Thailand	**Tjia (1996)**
Pacific	Fiji	Russell (1963)
	Galapagos	Prager (1991)
	French Polynesia	Trichet (1965); Bernier et al. (1990); Bernier and Dalongeville (1996)
	Marshall Islands	Schmalz (1971)
	Hawaii	Meyers (1987)
	Samoa Island, Tonga, Tuvalu	Dickinson (1999)
	Tahiti	Neumeier (1998)
	Japan	**Omoto (2001)**

2.2.3 Temporal distribution

Although the large majority of reported beachrock occurrences are of Holocene age, pre-Quaternary occurrences have been reported. These include Tertiary (Tanner, 1956), Mesozoic (Moore, 1973), Paleozoic (Tanner, 1956) and even Precambrian (Donaldson and Ricketts, 1979) beachrock occurrences. The potential of these occurrences as rough paleo-geographical indicators is low, given the large spread in latitudes (Gischler, 2007).

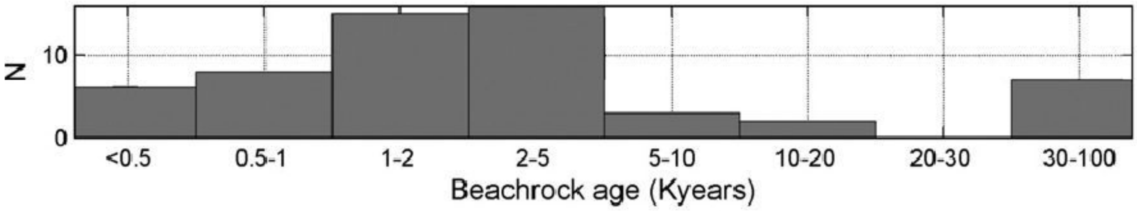


Figure 3 Beachrock age (Kyears) with *N* the number of reported occurences for each age bin, from Vousdoukas et al. (2007)

Figure 3 shows the temporal distribution of dated Holocene beachrocks, after Vousdoukas et al. (2007). The majority of these occurrences are thought to be 1000-5000 years old. It must be noted that only a small percentage of the reported beachrocks have been dated. Beachrocks usually contain biogenic material older than the cement, which may skew the carbon dating results towards older dates (Scoffin and Stoddart, 1983). The significance of the observed distribution is thus weakened by possible sampling and dating artifacts.

The small amount of beachrocks of age <1000 years can be accounted for by dating artifacts, but also by the fact that beachrock dating has focused on exposed formations (Vousdoukas et al., 2007). Many beachrock outcrops found exposed in the surf and swash zones extend into the onshore part of the beach. This part, buried by unconsolidated beach sediments, appears to be at a different (younger) stage of lithification that its seaward part. This observation relates to the theories of formation, which will be discussed in §2.4.

2.3 Characteristics

2.3.1 General observations

Beachrocks vary from small patches to very large outcrops, hundreds of meters wide and kilometers in length (Vousdoukas et al., 2007). The composition of beachrock constituent particles is similar to that of the adjacent shore. On tropical coasts and islands these constituent particles are often marine-derived carbonate grains, however, they can also be grains from siliciclastic, magmatic or metamorphic rocks.

The grains are usually moderately to very well sorted and range in size from sand to gravel, while the sorting is often better than that of the adjacent subtidal sediments. Banding or layering of beachrock (§2.2.1) might be due to the stronger cementation of fine-grained as opposed to coarse-grained layers (Gischler, 2007), caused by faster cementation of smaller pore spaces. Primary sediment structures are often preserved in the beachrock, which is an important point of attention for further research aiming for better understanding of beachrock formation (Knight, 2009). Apart from the bulk sediment, various artifacts can be found in the beachrock, for example WWII relics at Enewetak Atoll in the Pacific Ocean (Emery et al., 1954).

The discovery of even more recent artifacts suggests that beachrock formation can be a diagenetic process with time scales on the order of few years (Chivas et al., 1986). This was already noticed by Moresby (1835) who described inhabitants of Indo-Pacific islands harvesting beachrock for building stone, where new occurrences formed on the same beach within a few years. This suggestion is further reinforced by high-resolution radiometric dating of cements in coral reef slopes, showing growth rates of marine aragonite cements, comparable to those in beachrock cements, reaching 80-100 µm yr^{-1} (Grammer et al., 1993).

2.3.2 Cement mineralogy

Cementation of beachrock can occur both in the marine as well as the meteoric diagenetic environment. The process is influenced by the physico-chemical parameters of the diagenetic environment (Bathurst, 1975), where they grow under phreatic or vadose conditions. Cement mineralogy and morphology are thus indicative of the diagenetic environment (Gischler, 2007).

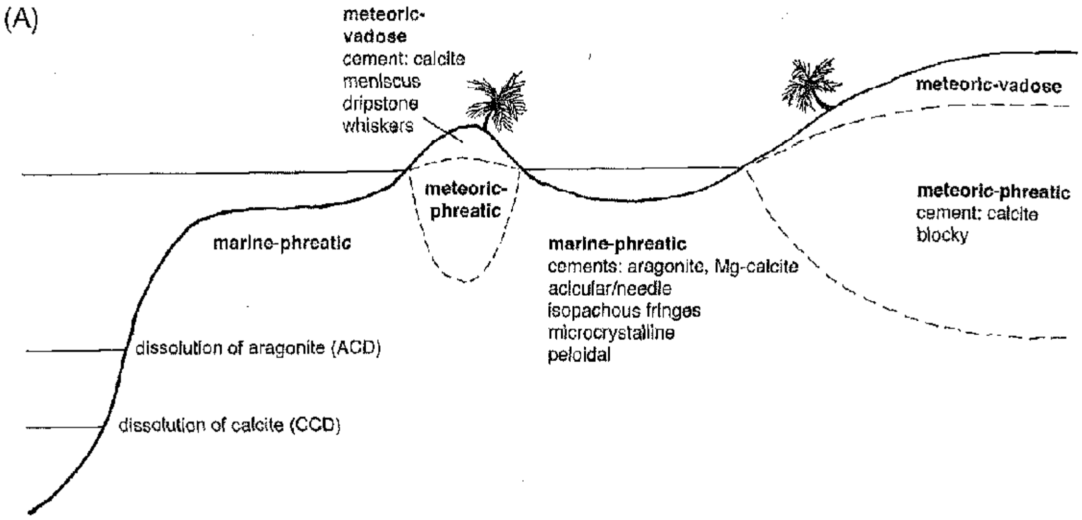


Figure 4 Diagenetic environments with associated cement mineralogy and morphology. From Gischler (2007)

Marine cements

Beachrock cements are usually composed predominantly of metastable carbonate phases formed in the marine-phreatic environment, being high Magnesian calcite (HMC) and aragonite (Ar) (Vousdoukas et al., 2007). The HMC commonly shows a micritic (microcrystalline) texture, or as rinds of bladed, fibrous or peloidal crystals. Other occurrences show HMC with bladed, fibrous or peloidal crystals. The aragonite cement can be found in the form of isopachous fringes of needles, often overlying a dark layer at the base, consisting of aragonite platelets rich in iron and sulphur. Small aragonite needles may form micritic cement. Less common are cements indicative of the marine-vadose zone, which may reflect marine cementation in the wave spray zone (Gischler, 2007). Here, meniscus or gravitational cement fabrics are found, as well as highly acicular whisker type cement fabrics (Gischler and Lomando, 1997).

Meteoric cements

Beachrock cements from meteoric waters may develop during precipitation from percolating $CaCO_3$-saturated rain water. This can occur during longer times of subaerial exposure, as in the case of Pleistocene lowstands of global sea-level. The typical type is LMC, showing dripstone fabrics in the meteoric-vadose diagenetic environment and blocky cement fabrics in the meteoric-phreatic environment (Gischler, 2007).

2.4 Mechanisms of formation

Several theories have been proposed to explain beachrock formation, which can be divided into physico-chemically and biologically induced precipitation of calcium carbonate. Most of the theories have been formulated to explain particular occurrences of beachrock, while each theory has been proven impossible for a different occurrence, suggesting the co-existence of different mechanisms.

Vousdoukas et al. (2007) listed the mechanisms proposed for reported occurrences, revealing a preference for the theory of direct cement precipitation. However, it must be noted that not all authors provide arguments for their proposed mechanisms and that not all theories may have been developed or available at the time of documentation of these occurrences.

Physico-chemical induction

Physico-chemical models explain marine carbonate cement precipitation by the soaking of beaches during high tides and evaporation of sea water during low tides (Gischler, 2007), enhanced by (daytime) solar warming of the beach (Scoffin and Stoddart, 1983). The beach sedimentary material itself can provide the necessary nuclei for the process to commence, whereas high temperatures causing a decrease in carbonate solubility and CO_2 degassing of inter-granular water during low tide further promote the process (Gischler and Lomando, 1997). The large vertical extent of beachrocks in microtidal areas indicates that cementation might also take place in the supratidal environment, by cements precipitated from sprayed marine waters (Kelletat, 2009a).

Early research suggested that cementation can take place directly from meteoric waters, (Russell, 1962), controlled by (a) the groundwater temperature and (b) the supply of carbonate particles to the meteoric phreatic zone (Russell and McIntire, 1965). However, beachrocks have also been found in arid areas (e.g. the Red Sea coast), and along coasts of islands too small to support a permanent fresh water table. Other authors suggest that the mixing of marine and meteoric water induces beachrock formation (Scoffin and Stoddart, 1983), as the solubility of $CaCO_3$ decreases with the salinity, resulting in carbonate saturation and precipitation.

De-gassing of carbonate-saturated groundwater has been experimentally proved as possible mechanism of beachrock formation (Hanor, 1978). Tidal oscillation of the water table causing vertical fluid dispersion can induce CO_2-degassing from seaward-flowing groundwaters. This theory can explain beachrock formation in small island settings, as it does not require a permanent freshwater table, but it may not be applicable in arid coasts.

Biological induction

Biological processes may have an important role in beachrock formation. Biological activity controls the partial pressure of CO_2 by its consumption, thus promoting the precipitation of $CaCO_3$ (Hopley, 1986). Ammonification of amino-acids, sulfate reduction and other bacterial processes taking place during organic matter degradation promote carbonate precipitation by raising the pH (Krumbein, 1979). Furthermore, organic matter may promote carbonate precipitation by raising locally the level of carbonate saturation, and promote carbonate nucleation (Webb et al., 1999).

2.5 Controls on beachrock formation

Related to the different mechanisms of beachrock formation, a wide range of possible controls on this process has been proposed (Figure 5). It is yet far from clear which are the predominant factors that control carbonate precipitation on beaches. The chemical process involves complex feedback mechanisms which are poorly understood while also hydrodynamic and sedimentological processes show complex interaction. As proper discussion of these controls requires in-depth description, only the controls most relevant to this study will be highlighted.

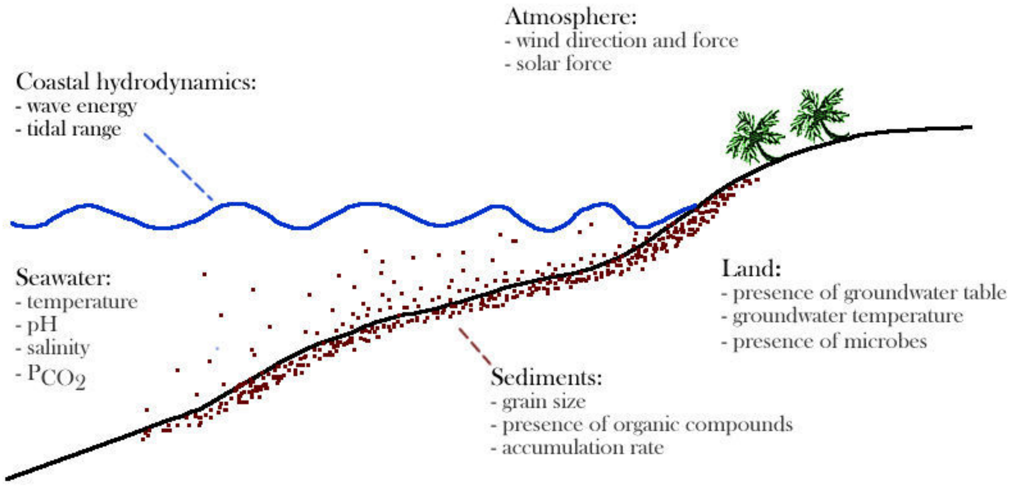


Figure 5 Possible controls on beachrock formation as listed by Vousdoukas et al (2007)

Coastal hydrodynamics appear to exert control on beachrock formation, primarily induced by wave energy and tidal range. As wave energy itself is a complex product of hydrodynamic processes, other parameters such as bathymetry and atmospheric conditions come into play. Higher wave energy may promote spraying of seawater and thus cement supply to the supratidal zone, while at the same time the increased agitation of beach sediment will limit the cementation process. Since formation takes place in the intra- or supratidal zone, the tidal range is also likely to be a significant control and might govern the thickness of the beachrock (Kelletat, 2009a).

Coastal morphodynamics (§3.3.1) are intimately linked with the hydrodynamic processes but have not been thoroughly reviewed as a possible control on beachrock formation. (Shinn) suggested that low accumulation rates promote carbonate cementation, however, (Ramkumar and PATTABHI, 2000) have reported sediment lithification by monsoon-induced onshore sediment transport. Several authors (e.g. (Blivi et al., 2002)) have mentioned beach stability as a control on beachrock formation. This aspect will be dealt with in greater detail in 0.

2.6 Significance of beachrock

2.6.1 Beachrock as a paleo-environmental indicator

The main paleo-environmental significance of beachrock is sea-level indication. Several authors have reconstructed Holocene and Pleistocene sea-level stands based on fossil beachrock occurrences (Gischler, 2007). Given the assumed intertidal genesis of beachrock, radiometric age dating is used to investigate the time of formation. Sea-level curves can be constructed from the acquired data, especially in places where different ridges of beachrocks are found. Mörner et al. (2004) even used the beachrock to claim a recent sea level fall in the Maldives, later to be heavily criticized by Kench et al. (2005).

The reliability of these interpretations might not be sufficient to fully support the major implications of these studies, especially those used to predict sea-level change in the near future. First, beachrock might not be restricted to the intertidal zone, as it can form in the supratidal spray zone (Hopley, 1986). Second, in macrotidal environments the sea-level datum obtained from beachrock may not be very precise (Gischler, 2007). Third, the preciseness of beachrock dating may be low as it reflects a mixture of time-averaged constituents and may be affected by the presence of biogenic material (Neumeier, 1999).

Beachrock could, given the predominant occurrence in tropical and subtropical latitudes, also be used as a rough paleo-geographical indicator (Gischler, 2007). However, since beachrock might also form in higher latitudes, its potential for this use is rather limited. Beachrock is also used to study ancient catastrophic events such as tsunamis, where dislocated slabs of beachrock are used as evidence for high energetic events to have taken place (Vött et al., 2008).

2.6.2 Beachrock as a natural defense mechanism

The influence of beachrock exposure on coastal morphodynamics is complex and highly case-specific. Several researchers have claimed that the presence of beachrock has protected coastlines from erosion (Dickinson, 1999), mainly in cases of small islands or atolls. However, no systematic or quantitative studies on the long-term effect of coastal protection by beachrock have been performed (Gischler, 2007). The wide range of geometrical and geotechnical aspects of the beachrock, plus the different large-scale settings that beachrock can be found in, makes the definition of a protective capacity unlikely. This topic is further dealt with in detail in Chapter 5.

Chapter 3 Theory of shoreline dynamics

3.1 Introduction

Beaches are sedimentary structures that can dissipate and absorb coastal wave energy, changing in profile to adjust to changes in the impinging wave energy (Bird, 2000). Sedimentary and hydrodynamic conditions affect the equilibrium profile around which beach cross-shore profiles oscillate. The beach system is thus a dynamic system showing a natural variability on very small to large time- and spatial scales. The notion of variability and the time scales associated with it are key to a more elaborate understanding of beachrock genesis and the role beachrock can play in shoreline evolution.

3.2 Nomenclature

The definition of the coastal zone or and its elements depends upon the interpreter. In this study, definitions as depicted in Figure 6 are used. It should be noted that different configurations of coastal zones exist, for which other definitions may be better suited, notably the steep coastal profile of Togo. However, for the purpose of this research, the given definition provides the necessary accuracy and is widely applicable. To address the genesis of beachrock, the primary interest is in the variability in the backshore zone, which is in turn defined by the variability of shore and shoreline. The distinction between *shoreline* and *coastline* is important, as this report discusses the variability of the *shoreline*. A shoreline will, especially on short term scales, show more variability than the coastline. When considering the impact of beachrock on coastal processes, reference is made here to *shoreline* evolution, but is directly linked to *coastline* evolution.

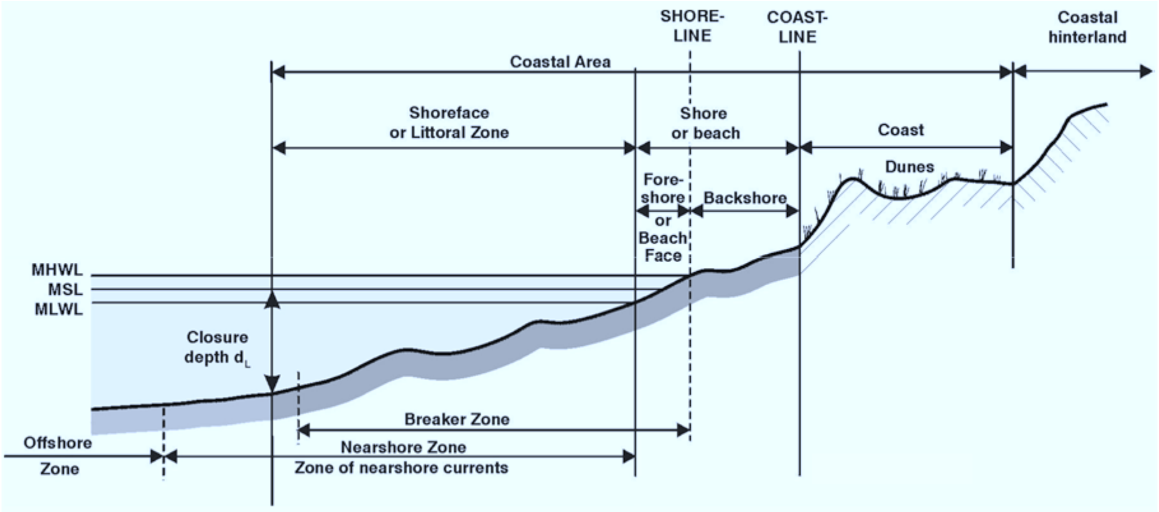


Figure 6 Coastal terminology. Source: http://www.coastalwiki.org

3.3 Important concepts and processes

3.3.1 Coastal morphodynamics

Sediment transport occurs predominantly in the surf zone, where waves continuously stir up material which is then transported by a longshore current (Bosboom and Stive, 2010). A gradient in sediment transport leads to coastal changes: a positive gradient leads to erosion, a negative gradient creates accretion, while a zero gradient means that there are no changes in morphology. The sea bottom will respond to a positive sediment gradient by erosion and thus lowering of the bottom. In turn, waves and tides respond to the changed cross-shore profile, changing the sediment transport rate again. Hydrodynamic processes and morphology are thus coupled by means of sediment transport, this coupling is termed the *morphodynamics* of the coastal system.

3.3.2 Equilibrium concept

According to the equilibrium concept, a stable coastal system is characterized by a morphological system that is in equilibrium with the forcing (waves, tides, currents). When this equilibrium is disturbed, the morphological system will adjust to reach a new equilibrium. The rate of adjustment depends on the difference between the actual situation and the to be achieved new equilibrium. This concept can prove useful in approximating adaptation processes on large time scales (Bosboom and Stive, 2010).

3.3.3 Sediment transport

Movement of sediment particles occurs when the bed shear stress, induced by combined wave-current motion, exceeds a certain critical velocity. Generally two modes of transport are discerned: bed load, where particles mainly roll and stay close to the bed, and suspended load, where grains are lifted and transported in suspension as long as flows are above the critical flow velocity. The distribution of sediment transport depends on the coastal profile, hydrodynamic conditions and sediment types. Sediment transport in the swash zone might be an important part of longshore transport (Horn, 2002), which is important when considering the impact of beachrock outcrops on shoreline evolution.

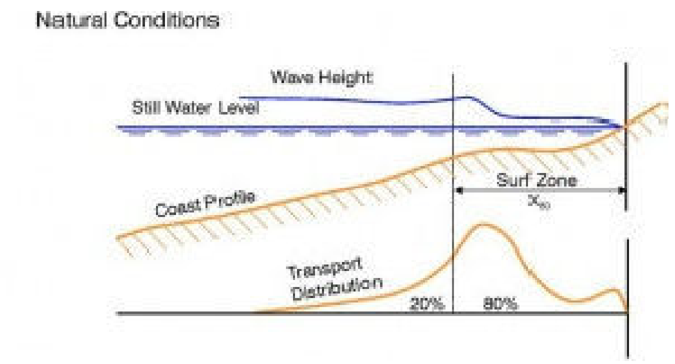


Figure 7 Example of longshore sediment transport distribution. Source: http://coastalwiki.org

3.4 Variability of shore and shoreline evolution

The variability of shore and shoreline evolution covers a wide range of different temporal and/or spatial scales. Given the different coastal settings and processes involved, quantification of this variability is highly case-specific. In a qualitative approach, Stive et al (2002) categorized different scales of natural shoreline variability with their associated causes and typical evolution types (

Scale	Natural causes	Typical evolutions
Very long term	sediment availability	(quasi-)linear trends
time scale: centuries to millennia space scale: ~ 100 km and more	relative sea-level changes	trend changes (reversal, asymptotic, damping)
	differential bottom changes	fluctuations (from (quasi-) cyclic to noncyclic)
	geological setting	
	long-term climate changes	
	paleomorphology (inherited morphology)	
Long term	relative sea-level changes	(quasi-)linear trends
time scale: decades to centuries; space scale: ~ 10 - 100 km	regional climate variations	fluctuations (from (quasi-) cyclic to noncyclic)
	coastal inlet cycles	trend changes (reversal, asymptotic, damping)
	sand waves'	

	extreme events	
Middle term time scale: years to decades space scale: ~ 1- 5 km	wave climate variations surf zone bar cycles extreme events	fluctuations (from (quasi-) cyclic to noncyclic) (quasi-)linear trends trend changes (reversal, asymptotic, damping)
Short term time scale: hours to years; space scale: ~10 m - 1 km	wave, tide and surge conditions seasonal climate variations	fluctuations (from (quasi-) cyclic to noncyclic) (quasi-)linear trends trend changes (reversal, asymptotic, damping)

Table 2). These scales will be discussed regarding their relation to beachrock genesis in §4.2.

