Origin and prospectivity of heavy mineral enriched sand deposits along the Somaliland coastal areas

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ABSTRACT

Sixty-one heavy mineral enriched samples along the Somaliland coast from Eil Sheikh to Ras Khatib, a distance of about 130 km, were analyzed using X-ray Fluorescence, X-ray Diffraction and SEM-EDS techniques. This study reveals that a considerable amount of heavy minerals is present along the Somaliland coast and confirms the presence of high concentration titanium and iron bearing minerals. However, the backshore deposits in the mouths of Waheen and Biyo Gure ephemeral rivers as well as raised paleo-beaches in the east of port city of Berbera demonstrate the highest level of titaniferous heavy minerals with most samples showing concentration greater than 50 wt %. The titanium detected in geochemical analysis occurs in the form of ilmenite, rutile, titanite and titaniferous magnetite. Also, present in minor or trace amounts, are garnet, zircon and monazite.

Heavy mineral accumulations in the east and west of Berbera have different mineralogical assemblages. The east of Berbera is dominated by quartz with moderate concentration of plagioclase, K-feldspar, magnetite, hematite and titanium bearing minerals, whereas in the west of Berbera, the dominant minerals are quartz, K-feldspar and plagioclase with variable proportions of ilmenite, rutile, mica, amphibole and pyroxene. These variations in mineral assemblages suggest different composition of the catchment areas that supply sediment to these deposits. The catchment area in the east of Berbera consists mainly of Proterozoic crystalline basement of the Qabri Bahar complex, Gabbro-Syenite belt and granitic intrusions that outcrop in Hudiso, Tulo Dibijao and surrounding areas. The primary sources of heavy minerals in the west of Berbera comprise of high-grade metamorphic rocks of the Mora and Qabri Bahar complexes as well as the Miocene volcanics that outcrop in Laferug and Hagabo areas.

The heavy mineral sand deposits observed along the Somaliland coast have the potential to provide commercially important heavy minerals, in particular ilmenite. It appears that prospects for development of the heavy mineral sands in the east of Berbera are better than those to the west of Berbera. In general, east of Berbera has wider beaches, better heavy mineral sands in the upper horizons and dune areas with heavier mineral sands. Furthermore, a series of raised paleo-beaches with high concentrations of heavy mineral sands are observed 1–2 km behind the shoreline. However, further investigation, including drilling and laboratory analyses, still needs to be carried out, particularly close to the entrance of Waheen and Biyo Gure ephemeral rivers to evaluate the potential quality and scale of the deposits.

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1. Introduction

Heavy mineral deposits are unconsolidated detritus sediments that accumulate in coastal environments both on beach and coastal sand dunes. These deposits derive from the weathering of pre-existing rocks of mainly high-grade metamorphic and igneous origin. Rivers and ephemeral streams transport the detrital sediments to the coastal areas where the action of waves, longshore currents, tides and winds mechanically sort and concentrate the dense minerals. These processes lead to the accumulation of distinct layers of dense sediments in a variety of coastal depositional environments, such as foreshore, shoreface, lagoonal and sand dune environments (Force et al., 2001).

Studies on heavy mineral deposits around the world including...
in Australia (Hou et al., 2011; Roy, 1999; Roy and Whitehouse, 2003; Roy et al., 2000), Brazil (Dillenburg et al., 2004; Leonardos, 1974), India (Acharya et al., 1998; Ali et al., 2001; Behera, 2003; Gujar et al., 2010; Rao, 1957), United States (Carpenter and Carpenter, 1991; Force et al. 2001; Pirkle et al., 1989) and Africa (Tyler and Minnitt, 2004; Van Gosen et al., 2014) have focused on the economic viability of these deposits. These studies have shown that heavy mineral deposits are the principal source of most of the world’s commercially produced ilmenite, rutile, zircon and monazite which are used for pigments and refractory industries (Van Gosen et al., 2014). Furthermore, Armstrong-Altrin et al. (2012, 2017, 2014, 2015b), Tapia-Fernandez et al. (2017) conducted mineralogy and geochemistry of coastal sands along the Gulf of Mexico. These studies described the textural differences among distinct depositional environments and recognized abundant heavy minerals such as magnetite, ilmenite, rutile and zircon.

Commercial evaluation of heavy mineral deposits in Somaliland has been somewhat neglected over the last 20 years. The presence of heavy mineral deposits in Somaliland was only reported by Abdalla et al. (1993) who analyzed twelve samples from black sand deposit of Batalaleh beach in Berbera. They reported grain sizes of black sand ranging between 0.063 and 1 mm. Gravity separation suggested a split of 59.4% of light (mainly quartz) and 40.76% of heavy minerals, which consist of magnetite (19.75%), ilmenite (8.33%), zircon (0.36%), monazite (0.27%), and rutile (0.18%) (Abdalla et al., 1993).

The purpose of this study is to explore the presence of titaniferous heavy mineral deposits along the Somaliland coast and assess the economic viability for mining these deposits. We collected heavy mineral sand samples from sixty-one locations of different environments along the coast. The main objective of this investigation was to determine the major mineralogy and elements of these samples as well as mineralogical phases within selected samples. In addition, we evaluated the compositional differences between the east and west of Berbera beach areas and inferred paleo-weathering and provenance. We recognized reasonable concentration of titaniferous heavy minerals of ilmenite and rutile as well as zircon in three different types of environments: backshores, paleo-beaches and sand dunes. The results indicate the economic potential of these deposits. However, more detailed studies are required to determine the grade, quality and scale of these deposits.

