Lithological effects on rocky coastline stability

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ABSTRACT

Rock coasts are perceived to be stable, however, recent occurrence of stacks of rocks and subsequent loss of some rocky coasts poses a challenge for research. This study sought to assess the impact of waves on the compressive/tensile strength of the rocks and further investigated the lithological properties of coastal material that influence shoreline change along the heterogeneous rock coast of the western region of Ghana. The study determined how the petrology and mineralogy of the various rocks types influence the stability of rocky shoreline. Data used included available historic topographic maps and images, Geological map, directional wave data, field measurements of rock hardness and rock samples collected for laboratory investigations. Schmidt’s hammer was used to measure in-situ rock hardness. Shoreline features for the study period (1974–2005) were extracted from multi-temporal dataset into a geodatabase, and change statistics computed by end point rate method using DSAS, an extension of Arc GIS software. Thin sections were produced from rock samples collected from the field, and petrographic and microscopic analyses were carried out on them. It was found that wave impact was minimal compared with the tensile strength of the rocks in the study area; thus wave is not the key geomorphic agent in the study area. The results showed shoreline accretion at few sites, whereas other parts of the rocky shoreline are eroding at varying degrees. It was observed that the site lithology of the rock coast as well as the quartz feldspar ratio content of the rocks influence the shoreline change rates, as quartz bearing rocks are often more resistant to weathering. It was also noted that the strength of the intact rock had moderate correlation with the shoreline change rates; instead the mineralogy, state of weathering and textural properties of the rocks explains the shoreline change rates along the coast.

1. Introduction

Coastline stability is an issue of concern to coastal planners, management, and engineers as the coast serves as home to between 23% and 60% of the world’s population (Al-Tahir and Ali, 2004; Church et al., 2006; Dadson et al., 2016; Hinrichsen, 1998). The preference of human habitation along the coast is probably due to food security, ocean transportation, recreation and modified atmospheric weather and climate (Stewart, 2008). It is however reported that most coastlines in the West African states are eroding at variable rates (Ibe and Awosika, 1991) and that sandy beaches are vulnerable to coastal erosion (Schlacher et al., 2007). Although coastal erosion is a natural process in coastal landform, its occurrence often poses risk to livelihoods and coastal assets. Oftentimes, coastal lands are permanently lost when coastal cliffs or rock shores collapse and retreat landward. Erosion of coastlines in Ghana are usually associated with loss of valuable lands and properties of coastal dwellers (Appeaning Addo et al., 2008). Shoreline change, which is the displacement of the land-sea interface (Boak and Turner, 2005), serves as a good indicator of coastal erosion (Srivastava et al., 2005) and thus shoreline change analyses could inform researches of the stability of coastlines.

Coastal landforms usually originate through geological processes and are modified by marine processes. The dynamics of coastal landforms often spans several geological time scale particularly for rock coasts, however, the recent occurrence of stacks of rocks and the subsequent loss of portions of some rocky coasts is an issue which call for research. Rock coast morphology is often attributed to lithology, structural configuration, waves, climate, and minor relative changes in sea level, which are very different worldwide (Woodroffe, 2002; Granja, 2004). Even though rocky shores account for more than 33% of the world’s coastlines, geomorphology of these shores have received little attention in scientific literature (Johnson, 1988; Sunamura, 1992).

