High-resolution geophysical survey for the exploration of near surface sand resources at the southern Kenyan coast using a multi source strategy

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INTRODUCTION

The nearshore coastal geology in large parts of the world is relatively unknown. However, economic interest in these nearshore areas is increasing, as valuable resources such as aggregates for harbour construction and mineral deposits experience increasing demand. The coastal zones were formed by large relative sea-level variations and changing sediment sources and supply. This results in an often complex setting with interacting depositional environments and associated morphology.

Nearshore coastal zones are often explored by carrying out shallow seismic surveys on a grid with a spacing of several hundred meters. The seismic data are then ground-truthed by a series of corings. This method works sufficiently in relatively uncomplicated areas with laterally continuous geology. In complex areas that have experienced periods of incision and deposition and consist of various sedimentary environments, working with a single geophysical method is not preferable as important indications for changing sedimentary environments are easily overlooked.

In this study we present the results of geophysical research in a previously unexplored area along the southern coastal zone of Kenya. This area has been assigned as a source area for the extraction of sand of sufficient quality for a harbour construction project nearby. The setting of the area is in front of a coral reef on a narrow passive continental shelf of 2 to 3 kilometers wide. Literature from the onshore area shows a complex geological history with periods of (relative) uplift and incision, and existing bathymetry charts suggest the presence of narrow valleys and submerged plateaus (Thompson, 1956; Oosterom, 1988; Abuodha, 2004). Because of the complexity and size of this area a geophysical survey was especially designed to explore near surface sand occurrences. The survey consisted of a combination of acquisition techniques and included a combined high-resolution swath bathymetry / side-scan sonar system and a chirp sub-bottom profiler. Using these methods, the area is mapped for potential sand occurrences.

METHODS

The equipment used for geophysical research of the southern coastal zone of Kenya consisted of a chirp sub-bottom profiler and a combined swath bathymetry - side-scan sonar system. All systems

acquired simultaneously. Recent studies using both systems in one sweep, showed that interference between both the systems is negligible and that the quality of the collected data was good.

Sub-bottom profiler

For this project an Edgetech SB512i sub-bottom profiler tow-fish was used. The system emits an acoustic signal of finite duration during which the frequency increases linearly. The acoustic signal is reflected by density contrasts within the shallow subsurface. Density contrasts are associated with changes in lithology. The received signal is transmitted to a computer system that processes and stores the data. The depth range below seabed that is covered by the signal depends on the material properties. A subsurface with high energy absorption leads to a smaller depth penetration. Maximum penetration in a sand body will be up to 7 meter, whereas in more fine-grained deposits the penetration can be up to over 20m. The result of the processed data is a profile that shows the primary reflectors with a minimum of noise.

With a ping rate of two pings per second, and a surveying speed of 3 to 4 knots, the coverage of the surveyed area was about 1.0m between each ping along the sailing line. A vertical resolution of 0.25m and a maximum penetration of 18m have been attained. The total track length of the survey was 780km.

Bathymetry and side-scan sonar

The bathymetry and side-scan sonar data were acquired with a Klein Hydrochart 5000 (HC5000) (Ai and Parent, 2011). This system can simultaneously collect high-resolution phase difference bathymetric sonar (PDBS) and high resolution multibeam side-scan sonar data. A CODA F185 motion sensor provided navigation and corrected the HC5000 data for ship motion.

The specifications of the HC5000 indicate that the system is accurate up to depths below the fish of approximately 50 meters. We used a maximum swath range of 100 meters (total swath 200 meters), which provided accurate data for most depths.

Ground truthing

For ground truthing, a total of 79 vibrocores reaching a depth of up to 5 meter were executed. The sediment logs were used for the interpretation of the geophysical data.