2. Geological setting

The study area is situated in the coastal region of the Somaliland coast along the southern Gulf of Aden that extends 130 km from Eil Sheikh to Ras Khatab between degrees longitude 44°15’E and 45°25’E (Figs. 1 and 2). Beyond Ras Khatab it is believed that most of the drainage falls outside the Proterozoic crystalline basement source belt, with the marine sediments showing noticeably lower heavy mineral sand concentrations. However, the dunes did still show a considerable volume of mafic minerals on scarps slopes.

The crystalline basement outcrops immediately to the south of the Somaliland coast in an east-west orientated strip running parallel to the escarpment of the Somaliland Plateau (Fig. 1). The basement is exposed as a result of uplift related to the separation of Africa from the Arabian Peninsula during the Oligocene-Miocene (Ali and Watts, 2015; Warden and Daniels, 1984). The basement consists of Proterozoic terranes (metamorphic and magmatic rocks), approximately 600 km by 30–60 km wide, extending from the Ethiopian border to Las Khoreh, and is considered to be the northeastern limb of the Mozambique belt (Abbate et al., 1993b; Farquharson, 1926; Greenwood, 1960; Sassì et al., 1993; Warden and Daniels, 1984). These terranes amalgamated during the Neo-proterozoic compressional event of island-arc and microcontinent terrane accretion that led formation of the Afro-Arabian margin of Gondwana (Al-Husseini, 2000; Husseini, 1989; Loosveld et al., 1996; Sassì et al., 1993; Warden and Daniels, 1982, 1984).

Kröner and Sassì (1996) reported the oldest rocks in the basement of Somaliland. They suggested that, from zircon ages, Somaliland basement consists of pre-Pan African Proterozoic crust ranging in age between ~1400 and ~1820 Ma. Four basement complexes outcrop in the drainage area: Qabar Bahar complex, Mora complex, Gabbro-Syenite belt and Younger Granites. The Qabar Bahar complex consists of high grade polymetamorphic layered paragneisses, migmatites, porphyritic orthogneisses and plagioclase-amphibolites (Kröner and Sassì, 1996; Sassì et al., 1993). The Mora complex, which occurs on the westernmost side of the drainage area, is characterized by the occurrence of abundant marbles, quartzites and amphibolites. These are associated with high grade paragneisses and migmatites, which are closely similar to those occurring in the Qabar Bahar complex (Kröner and Sassì, 1996; Sassì et al., 1993). The Gabbro-Syenite belt consists of numerous bodies of layered gabbro with minor alkaline granitoids (Dal Piaz, 1987). Field relationships indicate that the gabbros were intruded into already deformed rocks of the Qabar Bahar and the Mora complexes (Daniels et al., 1965; Hunt, 1960) and that the syenites and granitoids are slightly younger than the gabbros. The basement is intruded by granitoids that crosscut all rock complexes with radiometric ages of 515–550 Ma, known as Young Granites (Greenwood, 1960; Mason, 1962; Sassì et al., 1993).

The crystalline basement is covered by Mesozoic-Quaternary sedimentary and volcanic sequences. The Jurassic sequence consists of Adigrat sandstones which are conformably overlain by transgressive marine carbonates with minor interbedded marlstones of Bihendula Group (Ali and Watts, 2016). The Cretaceous succession consists of highly weathered coarse-grained quartz-rich sandstones (Ali and Watts, 2016). The early Cenozoic successions consist of carbonates of Auradu, Taleh (or Gypsum-Anhydrite Series) and Karkar Formations. Oligocene and Miocene sediments are mostly restricted to narrow and isolated sub-basins along the coastal belt bordering the Gulf of Aden (e.g. Daban basin), occasionally extending inland in low-lying regions. The sequence was deposited in localized grabens caused by the rifting of the Gulf of Aden. It consists of a thick sequence of red-brown, green sand and silts, gypsiferous sandstone, and gypsiferous sands and marls (Abbate et al., 1993a).

Furthermore, Early Miocene to Pliocene basalt and other volcanic rocks outcrop west of the port city of Berbera (Fig. 1) (MacFadyen, 1933; Mackay et al., 1954). The most prominent volcanic cone is Mount Elmis, 15 km southwest of Bulhar, which comprises basaltic lava flows that extend southwards and eastwards for 70 km. This volcanic activity occurred as a consequence of the Afar plume and the rifting of the Gulf of Aden (Ali, 2015).

Geomorphologically, the study area is divided into two main physiographic regions: (1) the lower-lying coastal plains along the Gulf of Aden (generally known as the Guben), lying between the plateau escarpment and the coast, and (2) the uplifted plateau escarpment (known as Golis) running east-west parallel to the Gulf of Aden coastline in an almost continuous line across the country. Long and narrow ephemeral streams dissect the plateau and the Guben, resulting in complex well-integrated dense drainage systems that transport sediments from crystalline basement in the south to the Gulf of Aden coastline in the north. In addition, the drainage patterns south of Berbera shift to the east and accordingly the marine sediments to the east and west of Berbera have different source rocks. Therefore, most of the drainage tributaries converge into Waaheen and Biyo Gure ephemeral rivers (Figs. 1 and 2).
Waaheen has very wide mouth and many tributaries. The catchment area of Waaheen covers the crystalline basement west of Berbera in the areas of Laferug and Hagabo which are dominated by the Qabri Bahar and Mora complexes as well as Miocene basalt. The Biyo Gure has a very narrow mouth and fewer tributaries. It drains crystalline basement outcropping in the Hudiso area which mainly consists of the Qabri Bahar complex and Gabbro-Syenite belt.