Scale	Natural causes	Typical evolutions
Very long term time scale: centuries to millennia space scale: ~ 100 km and more	sediment availability	(quasi-)linear trends
	relative sea-level changes	trend changes (reversal, asymptotic, damping)
	differential bottom changes	fluctuations (from (quasi-) cyclic to noncyclic)
	geological setting	
	long-term climate changes	
	paleomorphology (inherited morphology	
Long term time scale: decades to centuries; space scale: ~ 10 - 100 km	relative sea-level changes	(quasi-)linear trends
	regional climate variations	fluctuations (from (quasi-) cyclic to noncyclic)
	coastal inlet cycles	trend changes (reversal, asymptotic, damping)
	sand waves'	
	extreme events	
Middle term time scale: years to decades space scale: ~ 1- 5 km	wave climate variations	fluctuations (from (quasi-) cyclic to noncyclic)
	surf zone bar cycles	(quasi-)linear trends
	extreme events	trend changes (reversal, asymptotic, damping)
Short term time scale: hours to years; space scale: ~10 m - 1 km	wave, tide and surge conditions	fluctuations (from (quasi-) cyclic to noncyclic)
	seasonal climate variations	(quasi-)linear trends
		trend changes (reversal, asymptotic, damping)

Table 2 Scales of variability of shore and shoreline, after Stive et al (2002)

Chapter 4 Morphodynamic controls on beachrock genesis and occurrence

4.1 Introduction

Addressing the search for controls on beachrock genesis, Kaye (1959) stated that "the problem hinges more on an adequate explanation for the absence of beachrock from many beaches than on its presence in others". The morphodynamic state and variability of a beach is likely to be a limiting factor or indirect control on beachrock genesis as it affects the physicochemical environment inside the beach body. This control is exerted on the same small time scales as beachrock genesis takes place. Chapters 4.2-4.5 deal with this morphodynamic control on beachrock genesis.

On larger time scales, variability of the shoreline is likely to be a significant control on beachrock *occurrence*, as significant regression can cause exhumation and destruction of beachrock. This weathering and erosion of the beachrock is in turn related to the diagenetic history of the beachrock, as the degree and type of cementation determine the strength of the rock. Chapter 4.6 deals with these large-scale controls on beachrock *occurrence*.

The analysis of controls on beachrock *genesis* and *occurrence* can serve to assess the likelihood of finding beachrock in a certain setting. Furthermore, the proposed theories can be used to set up hypotheses which can be tested in the case study. This will be done in chapter 4.7.

4.2 Scales of beach stability

The morphodynamic state of a coastal system is one of the many possible controls on beachrock genesis (§2.5). Various authors proposed that beachrock genesis is favored by low agitation of beach particles; thus if a beach is "stable" (Kneale and Viles, 2000), (Desruelles et al., 2009). Other authors directly related the genesis of beachrocks to morphodynamic equilibrium of the coast (Blivi, 1998). Once sediments are fixed, the beachrock is thought to "lock" the beach profile (Vousdoukas et al., 2007) thus allowing further (dia-)genesis in a positive feedback loop.

Although the suggestion of beach particle agitation as a control can be intuitively justified, the upscaling to low accumulation rates or morphodynamic equilibrium does not take into account middle to long term scales of shoreline variability (§3.4). Most authors (e.g. Desruelles et al. (2009)) consider stability from a (quaternary) geological timescale ("very long term", centuries to millennia) in order to relate beachrock genesis to tectonic events or sea-level changes, while beachrock formation itself is thought to occur on a middle term (year to decades) scale. The very long term scale, e.g. the creation of a stable sand barrier, may be essential to allow for beachrock genesis, but the middle term and long term scales are much closer linked to the geometry and characteristics of the beachrock.

Assuming low variability on a very long term scale does thus not take into account the fact that shoreline variability on a shorter term scale may be significant to beachrock genesis. Shoreline movements in the order of meters may already limit beachrock genesis by the exposure and subsequent destruction of early-cementation stage beachrock in the swash zone. Subsequently, with a shoreline shift of several meters, also the mixing zones of marine and freshwater moves, thus possibly placing beachrock in a different physico-chemical environment. Although creation of an environment suitable for beachrock genesis might take place on a very long term scale, the more direct morphodynamic controls on beachrock genesis and preservation are therefore likely to be governed the middle and long term scales.

4.3 Diagenetic zones

Cementation of sand into a beachrock is influenced by the physicochemical characteristics of the diagenetic environment (§2.3.2). A beach body represents the transition area between the marine and the meteoric environment, whereas another distinction can be made between the phreatic and the vadose environment. The beach body can thus be conceptually divided into six diagenetic zones (Figure 8), including mixing zones where the pore water salinity is between that of the marine and the meteoric environment. Each zone is thought to have its specific cementation characteristics (Gischler, 2007). The configuration of these zones relates directly to the characteristics of the beachrock in terms of cementation and geometry.

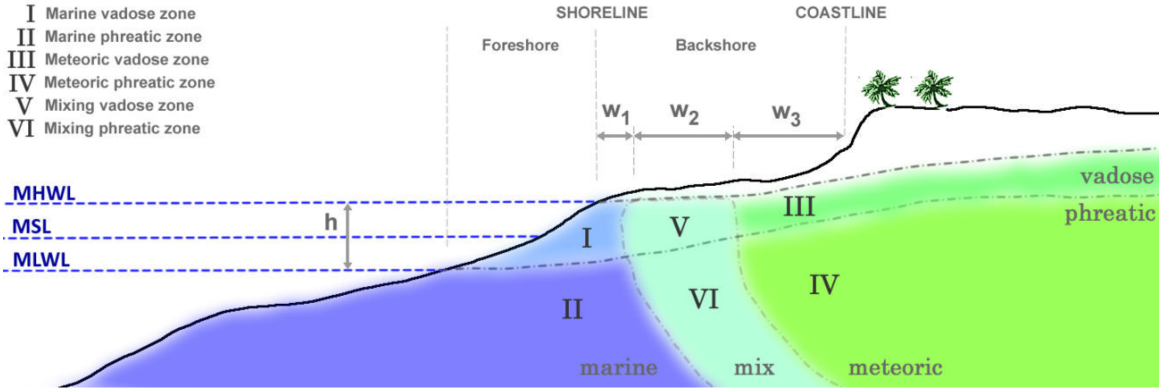


Figure 8 Schematic interpretation of diagenetic zones inside the beach body. In the mixing zone, pore water has a salinity between that of the marine and that of the meteoric zone. Based on (Gischler, 2007)

Considering a hypothetical stable beach with stable diagenetic zones, the geometry of the zones could be directly related to the geometry of the beachrock. The width of the mixing zone (w_2, Figure 8) and the difference between MHWL and MLWL (*h*) would then govern the dimensions of the beachrock. Furthermore, the diagenetic zones should be easily recognizable in the beachrock by their cement type.

We suggest that in reality the diagenetic zones are highly dynamic, which should be borne in mind when interpreting beachrock cements. The diagenetic zones are influenced by variations in sea water level, shoreline movements and variations in water flow from the inland.

4.4 Key processes

The processes that drive the absolute movement of diagenetic zones in space can be grouped into two categories. The first category constitutes those processes that occur in a sedimentary stable beach, i.e. variations in water flow. The second category consists of the processes involved in the movement of the beach body, predominantly shoreline movement. A complex coupling exists between processes from both categories.

4.4.1 Variations in water flow

The beach body is the boundary zone between a saline water influx and a freshwater influx. Ataie-Ashtiani et al. (1999) used a variable-density groundwater model to study the effects of tidal fluctuations on the intrusion of seawater into a beach. They found that tidal activity forces the seawater to intrude further inland and increases the size of the mixing zone. Furthermore, the configuration of the mixing zone changes radically with tidal fluctuations (Figure 9).

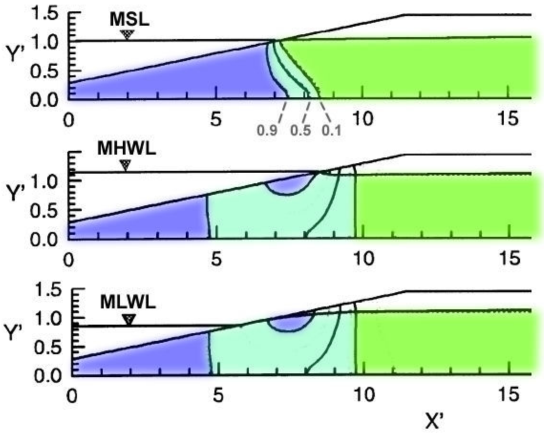


Figure 9 Influence of tidal oscillations on seawater intrusion. Indicated are 0.1, 0.5 and 0.9 salinity contours. Constant freshwater flux, tidal amplitude *A* = 1 m. Modified from (Ataie-Ashtiani et al., 1999)

Similar conclusions were drawn by Urish and McKenna (2004) from a field study of a sandy beach. The configuration of the diagenetic changes during a tidal cycle, although the changes are less radical than calculated by the models of Ataie-Ashtiani et al. Apart from the variable salinity boundaries, the variations in flow direction could also influence beachrock formation.

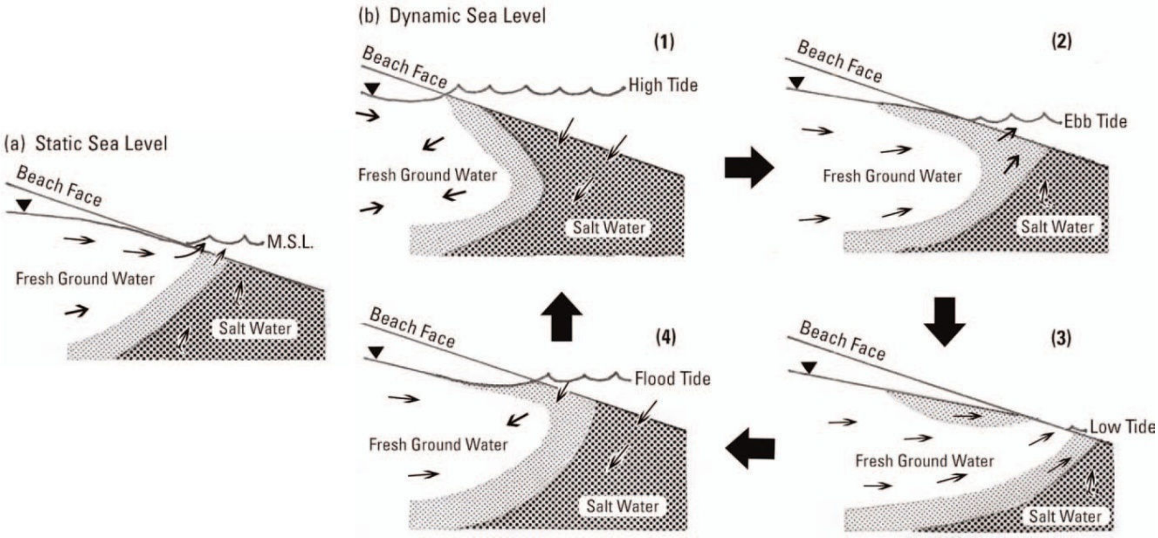


Figure 10 Beach ground water infiltration concept as proposed by Urish and McKenna (2004). (a) Static sea level (b) Tidal cycle. The arrows indicate the general direction and pattern of flow. The stippled pattern between fresh ground water and salt water indicates the mixing zone

There are a number of mechanisms that further affect beach water table oscillations and the subsequent movement of diagenetic zones: seasonal variations, barometric pressure changes due to weather and storm events and different types of waves reaching the coast (Horn. 2002). Although these mechanisms will not be discussed in detail here, it is clear that they will further increase the variability of the position of diagenetic zones. Another complicating factor is the decrease of porosity with the formation of beachrock, undoubtedly influencing beach ground water patterns.

4.4.2 Shoreline variations

On the short to middle term scale, shoreline movements are dominated by fluctuating trends, primarily caused by wave, tide and surge conditions and by seasonal climate variations (Stive et al., 2002). An example of a cyclic fluctuation is the seasonal profile change of a beach, i.e. a steep profile during the calm swell season and a more flat profile during seasons with more high-energetic wave conditions. Rey et al. (2004) found that sea-level fluctuations on a scale of multiple years caused beachrock in Galicia, Spain to be exhumed once every 4 years. Furthermore, extreme events such as storms may cause rapid shoreline movements.

4.5 Diagenetic history and shoreline movement

4.5.1 Diagenetic history of a beachrock

Bearing in mind the variability of diagenetic zones, it follows that the physico-chemical environment in which a new beachrock forms will continuously change during the process. As the diagenetic zones move due to shoreline movement or infiltration processes, the beachrock is placed in a different diagenetic zone. The sequence of zones, plus the time “spent” in each zone, thus determines the cementation characteristics of the beachrock. This diagenetic history of the beachrock defines in a sense the *maturity* of the beachrock, which might be key to its mechanical properties and thus to its resistance to weathering.

Amieux et al. (1989) used cathodoluminiscence to investigate the cement mineralogy of the beachrock outcropping along the coast of Togo. In a cross-section perpendicular to the shore, they observed precipitation zones with different “layers” of cementation. By relating the mineralogical properties of each layer cement to a diagenetic zone (§2.3.2), they reconstructed the diagenetic history of the beachrock. Subsequently, they made an attempt to relate this to shoreline movements as indicated in Figure 11. At the seaward side, an alternation of marine vadose/phreatic and mixing zone was found, indicating slight fluctuation of the shoreline. The overall pattern of cementation indicated a progradational phase followed by erosion.

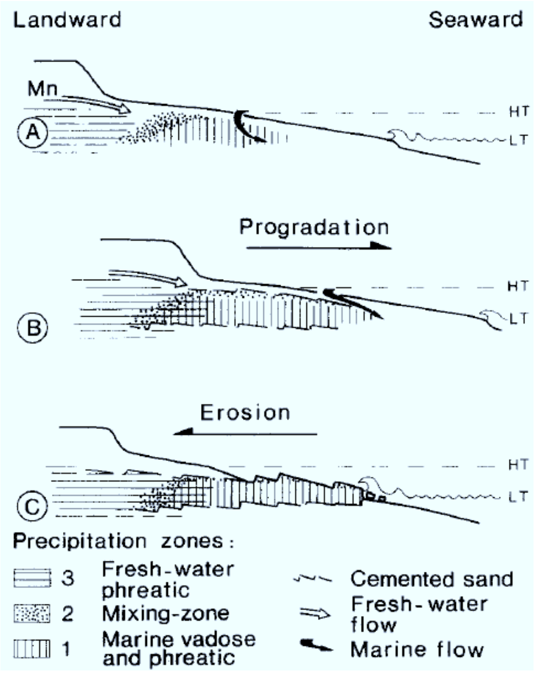


Figure 11 Evolution of a beach profile with beachrock as inferred from cathodoluminiscence by (Amieux et al., 1989).

4.5.2 Relating diagenetic history to shoreline movements

Amieux et al (1989) directly related the diagenetic history of a beachrock to trends in shoreline movement (progradation, erosion). However, this interpretation fails to address other factors influencing the diagenetic history of a beachrock. We propose that the interpretation should be contested on two points.

Firstly, Amieux et al (1989) inferred shoreline movement without considering the associated time scales. The “progradation” and “erosion” phases could thus be small time-scale fluctuations rather than large-scale trends. The current interpretation suggests both these phases occurred only once after formation of the beachrock, while in reality multiple cycles might have occurred.

Secondly, diagenetic processes can also alter, remove or replace existing cements. These processes corrupt the diagenetic history and make the interpretation of it more difficult. Alteration of cements can also occur upon subaerial exposure of the beachrock by microbial action. Turner (1999) suggested that in this additional diagenetic zone, case hardening under the influence of biota may have a significant influence on the properties of the beachrock.

4.6 Large-scale shoreline movement and beachrock occurrence

4.6.1 Beachrock destruction by large-scale shoreline movement

Once beachrock is formed, the development of the coast determines whether the beachrock remains buried or becomes exposed. Large time-scale shoreline movement is thus predominantly a control on the destruction and thus *occurrence* of beachrock rather than on its *genesis* or *generation*. This important distinction is often not made by researchers, i.e. Viera and De Ros (2006): “*The generation of beachrocks is apparently related to sea-level oscillations. However, it is still not clear whether the preferential conditions for beachrock formation are attained during sea-level rise, fall or stillstand.”*

Apart from not making the distinction between genesis and occurrence, Viera and De Ros (2006) refer to sea-level trends rather than the net development of the sedimentary system, i.e. transgression or regression. During transgressive periods, beachrock will become exposed and ultimately destructed. Stable or regressive periods will allow for conservation of the beachrock.

4.6.2 Beachrock as an indicator of a former shoreline

A beachrock found in the beach zone is not necessarily of the same age as the surrounding sediments. The destruction of beachrock upon exposure will depend on the cement characteristics of the rock and the hydrodynamic conditions to which it is exposed. Stronger beachrock may withstand periods of exposure and be later incorporated into younger sediments during a regressive period. After incorporation, new cementation or alteration of existing cements may occur inside the beach body.

Viera and De Ros (2006) mentioned the uncertainty in time of framework deposition to time of cementation. Cementation may start only hundreds to thousands years after deposition and the speed of cementation can vary substantially over time. Dating of beachrock-constituent organisms may thus only yield the maximum possible age of a beachrock. These factors limit the use of beachrock *cements* in paleo-environmental reconstruction. Alternatively, the analysis of weathering patterns might yield useful information on previous exposures and possibly hydrodynamic conditions during those exposures.

4.7 Conclusions and hypotheses

It is argued that beachrock *genesis* is controlled by small time-scale variations of processes that govern the inside-beach physico-chemical environment. These processes, related to groundwater flow and shoreline movement, influence the different diagenetic zones that exist within the beach body. The sand body that is being cemented will experience different diagenetic zones, which governs the final cement characteristics of the beachrock.

Detailed mineralogical investigation of beachrock cements is needed to prove this hypothesis. An interesting opportunity would be to investigate cement mineralogy of a beachrock that is currently under formation. The presence of different cement generations in such a beachrock would provide proof for the hypothesis. Furthermore, the resistance of a beachrock to weathering could be related to the cement properties caused by its diagenetic history.

At the same time, it is argued that the diagenetic history of a beachrock should not be directly linked to large-scale shoreline movement. The genesis of a single beachrock alignment is not likely to be governed by long term processes. Weathering patterns of a beachrock could have potential as paleo-environmental indicator.

Chapter 5 Morphodynamic impact of beachrock exposure

5.1 Introduction

Beachrock outcrops are likely to have a significant influence on shoreline dynamics. The activation of a hard, (quasi-) non-erodible structure in a shoreline profile will affect the shore equilibrium, forcing a response in hydrodynamic patterns and morphology. Research on this topic, however, is scarce and often highly case-specific, related to the many different appearances of beachrock and the many settings in which they are found. Table 3 shows an overview of the case-related research carried out on this topic, indicating a focus on island settings.

Table 3 Research carried out on the morphodynamic impact of beachrock exposure.

Location	Setting	Reference
Natal, South Africa	Linear clastic (sandy) shoreline	(Cooper, 1991)
Funafuti islands, Pacific Ocean	Atoll island	(Dickinson, 1999)
Lesbos, Greece	Island	(Vousdoukas et al., 2009)
La Palma, Canary Islands	Island	(Calvet et al., 2003)

There is a strong reason to believe that the interaction between beachrock outcropping and shoreline dynamics is highly setting-specific, as sediment budgets and forcing factors differ fundamentally. For atoll island settings, beachrock occurrence might be an important factor in their metastable state, as indicated by Dickinson (1999). In this chapter, an analysis is made of the case of a retreating linear clastic shoreline with buried beachrock formations, referred to as the Togo case. Furthermore, an analysis of impact of beachrock *genesis* on sediment budgets made by Cooper (1991) is discussed in §5.5.

The integral study of a retreating coast with buried, discontinuous shore-parallel barriers is an untouched topic of research. The approach chosen in this report is to divide the development into different cross-shore profiles using the equilibrium concept. For this approach, it is assumed that there is a single, uniform alignment beachrock, similar to an engineered structure. In reality, the appearance of beachrock is far more complex, with a considerable variation in geometry. Furthermore, different alignments can existed in one cross-shore profile. It should thus be kept in mind that the models presented here are all simplifications of reality.

5.2 Cross-shore profiles

5.2.1 Concept

The influence of a beachrock outcrop on shoreline dynamics will be largely determined by its geometry and position within the cross-shore profile. As coastal retreat continues, the position of the beachrock and thus its morphodynamic impact changes. Using the equilibrium concept as a basis (§3.3.2), this evolution is categorized into a set of schematized cross-shore profiles. In each profile, different processes play a role in determining the morphodynamic response to a change in hydraulic forcing.

The first important distinction is whether the beachrock is buried inside the beach, continuous in the foreshore or acting as a breakwater. Secondly, the geometry of the beachrock, especially the crest height in the beachrock is of importance. Apart from these two major demarcations, a large number of parameters related to the specific case will influence the morphodynamic evolution. The concept proposed here is thus merely a starting point for further, detailed investigation.