Coastline stability has been investigated from different perspectives. For instance, Rosser et al. (2013) studied the stability of the coast as a result of rocky cliff failures in the North Sea of the United Kingdom. It was observed from his study that failure propagation could operate...
independent of external environmental forces, and that they are closely tied to prevailing subaerial and oceanographic conditions. Violante (2009), determined geological processes that regulate rapid sediment transfers along rocky coasts. It was noted that proper comprehension of coastal mass wasting hazard requires the inclusion of marine and historical investigations from reliable past geological events occurring on land. The study of Brandolini et al. (2009) on the phenomenon of geomorphological instability along the rocky coast of the Tigullio Gulf revealed that useful information on evolution of landslides was obtained from in-depth analysis of the subsoil geology and monitoring activity. Other studies have debated whether waves or subaerial processes are the active morphologic agents for coastal evolution. While findings of some researches (e.g. Kennedy et al., 2011; Sunamura, 1977, 1992; Moura et al., 2011 among others) point to wave impact as associated to coastal evolution, findings of other studies show no direct correlation between coastal rock evolution and waves, rather subaerial processes (e.g. Kennedy et al., 2011; Stephenson and Kirk, 1998, 2000; Dickson et al., 2004). All these studies have linked the stability of rock coast to either waves or the geology of the area.
Sunamura (1992), also expressed the stability of the coast as a function of the erosive forces and the resistance of the coastal material. Under similar conditions of erosive forces, the resilience of the coastal material and therefore the geology determines/explains the stability of the shores particularly at rocky sites. Though the Sunamura’s relation is widely used, various physical properties of coastal material served as proxies for the erosive forces as well as the material resistance by different authors (Mano and Suzuki, 1999; Trenhaile, 1983; Wilcock, 1998). Limber et al. (2014), in their study assumed coastline retreat increases with wave energy and decreases with rock strength. Boye (2015), in her study along the western coast of Ghana associated the variability of the shoreline change in the area to the variability of the geological properties of the rocks. It is however, unclear how the inherent geological properties of rocks influence their stability or vulnerability to oceanic conditions. The present study seeks to probe the impact of waves on the coastal rocks, and further investigate how the petrology and mineralogy of the various rocks types influence the stability of rocky coastlines.

2. Study area

Ghana is a West African country bordered by Togo to the east, Cote D’Voire to the west, Burkina Fasso to the north and the Gulf of Guinea (Atlantic Ocean) to the south. The Western Region of Ghana lies within latitudes 4°40’ and 5°10’ north and longitudes 3°07’ and 1°40’ west (Figure 1) and the coastline stretches to about 192 km constituting about 35% of the Ghana coastline. The coast is generally low lying with topographic elevation not exceeding the 30 m above mean sea level (Boye, 2015). Waves approaching the shores of Ghana consist of swells originating from the oceanic area around the Antarctica continent and seas generated by local occurring winds (NA, 2019). The swell wave direction

Figure 3. Photographs of some parts of the rock coast of the study area.
Figure 4. Shoreline change rates and coastal rock strength along the rocky sections of the study area.

Table 1. Wave energy flux generated per section.

| Name of Section          | Angle of breaking wave crest with shore (°) | Wave Energy Flux factor (Pls) (N/s) | Potential Sediment Transport (N/s) | Sediment Transport per hour (N/hr) |
|--------------------------|---------------------------------------------|-------------------------------------|-----------------------------------|-----------------------------------|
| Dixcove-Shama            | 143.08                                      | -2698.980                           | -1052.602                         | -0.120                            |
| Cape Three Points - Atwiwa| 102.08                                      | 2724.064                            | 1062.385                          | 0.121                            |
| Axim-Princess Town       | 71.08                                       | 2515.772                            | 981.151                           | 0.112                            |
is almost always from the south or south-west with a primary period of 12 s and generally travels to the north-west. The significant wave height of the study area is generally between 0.9 m and 1.4 m, while the most common value in the region is 1.0 m. Tide along the coast of Ghana is regular and semi-diurnal; the tidal range is 0.90 m at Takoradi with the average Neap and Spring tide values increasing from west to east of the country (Hermas, 2016). The continental shelf (200 m water depth contour) has a generally regular near shore bathymetry with isobaths running parallel to the coast. The study area has large and small basins that discharge their fluvial sediment load to adequately nourish (1 x 10^3 tonnes of sediment per day) the shores daily thereby making the shores stable at the mouths of the rivers and lagoons (Boye et al., 2018). The general orientation of the coastline is categorized into three sections namely, Dixcove - Shama, Cape Three points – Atwiwa and Axim - Princess Town oriented at 46°, 87° and 118° respectively. The coastal material is composed of about 60% sandy beaches and 40% composite rock/sandy beaches (rocky headlands alternating with sandy bays).

The coastal rocks are heterogeneous with rock types ranging from granites, granitoids, through shales, sandstones to low strength soils (Kesse, 1985). The rocks in the region comprise extension of Paleo-proterozoic Birimian greenstone belt of the metavolcanic and meta-sedimentary, and intrusive granitoids to the coast, which are overlain by Neo-proterozoic and recent deposits of sediments. Some identifiable areas include, Shama, Axim, Cape Three Points and Ankobra areas. The Axim area is located at the southwestern end of the Ashanti belt and extends from the Ankobra River to the village of Anyaame. The area is dominated by Birimian units of interbedded metasediments and metavolcaniclastic, which are intruded by a NNE-SSW trending intermediate intrusive body, portions of which are porphyritic in texture. Birimian metavolcanic and Tarkwaian clastic units underlie the central portion of the area.