3. Methodology

Sixty-one samples were collected to assess the heavy-mineral content of coastal sediments in the study area (Fig. 2). Thirty of these samples were collected from the east of Berbera and thirty-one from the west of Berbera. The samples were collected in different environments such as backshores, paleo-beaches and dunes (Fig. 3). However, most of these samples were collected from the backshore areas as these contained the most visible concentration of heavy minerals and were more easily accessible. Few samples were collected from the raised paleo-beaches and dune fields immediately inland, which become more prominent to the east of Berbera. The study area and surrounding region are sparsely populated with few dirt roads connecting villages. Therefore, the area further east up to and around Siyara could not be accessed during this study due to access limitations. However, from satellite images (Fig. 2), this area does have heavy mineral sand deposit along the backshore areas and a large interior dune field with strong heavy mineral showings.

The sampling points were located at an interval of ~1–4 km, and they were collected from pits that were dug to a depth of 0.5–1 m. The pits were cleaned and controlled scrape of the sidewall formed the samples that weighed about 2 kg each. In some places, this was repeated at different beach levels. The paleo-beach was partially lithified and we were only able to collect surface samples during this study. The backshore and paleo-beach areas exhibit heavy mineral laminations that ranges in thickness from 0.5 to 10 cm. These laminations together with interbedded light sands are laterally continuous for at least hundreds of meters (Fig. 3). The sand dunes contain more or less discontinuous heavy mineral laminations.

The heavy mineral sand samples were processed and analyzed at the SGS South Africa (Pty) Ltd. An aliquat of each sample was pulverized and submitted for chemical analyses. The chemical analyses consisted of major element analyses including Fe₂O₃ and TiO₂ by Borate Fusion X-ray Fluorescence (XRF). In addition to this, ten samples were selected for X-ray Diffraction (XRD). A ~50 g aliquot was split from each of the ten samples and submitted for XRD. The samples were analyzed by XRD utilizing a Panalytical X’Pert Pro Diffractometer employing Co-Kα radiation. Data interpretation was done by means of Panalytical Highscore Plus analytical software and the PDF2 database. The XRD analysis was used to identify the major mineralogy of each sample. Due to the large number of samples, the resulting patterns underwent cluster analyses. The cluster analysis enabled identification of mineralogical similarities between the samples based on their XRD pattern. Furthermore, two of the samples (W16 and E1), one from the west of Berbera and other from the east of Berbera, were examined by Scanning Electron Microscope (SEM) to describe the major phases and to determine if titanium occurs in silicate phases.
4. Analytical results

4.1. Geochemistry and mineralogy

4.1.1. Major element concentrations

The major element concentrations of analyzed heavy mineral sands by XRF are listed in Tables 1a and 1b. The major element results show wide differences in composition among the samples from the east and west of Berbera. The SiO₂ content for the samples in the west of Berbera are quite variable from ~15 to 87 wt%. Among these samples, three samples (W16, W17 and W18) show low SiO₂ content ranging from 15 to 38 wt%. The TiO₂ concentration is also higher (11–20 wt%) in these three samples (Table 1a). Furthermore, these three samples are enriched in Fe₂O₃ (30–48 wt%). The variability of the SiO₂ content for the rest of the samples in the west of Berbera vary from 54 to 87 wt% (Table 1a). Similarly, there is a wide scatter in SiO₂ content for the samples in the east of Berbera ranging from 2 to 78 wt%. However, six samples (E9, E10, E20, E23, E24 and E25) have low SiO₂ content ranging from 2 to 34 wt% (Table 1b). Furthermore, these three samples are enriched in Fe₂O₃ (30–48 wt%). The variability of the SiO₂ content for the rest of the samples in the west of Berbera vary from 54 to 87 wt% (Table 1a). Similarly, there is a wide scatter in SiO₂ content for the samples in the east of Berbera ranging from 2 to 78 wt%. However, six samples (E9, E10, E20, E23, E24 and E25) have low SiO₂ content ranging from 2 to 34 wt% (Table 1b). As in the west of Berbera, these samples have high concentration of Fe₂O₃ and TiO₂, which probably reflect the abundance of Ti-bearing heavy minerals such as magnetite and ilmenite. The SiO₂ content variability of the rest of the samples is reduced to 45–78 wt% (Table 1b). Therefore, in general the samples from the west of Berbera have higher SiO₂ content than those in the east of Berbera.

The Al₂O₃ content ranges from 3.43 to 14.50 wt% and 1.39–14.3 wt% for the samples in the west and east of Berbera, respectively (Tables 1a and 1b). However, the average Al₂O₃ content is slightly higher in samples from the west of Berbera. Similarly, the average Al₂O₃/TiO₂ ratios are higher for the samples in the west of Berbera (Table 1a) than for those samples in the east of Berbera (Table 1b).