5.2.2 Buried beachrock

A buried beachrock is a beachrock present in the beach body but covered by a layer of loose sediment. Buried beachrocks exert morphological control on the beach profile, by setting the limit for erosion of the beach (Vousdoukas et al., 2007). Hard beachrock surfaces are thus thought to affect the free fluctuation of beach profiles, diminishing their ability to adapt in correspondence with changing wave energy.

Another important control is the decrease of beach porosity by the cementation of beach particles. The non-uniform decrease in porosity will influence beach hydrodynamics, i.e. by blocking or diverting the groundwater flow (see §4.4). The hydrodynamic state of the beach is in turn strongly coupled with its morphological behavior. While these processes are of great importance, this complex system is yet poorly understood. One of the effects that have been well documented, is the tendency of a beach with a high respectively low water table to show erosion or accretion (Horn, 2002). In this light, the influence of beach cementation might be of particular interest.

5.2.3 Beachrock continuous in foreshore

Once the beachrock is exhumed, it can block cross-shore sediment transport, thus locking the beach profile to a temporary equilibrium state. This process is often associated with significant morphological changes in the inner surf and swash zones, i.e. the formation of ‘scour steps’, affecting the cross-shore distribution of wave energy (Vousdoukas et al., 2009). Scouring of the seabed adjacent to the beachrock will start upon its first exposure in the foreshore zone as it limits cross-shore transport. Depending on its width and surface level, the beachrock will cause a temporary widening of the backshore.

Rossi (1988) has been the only researcher to carry out laboratory work on the implications of beachrock exposure in a cross-shore profile. This work examined the profile response of a beach to a beachrock exposed in the foreshore under the hydrodynamic conditions that occur on the Togo coast. The base of the beachrock was fixed on the non-erodible bottom, while a width (cross-shore) of 50, 25 and 10m was examined. The top of the beachrock was at 0,50 meter above MSL, while for the 50 m width test this was varied between +0,50, 0,00 and -0,50m. The test was performed on a 1/80 scale, representing a period of 3 years in nature.

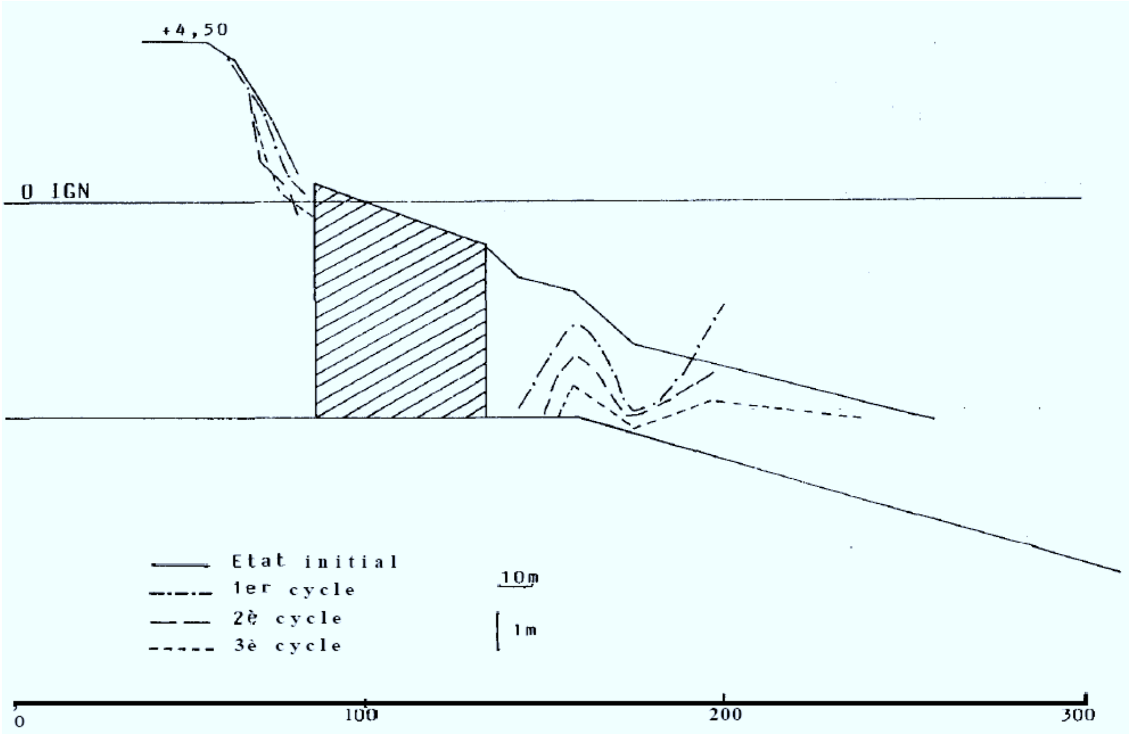


Figure 12 Beach profile response to a beachrock of 50 meter width at an altitude of 0,50m above MSL. IGN denotes MSL, Etat initial is the initial state (solid line). From Rossi (1988)

The reference test without beachrock exposure showed an average coastline retreat at MSL of around 15 m yr^{-1}, without having attained a new equilibrium profile. Tests with beachrock showed that for a width of 50m at +0,50m MSL, cross-shore sediment transport over the beachrock is almost completely blocked, causing extensive scouring of the seabed seaward of the beachrock. Shoreline retreat is at the order of 3-4 m yr^{-1}, reaching an equilibrium after 10 m of retreat. At a height of 0,00m MSL, retreat is in the order of 6 m yr^{-1} and appears to be going towards an equilibrium state, while at a height of -0,50m beach profile response is almost identical to that of the reference test. Variation of the width shows a similar pattern: at a width of 25m at +0,50m MSL coastal retreat is faster but appears to be going towards an equilibrium state, while for a width of 10m the influence of the beachrock in the profile becomes minimal and no signs of stabilization can be seen.

5.2.4 Emerged offshore beachrock

The influence of an emerged offshore beachrock in a cross-shore profile is essentially identical to that of engineered detached breakwaters, to which the morphodynamic response is reasonably understood. However, detached breakwaters are often segmented with breakwater lengths smaller than those of natural beachrock occurrences. Furthermore, the crest level of engineered breakwaters will generally be sufficiently high to effectively set water transport over the structure to zero, while the intertidal origin of the beachrock causes an often lower crest level, allowing water transport during high tides or extreme events.

Emerged detached breakwaters absorb practically all wave energy impinging on the coast. This affects the distribution of the longshore sediment transport The morphodynamic response to a detached breakwater is commonly described by using the dimensionless parameter $L_B^* = \frac{L_B}{x}$, with L_B being the length of the breakwater and x the distance to the shoreline. An engineering guideline is then that for $L_B^* > 0.9$ a tombolo will form behind the breakwater, i.e. accretion will connect the breakwater to the land. An example of how these guidelines could be used for the Togo case is discussed in §9.1.2.

5.2.5 Submerged offshore beachrock

The characteristics of and processes governing shoreline response to emerged and submerged structures are fundamentally different (Ranasinghe and Turner, 2006). Shoreline response to submerged structures is much less understood, indicated by the fact that even the *mode* of response (i.e. erosion or accretion) cannot be scientifically accounted for. Beachrocks operate in the boundary zone between submerged and emerged structures, determined by their initial surface level and further complicated by tidal fluctuations and lowering of the surface level by weathering.

Submerged coastal protection structures are becoming increasingly popular due to a perceived ability to protect the beach without loss of beach amenity or negative aesthetic impact (Ranasinghe and Turner, 2006). The volume of research dedicated to this type of beach protection is growing fast, but most applications have been highly experimental as no proper engineering guidelines exist. Furthermore, identical to emerged beachrocks, geometric differences limit the comparison between engineered and natural structures.

Another parallel can be drawn to perched beaches, i.e. an artificially created beach profile using a submerged toe structure. This toe structure is used to effectively move the existing beach profile seaward while limiting the amount of sediment necessary. Dean (1991) proposed a formulation for the beach equilibrium profile of such a beach, later modified by Gonzalez et al. (1999). In this approach, the energy fluxes over the submerged barrier are evaluated. The resulting formulations might be useful to assess the influence of a submerged barrier on shoreline development. It should be noted that these formulations apply only to barriers which do not induce wave breaking at their crest.

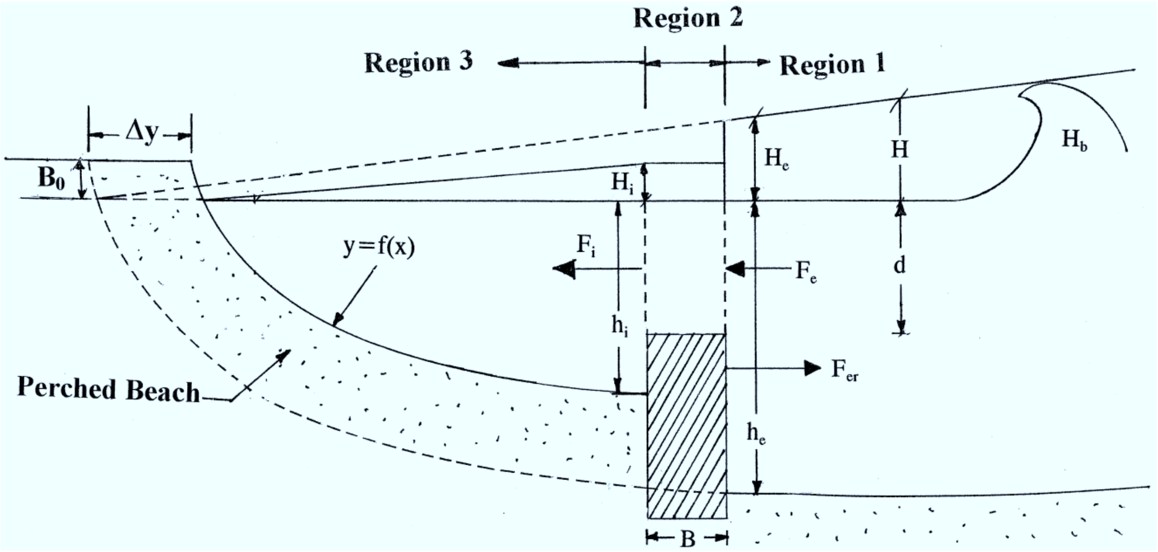


Figure 13 Sketch of a perched beach with approach to solve equilibrium profile using energy fluxes from Gourlay (1994). Fx denotes an energy flux. Part of the incoming wave energy is reflected by the submerged barrier.

5.3 Modeling retreat of a coast with buried beachrock

Most coastal engineering problems are determined by an initial equilibrium disturbance (man-induced or natural; short term or trend) which are mitigated by hard (engineered structures) or soft (sand nourishment) measures. As a result, the majority of research and analytical methods available focuses on these problems. Thus, the response of a coastline to the placement of a hard structure in the shoreface zone is reasonably well understood. In contrast, the response of a retreating coastline to existing buried hard structures has, as far as known by the author, not been examined yet.

Modern coastal engineering practice involves the use of process-based modeling software for analysis and design purposes. Using these models wisely, they are capable of producing realistic results for many common coastal engineering problems. Validation of model results with laboratory scale tests or natural analogue investigation forms an integral part of the development of these models.

Modeling the retreat of a coast with discontinuous buried beachrock at different crest levels, both submerged and emerged as in the Togo case, is not yet feasible with the current models (R. Ranasinghe, pers. comm.). The near-shore morphodynamic processes that play a key role in this problem are on the frontier of current research. One of these topics is the poorly understood response of a coastline to submerged barriers (§5.2.5). In order to evaluate the Togo case with modeling software, further development on these topics is necessary.

A different approach used in coastal engineering is the application of engineering guidelines for hard structures. These guidelines, as discussed in §5.2.4, are based upon theoretical analysis and practical experience. How these engineering guidelines can be used in the Togo case is further discussed in §9.1.2.

5.4 Complications in nature

The appearance of beachrock in nature is highly complex. Natural variation in the occurrence of beachrock make the problem far more complex than can be accounted for with the models presented here. From a lateral (longshore) perspective, adjacent areas with different settings (submerged/emerged/..) will show particular hydrodynamic and sedimentary interactions which are not addressed in current engineering practice. Engineered structures are designed to avoid certain interactions that are unwanted or too difficult to predict.

Furthermore, the rock mass properties of beachrock show a large natural variation, unlike engineered structures. As a result, beachrock can exhibit zones of lower strength, which is of major importance when it acts as a natural shoreline protection mechanism. A better understanding of the genesis of beachrock can aid in analyzing and predicting the variation in rock mass properties. Furthermore, it is important to understand which weathering processes are dominant in the degradation of beachrock.

5.5 Impact of beachrock genesis on sediment budgets

Apart from the morphodynamic impact of the exposure of existing beachrock, also the *genesis* of beachrock could have impact on the coastal system. Cooper (1991) states, in a study of beachrocks along the South African coast near Mozambique, that the volumetric loss of sediments through beachrock *genesis* may be significant in the sediment budget in certain coastal settings. A simple calculation of volume of lithified sand (120,000 m^3/km of coast in the South Africa case) combined with the knowledge that lithification could take place on a year to decade scale, yields a theoretical potential loss of volume that is comparable to that of landward aeolian transport (3,000 m^3/km/yr for the same case).

It should be noted that Cooper addresses with this calculation of yearly losses, the impact of beachrock *genesis* on sediment budgets. However, when assuming that (1) beachrock lithification takes place inside the beach body and (2) formation of beachrock requires “stability of the beach”, the significance of this loss is low. When considering beachrock exposure during coastal retreat, calculation of volumetric loss with respect to other changes in the sediment budget might be an indicator of the importance of beachrock in the total process.

5.6 Beachrock weathering

The weathering of beachrock is a topic that has received little attention in research. There have been no attempts made to quantify the rate of destruction of beachrocks, whereas only limited information is available regarding the mode of destruction.

Beachrock outcrops that have been exposed for longer periods of time show various weathering patterns. Potholes are features of mechanical erosion, caused by wave-induced movement of larger loose sediment particles that have become trapped in beachrock cracks (Russell, 1962). Ridge-furrow systems in beachrock may develop from freshwater rilling and/or backwash channelling on the lower foreshore while the beachrock is only in early stage of cementation (McLean, 1967). Elongation, widening and deepening of furrows is then accomplished mainly by corrasion. Chemical weathering from seawater can create dissolution and weathering basins in beachrocks, as decrease in seawater pH and other environmental parameters increase carbonate solubility (Miller and Mason, 1994). Further chemical interactions are likely to be complex, as carbonate precipitation, diagenesis and dissolution are diachronic processes.

Rossi (1988) has proposed basic guidelines to assess the suitability of beachrock as a shoreline defense, including those related to the resistance to weathering. In his opinion, a beachrock should be at least 2,5 m thick with an average *resistance a l'ecrasement* ("crushing resistance") of 250 kg cm^{-2}. This suggestion is made without reference of testing method or test results and thus requires validation.

5.7 Conclusions and hypotheses

The morphodynamic impact of beachrock exposures is highly dependent on the setting in which the beachrock occurs. In this chapter, the case of a retreating sandy shoreline was investigated. In such a case, the morphodynamic response of the coastline can be assessed by looking at the position of the beachrock in the cross-shore profile. For each position, different morphodynamic processes will come into play.

Many of these processes are only poorly understood. When the beachrock is still inside the beach body, it will affect beach groundwater flow, which is in turn linked to sediment transport. Once the beachrock becomes exposed, it will lock the beach profile to a temporary equilibrium state as it blocks cross-shore sediment transport. Long-shore sediment transport or extreme events can cause further retreat of the coastline. A new equilibrium profile will ultimately be established, on which the crest level of the beachrock (emerged or submerged) is of major influence. The integral study of this case, a retreating sandy coast with buried, has never been performed.

When addressing the impact on shoreline development, it is important to stress the differences between beachrocks and engineered structures. Beachrocks exhibit a natural variation in rock mass properties that define their resistance to weathering. A better understanding of beachrock genesis can help to analyze and predict these variations.

Part II Case Study

Chapter 6 Case introduction

6.1 Overview

On the Togo shoreline, an elongated occurrence of beachrock has been exposed in since the 1980's. Upon completion of the Akosombo dam in the Volta river (Ghana) in 1965, sediment supply to the Gulf of Benin was cut, causing erosion and exposure of buried beachrock (Blivi, 1998). The construction of a deepwater port at Lomé (Togo) further aggravated this process, whereas erosion continued along over 100km of shoreline.

The coast retreat rates are in the order of 4 m year-1(Rossi, 1988). The beachrock present in the surf zone acts as a barrier, and thus as a buffer in coastal erosion. However, it is unknown at which rate the beachrocks are eroded (Gischler, 2007), which zones are most vulnerable to erosion and how the beachrock formation will continue to 'protect' the shoreline in the near future.

The Togo shoreline is a unique case to study beachrock erosion. The fact that the beachrock has only recently been exposed provides important system boundaries, whereas the availability of data covering the full time span of exposure allows for an unprecedented study into the relationship between beachrock characteristics and shoreline evolution.

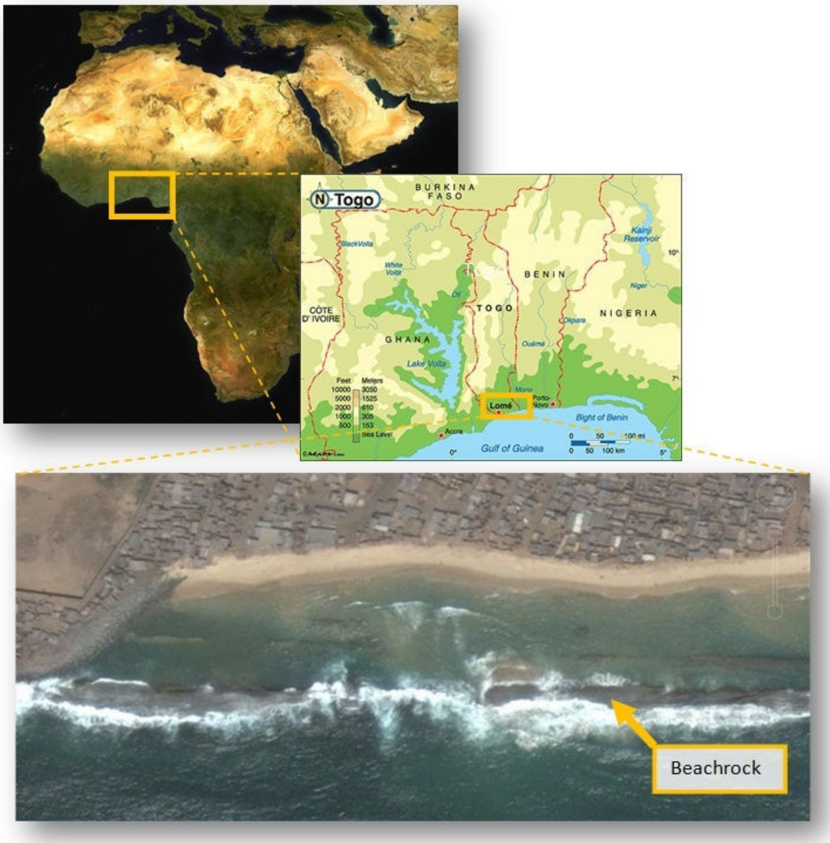


Figure 14 Location of study. Image courtesy: eosnap.com. maps.com, Google earth

6.2 About Togo

Togo is bordered by Ghana to the west, Benin to the east and Burkina Faso to the north, covering an area of 56.600 km^2 (1,36 times the area of the Netherlands). The economy of the 6.7 million inhabitatants is mainly driven by agriculture, such as cotton, coffee and cocoa. The littoral zone, defined as the area from the coastline to 50km inwards, covers 11% of the total area of Togo while it is home to 42% of the Togolese population (UNEP, 2007). The usage of this land has increased heavily following the fast growth of the population, having quintupled since Togo's independence in 1960. Furthermore, urbanization has caused the capital Lomé and other coastal cities to expand rapidly.

Figure 15 Coastal evolution at PK20 1985-2009: Appearance of beachrock, destruction of old road and increased population pressure. Images courtesy CGILE

6.3 Regional geology and setting

6.3.1 Environmental setting

The present-day Togo coastline forms part of a sand barrier-lagoon system, fed by several small coastal rivers and by the Volta River in Ghana. The latter has a drainage area of 390.000 km2, consisting of a wide variety of lithologic facies with predominant sandstone terranes (Anthony and Blivi, 1999). Before the completion of the Akosombo dam 60 km upstream from the sea, the Volta river discharge varied between 1000 m^3/s in the dry season and 6000 m^3/s in the wet season. The sand load carried by the river and inserted into the longshore drift system has been estimated at 10^6 m^3/year (WLDelft, 1986). East of the Volta river, the Ouémé and the Mono are the largest rivers feeding the lagoonal and lacustrine system.

The Bight of Benin coastline is exposed to a constant, low- to moderate energy (H=0.5-1.5m), long-period (T=10-15s) Atlantic swells, generating a very high longshore sand drift. As the Akosombo dam cut the sediment supply to the delta, this sand is thought to originate from reworking of delta mouth deposits, with rates recorded up to 1.5 x 10^6 m^3/year (Rossi, 1989). The coastline is cyclone- and storm-free with a mean tidal range of 1 m and a mean spring tidal range of 1.5-2.0 m.

6.3.2 Morphological setting and controls

The barrier system bounds a coastal plateau of Tertiary to Quaternary age consisting of two entities. One entity is a Mio/Pliocene formation of fluviatile and sheetwash sands, sandy clays and gravels, named "Continental Terminal". The second entity is the "Terre de Barre", an Early Quaternary sheetwash sediments deposit of fine quartz sands and kaolinite, originating from lateritic soils upland. Both entities are unfossiliferous (Anthony and Blivi, 1999).