GEOLOGICAL SETTING

The Kenyan coast is part of a passive continental margin. The continental shelf is 2-3 km wide with depths dropping off to over 200 meters within less than 4 km from the coastline in most places. Reefs run parallel to the entire shoreline at a distance of 1-2 km, only locally intersected by rivers. The coastal zone has experienced eustatic sea-level oscillations and/or isostatic and differential tectonic movements, which reflected by elevated coastal terraces onshore and submerged terraces offshore (Abuodha, 2004; Oosterom, 1988; Thompson, 1956).

The survey area is offshore of a fringing coral reef with shallow back-reef lagoons. In the north, the reef is interrupted by the entrance of the Mombasa creek systems, in the south the reef is interrupted by a River. The cliffed coast on the landward side of the lagoon mainly consists of Pleistocene reef limestones and back-reef deposits. Further, inland, the rock formations consist of a thick sequence of mainly shales, sandstones and conglomerates of Upper Carboniferous to Upper Jurassic age, gently dipping towards the coast (Rees et al., 1996).

In such a setting, the sediments offshore are expected to be dominated by mainly carbonates derived from the reef / back reef system, and possibly siliciclastics from present day or ancient fluvial systems. The back-reef deposits will mainly consist of carbonate sand, silt and mud, while the slope in front of the reef will probably consist of coarser sediments, including reef limestone blocks, gravel and sand. More distal, these slopes may grade into sands and mud. Note that especially in the back-reef environment, cementation can take place in relatively young sediments. Siliciclastics are mainly expected in areas with a sediment source from the inland catchments.

RESULTS

A series of 48 lines, with a spacing of 50m were recorded parallel to the coast, and for correlation purposes, 99 cross-lines were recorded perpendicular to the coast, with a spacing of 250m. The 50m spacing was chosen because of the expected complexity of outcrop systems and the 250m spacing was chosen in order to obtain also sufficient coverage with the side-scan sonar in this direction.

Seismics

Two reflectors were interpreted in the area of interest, the seabed reflector and a base sediment reflector (Figure 1). The seabed reflector was very strong, suggesting absence of soft material (e.g. mud) at the top. The second reflector was interpreted as the boundary between the base of unconsolidated sediments and the top of hardrock. This reflector varied from very strong to weak to invisible if the sediments on top of the hardrock were over 6 meter. The outcrops are characterised by an irregular surface appearance and a smudgy (scattered) reflection signal and lack of reflectors below the sea- floor reflector.

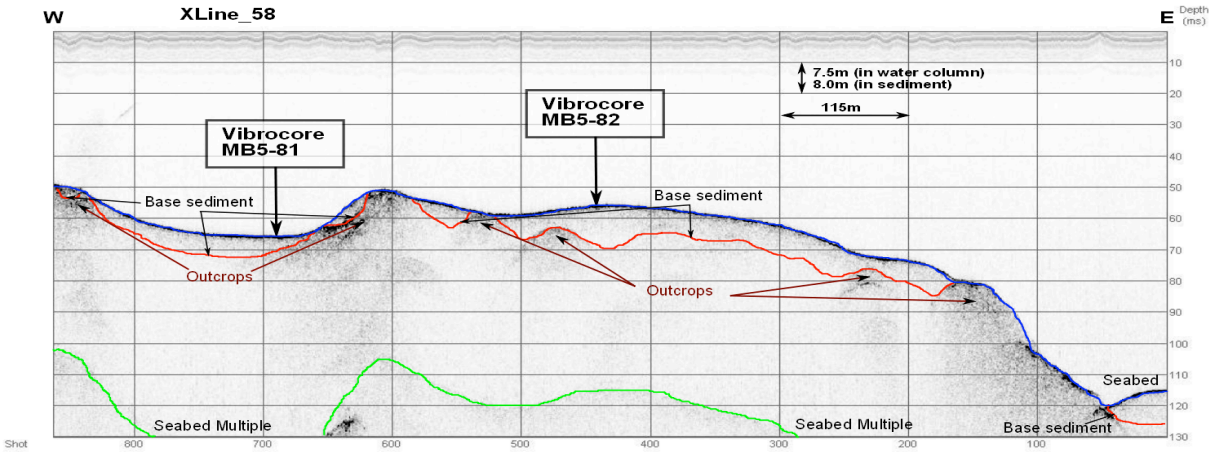

Figure 1. Example of an interpreted W-E seismic cross-section in the area, showing hardrock outcrops, locally covered by a sediment body, the base of which is indicated by the "base sediment reflector".