In addition, on average the CaO and MgO contents are slightly higher in the samples from the east of Berbera compare to those samples in the west of Berbera. In contrast, the samples from the east of Berbera are slightly depleted in K₂O and Na₂O contents compared to those samples in the west of Berbera (Tables 1a and 1b). The variations in the remaining major elements (e.g. MnO and P₂O₅) are not significant for both samples from the east and west of Berbera. The differences in concentration of major elements among the samples in the east and west of Berbera probably indicate effect of sediment sorting or most likely differences in source rocks.

4.1.2. Mineralogy based on XRD

Table 2 shows the general mineral assemblages and abundances which were calculated using XRD data of ten selected samples. The crystalline phases that were detected by XRD are shown in the diffractograms (Fig. 4a and j). The XRF results indicate that generally samples have a high SiO₂ content, this was confirmed with the diffractograms, which showed prominent peaks for silica bearing minerals like quartz and plagioclase. On XRD examination, some of the samples (e.g. W16) revealed that they are constituted of ilmenite and rutile, with minor amounts of monazite and zircon. Geochemical data also reveal a strong presence of iron bearing minerals, hematite and magnetite. The remaining mineral assemblage was generally concentrated with amphiboles, calcite and garnet.

4.2. Texture and mineralogical compositions based on SEM analysis

The SEM examination was conducted in order to describe the
major phases as well as to determine if titanium occurs as silicate phases such as biotite. In addition, it was used to identify and confirm the presence of certain titanium bearing minerals as well as their associated minerals. From the microphotographs taken, relative textures between the various minerals can also be seen. Two samples were selected to undergo analysis by SEM. The selection of the two samples (W16 and E1) were based on the XRD and XRF results. Samples showing adequate titanium concentrations were chosen. The SEM microphotographs and EDS (Energy Dispersive Spectroscopy) spectrums are shown in Figs. 5–8 and depict range of minerals found within the selected samples.

The samples from the backshores in all cases showed the sands to be well sorted. In addition, the heavy minerals show a similar pattern of grain size distribution from backshores, paleo-beach to dunes and are dominantly in the size of 100–350 μm. However, silty intercalations are observed at the mouths of Waheen and Biyo Gure ephemeral rivers.

The particles of sample W16 range from about 40 to 350 μm in size (Fig. 5). Most mineral grains appear to be at least partially liberated. The mineral grains in sample E1 are also liberated and vary in size from 104 to 625 μm (Fig. 7). Quartz grains appear to be amongst the larger grains. Overall, the heavy mineral assemblages recorded in this study consists of ilmenite, rutile, magnetite and minor amount of zircon (Figs. 5–8). Besides these minerals, other heavy minerals observed include pyroxene, amphibole, garnet and epidote. Trace amounts of cerium was also detected in the form of monazite (Fig. 6h). In addition, minor concentration of phosphorous (P₂O₅) that were observed in the XRF analysis (Table 1) occur in the form of apatite and monazite as indicated from the SEM analysis (Fig. 6g and h).

Generally, ilmenite is the dominant heavy mineral, and it comprises, on average, 30 wt% of the assemblage in cluster 1 (Table 3). Ilmenite mostly occurs as opaque subhedral to euhedral grains (Figs. 5a and 7a). Some ilmenite occurs as lens-shape polycrystalline grains due to intergrowths of magnetite and ilmenite (Fig. 7a). The ilmenite that concentrates in cluster 1 (Table 3) generally contains 67% TiO₂ and 33% Fe₂O₃ (Fig. 8a and Table 2). The average rutile content of cluster 1 (Table 3) is 2.5–3.2 wt%. It occurs as dark red to brownish in color. Grains are rounded to sub-rounded in shape, which indicates that they are sourced from reworked sediments (Fig. 5a). Some rutile samples are in anhedral form, which indicates that the sediments are immature and may be derived from adjoining acidic igneous and metamorphic rocks.

The magnetite occurs as octahedral or rounded grains with thin exsolution of ilmenite (Figs. 5a and 7a). Two types (fresh and altered) of magnetite are observed (Fig. 6c and d). The fresh magnetite grains are sub-angular whereas the altered grains contain titanium (Figs. 5a and 7a). The amphiboles occur in blue or green, slightly rounded prismatic crystals (Figs. 5 and 7). The apatite is found as colorless or whitish, rounded grains (Fig. 5). The sphene generically occur as rounded, brownish yellow, anhedral grains. Polycrystalline grains due to intergrowths of sphene, apatite and plagioclase is sometimes observed (Fig. 7b). The monazite grains are yellow to reddish characterized by rounded to well-rounded shape, and its presence indicates that they are derived probably from orthopyroxene granite (Fig. 5b). Monazite concentration is generally <0.2 wt%. Garnet grains (17.6–31.2 wt% for samples W16–W18) are mainly colorless with sharp edges that

Fig. 3. Field photos showing a) heavy mineral deposit in a beach east of Berbera, b) sample location showing laminations of heavy mineral sands. The depth and width of the pit are ~0.5 m and 0.3 m respectively. d) Raised paleo-beach exhibiting evidence of heavy mineral sands. e) Sand dunes in northeast of Berbera.
suggest a short transport. Zircon comprises on average 0.5 wt% of the heavy mineral assemblage but ranges up to 1.5 wt% in samples W11 and W16 of cluster 1 (Table 3). Zircon grains are typically well rounded. Although present in minor quantities it is present in all of the samples analyzed throughout the area. However, zircon shows a higher percentage in the western area of Berbera close to the mouth of Waahleen ephemeral river which indicate zircon bearing rocks (probably high-grade metamorphic rocks of Qabri Bahar complex) in the catchment areas of Waahleen ephemeral river.