The coastal plateau shows what has been interpreted as horst and graben structures and was deeply cut by rivers during postglacial regression, leaving depressions now occupied by marshy wetlands and lagoons. The Quaternary deposits in these re-entrants have a maximum thickness of 150 m and reflect several cycles of regressive and transgressive sedimentation.

Another important structural control on the development of the coastal system is the limited shelf width, favouring the elaboration of a transform margin bounded by a 15-33km wide shelf. The coast shows a moderately steep upper shoreface with a gradient ranging between 1:20 and 1:50 up to 10 meters depth, which is thought to be the outer limit of significant wave action. The lower shoreface is generally low-gradient beyond this depth.

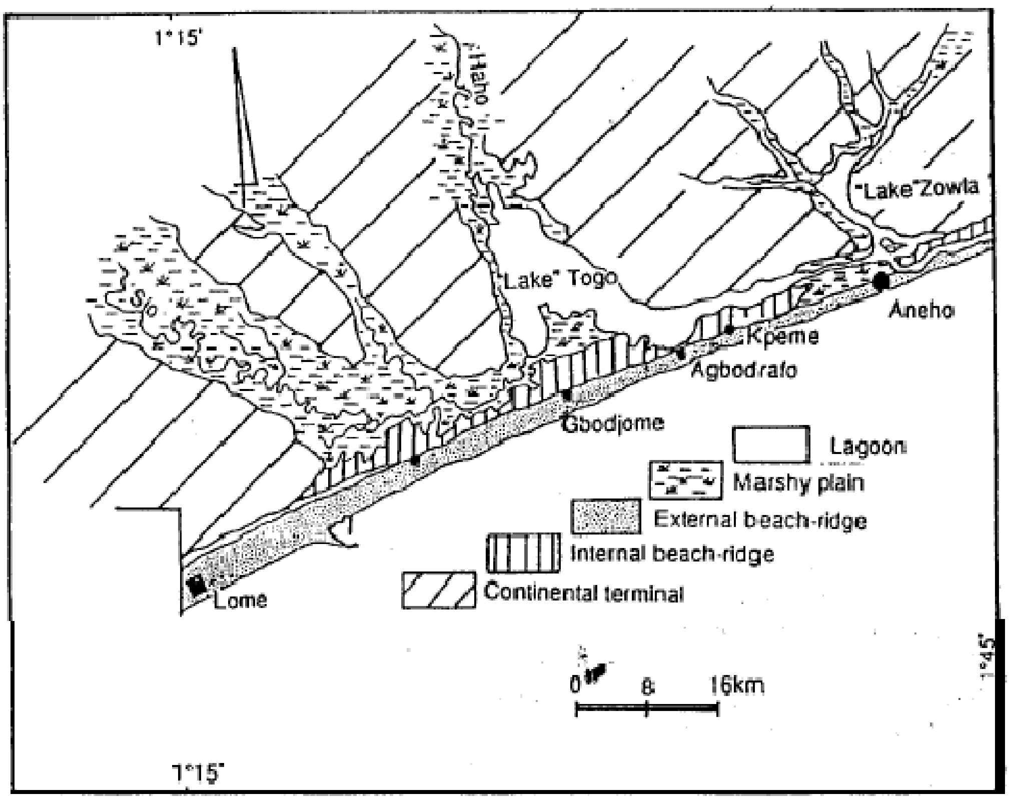


Figure 16 Geomorphology of the Togo coastline. From Blivi (1993)

6.3.3 Sedimentary facies

The beach and shoreface sands of the barrier deposits vary in thickness from less than 5 m on the landward part to 20 m seaward. Borehole logs show an 8-15m thick unit of beach and upper shoreface sand, with gravel patches from various crystalline and sedimentary source rocks, and shelly debris. The beach sand is >80% quartz with minor fractions of feldspars (up to 10%), shelly debris (5-15%) and heavy minerals (1-5%). The quartz sand is medium to coarse ($D_{50}=0.6\ mm$) and subangular to subrounded (Anthony and Blivi, 1999).

Blivi et al. (2002) indicate that sands supplied by the Volta are texturally and mineralogically distinct to those originating from the coastal plateau. The inner barrier (Figure 17), composed mainly of sediments from the latter source, has a lower to zero carbonate content, while the heavy mineral suite is diversified and dominated by iron concretions (such as limonite) and worn ubiquitous minerals, such as zircon, tourmaline, rutile, sphene and disthene. The outer barrier sediments commonly include fine gravel fragments from crystalline source rocks, while the heavy mineral fraction is dominated by a set of easily weatherable minerals (garnet, epidote, amphibolite and green hornblende).

6.4 Morphosedimentary evolution

6.4.1 Transgressive barrier development

Interpretation of the Late Quaternary infill of rivermouths in Benin indicates that the Terre de Barre formation was , during the Holocene sea-level rise, transgressed by marsh and lagoonal mud deposited behind transgressive sand barriers (Anthony, 1995). Initial aggradation of these sand bodies is thought to be significant and at high rates, with the fine-grained river sediment trapped behind them. In the last phase of the transgression, tidal, wave- and washover sediments were deposited.

6.4.2 Inner barrier development

The structural controls exerted by the Continental Terminal headlands caused a segmented pattern of development of the inner barrier. Sand eroded from Late Pleistocene cliffs and longshore transport from the Volta river provided sediments for rapid beach and shoreface progradation, thus preserving the transgressive-aggradation sandy and muddy facies on the shelf. Successive progradation of spits eastward progressively closed off the Zio and Haho estuaries in Togo (creating the Togo lagoon) and the Mono and Couffo estuaries in Benin (Blivi et al., 2002). Further East in Benin and Nigeria, spit progression across eastuaries was probably constrained by a smaller sediment supply and by the existence of deeper estuary-mouth shoals.

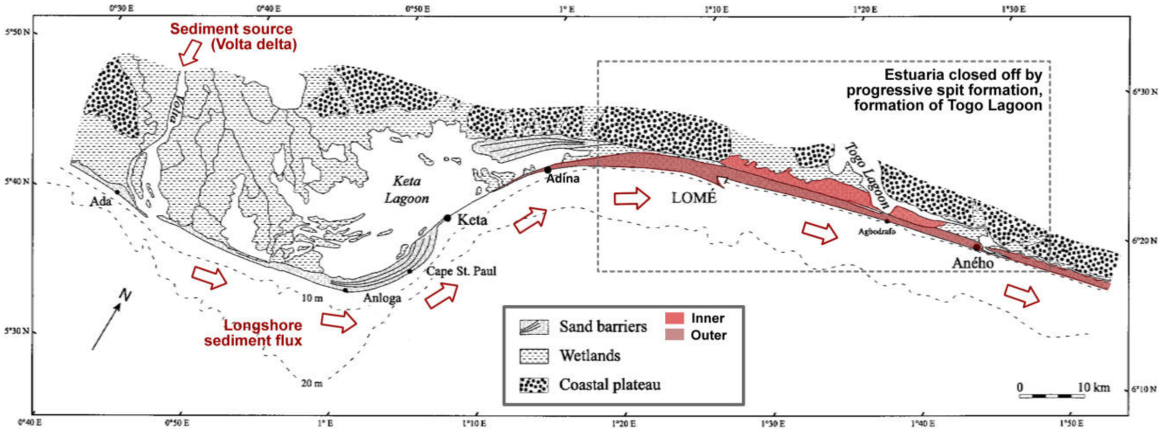


Figure 17 The barrier-lagoon system of Eastern Ghana and Togo. Modified from Anthony and Blivi (1999)

6.4.3 Outer barrier progradation

After shoreline regularization by the development of the inner barrier, the succeeding phase involved the development of an outer barrier. This more continuous barrier is directly linked to a transition of massive sediment sourcing by the Volta. This is also indicated by the updrift narrowing of the proximal part from Lomé westward, representing progressive delta-ward migration of the hinge point.

The barrier types characterising this phase are depicted in Figure 18. Anthony and Blivi (1999) state that during the progradion phase, the delta front exhibited a regressive barrier, while the section between Keta and Adina was essentially stationary. From Adina eastward to Benin, the coast was characterised by a regressive barrier, except for the Aného inlet area. Here, the marshes and lagoon diverted eastward by the barrier system are partially drained into the sea, as the coastal plateau is in close proximity of, and thus increases pressure on the barrier system.

6.4.4 Equilibrium drift-alignment

While radiocarbon ages indicate little net progradation of the barrier near Ada and Anloga, the behaviour over the past 5000 to 6000 years of the barrier here remains speculative. Radiocarbon ages taken downdrift suggest that the progradation of the barrier system in Togo and Benin was relatively rapid (5000 to 3000 yr B.P) and that it was followed by a phase of equilibrium drift-alignment; morphological stability obtained by an equilibrium of processes involving shoreline orientation, nearshore profiles and hydrodynamic regime.

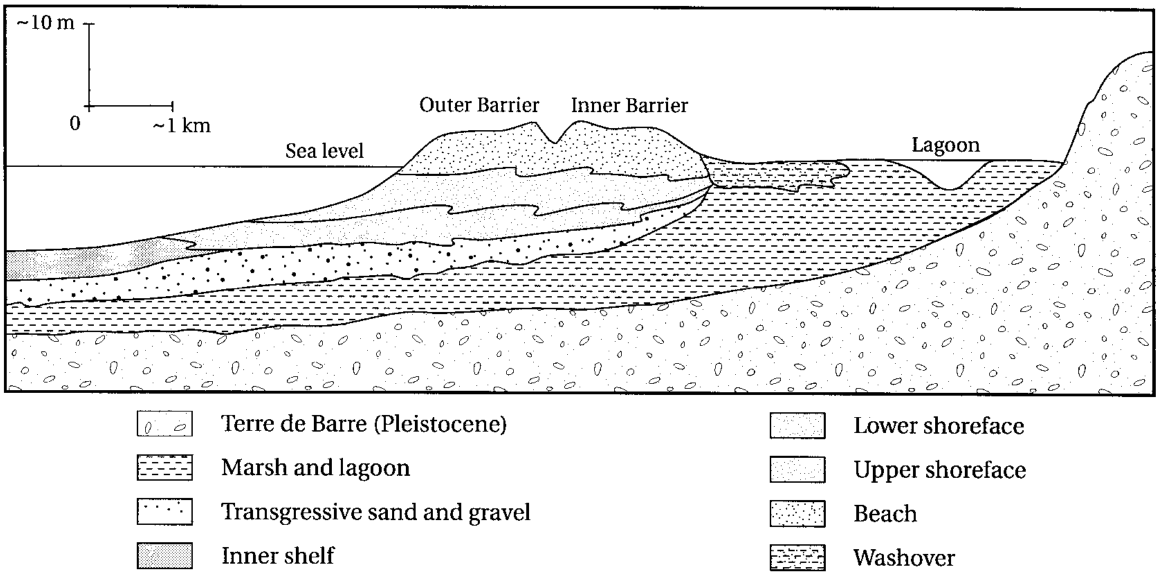


Figure 18 Schematic stratigraphic cross-section, based on the coastline of Togo between Lomé and Aného. From Anthony and Blivi (1999)

6.4.5 Recent developments

The equilibrium drift-alignment of the Bight of Benin sand barrier system has been confirmed by the existence of European settlements from the 16th century and onwards (Anthony and Blivi, 1999). There is evidence to suggest that from 1850, reworking of delta mouth deposits was necessary to meet the sediment budget imposed by the strong longshore current, thus causing fluctuations in the shoreline profile in the Volta Delta region. The stability of the total barrier system was later severely compromised under anthropogenic influence, starting with the construction of the Akosombo dam on the Volta river in 1961. The subsequent drastic reduction in sand supply caused further reworking of the Delta sediments and erosion along the Bight of Benin coast. The inauguration of the Lomé deepwater port in 1967 caused an even greater perturbation in the longshore sediment dynamics, causing heavy erosion eastward and accretion on the westward side of the port. These recent developments have now effectively segmented the coastal system.

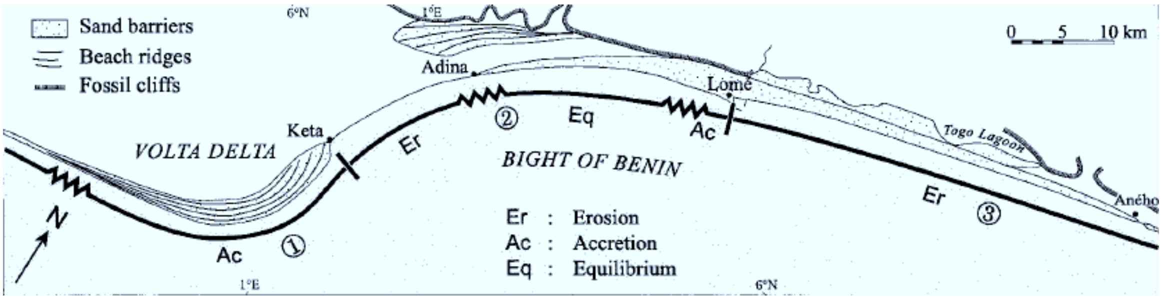


Figure 19 Segmentation of the former unique sediment cell in the Bight of Benin by recent developments. From (Anthony and Blivi, 1999)

Substantial sequestering of sand from the Volta Delta mouth created a prograding beach-ridge spit complex (Figure 19; zone 1). Recent fieldwork shows increased spit accumulation since 1992 with a probable shift to a less swash-aligned configuration, allowing Volta sand to 'leak' towards the erosional zones (Anthony and Blivi, 1999). The barrier-lagoon system has been segmented into two cells by the construction of the Lomé port. The coastline between Adina and Lomé (zone 2) shows overall net stability while the part closest to the Lomé part shows aggradation. Directly east of the Lomé port (zone 3), the coastline has retreated over 200 meters, while erosion progressively continues eastward. The zone of Kpémé, where the phosphate factory is located, has been protected from erosion by the construction of a groyne field, effectively shifting the erosion more eastward to Aného and Bénin. The sealing of the Aného inlet by a sediment spit has now been reduced from 11 months to 8 months per year, causing saltwater intrusion into the hitherto freshwater lagoon of Togo.

Chapter 7 Data review and methodology

7.1 Available data

Previous research has yielded a considerable amount of data on both the provenance and the characteristics of beachrock as well as on the geomorphological evolution of the Bight of Benin coast. The hydrodynamic environment has been studied in less detail, but the available documentation proved sufficient for the purposes of this report. Unpublished aerial photographs were provided by the Togo *Centre de Gestion Integrée du Littoral et de l'environnement* (CGILE).

Table 4 List of data types and used sources

List of available data

Category	Type	Source
Beachrock	Refraction seismics, $CaCO_3$ contents, particle size	Blivi (1998)
	Cathodoluminiscence	(Amieux et al., 1989)
	Dating	(Anthony and Blivi, 1999)
Shoreline	Aerial photography (1986 and 2009)	CGILE (unpublished)
Hydrodynamic	Tidal parameters	(Rossi, 1989) ; (UNEP, 2007)
	Sediment type and transport	(Rossi, 1989)

The consistency of the available data on the beachrock formation is generally poor. Research carried out has focused on sites of specific economic interest, e.g. at the former Tropicana hotel and at the Kpémé wharf. Furthermore, documentation often lacks accurate sampling locations, which severely limits its use given the large lateral variation. Last, there is a very limited temporal range with all data having been acquired between 1973 and 1987.

7.2 Interpretation of airborne photography

Airborne photography was provided by CGILE. The set of imagery obtained in 2009 consists of around 300 high-resolution images, covering the full coastline of Togo. The set of imagery obtained in 1985 was unfortunately of poor quality and available in digital format only for a limited part of the Togolese coast. These images were interpreted to derive information on the geometry of different beachrock alignments as well as shoreline retreat.

The provided images had not been orthorectified nor georeferenced. Orthorectification was not performed as the topography of the littoral zone is very flat. On location, images were georeferenced with use of Google Earth software. Features on the land were used as landmarks for referencing. As georeferencing was performed with a focus on the continuity of the shoreline, the used methodology provided sufficient accuracy for further interpretation.

Figure 20 Georeferencing with Google Earth

Subsequently, interpretation of the images was performed by tracing of the different elements of the beach system (coastline, shoreline and beachrock). Here, shoreline is arguably chosen to be the limit of the wetted beach at the time of image capture and has limited significance. The beachrock elements are subdivided into (a) emerged (b) overwashed (c) submerged and (d) uncertain parts. This categorization merely served as an aid for the site selection and visits, as it is highly sensitive to interpretation errors. The features drawn in Google Earth were subsequently imported into Quantum GIS (QGIS) and converted to the shapefile format, which allows for more advanced interpretation and site selection for the field campaign.

Figure 21 Interpretation of airborne photography

7.3 Field campaign methodology

A field campaign was carried out after review of the available data and the setup of hypotheses. Data acquisition consisted of visual interpretation and sampling. In a first phase, several days were spent in the field describing the coastline and beachrock in transects (Appendix A). Together with the interpretation of aerial photography, a selection of sites of specific interest was made, withstanding the accessibility of the beachrock. In the second phase, these sites were examined in greater detail. Each site has been thoroughly described and photographed. Furthermore, samples have been taken using a standard geological hammer.

Upon return in the Netherlands, polished thin sections of the samples were made for microscopic investigation. Optical microscopy was performed with a standard Leica apparatus. Further detailed investigation was carried out using Environmental Scanning Electron Microscopy (ESEM), using a Philips XL 30 ESEM apparatus.

Chapter 8 Case study results

8.1 Shoreline development, prospects and mitigation

8.1.1 Recent shoreline development

Shoreline movement from 1964 (start of the construction of the Lomé port) until 2009 has been determined with the use of existing reports (WLDelft, 1986) and airborne photography. There exists no evidence to suggest that the Togo coastline showed significant movement in the recent years before 1964 (Rossi, 1989). Unfortunately, no data for the 1985-2009 period were available on the transect PK (*Pointe Kilometrique*) 26-46. Furthermore, it should be noted that the measurements for this period have been made with a higher resolution, which explains the greater oscillations in the shoreline.

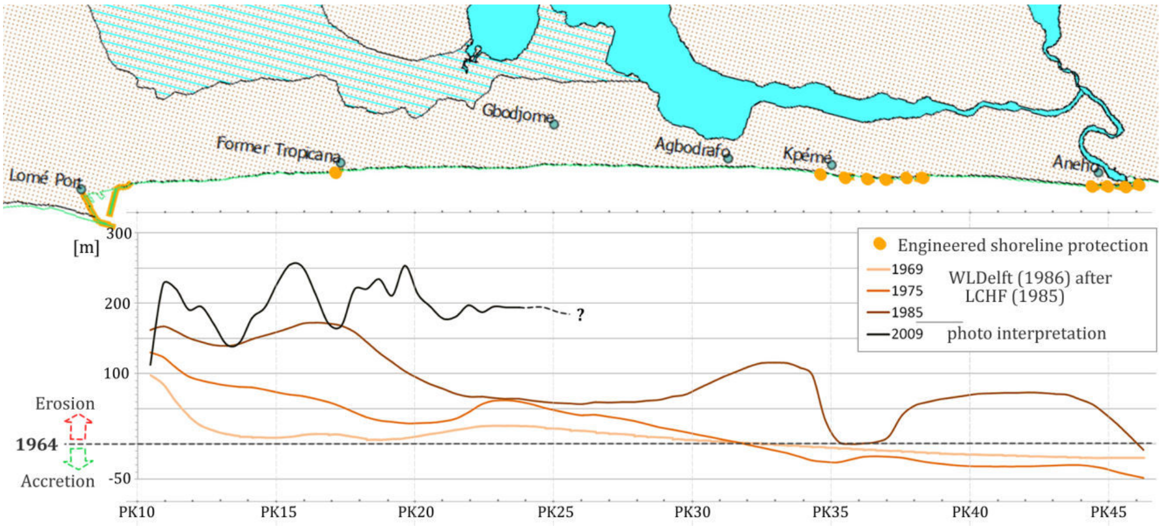


Figure 22 Recent coastline development along the Togo coast East of Lomé harbour. PK denotes the kilometer mark from the Ghanese border in the West.

The development of the shoreline east of Lomé after 1964 can be seen as a wave of erosion travelling eastward (WLDelft, 1986). The apparition of the beachrock formation directly east of Lomé port in 1984 meant that erosion was temporarily halted locally, causing a second wave of erosion to propagate east while rapidly exposing the beachrock. In the early 1980's, the retreat of the coastline posed a direct threat to phosphate factory at Kpémé, which is of major importance to the Togolese economy. Construction of a groyne field effectively shifted erosion eastward towards Aného, where coastal defense works were erected in the 1990's. At present day, the effects of the longshore current interruption at Lomé port reach up to the coast of Benin. Coastline retreat continues on the Togolese coast, in which the natural protection provided by beachrock plays an important role (described in detail in §8.3).

8.1.2 Existing mitigation measures

Mitigation of coastline retreat up to date has consisted solely of emergency protection of the Lomé port, Kpémé and Aného area. Although various external expert committees (WLDelft, 1986) have suggested the use of an artificial sediment bypass of the Lomé port, no structural mitigation as such is under consideration at present. In the Kpémé area, protection of the coast is secured by the use of groynes, while at Aného a combination of a seawall and groynes is put in place. Both systems, erected in 1988, offer sufficient protection. Apart from an extension of the seawall directly east of the Lomé port, no other protection measures have been carried out since.

Figure 23 Groyne field erected for the protection of the Kpémé phosphate industry (background)

Blivi (2001) studied the possible mitigation measures whilst taking into account the presence of beachrocks as a natural defense mechanism. Blivi suggests that the use of groynes is inadequate and that the appropriate mitigation measures should be found in seawall revetments, either on top of the beachrock or on the coastline behind the beachrock. These measures should then focus on the industrial areas and the area where the road between Lomé and Bénin is closest to the coastline.

8.2 Beachrock characteristics

8.2.1 General observations

The beachrock outcropping on the Togolese coast is rather special in terms of global occurrences. The beachrock is found along the full sand-barrier system of the Bight of Benin, covering Togo, Benin and parts of Ghana and Nigeria. Furthermore, single alignments (i.e. an outcrop along a continuous line) can reach up to more than 10 km in length, while most reported occurrences show a length in the order of 10 to 100 meters.