Bathymetry and side-scan sonar

After processing and editing of the bathymetric data, a bathymetric model of the survey area was constructed with a grid-cell size of 2x2m. The depth is indicated in meters below Lowest Astronomical Tide (LAT). The model shows shallow areas of around 10 meters in front of the harbour entrance and in front of the coral reefs, a wider plateau with depth ranging from 35 – 45 meters and a steep cliff going down to depths of more than 80 meters. Several areas clearly show a rough seabed morphology, with pinnacles, cliffs and steep-walled channels, while other areas show smoother terrain. The bathymetric model allows for a large-scale classification into morphological units.
The Side-scan sonar data were processed and mosaiced. On the resulting acoustic sea-bed images rock outcrops as well as the character of the sea-bed sediment (e.g. course or fine) and the presence of rubble and boulders can be identified.

INTERPRETATION

The sediment thickness model derived from the sub-bottom profiler data shows several areas with an unconsolidated sediment cover of several meters. Areas interpreted from the bathymetry data (Figure 2) and side-scan sonar data confirm the presence of these unconsolidated sediment bodies. The side-scan sonar provides additional information about the sediment character of these sediment bodies, while the bathymetry model provides information about the geometry and morphology of the sediment bodies. In combination with vibrocore data providing information about the sediment types, different geomorphological units could be identified in the surveyed near-coastal zone. Working with such units has the advantage that sediment composition (e.g. siliciclastic or carbonate), gradual

variations in grain size and sorting, and potential threats for damage to dredging equipment can be predicted within the units.

The side-scan sonar images indicate that these areas have a smooth surface without notable rubble or rocky outcrops. Other areas show an irregular surface, consisting, e.g., of rock pinnacles and boulders and do not appear promising for sand extraction.

The combination of the acoustic systems applied in this study provides insight in the regional submerged near-surface geology and can be used to classify the study area in morphological units in front of the coast. In this section the units that were identified in the area of interest are presented and discussed.