The SEM EDS spectrum of the ilmenite, magnetite plagioclase, amphibole, apatite and monazite are shown in Figs. 6 and 8. The SEM images show the detrital grains (e.g. magnetite, ilmenite, rutile and amphiboles) that are characterized by mechanical breaking such as conchoidal to sub-conchoidal fractures and irregular cracks (Fig. 6), which indicate that these grains are freshly derived and underwent limited transportation. Alternatively, the conchoidal to sub-conchoidal fractures may indicate the grains were subjected to high energy environment developed by wave induced collision.

4.3. Cluster analysis

Four clusters were identified and Fig. 4 shows the diffractograms of selected samples from each cluster. The samples of different clusters are listed in Table 3. These samples were clustered based on their mineralogical similarities. Detailed descriptions of the mineralogy of each cluster are given below.

Cluster 1: Samples of this cluster are dominated by heavy mineral assemblages including varying amounts of ilmenite, rutile, zircon and minor amounts of monazite. Sample W16 in cluster 1 is primarily dominated by titanium bearing minerals namely ilmenite, rutile and titanite as well as amphiboles. There are also trace amounts of zircon present. Magnetite, hematite, and garnet in the form of almandine, make up the rest of the mineral assemblage. Quartz and plagioclase are also present in minor amounts. This mineralogy is similar for all samples of this cluster.

Cluster 2: Samples in this cluster are dominated by quartz and to a lesser extent K-feldspar and plagioclase. There is also a fair amount of mica present. Amphibole, rutile and pyroxene are present in variable proportions. Calcite, chloride and biotite appear in small amounts in samples of this cluster. Trace amounts of ilmenite were detected. Sample W24 was the most representative sample of this cluster. In addition to conforming to the basic mineralogy of cluster 2, sample E1 displayed trace amounts of rutile and titanite. Sample W19 of cluster 2 also contained minor amounts of titanite. Most of the samples in this cluster occur in the west of Berbera (Fig. 2).

Cluster 3: Samples in cluster 3 are dominated by quartz and...
mainly occur in the east of Berbera. Plagioclase and K-feldspar are present to a lesser extent. Moderate amounts of magnetite, hematite, titanium bearing minerals, calcite, biotite and gypsum were also detected. There were also trace amounts of sphene. Amphibole was present in variable amounts. This mineralogy was characteristic of sample E2, which showed mineralogical similarities with the rest of the samples in this cluster.

Cluster 4: The most representative sample of this cluster is sample E6 which is dominated by K-feldspar, plagioclase and quartz. Samples of this cluster also displayed the presence of minor amounts of amphibole and calcite. Trace amounts of gypsum, biotite, chlorite and rutile were also detected. Sample E3 depicted

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Table 1b: Geochemical results of samples collected from the east of Berbera showing major element concentration in weight %. For sample location see Fig. 2.

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Table 2: Mineral assemblages and abundances in weight % for ten selected samples. For sample location see Fig. 2.
similar mineralogical characteristics. Sample E4 also contained the overall mineral assemblage of cluster 4 but did not display the presence of gypsum. Sample E5 indicates quartz and plagioclase dominate mineral assemblage. K-feldspar and biotite was present in variable proportions. The remaining mineral assemblage was made up of minor amounts of amphibole, chlorite calcite and titanite.

Fig. 4. Diffractogram showing the composition of samples a) W24, b) W19, c) W16, d) W8, e) E1, f) E2, g) E3, h) E6, i) E4 and j) E5. For sample location see Fig. 2.

5. Discussion

5.1. Heavy mineral content

A total of sixty-one samples were collected along the Somaliland coast from Eil Sheikh in the west to Ras Khatib in the east from backshores, paleo-beaches and sand dunes deposits. The study
shows that the Somaliland coast contains high concentration of heavy mineral sands, which were derived from erosion of the nearby crystalline basement that outcrops along a narrow belt parallel to the coast.

The results of the geochemical analyses indicate that generally samples collected from the east and west of Berbera have a high SiO2 content (Tables 1a, 1b and 2). This observation was confirmed with the XRD analysis and diffractograms (Fig. 4). The geochemical composition also reveals a strong presence of iron bearing minerals, hematite and magnetite, which were identified in both XRD and SEM analysis. In addition, samples in cluster 1 (W16–W19 in the west and E9–E13 in the east) show the highest concentration for titanium and iron bearing minerals (Table 3). These samples vary between 43.1 and 69.0 wt% of titaniferous heavy minerals with most samples showing concentration greater than 50 wt% (Table 3). The titanium detected in geochemical analysis was confirmed to occur in the form of ilmenite, rutile, titanite and titaniferous magnetite. Compared to ilmenite, rutile has lower amount of Fe and Mn (Fig. 6a and b). The titaniferous magnetite contains ~9% of TiO2 (Fig. 6d). In addition, trace amounts of titanium (~0.85% TiO2) were