Figure 24 Beach near Lomé port (PK12) with the main formation protecting the coast. See transect T1 (appendix X)

Apart from the beachrock that is now visible on the coastline (*main formation* from here on), more alignments have been found, buried in the shoreface zone and at depth in the mainland. Around 100 to 200 meter seaward from the main formation, another beachrock has been found at MSL -6m to -8m, buried under 1-3m of coarse sediments (Blivi (1998); Rossi, (1988)). Inland, a third beachrock alignment has been found using seismic refraction, situated at 50 to 100 meters landward of the *main formation*.

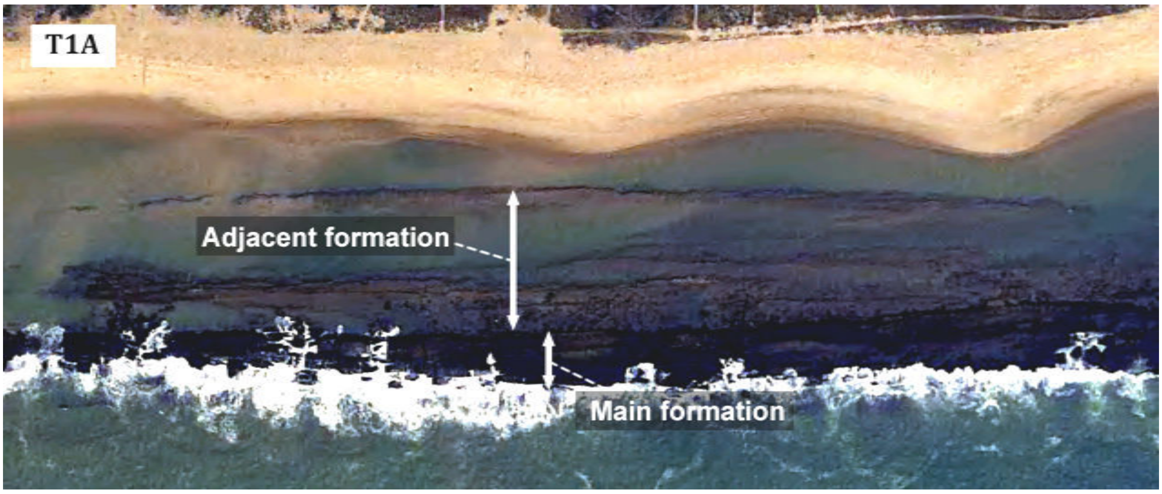


Figure 25 Aerial photograph showing the *main formation* (below) connected with the shoreline by beachrock of lower altitude and different appearance (*adjacent formation*)

These observations have been made in the 1980's and can now be verified and corrected as erosion of the coastline has continued and more beachrock is exposed. In general, the main formation is continuous over large lengths and has a width of 10 to 30 meter. Over large parts of the coast, beachrock at lower altitude and different appearance partly or fully covers the foreshore area between the *main formation* and the shoreline (Figure 25, *adjacent formation* from here on). Furthermore, parts of the coast that are currently eroding fast show newly exposed beachrock, undergoing weathering and erosion and finally disappearing.

The continuity of the main formation decreases towards the east, particularly from PK22. The beachrock becomes very segmented and shows shifts in its cross-shore position. Even further east, the main formation is currently being exposed or yet covered by the beach, which prohibits a proper understanding of its geometry.

8.2.2 Appearance, lithofacies and weathering

The beachrock in Togo shows a high variation in sedimentological characteristics and weathering patterns. Vieira and De Ros (2006) categorized beachrock outcrops in Brazil into lithofacies using their sedimentological characteristics and interpreted the paleoenvironmental setting of each facies. A similar time-consuming quantitative approach could be followed for the Togo case but is outside of the scope of this study.

Main formation

The main formation is characterized by a very hard, slightly seaward inclined (1-3°) upper surface, 5-10 meters wide (cross-shore). At both land- and seaward side, smaller banks (2-4 m width) with higher inclinations (5-8°) can be found. In contradiction to observations made by Blivi (1998), the top surface of this alignment is generally smooth and does not contain many discontinuities (cavities, fractures, diaclases). The top surface can be populated by biota, where emerging parts tend to show higher amounts of vegetation. The specific biota species have not

Figure 26 Relatively smooth top surface of the main formation

been determined in this study. The main formation is often populated with sea urchins feeding on the algae.

Figure 27 Left: Dense vegetation on surface of the main formation. Right: cross-section of the main formation, note layering of dark material and different biota present.

In a vertical section through the main formation the upper unit, thickness up to 40 cm, shows highly continuous, thin dark rims (spacing 1-3 cm). Figure 28 shows the occurrence of similar dark rims inside the beach body. The latter are concentrations of organic material or microbial mats. This top unit shows a higher resistance to weathering than the more homogeneous unit beneath. The lower unit is thought to extend to the bottom of the beachrock, which can be up to 7 meters below top surface (Blivi, 1998).

Figure 28 Layering in the main formation

Microscopic investigation shows that in the main formation, pore spaces are partially to completely filled with micritic cement (Figure 29). In the top layers, fibers of organic material can be observed, collated to the beachrock particles by micritic cement. More microscopic images and sample locations can be found in appendix A.

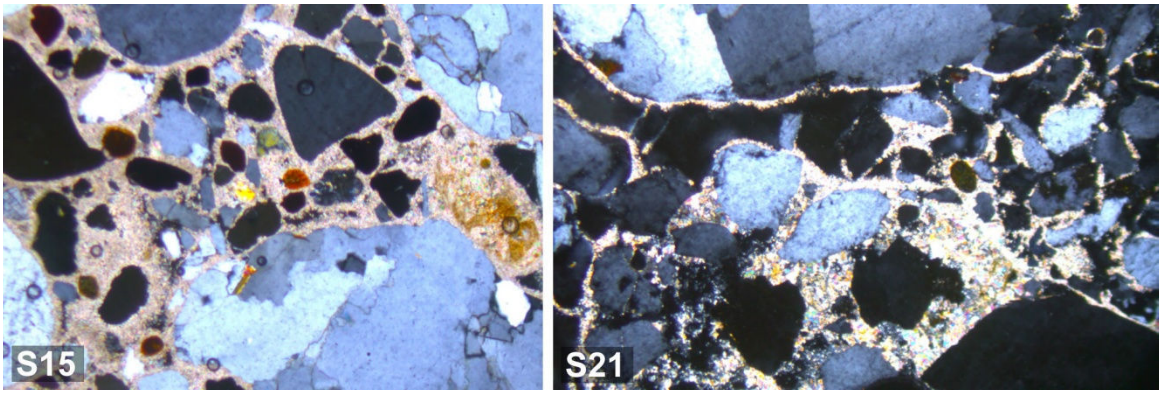


Figure 29 Microscopic images of samples S15 (left) and S21 (right). The pore spaces in S15 are completely filled with cement, while in S21 some grains only have a rim of micritic cement. Images taken at 4x magnification.

Weathering and erosion of the main formation produces rectangular shapes (Figure 30). These very regular patterns indicate that mechanical weathering is the dominant mode of destruction. The alternation of stronger and weaker layers in the beachrock produces banks in the structure (Figure 30, right). The specific patterns of weathering cracks could be caused by tension as a result of undercutting, which will be further discussed in §8.3. The weathering patterns in recently uncovered beachrock indicate that the beachrock has been exposed prior to the current exposure. Sections of very strong beachrock from the main formation under a thin veneer of beach sand show large rectangular fractures and dislocated blocks, similar to the weathering patterns of the main formation that is situated offshore.

Figure 30 Weathering patterns in the main formation

Adjacent formation(s)

The adjacent formations show a wide variety of characteristics, in composition, geometry and weathering patterns. These differences can be explained by variation in maturity of the beachrock, *i.e.* the different degrees and types of cementation. The weathering patterns might also be influenced by the position of the rock and the direction of currents running over its surface.

Figure 31 Adjacent beachrock formation(s)

Other cementation phenomena

As mentioned in §2.2.1, cementation is a common phenomenon in coastal settings, especially in warmer climates. Figure 32a shows thin slabs of sand which are in congruence with the surrounding beach profile. This could be an example of beachrock under formation, i.e. that initial cementation took place only recently (<10 years ago), when the coastline was situated a few more meters seaward. Figure 32b shows a body of cemented sand with characteristics very distinct from beachrock. The body has a very irregular shape, shows no layering and seems to have a rather high porosity compared to beachrock.

Figure 32 a: thin slabs of cemented sand, possibly beachrock under formation. b: cemented sand (calcrete)1-1.5m above MSL

8.3 Shoreline response to beachrock exposure

8.3.1 Deceleration effect

In a cross-shore section, the apparition of beachrock causes a temporary slow-down in the retreat of the coastline. At places where the main formation is covered under a thin veneer of loose sediment, the beach profile changes, increasing the width of the beach (Figure 33). Under normal hydrodynamic conditions, the beachrock blocks the cross-shore transport of sediment, which causes lateral translation of erosion. The hypothesis of deceleration of shoreline retreat is backed by the large percentage of the total coastline that is currently in this state.

Figure 33 Increased beach width caused by underlying beachrock

Further retreat of the coast can be caused by:

a) Long-shore erosion waves landward of beachrock. At some locations, the main formation has been breached, allowing cross-shore sediment transport. Erosion of the beach landward of the beachrock will then spread from this location.
b) Extreme hydrodynamic conditions (storm). Episodic events characterized by higher wave energy and water levels may allow for cross-shore sediment transport over the beachrock.
c) Human intervention. The apparition of beachrock has made it hazardous for fisher(wo-)men to access the sea past the beachrock, given the limited number of places where the beachrock can be passed and the dangerous currents in those areas. Many of them have turned to sand and shell extraction as an alternative source of income. The extractions are by hand, but can add up to considerable volumes . Beach sand extraction is illegal but largely tolerated since the government cannot ensure other possibilities for employment.

Figure 34 Sand extraction

The coastline seems to reach an equilibrium state with a lagoon of around 100m width behind the beachrock barrier, when coastal retreat rates decrease to ranges of 1-2 m year^{-1}, in accordance with the equilibrium beach profile concept outlined in §3.3.2. The coastline directly east of the Lomé harbour, PK11-13 (transect 1), has reached this phase. At locations where the beachrock barrier is breached, the coastline is situated further landward. With the information available, it was not possible to certify that a new equilibrium has been reached at those locations.

8.3.2 Beachrock breaching

The main formation is interrupted at a small number of places by gaps of up to 100 meter in length (see Transects appendix). These gaps can be the result of either a former environment not suitable for beachrock formation (i.e. a river outlet) or of the weathering and erosion of the beachrock that used to be in place. To prove the former, underwater investigation and detailed sedimentological investigation could be performed. At a number of places, dislocated blocks of beachrock can be found, indirect proof of the second mechanism (Figure 35).

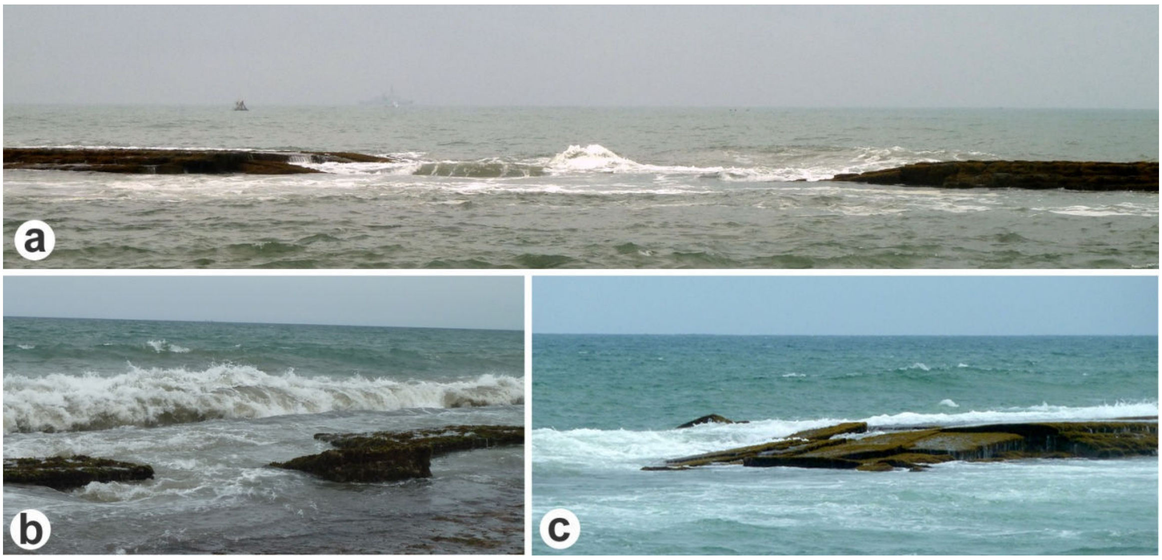


Figure 35 a: Gap in main formation caused by beachrock breaching, b+c: dislocated blocks

The breaching of the beachrock barrier and the observed weathering patterns can be explained by undercutting. At locations with a concentration of waves or steeper inherited beach profile, the wave energy reaching the beachrock barrier is higher, causing a faster scouring of the seabed adjacent to the barrier (§5.2.3). When the seabed becomes lower than the beachrock bottom, undercutting starts, causing tensile stress to develop within the beachrock. This can cause tension cracks, either along existing discontinuities or new. Dislocation of breached blocks (Figure 35a) progresses into a collapse of the barrier, allowing for cross-shore sediment transport to be activated which further increases the scouring (Figure 36).

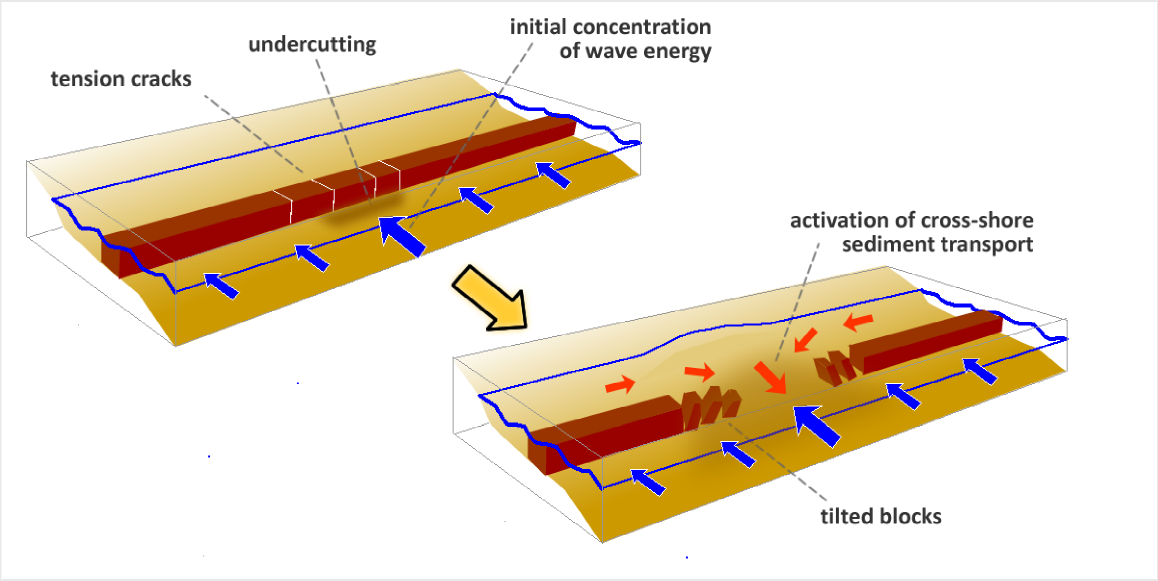


Figure 36 Undercutting causing beachrock breaching. Concentration of wave energy or variations in beachrock mass properties can be driving factors for breaching.

Examination of aerial photographs indicates that the beachrock was already breached before its recent exposure. This is supported by the observation of breached beachrock beneath a thin veneer of sand on-site. Together, this indicates that the beachrock must have been exhumated before, and for a substantial amount of time and/or under more severe hydrodynamic conditions. Quantification of the rate of destruction remains difficult. According to local sources, no visible deterioration in the state of the beachrock has occurred during the recent exposure. However, these processes occur beneath the sea (undercutting) or on a small scale in the beachrock (tension cracks), which are both difficult locations to investigate.

8.3.3 Direction of erosion and associated weathering patterns

Erosion landward of the main formation develops from locations where the beachrock barrier has been breached allowing for cross-shore sediment transport. At these locations, an asymmetrical coastline profile develops as shown in Figure 37. This could be caused by the circulation pattern landward of the beachrock opening.

Figure 37 Asymmetrical erosion profiles. Further erosion progression from right gap is blocked by the presence of beachrock behind the main formation.

Once cross-shore sediment transport is possible, erosion can progress in longshore direction landward of the beachrock. Investigation of shoreline movement clearly indicates that the direction of erosion is mainly westward, i.e. opposite the longshore current on the seaward side of the beachrock barrier. Thus, on westward directions from each gap, the water washing over the beachrock barrier subsequently travels eastward towards the gap and back into the longshore current, taking beach sediment particles along. This pattern could be described as a *ridge and runnel* system, where in contrast to normal use of the term, the ridge is non-erodible. Erosion in the ridge and runnel system is fast and creates distinct straight edges on the beachrock ridge, sometimes undercutting by faster erosion of weaker beachrock layers.

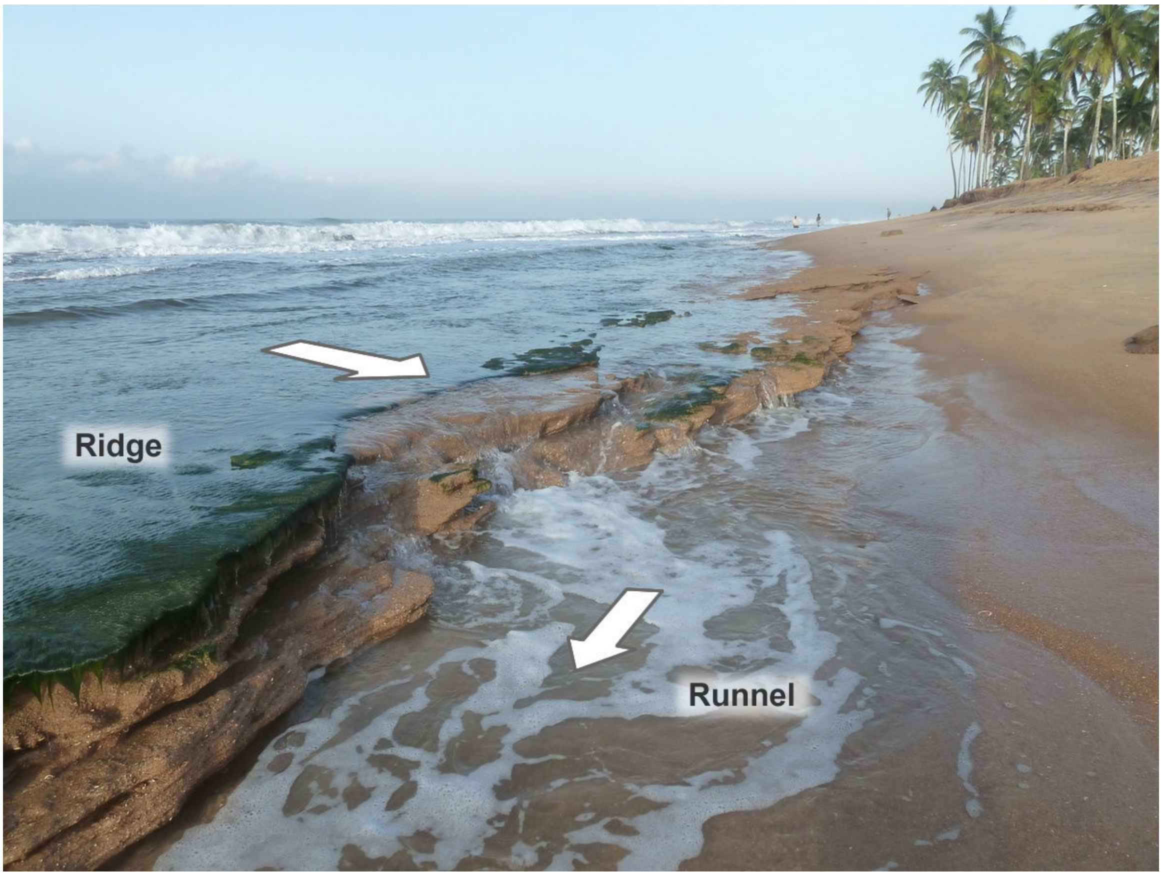


Figure 38 Ridge and runnel system. Arrows indicate direction of water. Erosion produces sharp cliffs on landward side of mature beachrock.

On the eastward side of the gap, the development of a ridge and runnel system seems to be slower. Here, erosion of less mature beachrock is characterized by swash/backwash rilling channels, as the water cannot move in longshore direction. The spacing between and depth of the channels is thought to be related to the wave energy (McLean, 1967). It is unsure whether these rilling channels originate from the current or an earlier exposure. Rilling channels were found buried beneath up to 5 cm of sand, but this could be a result of seasonal variation in beach profile. Deeper excavation or long-term observation could provide clarity on this point.

Figure 39 Swash/backwash rilling channels in less mature beachrock

Different erosional settings are thus characterized by specific erosion patterns in the adjacent formation. From each barrier, erosion progresses the fastest westward, characterized by ridge and runnel systems. Eastward, and in general at places where beachrock is continuous in the foreshore and no longshore water current exists, the adjacent formation shows rilling channels. This basic demarcation is depicted in Figure 40 and could be used for interpreting paleo-erosion patterns.