The Ankobra area is located at the southern end of the Ashanti Belt, near the Kumasi Basin. The area is highly sheared as it is found within the contact between the belt and the basin. Massive andesitic and basaltic flows, tuff and Tarkwaian clastic units (phyllite and quartzite) are the main rock types intruded by large felsic belt-type granitoid. Occasional interbedded schist and cherty horizons are present in the metasedimentary unit. The Cape Three Points area is the southernmost point in the country, and features a range of flat-topped, steep sided hills that crest at about 30 m above mean sea level. The Cape Three Points band of Birimian greenstone units is located in the central portion of the southwesternmost end of the Ashanti Belt. The band is wedged between two large intermediate granitoid complexes; on the eastern side is the Dixcove complex whereas on the western side, there is the Prince’s Town complex. Both of these granitoids are dominated by hornblende-bearing phases that are tonalite to granodiorite in composition (Loh et al., 1995). The coastal area is dominated by ultramafic intrusion varying in composition from peridotite to pyroxene and dunite (Loh et al., 1995).

Mafic intrusive rocks are encountered in this study at Akitekyi, Mpohor and around Axim town. At Akitekyi, the mafic intrusives are ultramafic metaperidotites, altered fine grained dunitic rocks and gabbro/norite intrusive rocks. Similarly, gabbrroic rocks are found in north of Mpohor and Axim town. Sedimentary and metasedimentary rocks such as sandstones, silt and shales are found in Ajua, Butre, Punpun, Sekondi and Asemkew. Contact between the Ajua shale and granitoid is seen at Asemkew and the shale is underlain by conglomerate. Between Axim and Nkubem are Tarkwaian sediments made up of greyish – green quartzite and arkoses inter-bedded with silt sediments.

### Table 2. Mean compressive/tensile strength of coastal rocks per section.

| Name of Section          | Selected Samples | Rebound Values | Median | Compressive Strength/Mpa | Tensile Strength/Mpa |
|--------------------------|------------------|----------------|--------|--------------------------|----------------------|
| Shama-Dixcove            | SC1              | 44.46          | 44.48  | 32.304                   | 1.989                |
|                          | AB1              | 45.85          |        |                          |                      |
|                          | ADC1             | 33.5           |        |                          |                      |
|                          | PUC1             | 44.5           |        |                          |                      |
|                          | MPC1             | 46.27          |        |                          |                      |
|                          | ASC1             | 44.08          |        |                          |                      |
| Atwiwa -Cape Three Points| ATC1             | 50.94          | 50.94  | 36.121                   | 2.104                |
|                          | KTC1             | 58.56          |        |                          |                      |
|                          | C3PC1            | 47             |        |                          |                      |
| Princess Town - Axim     |                  | 52.25          | 46.73  | 33.633                   | 2.030                |
|                          |                  | 44.08          |        |                          |                      |
|                          |                  | 42.67          |        |                          |                      |
|                          |                  | 49.38          |        |                          |                      |
of the study area were also determined. The potential sediment transported alongshore (Q) due to breaking waves was computed using the CERC Eq. (1) which is based on the wave energy flux (Pls) (Bayram et al., 2001; Kumar et al., 2003; Van Wellen et al., 2000).

\[
Q = K \times \frac{P_{ls}}{C^{16}} = K \times \frac{H_b^2 \times C_{gb} \times \sin(2\alpha)}{C^{17}}
\]

where, 
- \(Q\) = longshore sediment transport
- \(H_b\) = wave height at breaking
- \(C_{gb}\) = wave celerity at breaking
- \(\alpha\) = angle of the breaking wave crest with the shoreline
- \(\gamma\) = specific weight of water
- \(K\) = empirical coefficient

From a systematic sampling of the study area at 2 km intervals rock exposures within the study sites were identified (total of 29 sites were identified), and their surface hardness measured as an indicator of their resistance to coastal erosion. The internal resistance of the rocks to externally exerted stress (which is a measure of their strengths) were measured by means of a Schmidt’s or Rebound hammer. The Schmidt’s technique was adopted following the American Society for Testing Material (ASTM D5873) procedure since it provides a simple, quick, accurate and non-destructive test results (Hack and Huisman, 2002). The correlation between the measured rebound values of rocks and their corresponding shoreline change rates was determined. The petrographic aspect of the study comprises field work and subsequent microscopy analysis of the rock. Thin sections were prepared from the rock samples collected from the field (see Figure 2) and analysed. Figure 3 shows some