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**Fig. 5.** a) SEM (Scanning Electron Microscope) microphotograph displaying variation of mineral grains in an area of sample W16. Where Mgt: magnetite; Plag: plagioclase; Rt: rutile; Ilm: ilmenite; Apt: apatite and Amp: amphibole. b) SEM microphotograph of the mineral monazite. It occurs as a liberated mineral within sample W16, where Thr: thorium and Mnz: monazite.
detected in amphiboles (Fig. 6f). The split within the heavy mineral fraction is fairly uniform with ilmenite and rutile comprising 20–40 wt% and magnetite forming 5–20 wt%. The remainder of the heavy mineral fraction is non-magnetic and dominated by garnet, zircon and monazite. In view of the SEM analysis most grains appear to be liberated as observed in samples W16 and E1 (Figs. 5 and 7). Sample E1, however, shows examples of ilmenite occurring as exsolution in magnetite. Furthermore, the monazite grains

Fig. 6. SEM EDS (Energy Dispersive Spectroscopy) spectrum of sample W16 (grains shown in Fig. 5a) showing a) ilmenite. Most mineral grains are liberated, however in some cases ilmenite occurs as exsolution in magnetite. This was common throughout the sample. Trace amounts of manganese (~1%) were found. b) rutile, c) magnetite, d) titaniferous magnetite. This grain contains ~9% of TiO₂. e) plagioclase f) amphibole. Trace amounts of titanium, (~0.85% TiO₂) were detected in amphiboles of this sample. g) apatite. h) monazite, which occurs as a liberated mineral within sample W16, where Thr: thorium and Mnz: monazite.
contain variable amounts of thorium and in some cases showed
discrete grains of thorite locked within the monazite grain (Figs. 5b
and 6h). The P$_2$O$_5$ content of the monazite grains is also higher than
that of the apatite grains (Fig. 6g and h).

5.2. Sediment maturity and source rock characteristics

The SiO$_2$/Al$_2$O$_3$ ratio is widely used to determine the textural
maturity of sediments with high ratios indicating compositionally
matured sediments (Armstrong-Altrin et al., 2012, 2014, 2015a,
2015b). In this study, the average SiO$_2$/Al$_2$O$_3$ ratios of the samples
from the east and west of Berbera are similar with average values of
~9.57 and ~9.63 respectively. However, the samples (e.g. E8–E10
and W15–W18) collected closer to the mouths of Waheen and
Biyo Gure ephemeral rivers have relatively lower SiO$_2$/Al$_2$O$_3$ ratios
than those farther from the river mouths (e.g. E1, E2, W8, W9)
indicating compositional immaturity.

Furthermore, the Al$_2$O$_3$/TiO$_2$ ratio is used to determine source
rock type with low values (<14) indicating mafic source rock and
high values (>28) suggesting felsic source rocks (Armstrong-Altrin

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**Fig. 7.** a) SEM microphotograph of the mineral assemblage in an area of sample E1. Where Ilm: ilmenite; Qtz: quartz; Mgt: magnetite; Amp: amphibole and Plag: plagioclase. b) SEM microphotograph showing an intergrowth of minerals, where mineral 1 is sphene, mineral 2 is apatite and mineral 3 is plagioclase.
et al., 2012, 2017; Girty et al., 1996; Ramos-Vázquez et al., 2017). In this study, the Al₂O₃/TiO₂ ratios for the samples collected from the east of Berbera range from ~0.1 to 29.8 with an average value of ~8.52. The Al₂O₃/TiO₂ ratios for the samples collected from the west of Berbera vary from 0.23 to 45.31 with an average value of 10.62. The range in Al₂O₃/TiO₂ ratios indicates a combination of sediments derived from different source rocks. However, in general Al₂O₃/TiO₂ ratios probably indicate the samples from the east of Berbera were mostly derived from mafic to intermediate source rocks, whereas the samples from the west of Berbera were probably derived from intermediate to felsic source rocks. Conversely, the longshore currents may have mixed sediments derived from different sources.

Similarly, major element based discriminant function diagram is widely used to distinguish four major provenance types: mafic, intermediate, felsic, and quartzose recycled (Armstrong-Altrin et al., 2015a, 2015b; Ramos-Vázquez et al., 2017; Roser and Korsch, 1988). In this study, most of the samples of the east and west of Berbera mainly plot in the felsic and quartzose provinces. However, few samples plot in the intermediate and mafic igneous

![Fig. 8. SEM EDS spectrum of sample E1 (grains shown in Fig. 7a) showing a) an ilmenite grain, constituting ~67% TiO₂ and 33% Fe₂O₃. b) a magnetite grain. Magnetite grains of sample E1 do not contain any TiO₂. c) an amphibole. Amphiboles of the sample E1 does not display the presence of TiO₂. d) SEM EDS spectrum of the plagioclase (mineral 3) shown in Fig. 7b. e) SEM EDS spectrum of the apatite (mineral 2) shown in Fig. 7b. f) SEM EDS spectrum of the sphene (mineral 1) shown in Fig. 7b.](#)

| Table 3 |
| Sample cluster classification. For sample location see Fig. 2. |

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5.3. West of Berbera

Heavy mineral concentration in the west of Berbera ranges between 4.1 and 69.0 wt% (Tables 1a and 2). The most common heavy mineral assemblages observed are magnetite and ilmenite. Other heavy minerals include garnet, zircon, rutile, sphene, apatite and monazite. However, the concentration of heavy minerals in the area varies considerably. In samples W16, W17 and W18 close to Geri, the concentration of titaniferous heavy minerals is high (43.1–60.0 wt%). These samples were collected at the entrance of the Waaheen ephemeral river to the sea. These samples are also rich in garnet and other heavy minerals. Samples collected away from the Waaheen tend to have lower concentration. Therefore, the trend of heavy mineral concentration show that the concentration decreases east and west away from the Waaheen ephemeral river.