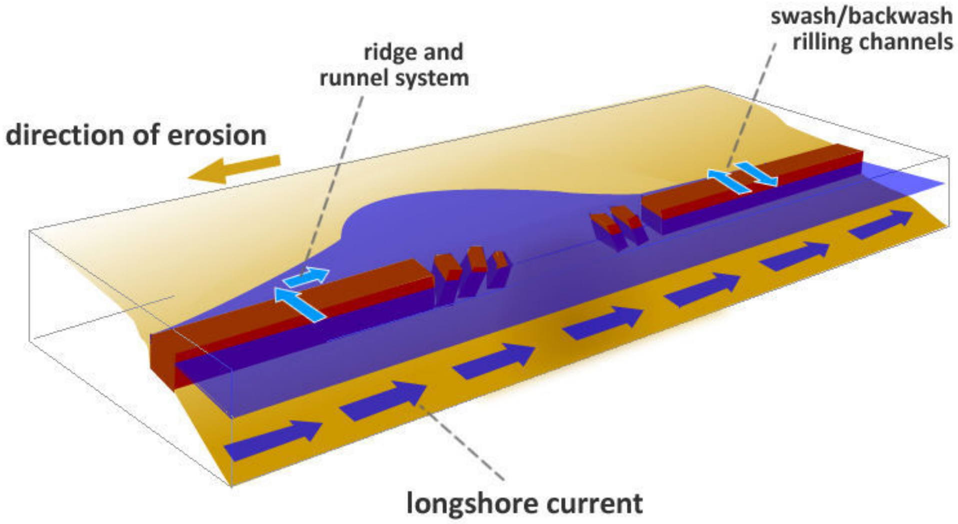


Figure 40 Interpretation of direction of erosion and associated weathering patterns

Part III Synthesis

Chapter 9 Discussion

9.1 Shoreline response models

9.1.1 Phased Retreat Model

Using the different theoretical cross-shore profiles of a retreating coast with buried non-erodible obstacles (§5.2), the shoreline has been categorized into phases, referred to as the Phased Retreat Model (Figure 42). The primary purpose of this approach is to analyze the retreat of such a coast and to see how longshore processes interact with the theoretical 2D cross-shore evolution. Finally, this would lead to a more precise definition of future coastline retreat and vulnerable zones.

The presented model hinges strongly on the equilibrium concept (§3.3.2). In Phase 0, the coastal is assumed to be in an initial equilibrium state. A change in forcing factors causes the coast to retreat, thus uncovering the buried beachrock (Phase 1). In Phase 2, a temporary equilibrium is obtained, as the beachrock effectively blocks cross-shore sediment transport (§5.2.3). Once this equilibrium is disturbed by erosion landward of the beachrock (§8.3.1), coastal retreat continues (Phase 3). Phase 4 can be considered an equilibrium phase where the coastline is stable until the beachrock disintegrates and loses its barrier function. Once the beachrock barrier is breached, coastal retreat will continue (Phase 5) until a new equilibrium profile is obtained (Phase 6).

Interactions between adjacent parts of a coast in a different phase are like to have a major impact on the development of the coast. Sediment transport over the beachrock barrier in the cross-shore section will occur only sporadically, depending on crest width and height and hydrodynamic conditions. Thus, erosion landward of the beachrock is governed by long-shore processes. This theory is supported by the observations made in §8.3, where also the preferential direction of erosion becomes apparent. Figure 41 presents a schematized plan view of a coastline with the associated phases.

The presented approach is a very simplified model of the reality. The phases have been defined for the case of a single, intact beachrock alignment, for which the normal evolution would be phase 1,2,3,4,5,6. A cross-shore profile with two alignments could for instance follow the evolution phase 1,2 (apparition first alignment),3,2 (apparition second alignment),3,4,5,6. Furthermore, the coast is assumed to be of homogeneous composition and the hydrodynamic conditions to be uniform.

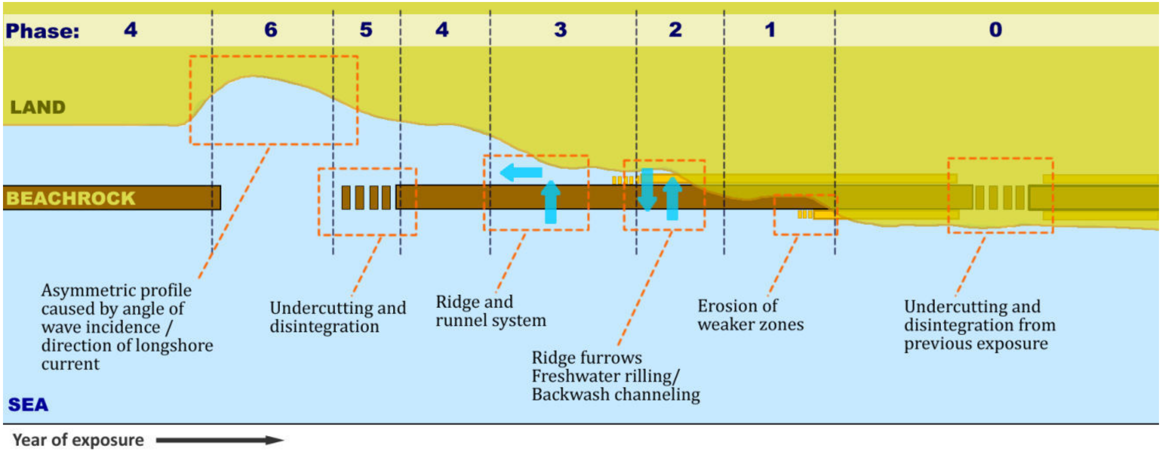


Figure 41 Schematized plan view of coastline with indication of phases and features.

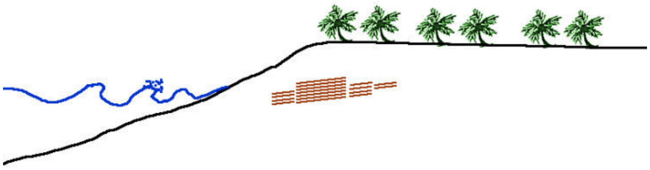
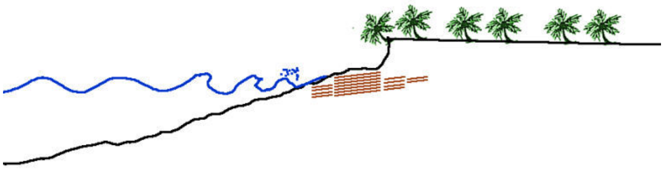
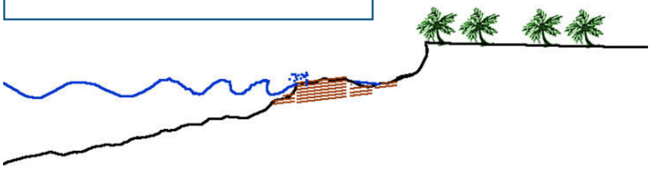
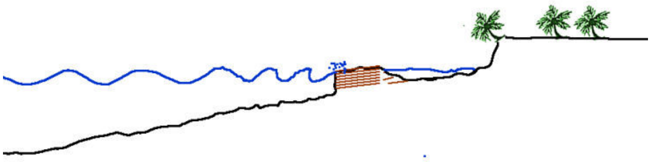
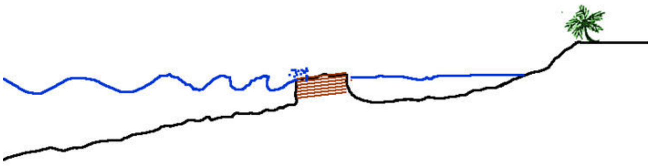
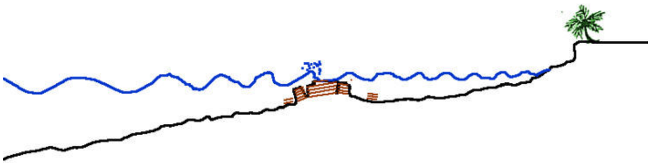
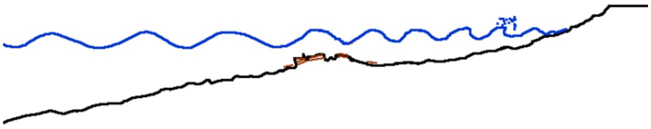
Phase	Description	Sketch
0	Beachrock is still inside beach body and does not exert control on beach profile. Beach profile is in equilibrium.	
1	Erosion starts, shoreline retreat. Buried beachrock formation starts to exert control on beach profile -> not in equilibrium.	 decelerated shoreline retreat
2	Exposure of beachrock, (case hardening of top surface?), preferential erosion of weaker (outer) parts of beachrock.	
3	Beachrock no longer continuous in beach profile but clearly distinct obstacle. Weaker parts almost completely removed. Scour steps both at sea- and landward side; undercutting at seaward side.	 accelerated shoreline retreat
4	Beach reaches new equilibrium profile, erosion is shifted laterally. Continued weathering and undercutting of beachrock.	
	quasi- equilibrium	
5	Beachrock disintegration and submergence; increase of wave energy reaching the coast, destabilization of equilibrium and erosion	 accelerated shoreline retreat
6	New equilibrium profile; beachrock submerged or fully disintegrated to debris.	

Figure 42Phases of a eroding shoreline with a single continuous beachrock formation.

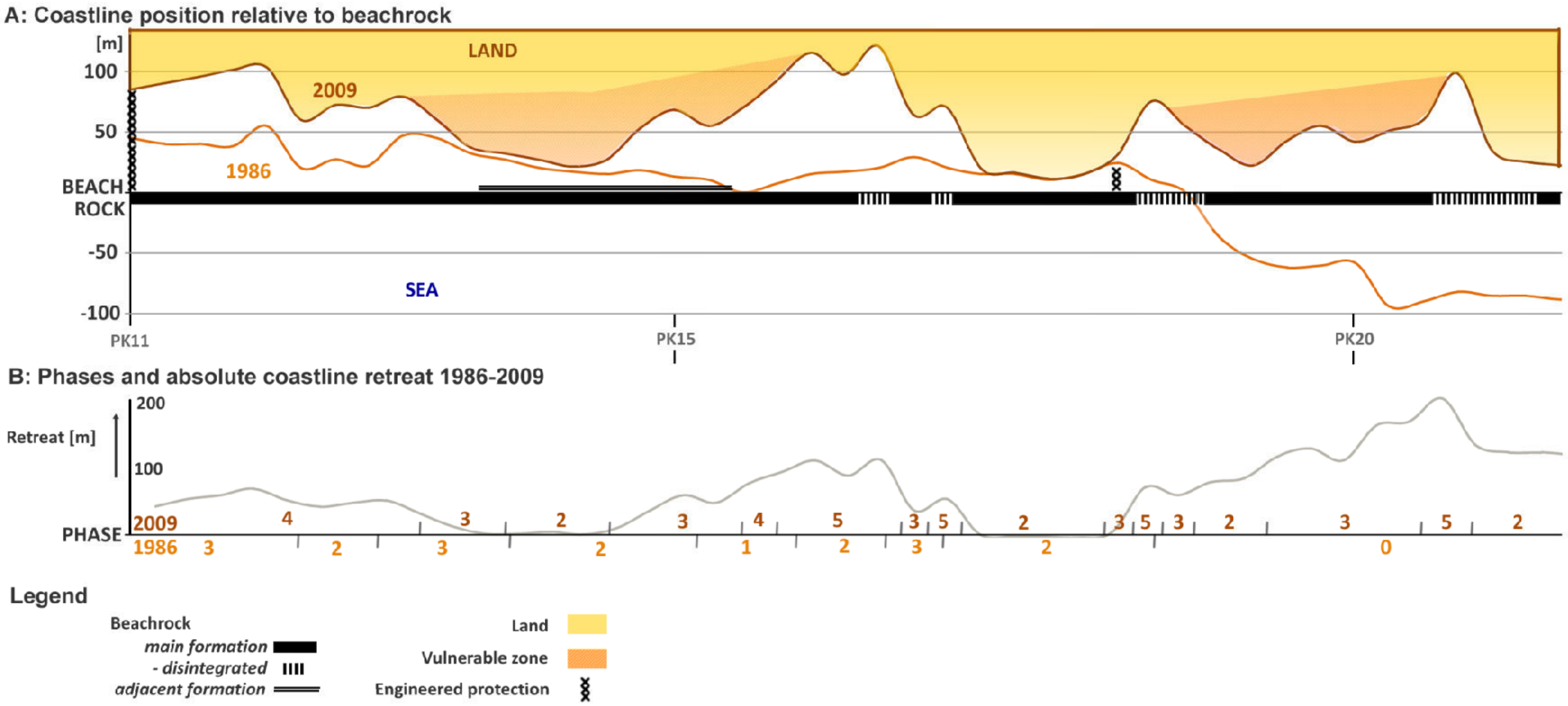


Figure 43 A: Coastline position relative to beachrock. Graph indicates the position of the coastline with respect to the main beachrock formation. B: Coastline retreat 1986-2009 and associated phases.

9.1.2 Hypothetical Equilibrium Model

The Phased Retreat Model is a purely qualitative approach to the Togo case and does not allow for calculation of shoreline movement. A different, more quantitative approach to determine shoreline evolution landward of the beachrock is by using a hypothetical equilibrium shoreline.

The Hypothetical Equilibrium Model is depicted in Figure 44. In an initial stage, the shoreline was in equilibrium with a longshore sediment transport rate Q. Subsequently, for a period of time T, the sediment influx on the left boundary is diminished to $(1-\alpha)Q$, while on the right boundary the sediment outflux Q is maintained. In a setting *without* buried obstacles, the difference in longshore sediment budget would be compensated by a uniform retreat of the coastline, providing the missing sediment αQ. After time T, as sediment influx on the left boundary was restored to Q, the coastline would reach a new equilibrium, yielding the Hypothetical Equilibrium Shoreline.

In a setting *with* buried obstacles, the ability of the coast to respond to the higher sediment demand would be limited. Defining the cross-shore transport over the reference frame $(\alpha-\beta)Q$, the sediment flux on the right hand boundary is reduced to $(1-(\alpha+\beta))Q$. This would effectively shifting erosion rightward outside the reference frame.

Shoreline evolution landward of the beachrock can now be evaluated using the hypothetical equilibrium shoreline. Taking this hypothetical state as a starting point, an analogy is found in the construction of offshore segment breakwaters in combination with sand nourishment βQ. This problem could then be evaluated using either modeling software or engineering guidelines for offshore breakwaters. The question whether this approach is valid, i.e. whether erosion from the original shoreline gives the same results as accretion from the hypothetical equilibrium shoreline, could also be evaluated using modeling software.

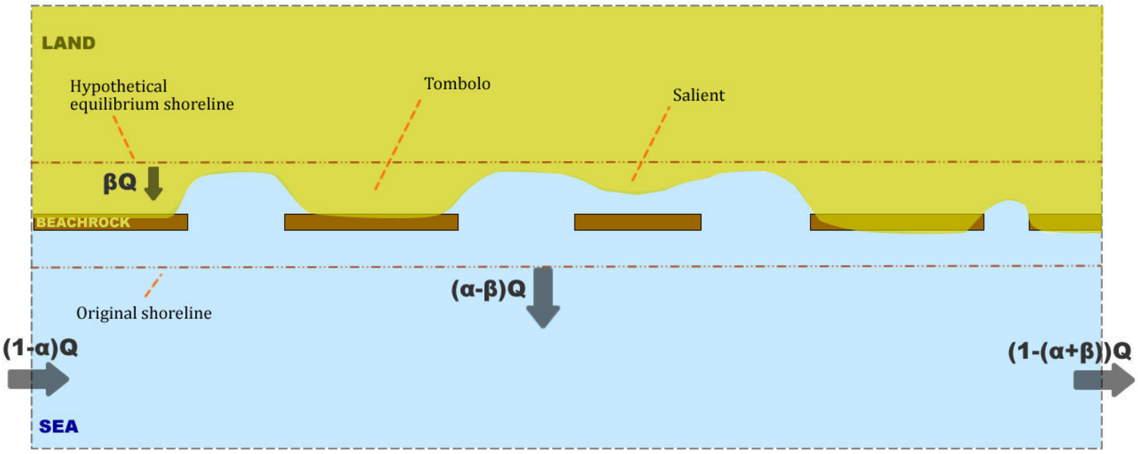


Figure 44 Schematized theoretical response of a retreating coastline to a buried beachrock formation.

9.1.3 Beachrock degradation

In the presented models, beachrocks are considered equal to engineered structures regarding their mass properties and thus their resistance to weathering. In reality, a large variation in rock mass properties and geometry can occur within a single beachrock formation. In order to assess the life span of a beachrock in the function of shoreline protector, it is important to understand the driving factors behind this variation. Equally important is to assess the dominant mode of weathering, in the light of the function of the beachrock under consideration (here: shoreline protection). In the Togo case, it is found that the dominant mode of weathering of the main formation is beachrock breaching caused by undercutting. The influence of rock mass properties and concentration of wave energy on the occurrence of beachrock breaching still needs to be assessed.

9.1.4 Future coastline development

The loss of territory in the littoral zone is a major problem for Togo. Togo's principal industries (phosphates, transport) and possible industries (tourism) heavily depend on the future development of the coastline. Erosion forecasts using sediment budget models have been made by external expert committees in the 1980's (WLDelft, 1986). More recent predictions have been unrepresentative of the complexity of this coastal system, involving linear extrapolation of decadal coastline retreat rates (Figure 45). In 2008, a monitoring programme was put to action to follow the coastline retreat on a 3-year interval basis. The first results from this programme still need to be analyzed.

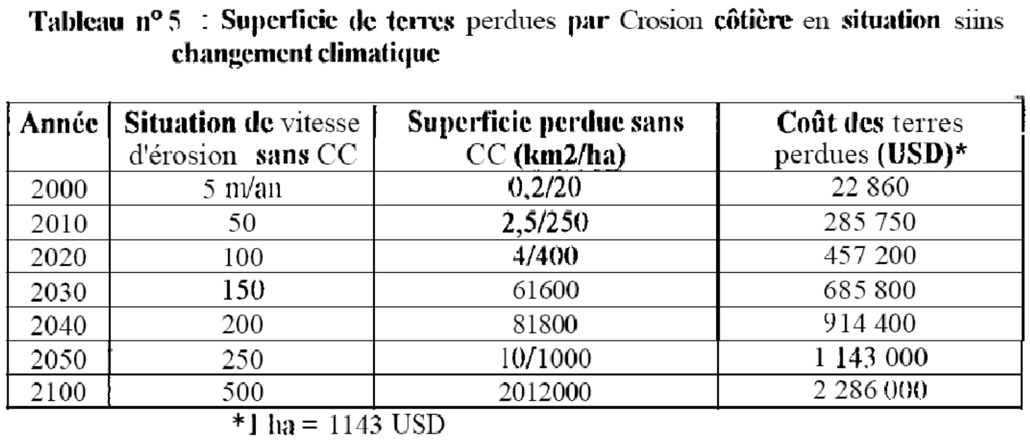


Tableau n° 5 : Superficie de terres perdues **par** Crosion **côtière** en **situation** siins **changement climatique**

Année	**Situation de** vitesse d'érosion **sans** CC	**Superficie perdue sans** CC **(km2/ha)**	**Coût des** terres perdues **(USD)***
2000	5 m/an	0,2/20	22 860
2010	50	2,5/250	285 750
2020	100	4/400	457 200
2030	150	61600	685 800
2040	200	81800	914 400
2050	250	10/1000	1 143 000
2100	500	2012000	2 286 000

*1 ha = 1143 USD

Figure 45 Land surface lost by coastal erosion without climate change, from Blivi (2004). Second column indicates the landward shift of the coastline in meters based on linear extrapolation of yearly average retreat rates. The third column relates this to land surface lost, which is subsequently translated to economic loss in US dollars (fourth column).

WLDelft (1986) calculated that sediment would commence to bypass the Lomé port from 1997 onwards. The sediment bypassing the harbor's breakwater would partly enter the sheltered harbour waters. Decreasing depths in the harbour caused by siltation can be prevented by construction an extension to the existing breakwater or by dredging operations. To the knowledge of the author, no such measures are planned at this point. Meanwhile, the building of a new container terminal at the port has been approved[1], further increasing the pressure on the well-functioning of the port.

Using the Phased Retreat Model and the information on direction of erosion as observed in the field, it is possible to make more detailed predictions for the future coastline development of the affected zone. Figure 43A shows how the coastline has developed over the period 1986-2009 in the zone PK11-PK21, directly east of the Lomé harbour. By plotting the distance between the coastline and the main beachrock formation, it can clearly be seen that (a) coastline retreat is greater at locations where the main formation is breached, and that (b) erosion travels westward from these locations.

With observations (a) and (b), plus the categorization into phases as depicted in Figure 43B, an analysis of zones of increased vulnerability is made. Withstanding that the total rate of sediment supplied to the longshore current remains stable, these areas are likely to be worn away within two decades. In areas that are currently in phase 4, coastal retreat is decelerated to rates of 0-2 m year^{-1}. Using the Phased Retreat Model thus provides a substantial advantage over using linear extrapolation of recent coastal retreat rates as done by Blivi (2001).

9.1.5 Implications for mitigation

To mitigate coastal retreat with hard measures (constructions) over long stretches of coast, and to do so cost efficiently, requires an intelligent engineering approach. The method of choice should depend on the phase in which the coast currently is. In phase 0, mitigation is a standard problem for which

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[1] Source: http://www.dredgingtoday.com/2011/07/19/togo-lome-port-to-get-new-container-terminal/ . Retrieved August 1st, 2011

many engineering solutions have proven successful. The groyne field erected at the Kpémé phosphate industry area is an example of effective mitigation.

Once in phase 1 or higher, mitigation of retreat becomes more complex. The purpose of mitigation is to reinforce an existing equilibrium profile, or to engineer an artificial equilibrium. From that point of view, the most effective method is to reinforce those areas that are currently in phase 2 or 4 by blocking any longshore current landward of the beachrock. A clear example is the groyne constructed at the former Tropicana hotel (PK18), which protects the coastline over more than a kilometer length (Figure 46). The groyne blocks the longshore sediment transport east of the protected zone, which is bounded in the west by another breach in the main beachrock formation. Here, erosion travels westward, leaving the protected zone unaffected.