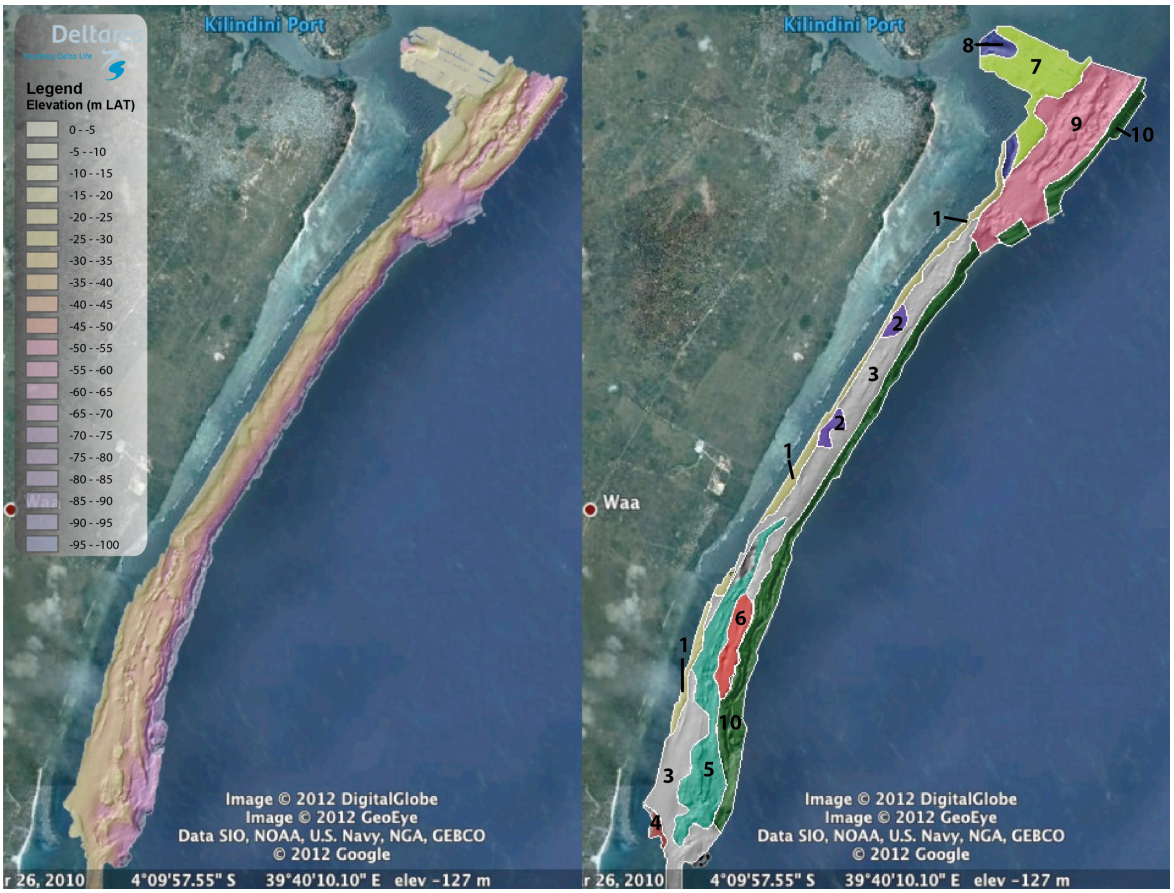

Figure 2. (left) bathymetrical model of the study area and (right) identified morphological units. The image is 15 kilometers wide and 22 kilometers high.

1. Reef slope

In front of the reefs, steep slopes are present. On the side-scan sonar images rubble and boulders can be recognized on these slopes, suggesting very coarse deposits. These slopes are interpreted as reef-front deposits consisting of eroded reef material. The deposits are expected to consist of badly-sorted carbonate components, ranging from sand to (very big) boulders.

2. Submerged fans

In certain areas, gently-dipping submerged fans are present. When plotted on air photographs, these submarine fans coincide with openings in the reef front. This suggests that the fans are fed by back-reef sediments that are transported seawards, probably during (storm) surges. The side-scan sonar images show a regular smooth surface at these locations, suggesting unconsolidated fine-grained sediments.

The back-reef deposits consist of calcareous (skeletal) sand, silt and mud. Therefore, the submarine fans most likely consist of the same material, but possibly sorting takes place during transport, leading to relatively finer sediment in the distal part of the fans.

3. Submerged plateau:

The submarine fans spread out on a submarine plateau with a depth of 35 to 45 meters below LAT. The seismic data suggest the occurrence of a thin layer (<1m) of sediment on this plateau. A smooth area in the south appears to have a thicker cover. The side-scan sonar data and the bathymetry support this interpretation and show a surface with a sediment cover regularly interrupted by rocky outcrops, often aligned parallel to the coast. This plateau is interpreted as a drowned back reef environment, with patch reefs sticking through the surface sediments.

4. Delta front

In the south of the survey area, a river flows into the lagoon and through an opening in the coral reef. In front of this opening a submerged fan is present in the bathymetry and seismic data, interpreted as a delta front. Because the river catchment is mainly situated in shale and sandstone formations, sediments in the delta front are expected to contain terrestrial (siliciclastic) material. However, the side-scan sonar images at this location do not fully support this interpretation and indicate rubble on the sea-bottom. This suggests that also eroded reef material may be transported from the reefs and lagoons to be deposited in this submerged fan. The submerged plateau in front of this interpreted delta front appears to have a sediment cover of about two meter. These deposits do show a fine texture on the side-scan sonar images, and may also consist of the sediments transported by the river.