Figure 6. Photomicrographs of thin sections of some rock samples along the coast (a&b): granodiorite shows phenaritic lath of plagioclase with pyroxene inclusions (c): granite with subhedral grains of feldspars (orthoclase and plagioclase) interlock in anhedral quartz, d) fine to medium grain dioritic rock with plagioclase and quartz in fine groundmass of biotite, hornblende and quartz, e) porphyritic hornblende granodiorite at cape three, f) sandstone.
photographs taken at selected sites of the rock coasts. Point-counting was adopted to determine the approximate modal composition of the rock samples.

4. Results

The shoreline change computed showed both accretion and recession taking place along the rock coast of the study area. The spatio-temporal changes in the shoreline at the rocky sites over the 31 years period of the shoreline analysis (i.e. 1974 – 2005) is shown in Figure 4. The results revealed minimal accretion or no erosion at few sites (12.5%) such as Akyenin (+0.56 m/yr) and Ankobra Beach (+0.05 m/yr). Minimal shoreline recession rates of < -0.5 m/yr was recorded at 50% of the sample sites over the study period (these sites include Axim, Agyembra, Cape Three Points, Adwowa, Dixcove, Ekuasi, Pumpuni, Esikado and Butre). Moderate shoreline change rates of < -1.0 m/yr was recorded at 28% of the sample sites (Shama, Aboadze, Akyinim, Mia mea and Ajan) whereas relatively high shoreline recession rates of > -1.0 m/yr were observed at 10% of the sites (Aboesi, Nkontompo, Prusi Akatakyie, Prince’s Town and Mia mea). The relatively high recession sites include

| Shoreline change rate Category | Sample Point | Sample ID | Field Petrographic Description |
|------------------------------|--------------|-----------|-------------------------------|
| Relatively High Erosive Sites (r ≥ -1 m/yr) | Abuesi | | Foliated gneiss with quartz veins |
| | Nkontompo | MPC1 | Highly weathered shales |
| | Prusi Akatakyie | | Fine grained, dark metamorphic rock with network of quartzofeldspathic veinlets likely to be shear zone |
| | Prince’s Town | | Highly jointed granitic rock with quartz vein |
| | Mia mea | | |
| Intermediate Erosive Sites (0.5 ≤ r < 1 m/yr) | Shama | SCI | Highly jointed, moderately weathered granitic rock |
| | Aboadze | AB1 | Weathered massive sandstone |
| | Akyinim | ATC1 | Granitoids with coarse grained quartzofeldspathic dykes |
| | Adjua | | Highly jointed granitic rock with quartz vein |
| Low Erosive Sites (r < -0.5 m/yr) | Ekuasi/Sekondi | KTC1 | Massive sandstone |
| | Ketakor | KTC1 | Belt-type granitoids with abundant mafic minerals |
| | Butre | | Highly jointed greenish fine grained igneous rocks |
| | Adjua | ADC1 | Adjua Shales inter bedded with sandstone |
| | Enskado | | Gneiss with pegmatite intrusions |
| | Esiwon | | Sandstone, sea stack and isolated pegmatic veins. |
| | Pumpuni | PUC1 | Very fine grained shales with interbedded sandstone. |
| | Agyembra | | |
| | Ankobra | | Red brown fine grained foliated metamorphic rock |
| | Ekuasi/Sekondi | | Massive sandstone |
| | Ketakor | KTC1 | Belt-type granitoids with more mafic minerals |
| | Cape Three Point | C3PC1 | Highly jointed porphyritic granitoids |

Figure 7. Histogram of quartz/feldspar ratio and shoreline recession rate.
Note: Qtz = Quartz, Feld = Plagioclase Feldspar, K-feld = k-feldspar, Acc = Accessory minerals, Ss = Sandstone.
sites experiencing high erosion are dominated by granites and granodiorite which have low quartz to feldspar ratio (i.e. 0.1–0.6) and have phaneritic grains of plagioclase and hornblende. Sites with Q/F ratio of between 0.1 - 0.6 gives an indication that the feldspars in the rocks have undergone chemical weathering due to constant interaction with water and carbon dioxide to produce clay mineral through the process of hydrolysis. Whereas feldspar may be altered to form clay minerals, quartz remains unchanged and resistant to erosion. Sections of the coast covered with sedimentary rocks have high Q/F ratio and tend to experience low shoreline change rates, as quartz bearing rocks are often more resistant to weathering.