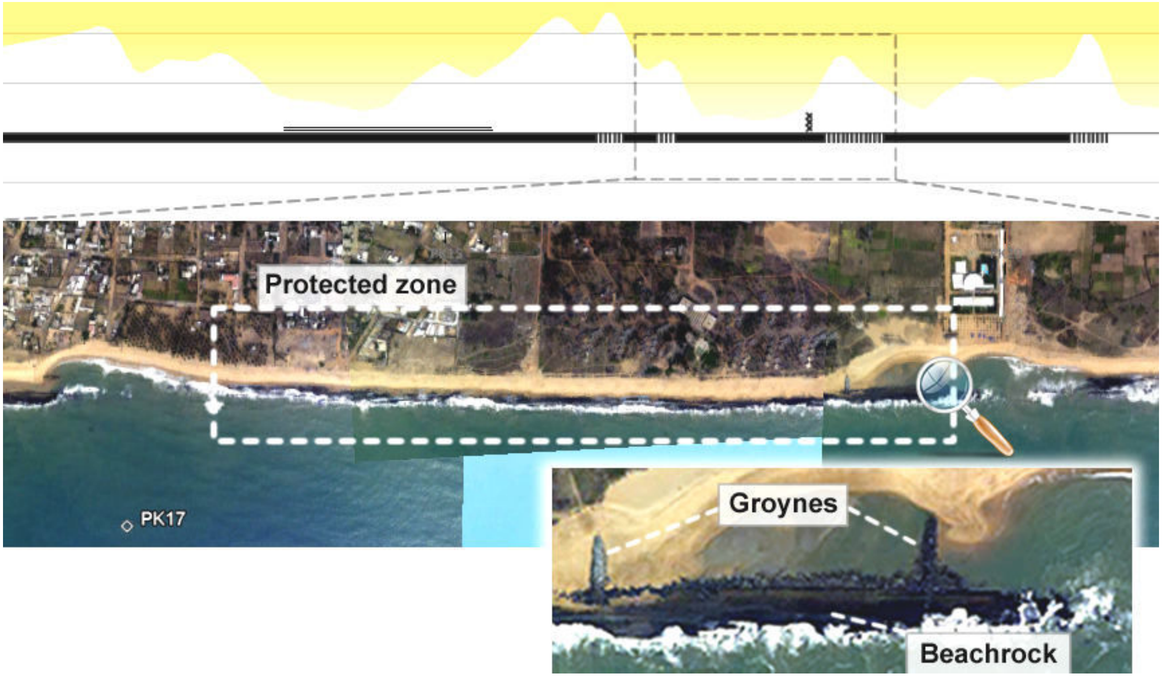


Figure 46 Mitigation measures at former Tropicana hotel. Groynes effectively block longshore transport landward of the main beachrock formation, thus protecting the coast westward up to the next point where the barrier has been breached

A similar, shore-perpendicular structure might also be effective when the coast is already in phase 3-4. Closing of the breaches in the beachrock is another option, but could be difficult and expensive. Enhancement of the main formation by placing structures on top would limit the overwash of seawater, but would also be rather expensive. Finally, reinforcement of the main formation, e.g. by armoring its seaward side, might be an option. Such measures require a thorough study and extensive testing should they be applied.

9.2 Beachrock genesis

9.2.1 Diagenetic zones

In chapter 4.5, the diagenetic history of beachrocks was discussed. Field observations confirmed that beachrock can be found in various stages of lithification. Evidence was found to suggest that the adjacent formation is eroded preferentially, showing specific erosional features (§9.3). However, no microscopic evidence was found to link diagenetic zones to cementation characteristics. The cements are too small for further analysis, which makes it impossible to determine in which diagenetic zone they were formed. As such, the diagenetic history of the beachrock cannot be linked to the mass properties of the beachrock.

9.2.2 Beachrock and variability of shoreline

Starting from the idea that cementation is a common phenomenon in tropic and subtropic regions, the answer to the question why beachrock is *absent* from many areas could be partially answered by looking at the variability of shore and shoreline. A too high variability in shoreline may disturb beachrock formation in an early phase. At the same time, a certain progression of the coast and the associated movement of diagenetic zones might be key to the *maturation* of a beachrock. A safe conclusion is that genesis and early diagenesis of beachrock is strongly influenced by small-scale shoreline variability. This small scale variability is in turn dominated by fluctuations rather than trends.

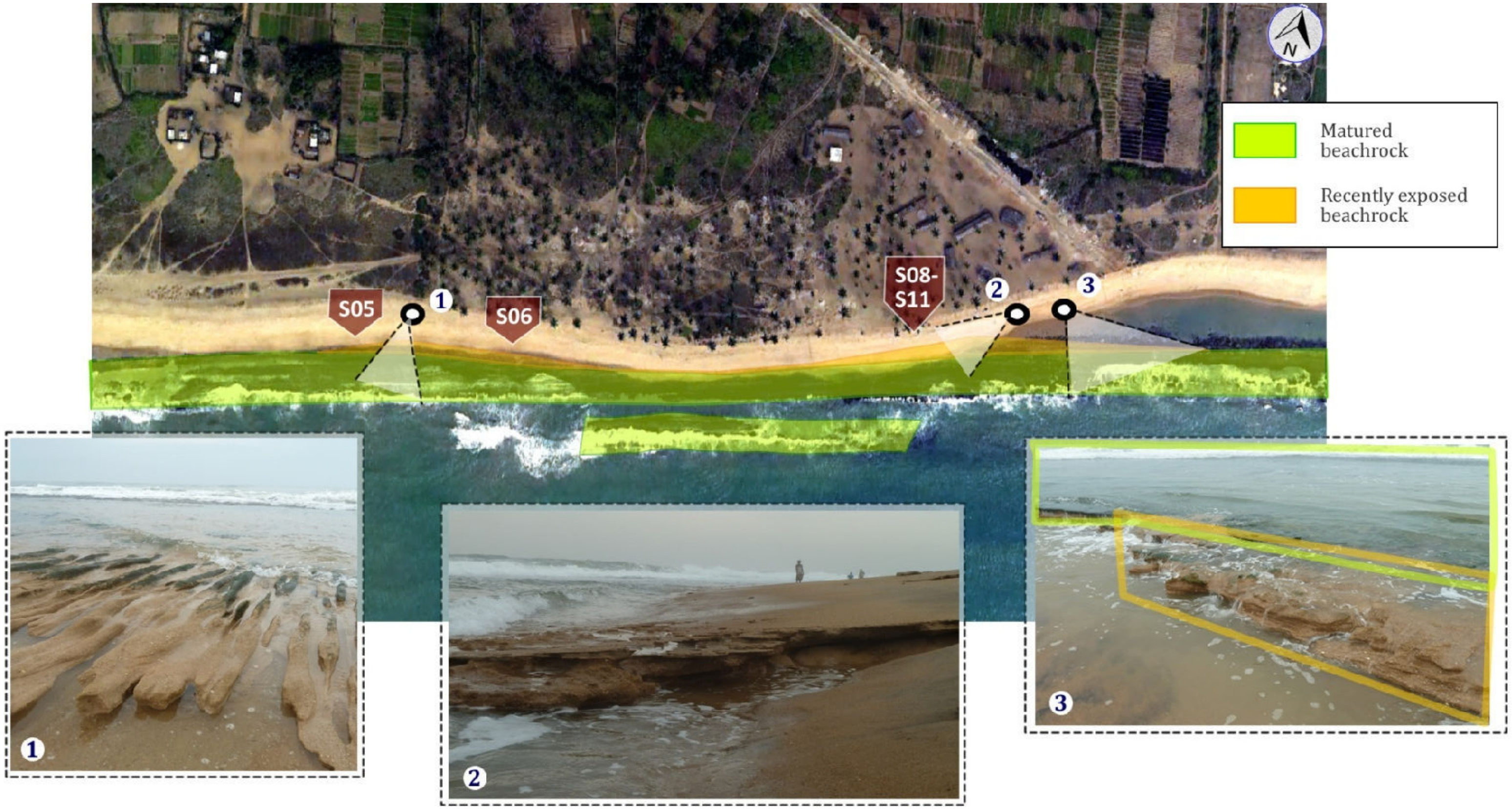
Amieux et al. (1989) used cement characteristics to establish trends in recent coastline development, consisting of a phase of small shoreline variation followed by progradation and subsequently erosion. This theory can be contested on three main points. First, tidal variation can completely change the configuration of diagenetic zones within one tidal cycle. Second, theoretical review of shoreline dynamics showed that the amplitude of small scale variations is greater than suggested by Amieux et al. The cementation characteristics which should lead to the proposed sequence of trends (progradation - erosion) can thus in reality be small-scale fluctuations. Third, investigation of weathering patterns shows that the main formation has experienced at least one exposure prior to the current one. That means that since formation of the beachrock, a progradation - erosion sequence has occurred at least twice.

9.2.3 Paleo-environmental indication

In general, relating beachrock genesis to large-scale trends means neglecting processes on intermediate timescales. Any paleo-environmental indication that directly relates a single beachrock occurrence to large-scale trends is thus oversimplified and not justified as such. The spatial arrangement of multiple beachrock alignments does bear potential for determination of large-scale trends, as every single alignment is an indicator of a former shoreline.

Investigation of erosional features in beachrock can yield information about hydrodynamic conditions during exposures prior to current day. In Togo, erosion features indicate that the beachrock must have been exposed before during a longer period of time, or under more severe hydrodynamic conditions. Vött et al. (2008) interpreted erosional features in beachrock as initially fractured by seismic events and later transported by a tsunami.

At PK19. Tombolo geometry: inner part in phase 2, outer parts in phase 3. First exposure of beachrock after 1985; now the tombolo is being eroded from the east and west side. Inset 1 shows ridge furrows systems in recently exposed beachrock (foreground), created by backwash channeling/ mechanical erosion (McLean, 1967), while in the background algal mats are present causing case hardening of the beachrock (Turner, 1999). Inset 2 and 3 show a ridge and runnel system (Dabrio and Polo, 1981). Beachrock profile is determined by the buried beachrock formation. After removal of the top beachrock layer, the rate of erosion increases (inset 2) as lower parts are weaker. Inset 3 shows a width inversely related to the time of exposure towards the east, caused by a slow erosion of beachrock parts not covered with algal mats.



9.4 Coastal Management in Togo

9.4.1 Current practice

Since the first human intervention in 1967, the construction of the Lomé harbour, management of the coastal zone of Togo has consisted solely of ad hoc measures. Engineering protection comprised of groyne fields at the Kpémé phosphate industry area, the Aného village and the former Tropicana hotel. At Aného, new revetments are constructed at this moment to protect the spit on which the village is located from the direct threat of ongoing erosion (Figure 47).

Figure 47 Revetments at Aného, west of the inlet. Continued erosion threatened the village of Aného.

In the 1980's, the strong coastline erosion immediately after construction of Lomé harbour urged the Togolese government to seek for suitable mitigation measures. As similar problems arose along other parts of the Bight of Benin coastline, external expert teams were called in for help, partly with financial aid of the European Committee. WLDelft (1986) calculated that the use of soft measures (a sand bypass) would be the best and, in the long run, most cost-effective method. This suggestion has however never been implemented. More recent (national) reports (e.g. Blivi (2001)) lack a solid quantitative basis and fail to address the complexity of the coastal system. Moreover, existing data on coastline retreat is incomplete and inconsistent.

At the same time, the importance of the problem is acknowledged and more long-term solutions are sought after. A recently inaugurated monitoring scheme will follow the developments of the coastline on a 3-year basis. New investments in coastal protection will draw heavily on the country's modest budget and are not foreseen at this moment. With the construction of a new container and the inflow of sediment passing the breakwater, maintenance dredging will be necessary in the coming years.

9.4.2 Integrated Coastal Zone Management

Integrated Coastal Zone Management (ICZM)[2] is defined as "*the comprehensive assessment, setting of objectives, planning and management of coastal systems and resources, taking into account traditional, cultural and historical perspectives and conflicting interests and uses; it is a continuous and evolutionary process for achieving sustainable development.*" In essence, ICZM is a range of concepts and techniques that should be adapted to different situations (Bosboom and Stive, 2010).

Application of this philosophy to the Togo case requires a definition of the coastal system boundaries beyond country borders. The effects of the construction of the Lomé harbour reach up to the coast of Bénin, which should be incorporated in the search for sustainable management. The current practice does not include a sand bypass for the Lomé harbour, thus the sediment deficit eastward will remain and shift more towards Bénin. Proof is delivered by the extending of the opening period

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[2] See http://ec.europa.eu/environment/iczm

of the Aného inlet, causing salinization of the lagoonal area. This process is likely to continue and aggravate under the current practice of mitigation.

In order to apply ICZM, a thorough, quantitative understanding of the current development of the Togolese coast is indispensible. Measurements of coastline movement and detailed calculations on sediment transport should allow for an evidence-based prediction of future coastal development. Although the findings of this report indicate that the retreat of a shore with buried obstacles is more complex than what is common in practice, calculations of transport volumes of sediment should suffice for a proper understanding of the current dynamics.

Recommendations for an approach in the light of ICZM are summarized in Table 5. As it is not economically feasible to protect Togo's full coastline, the current practice of protection of areas of main importance can be continued. The shoreline response model presented in this study can be used to determine vulnerable zones, for which the strategy of *managed retreat* can be applied. New mitigation measures should be designed in accordance with the phases theory and using the existing beachrock barriers. Finally, research into the long-term effects of the decreased sealing period of the Aného inlet should be carried out.

Table 5 Recommendations for future coastal management in Togo

	CURRENT	PROPOSED
Monitoring	3-yr interval	3-yr interval (general)
		2-month interval (selected sites)
	Fragmented historic analysis	Complete and check consistency
	Coastline development only	Add measurements of beach profiles
		Add observation of beachrock weathering
		Monitor scouring of seabed around beachrock
Prediction	Linear extrapolation of 3-yr interval rates	Application of phases model
		More data-driven analysis
		Localization of breaches in buried beachrock
Mitigation	Hard measures only	Reconsider soft measures for long-term
	Beachrock-incorporating structures	Beachrock-incorporating structures primarily aimed at blocking long-shore sediment flux
	Zones of specific focus	Add focus on long-term effects at Aného lagoon inlet

Chapter 10 Conclusions and Recommendations

10.1 Conclusions

For each research question, the most important conclusions are presented here.

What is the provenance of beachrock along the coast of Togo, what are its characteristics in terms of geometry, cementation type/degree and discontinuities and how can they be related to its degradation?

> **Beachrock is present along major parts of the Togolese coast and plays a significant role in current coastal evolution.** A main formation, 5-10 meters wide bank, crest at or just above MSL, effectively blocks cross-shore sediment transport. An adjacent formation shows a high variation in appearance and is generally of lower strength.
>
> **Undercutting is likely to be the dominant mode of weathering of the main formation.** At multiple locations, the main formation is breached over widths up to 100 meter. Observations of tilted blocks and existing research indicate that seabed scouring followed by undercutting is probably the prevailing mode of weathering. Understanding the difference between beachrock and engineered structures is vital to assess their role in shoreline evolution.

What is the influence of shore and shoreline variation on the formation of beachrock, and how can this be used in paleo-environmental reconstruction?

> **Small-scale shoreline variability has a large influence on beachrock genesis and early diagenesis.** On a time scale from tidal cycle to decades, shore and shoreline show considerable variability. Diagenetic zones and thus cementation of beachrock are directly related to this variability. The diagenetic history of a beachrock might be key to its cementation characteristics. As such, the *maturity* of a beachrock is strongly linked to small-scale shoreline variability.
>
> **Beachrock weathering and the spatial configuration of multiple beachrock alignments have potential as paleo-environmental indicators for large-scale trends.** The paleo-environmental significance of the genetic characteristics of a single beachrock is limited to sea-level indication. Weathering patterns can indicate prior exposures or possibly extreme events. Multiple alignments can be evidence of large-scale coastal development trends.

What is the morphodynamic response of a retreating sandy coast to a buried beachrock formation, and how can this knowledge be used to better predict future shoreline evolution?

> **Retreat of a beach with buried discontinuous barriers is a yet untouched topic of research.** The topic comprises of several phenomena and processes that are poorly understood, predominantly nearshore morphodynamic processes. The Togo case can be valuable to gain new insights on these processes.
>
> **A conceptual model was developed to address this topic using phases of coastline retreat.** Each phase represents a different cross-shore configuration as coastal retreat continues and beachrock is exhumed. The phases relate to the concept of beach equilibrium profiles. Longshore sediment processes are found to play a key role in coastal retreat.
>
> **A significant lack of data and expertise needs to be overcome for Togo to upgrade their coastal management strategy to the philosophy of Integrated Coastal Zone Management.** Budget constraints cause the Togolese government to take only ad-hoc mitigation measures in case of direct threats. However, on the long run, a more structured approach may be more cost-effective.

10.2 Recommendations

The coastline of Togo is a unique case of interaction between beachrock formations and shoreline evolution. Given the wide variety of processes of which these interactions exist, this report should be considered an exploration for further research opportunities. The major recommendations for further research, as well as for management of the coastal zone in Togo, are presented below.

Further evaluate the theories of beachrock formation with respect to variability of diagenetic zones. Certain proposed mechanisms, such as CO_2-degassing from seaward flowing groundwater, are likely to be sensitive to this variability. Laboratory tests of cementation under simulated natural variability might yield useful new insights on the controls that influence each mechanism.

Focus new research of using beachrock as a paleo-environmental indicator on weathering patterns. The significance of the diagenetic history of a beachrock in paleo-environmental reconstruction is low. Analysis of weathering patterns might provide useful information on previous exposure, including the hydrodynamic conditions to which it was exposed.

Use the Togo case to evaluate morphodynamic models in coastal engineering. The coast of Togo is a rare example of a retreating coast with buried discontinuous barriers. Process-based morphodynamic models can be tested using the existing data, focusing on near-shore processes.

Upgrade coastal zone management in Togo to the philosophy of Integral Coastal Zone Management. Upgrade the current monitoring plan and use the phases model to assess future shoreline development.

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Appendix A. Beachrock samples and microscopic images

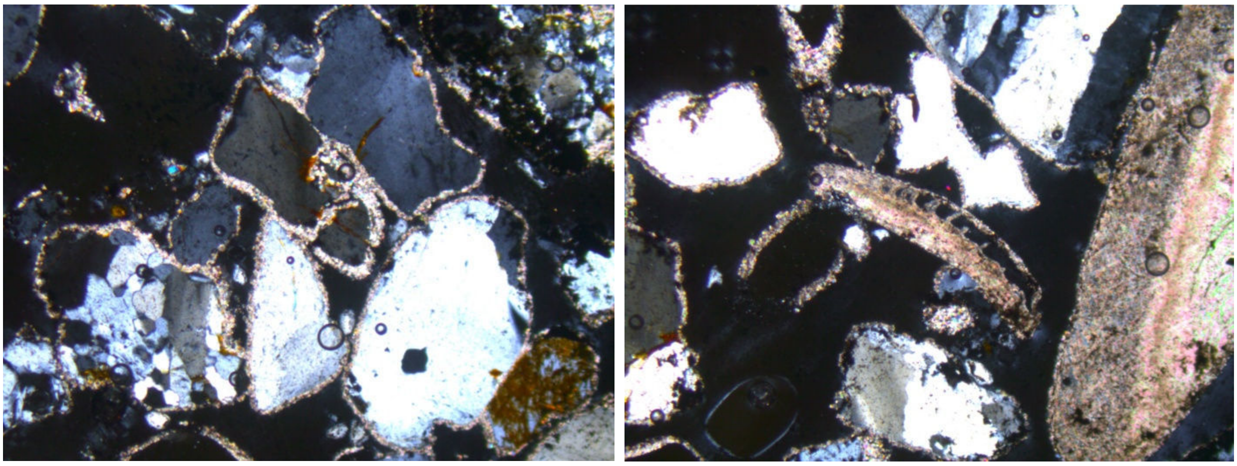
S01

Transect T2

Beachrock found on existing beach, is possibly currently forming.

Outcrop:

Optical microscopy:



Observations: Thin rims of micritic cement. No filled pore spaces.

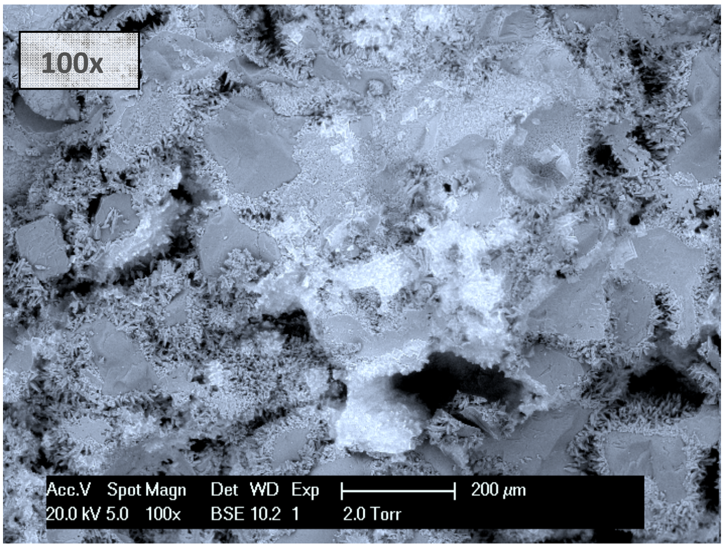
S08

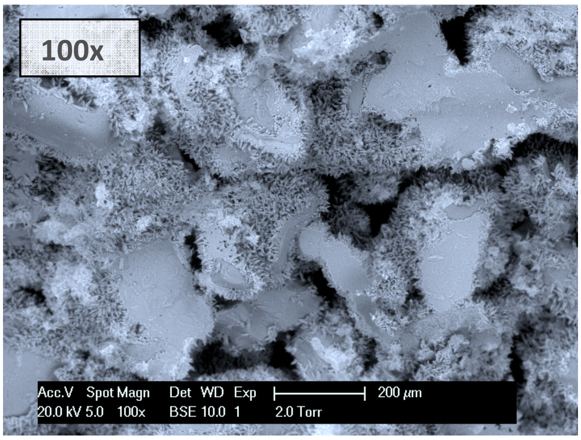
Transect T4

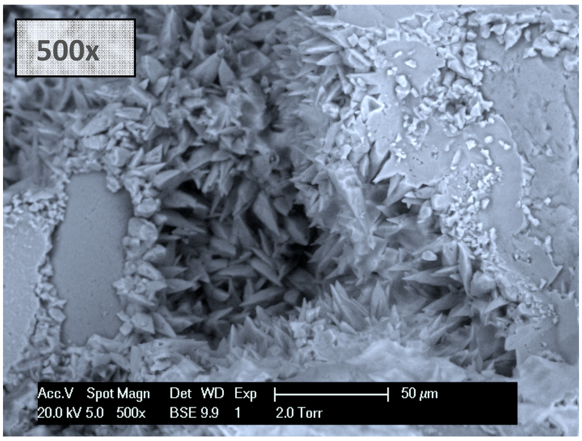
Beachrock from adjacent formation, recently exposed.