5. Reef pinnacles

The submarine plateau in the south is littered with steep pinnacles. We interpret these pinnacles that are often aligned as drowned patch reefs that may have kept in pace with sea level rise for a while. The tops of the pinnacles are up to 30 meters below the sea-surface, and living corals may be still be present at this depth.

6. Submerged back-reef deposits

In front of the pinnacles in the southern part, an area covered with a sediment layer of several meters thick is present. This is evident from the sediment thickness map derived from the seismics, but also from the bathymetry map where a smooth blanket with some large scale scour holes is present. Also the side-scan sonar images suggest loose sediment at this location. This isolated sediment cover has no obvious source. Therefore, we tentatively interpret the sediment body as submerged back-reef deposits. Another explanation could be that the sediments are the remnants of former submarine fans (in front of the reefs producing the aligned pinnacles) deposited during a stage with lower sea levels, or eolian dunes formed during a lowstand period. An equivalent of the latter are also preserved onshore as the Kilindini Formation on a Pleistocene coastal terrace (Rees, 1996; Abuodha, 2004).

7. Wave-cut platform

In the northern part of the survey area, a shallow platform can be recognized with a depth of about 8 meters. The flatness of this unit suggests that it is a former wave-cut platform during a stage with lower sea-level. A submarine terrace with this depth was first recognized by Thompson (1956). The side-scan sonar images indicate a rocky surface littered with boulders.

8. Incised channels

Through the wave-cut platform, steep-walled meandering channels have been incised during low stand periods. The bottom level of these channels is currently about 40 meters deep. The bathymetric map and seismics suggest a sediment body overlying the base of the channel. Sediments in this unit are probably a mixture between carbonate material from back-reef deposits, and siliciclastic material from the river catchments and estuary inland of Mombasa.

9. Incised platform
In the north, the submarine plateau is incised by deep channels, with a base level of about 60 meters LAT. These channels were probably formed during a lowstand period and are the seaward equivalent of the narrow incised valleys around Mombasa.

10. paleo-reef front
Seaward of all units described here is a steep submarine cliff dropping from 40 m to over 80 m depth. This cliff may be a former fringing reef front that was drowned after a lowstand period. During the sea-level rise the coast stepped backwards and a new fringing reef was formed in front of the coast. The origin of this cliff is possibly also fault related, as the NNE –SSW orientation is parallel to the major faults in this area (Abuodha, 2004).

Of these systems, we expect the Units 2, 3 (in the south), 4 and 6 to be the most promising for potential sand extraction. The incised channels of Unit 8 appear to have a sediment infill, especially on the seaward side, but the incised channels are very narrow in extent which may imply navigational complications while dredging. The sand extraction potential for the other units is very low, as big boulders may be present (Unit 1), abundant rock pinnacles may stick out from the sea bed (Unit 5), they consist of a rocky flat surface (Unit 7), they consist of deep channels flanked by steep cliffs with only patchy sediment pockets (Unit 9), or they consist of rocky outcrops flanked by a steep-walled cliff dropping to depths of over 80 meters (Unit 10).

CONCLUSION

A multi-source geophysical exploration strategy in complex areas facilitates the interpretation and allows the translation of geophysical data into geomorphological units. Working with geomorphological units enables a more comprehensive prediction of sediment character (e.g. grain size, sorting), sediment chemistry, lateral and vertical variations within units and the presence of potential hazardous objects for dredging equipment. Other areas can be discarded due to the presence of cliffs, rocky surfaces, large boulders or high content of fine sediments. Knowledge of these factors allows for an improved estimation and can reduce costs in later stages of the project. In addition, the enhanced knowledge of depositional environments can be used for reducing environmental risk.

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