In the case of the granodiorite as pertains in Cape Three Points (Table 2) the rocks composed mainly of k-feldspar and plagioclase feldspar with little amount of quartz (<5%). When such rocks undergo weathering process the most common products would be clay minerals, quartz and dissolved ions most of which tends to be washed into the ocean leaving only the quartz as the primary constituent of sand. As weathering continues and most of the products of weathering are washed offshore, the shore as well as the beach at that section of the coast would be depleted of coastal material thus the shoreline would continue to recede. The effect of weathering is seen from the regression graphs in Figures 8 and 9. There is a negative correlation between the strength of the rock and its Q/F ratio. This is contrary to the well-established fact by Meriam et al. (1970) and Mendes et al. (1966) that as quartz and feldspar ratio increases the mechanical property (tensile strength) of the rock increases. In this study, instead of the strength of the rocks increase as Q/F ratio increases it rather decreases. The only reason for this trend is the effect of weathered feldspar in the rocks. The clay minerals that are formed as weathering product of feldspar are washed away by waves/currents and this creates or increases the intergranular pores in the rocks causing weakness in the strength of the rocks, and for that matter erosion of the shoreline also increases as seen in Figure 8. Rocky shore in the study area experiencing intermediate rate of erosion have quartz to feldspar ratio ranging from 0.7 to 3 with medium grain sizes of minerals. Less erosive areas have rocks with quartz to feldspar ratio ranging from 4.7 to 7.5 and are more stable due to the modal composition of quartz mineral.

Figure 7, shows clearly the effect of lithology (mineralogical composition) on the recession rate of the shoreline in the study area. Most of the areas with high quartz/feldspar ratio such as Adjua, Punpuni and Asemmkaw exhibited minimal recession rates with the exception of Aboadze where the rate of recession was relatively high. Field investigations show that the Aboadzi shore is partly covered with weathered sandstone and sandy beach. Despite the high quartz content of the sandstone however, the sandy beach is eroding at a faster rate resulting in the formation of stacks (see Figure 9). In addition, the presence of groins at the shore gives an indication of previous knowledge of high rate of erosion in that area. Other factors such as production and distribution of beach sediment either from fluvial process or waves may also account for this anomaly. Figure 8 shows moderate correlation (Taylor, 1990) between the rock strength and the shoreline change rate, thus the strength of the intact rock have some effect on the shoreline change rates in the study area. However, the rock resistance to erosion is more dependent on the state of weathering and the nature of weaknesses in the rock. From Table 4, it is evident that the factors that control the variation in the shoreline change rate at the study area are mineralogy and textural properties of the rocks along the coast (see Figure 10).

6. Conclusions

The study has shown that wave impact is not the key agent driving the evolution of the rock coast at the study area. The study also revealed that some portions of the rocky sites of the shore are accreting while erosion is taking place at most sections. Generally, the area lithology of the rocky coast influences the shoreline change rates that pertains at that site. It was observed that the quartz/feldspar ratio content of the coastal rocks in the study area explain to some extent the shoreline recession rates recorded at those sites. Again the degree of weathering taking place in the rocks is linked to the recession rate at those sites. Sections of the rock coast with sandstones have high Q/F ratio and tend to experience low shoreline change rates, as quartz bearing rocks are often more resistant to weathering. It was also noted that the strength of the intact rock had moderate correlation with the shoreline change rates; instead the mineralogy, state of weathering and textural properties of the rocks explains the shoreline change rates along the coast. This study has demonstrated that the rocky coast in the case study area are eroding gradually as against the general perception that rocky shores are stable. The study also informs coastal management to formulate policies regarding the type of material to use for sea defence projects. This method applied in this study could replicated along rock coast that have granitoids such as White Cliffs of dover in England, Normandy beach of France, Queensland of Australia and cook Island of New Zealand.

Declarations

Author contribution statement

C. B. Boye: Conceived and designed the experiments; Performed the experiments; Wrote the paper.
E. B. Fiadonu: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
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The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

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