The observed heavy mineral assemblages suggest derivation of these minerals from the uplifted plateau of Mora and Qabri Bahar complexes as well as the Miocene volcanics that outcrop in the catchment area (Laferug and Hagabo) of Waaheen ephemeral river. In the Laferug area, the crystalline basement is composed of pink gneisses that consists of pink feldspar with varying amounts of quartz (Hunt, 1960). In addition, hornblende schists and gneisses with or without biotite also outcrop in the area. Therefore, feldspathic gneisses that outcrop in the catchment area appears to be the major source for the high concentration of K-feldspar and other heavy mineral assemblages that was observed from the samples collected in the west of Berbera. The major element provenance discriminant diagram (Fig. 9) also supports this interpretation.

5.4. East of Berbera

Backshore: As in the west, the eastern Berbera backshore sands are highly visible and can be seen clearly on satellite images (Fig. 2). The latter was one of the most valuable tools along a shoreline with difficult access, and gives a good indication of their development as well as the amount of heavy mineral in the back dunes. The deposits appear quite classical in most respects and the formation and profile of the beaches are similarly uniform. The beaches were found to contain strong heavy mineral development and the beach itself was better developed showing a clear strandline, high tide berms, storm berm and backshore mineralization (Fig. 3). Overall, widths were greater than those found in the west of Berbera although the same rhythmic layering was evident.

The samples of backshore sediments in the east of Berbera (E1–E31) exhibit a noticeable variation in heavy mineral content, which consists of ilmenite, rutile and zircon. The mineral grains are well liberated, rounded to sub-rounded. However, in some cases ilmenite occurs as exsolution in magnetite (Fig. 7). Although it is not as enriched in the higher value zircon and rutile as in the west of Berbera and other classical deposits, for example heavy mineral sand deposits in Australia (Roy, 1999; Roy and Whitehouse, 2003; Roy et al., 2000) and Gulf of Mexico (Tapia-Fernandez et al., 2017), the high ilmenite grades and proximity to the existing deep-water port of Berbera could lead to better commercial prospects for mining.

The results of this study agree well with that of Abdalla et al.

Fig. 9. Major element provenance discriminant function diagram (Roser and Korsch, 1988) for samples collected from the east and west of Berbera. The discriminant functions are: discriminant function 1 = (−1.773 × TiO₂) + (0.607 × Al₂O₃) + (0.760 × Fe₂O₃) + (−1.5 × MgO) + (0.616 × CaO) + (0.509 × Na₂O) + (0.509 × K₂O) + (9.09); discriminant function 2 = (0.445 × TiO₂) + (0.07 × Al₂O₃) + (−0.25 × Fe₂O₃) + (−1.142 × MgO) + (0.438 × CaO) + (1.475 × Na₂O) + (1.426 × K₂O) + (−6.861).
and E25 contain 23.3 wt% and 54.9 wt% of Fe2O3 respectively and hornblende, sphene, apatite and epidote. For example, samples E23 (ilmenite) with minor concentration of zircon, garnet, monazite, predominantly magnetite and titanium minerals (rutile and E26 contain high concentration of heavy minerals that consist of Fe2O3 and TiO2 respectively (Table 1b). Gabbro-Syenite belt) and Younger Granites (including Dailmole granite) (Hunt, 1960; Sassi et al., 1993; Warden and Daniels, 1984). These are intruded by gabbro (the Gabbro-Syenite belt) and Younger Granites (including Daimole granite) (Hunt, 1960; Sassi et al., 1993). In Hudiso area, the basement consists of a wide range of mainly meta-psammite rocks that range from felsspatic gneisses through quartz-biotite schists and gneisses to banded migmatic gneisses. In this area magnetite and to a lesser extend sphe and apatite become abundant (Hunt, 1960). Therefore, the composition of the catchment area indicates that these rocks are the predominant source of the high concentration of magnetite, quartz and other heavy minerals observed in the east of Berbera. In support of this interpretation, the discriminant function diagram (Fig. 9) shows samples from the east of Berbera plot in all four provenances (mafic, intermediate, felsic and quartzose), which indicate the samples were derived from source rocks that have wide range of composition from the high-grade metamorphic sequences of Qabri Bahar Series to Gabbro-Syenite belt and Younger Granites.

5.5. Concentration of heavy minerals and its economic importance

Heavy mineral sand deposits in Somaliland coastline have relatively high ilmenite and magnetite concentrations, with medium-low grade rutile, and zircon concentrations. But they are voluminous and cover areas that potentially comprise hundreds of square kilometers. Therefore, these deposits could be of interest due to their large volume and easy to mine operations because of their unconsolidated nature and the fact that the area is sparsely populated with little or no vegetation cover. In particular, this study indicates that the most important heavy mineral deposits are found at the mouths of Waabheen and Biyo Gure ephemeral rivers. However, the available data on the heavy mineral deposits is currently inadequate for definitive evaluation of either the quantitative or qualitative factors of the resource. Nevertheless, it is anticipated that deposits of this type will become more important in the future and demonstrate potential for commercial mining in these two areas.