Outcrop:

ESEM:







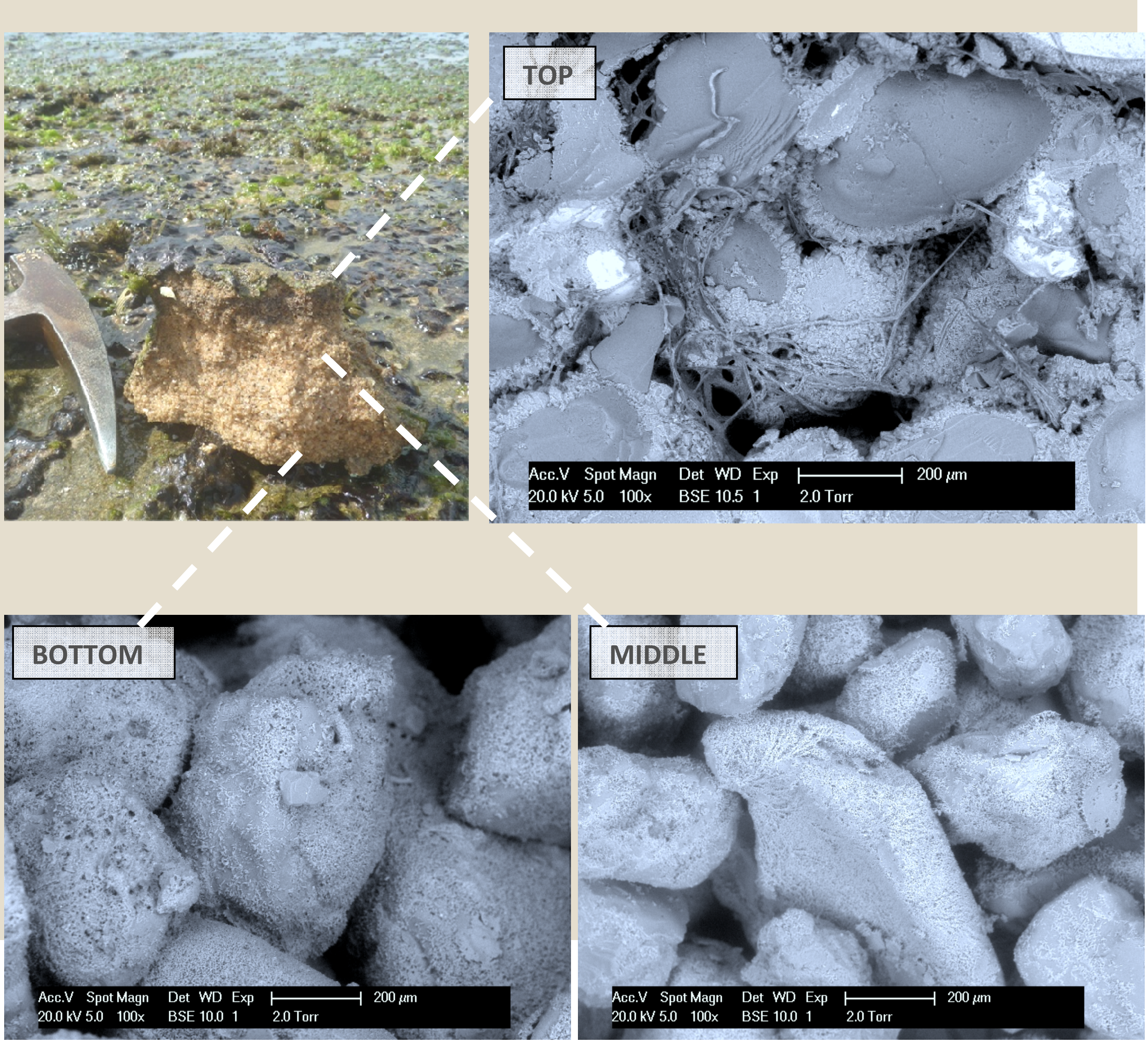
Observations: Cement in needle shape, length around 20 µm.

S13

Transect T4

Beachrock from main formation, heavily populated with biota.

Outcrop: **ESEM:**



Observations: Top sample shows algae fibers consolidated in the cements. Cements form a thicker rim than in S08 and have a less profound needle shape. Middle and bottom samples do not show algae fibers, cement rims seem to be thinner.

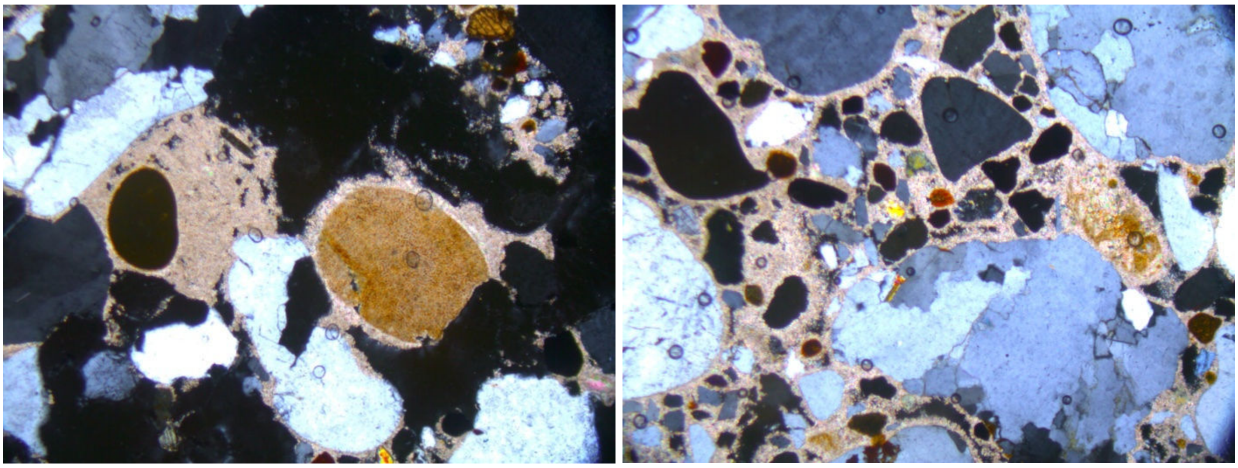
S15

Transect T5

Main formation, landward side. Very strong beachrock.

Outcrop:

Optical microscopy:



Observations: Pore space completely filled with cements.

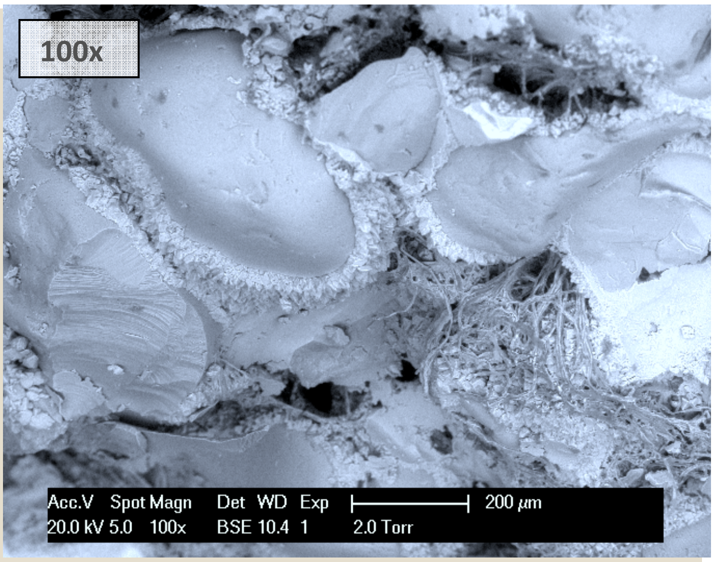
S13

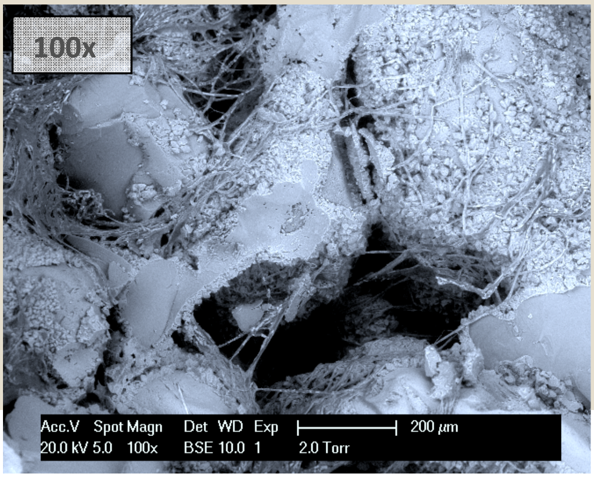
Transect T4

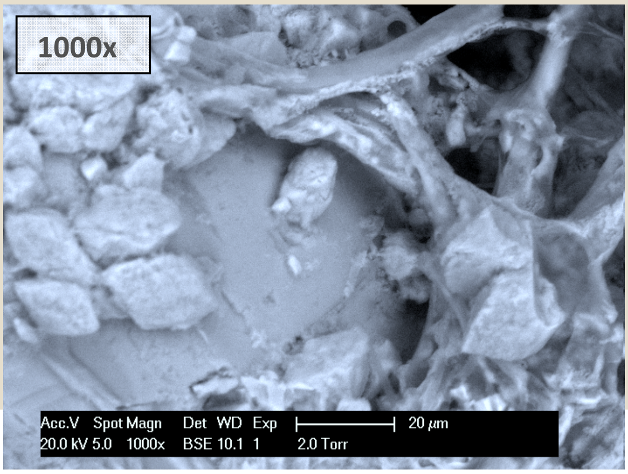
Beachrock from main formation, layers.

Outcrop:

ESEM:







Observations: Presence of algae fibers. Detail (1000x) image shows how cements fix the fibers on the surface of the grains.

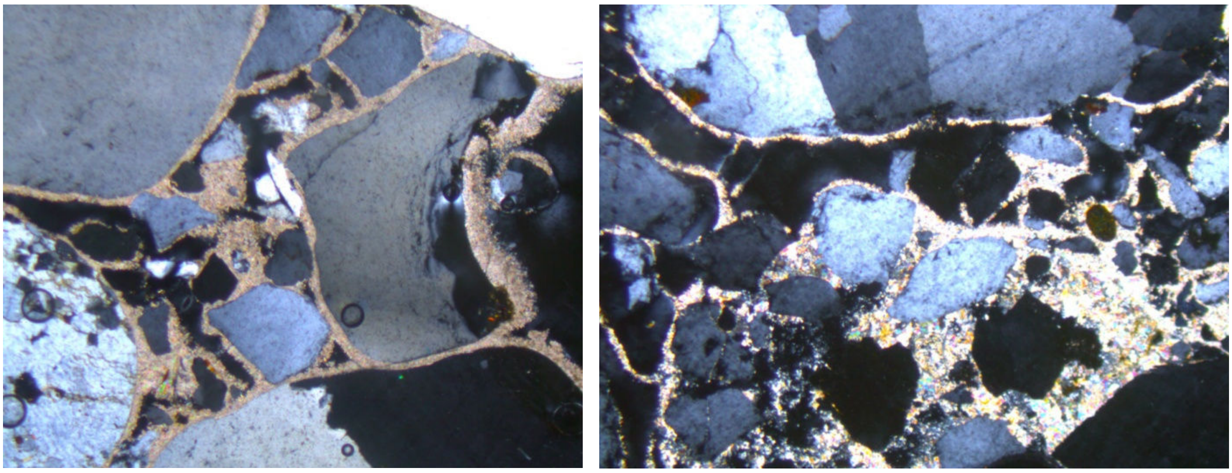
S21

Transect T4

Main formation, top. Arrow indicates top surface. Hardened surface, strong.

Outcrop:

Optical microscopy



Observations: Partially filled pore space. Spots with completely filled pore spaces, other parts with only thin cement rims.

Appendix B. Transects

The full coastline of Togo has been investigated during 10 days of fieldwork. The parts that are most interesting for this study have been described in detail in transects. For each transect, the observations of beachrock made in the field have been described and sampling locations have been indicated. All aerial photographs in this appendix date from 2009 and are courtesy of CGILE.

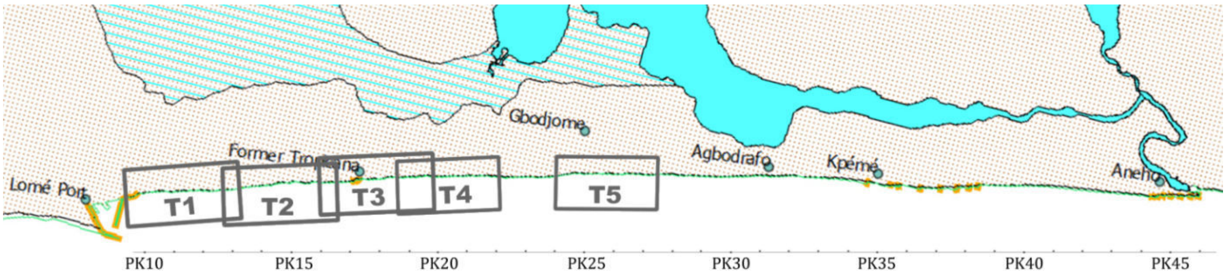


Figure 48 Location of transects T1 to T5

Transect T1

Location: PK11-PK13
Observed on: 24-05-2011

Description:

(1) Single continuous emerged alignment of beachrock at 50-100 m from coastline over full transect length. Width approx. 30m . Upper surface seems flat on meter-scale.

(2) Dislocated fragment of beachrock at seaward position of (1).

(3) Dislocated fragments of beachrock at landward position of (1). Typical diameter of 2-3m.

(4) Semi-continuous submerged alignment of beachrock at 10-50 m from coastline over 1 km length. Width up to 50 m. (Detail A: Figure 1)

Figure 1 Transect 1, detail T1A: semi-continuous submerged beachrock

Figure 2 Transect #1. Upper image: plan view with indicators, images courtesy CGILE (2009). Lower image: Panoramic view of beachrock alignment (1)

Transect T2

Location: PK13 - PK 16
Observed on: 24-05-2011

Description:

(1) Continuation from Transect #1: Single continuous emerged alignment of beachrock at 50-100 m from coastline over full transect length. Width approx. 30m . Upper surface seems flat on meter-scale.
(2) Continuous alignment(s) of beachrock at MSL at 10-50 m from coastline over 1 km length. Width around 100 m.
(3) Possible continuation of (2) beneath beach surface.
(4) Indication of beachrock under formation. Thin (3-5cm) wedges in congruence (inclination, grains) with beach environment. Sample taken (S01). (Detail A: Figure 3)

Figure 3 Transect #2, detail T2A: Indication of beachrock under formation.

Figure 4 Transect #2. Upper image: plan view with indicators, image courtesy CGILE (2009). Lower image: detail of higher sea

Transect T3

Location: PK16-PK19

Observed on: 24-05-2011, 07-06-2011

Description:

(1) Continuation from Transect #2: Single emerged alignment of beachrock at 50-100 m from coastline, now discontinuous. Width approx. 30m .

(2) Continuation of (1) but now discontinuous as a part of the beach profile. Shows signs of highly differential weathering with very abrupt ends (Detail A)

(3) Continuation from Transect #2: Continuous alignment(s) of beachrock at MSL at 10-50 m from coastline. Width around 100 m. Ends approx. 200m west of PK16.

(4) Engineered structure: breakwater (shore-parallel) constructed on top of (2), plus groynes at ends (shore-perpendicular). (Detail B: Figure 5)

o

Figure 5 Transect #3 Detail B: Engineered structures

Figure 6 Transect T3. Upper image: plan view with indicators. Image courtesy CGILE (2009). Lower image: Detail A - indication of highly differential weathering

Transect T4

Location: PK19-PK22
Observed on: 01-06-2011

Description:
(1) Continuation from transect #3, single beachrock attached to beach profile.
(2) Single alignment of beachrock at 50 m from shoreline. Shows high degree of weathering resulting in displacement of beachrock blocks of rectangular shape (lower photo).
(3) Single alignment of beachrock again attached to beach profile.

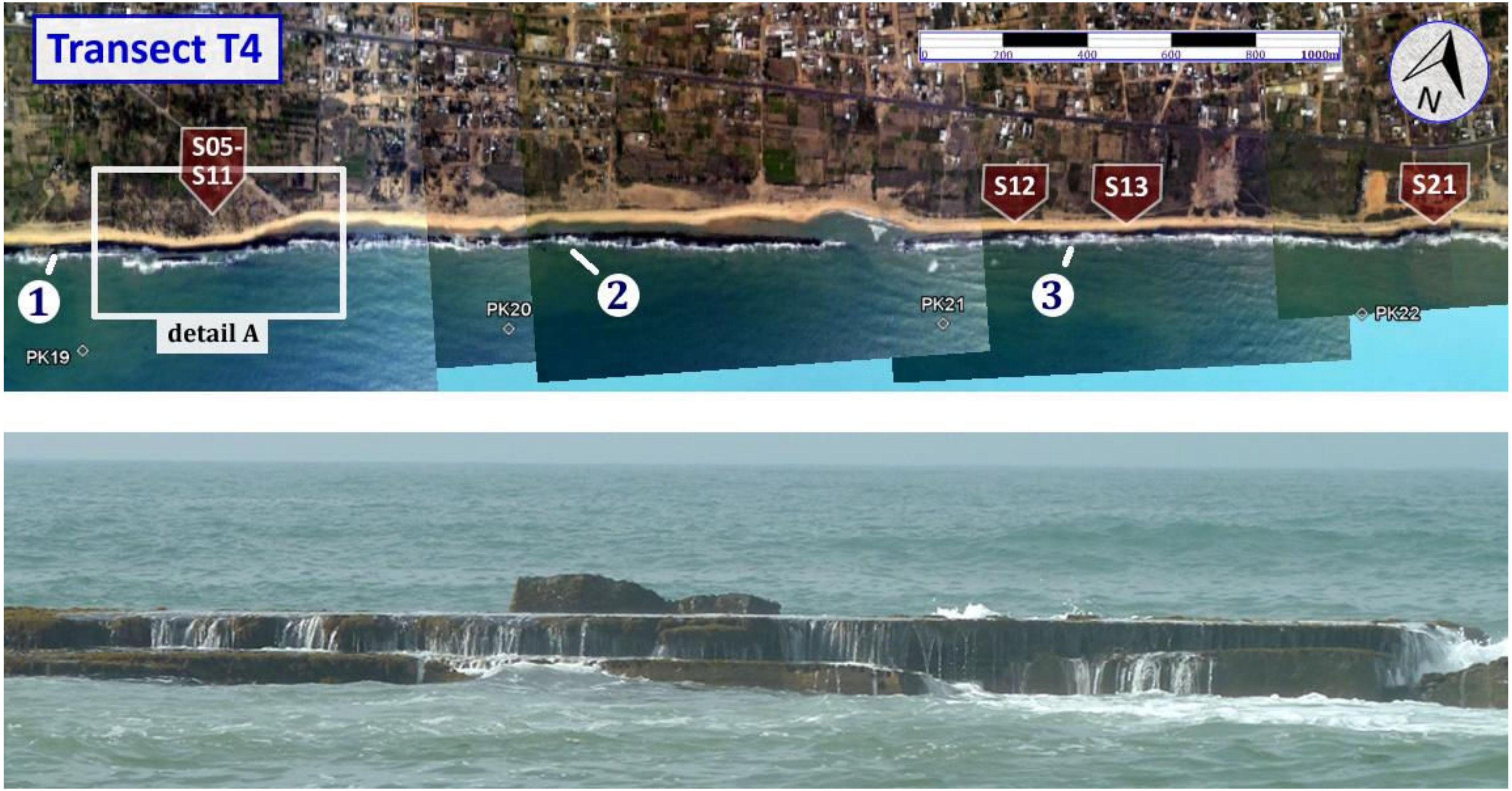


Figure 7 Transect T4. Upper image: aerial image courtesy CGILE (2009). Lower image: rectangular geometry of main formation

Transect T5

Location: PK25-PK27
Observed on: 01-06-2011

Description:
(1) Single emerged beachrock at 10-50 meters from shoreline, with sudden break at eastern side.
(2) Single beachrock in continuation with beach profile.
(3) Double alignment of beachrock, partly covered in beach profile. Alignment seems to show a slight curvature. Abrupt endings at both eastern and western outer end.
(4) Zone of scattered small (less than 50 m in length) beachrock alignments.

Figure 8 Transect T5, point 4: Scattered beachrock alignments, unusually high inclination (11°)

Figure 9 Upper image: plan view with indicators, image courtesy CGILE (2009). Lower image: detail at location two with inclinations and sample locations