There are a number of positive indications for economic concentration of heavy mineral sand deposits in Somaliland coast, in particular east of Berbera. These include a good backshore development, paleo-beaches and mineral concentration in back-beach dunes. These factors indicate a very sizeable block of ground, considerably larger than anything observed in other deposits in eastern Africa. Volumes should easily exceed any minimum for economic development and the geographical setting should allow for a small scale or pilot operation to proceed in higher grade areas. For example, the Kwale heavy mineral sand deposit in southwest of Mombasa, Kenya has 146 Mt of measured resources with 2.59% of ilmenite, 0.65% rutile, 0.29% zircon (Tyler and Minnitt, 2004; Van Gosen et al., 2014). The Kwale deposit has low grades of heavy minerals and is much smaller deposit than the heavy mineral deposits that this study observed in Somaliland coastline.

Furthermore, the raised paleo-beach in the east of Berbera is promising as several of the east African deposits (e.g. Fort Dauphin mine in Madagascar and Kwale Deposit in Kenya) show their best mineral development in these interior ancient beach sands (Tyler and Minnitt, 2004; Van Gosen et al., 2014). For example, the entire area between the present shore and the raised paleo-beach should be viewed as highly prospective. Effectively this would create a large block of some 50 km2 of potentially mineralized ground and a prime target for proving a heavy mineral sand resource. For the purpose of this study, only surface grab samples were taken, however there exists significant potential for increased valuable heavy mineral accumulations at depth, which should be the focus of future study.

Another major advantage for future development of this resource is that the deposits are located in very close proximity to Berbera, the only major deep-water port in Somaliland. In addition, road access to the deposits is adequate. Therefore, the magnetite may also be a valuable component given potentially low land transport costs to port.

The heavy mineral deposits which have been investigated along the coast of Somaliland are presently recognized as being a potential commercial resource. Nevertheless, further detailed investigation of identified heavy mineral deposits, including drilling and
laboratory analyses are required, with the aim of locating high grade areas to conduct further feasibility studies for mine development, and determine reserves of ilmenite, rutile, zircon, magnetite and other heavy minerals over identified deposits.

6. Conclusions

Sixty-one samples were collected from backshores, raised paleo-beaches and sand dunes along Somaliland coastline from Eil Sheikh to Ras Khatib to study their heavy mineral assemblage. The XRF, XRD and SEM-EDS analyses show that Somaliland coast has high potential for heavy mineral deposits. In summary, this study identified that:

- Medium and high grade detrital ilmenite and magnetite, with less abundant rutile, zircon, and monazite, occur at backshores, raised paleo-beaches and in dunes. These combined aspects indicate a good possibility of obtaining a viable deposit within the areas investigated.
- Backshore deposits of the Waaheen and Biyo Gure mouths and raised paleo-beach in the east of Berbera have good amount of titaniferous heavy minerals with most samples greater than 50 wt%. These minerals occur in the form of ilmenite, rutile and titaniferous magnetite, with minor zircon concentrations.
- The major element concentrations indicated that the samples from the east and west of Berbera were derived from rocks that cover all four provenances (mafic, intermediate, felsic and quartzose).
- The variations in observed mineral assemblages in the east and west of Berbera areas are probably due to the different source rocks in the catchment areas of these two areas. The east of Berbera is dominated by moderate concentration of plagioclase, K-feldspar, magnetite, hematite and titanium bearing minerals. These are derived from Qabri Bahar complex and Gabбро-Syenite belt as well as granitic intrusions that outcrop in Hudiso, Tulo Dibbio and surrounding areas. Whereas in the west of Berbera, the dominant minerals are quartz, K-feldspar and plagioclase with variable proportions of ilmenite, rutile, mica, amphibole and pyroxene. The primary sources of heavy minerals are Qabri Bahar and Mora complexes in Laferug and Hagabo areas, which comprise of high-grade metamorphic rocks of Mora and Qabri Bahar complexes as well as Miocene volcanics.
- Development prospects for the mineral sands in the east of Berbera are better than those in the west of Berbera. The east of Berbera has wider beaches, better heavy mineral sands accumulations in the upper horizons and dune areas carry heavier mineral sands than those in the west of Berbera. Furthermore, a series of paleo-beaches 1–2 km behind the shoreline with higher heavy minerals concentrations are observed. In addition, it is closer to the Berbera port and it has a better road access than west of Berbera.

Acknowledgements

We wish to thank the Somaliland Ministry of Mines and Energy for supporting this study. Special thanks to Mohammed Ibrahim Abdi, Awil Awi and elders of Bulhar village for assisting the fieldwork conducted in the western Berbera. We are grateful to Suleiman Mohamed Ali, Abdullahi Ismail Mataan and Omar Abokor Jama (former deputy manager of Berbera port) for assisting our fieldwork in the eastern Berbera area. We thank John S. Armstrong-Altrin for his helpful comments on an earlier version of the paper.

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