GEOCHEMISTRY OF THE GULF OF ADEN BEACH SANDS, AL-MUKALLA, YEMEN: PROVENANCE AND TECTONIC SETTING IMPLICATIONS

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ABSTRACT

This research concerns with the mineralogical and geochemical composition of the Gulf of Aden shallow subsurface beach sands to identify the composition and tectonic setting of source area. The study discusses the limitation of using weathering indices and the factors hampered using these indices. Three shallow cores (1-1.5 m long) were collected from the coastal area at the mouth of wadis. Fuwwah (I), Ar Rukayb (II) and Shuhair (III) near Al-Mukalla, Yemen. The sediments are dominated by well to moderately well sorted fine-grained sands. The methodology is insufficient and therefore, geochemical mineralogical and petrographic studies (von Eynatten et al., 2003; Armstrong-Altrin, 2009; Tao et al., 2014; Zhang, 2014; Zaid, 2015; Tawfik et al., 2017). Relying solely on mineralogical investigations without geochemical analysis often provides complementary data to mineralogical analysis (Kroonenberg, 1990; Armstrong-Altrin, 2009). Several approaches have been employed to extract this information ranging from petrographic analysis, framework detrital mode and geochemical analysis and/or their combinations. However, the bulk sediment geochemistry is still more suitable than any other approach or can complement mineralogical and petrographical studies (von Eynatten et al., 2003; Armstrong-Altrin, 2009; Armstrong-Altrin et al., 2014; Zhang, 2014). Unconsolidated beach sands lack diagenetic imprints and therefore, their composition primarily reflects the provenance and geotectonic setting of the source area (Carranza-Edwards et al., 2009; Armstrong-Altrin et al., 2015; Zaid, 2015).

Along the young continental margins of Yemen, the coastal area receives sediments from multiple sources including the rift related magmatic rocks, sedimentary successions and underlying Pan-African basement exposed on the uplifted shoulders of the rift. The Gulf of Aden provides a unique site to study the provenance of rift related sediments. East of the Gulf of Aden, the sediments are transported to the coastal area by intermittently active wadis, local watersheds draining into the Gulf of Aden and by longshore transportation. They transport detritus derived from Mesozoic and Cenozoic sedimentary rocks (Garzanti et al., 2001). The provenance of the Gulf of Aden has not been comprehensively investigated. The present study introduces the first attempt to interpret the provenance and tectonic implications of the Gulf of Aden beach sands and its provenance and tectonic setting implications. Acta Geodyn. Geomater., 15, No. 1 (193), 55–69, 2019. DOI: 10.13168/AGG.2019.0005


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1. INTRODUCTION

The mineralogical and chemical composition of clastic sediments provides information important to interpret the provenance, tectonic setting and the complex interplay of weathering, recycling, hydraulic sorting during transportation and deposition and the post-depositional alteration (Lacassie et al., 2004; Ohta and Arai, 2007; Armstrong-Altrin, 2009; Hossain et al., 2010; Tao et al., 2014; Zhang, 2014; Zaid, 2015; Tawfik et al., 2017). Relying solely on mineralogical investigations without geochemical analysis is insufficient and therefore, geochemical analysis often provides complementary data to mineralogical analysis (Kroonenberg, 1990; Armstrong-Altrin, 2009). Several approaches have been employed to extract this information ranging from petrographic analysis, framework detrital mode and geochemical analysis and/or their combinations. However, the bulk sediment geochemistry is still more suitable than any other approach or can complement mineralogical and petrographical studies (von Eynatten et al., 2003; Armstrong-Altrin, 2009; Armstrong-Altrin et al., 2014; Zhang, 2014). Unconsolidated beach sands lack diagenetic imprints and therefore, their composition primarily reflects the provenance and geotectonic setting of the source area (Carranza-Edwards et al., 2009; Armstrong-Altrin et al., 2015; Zaid, 2015).
Fig. 1 Location map of the area of study showing the locations of collected cores.

setting of the Gulf of Aden beach sands near Al-Mukalla (Fig. 1) using geochemical and mineralogical proxies. The study will also discuss the source rock weathering conditions and the circumstances under which the use of weathering indices is inapplicable.

2. GEOLOGIC BACKGROUND

Throughout the Phanerozoic, the continental margin of the Yemen is a passive type margin and contains a series of NW-SE trending rift basins. These basins are the Jurassic-Cretaceous and the Oligocene-Pliocene rift basins related to the breakup of Gondwana and the opening of the Red Sea and the Gulf of Aden, respectively (Bott et al., 1992; Beydoun et al., 1996; Bosence, 1997; D’Acremont et al., 2005; As-Saruri et al., 2010). The Gulf of Aden, south of Yemen is a young and narrow oceanic basin oriented N75°E, strikes obliquely (50°) to the N25°E (D’Acremont et al., 2005).

The Mesozoic extensional tectonics in the Yemen resulted from the rifting between East Africa and West India led to the development of the WNW-ESE Say’un-Masilah and the E-W Jiza– Qamar basins (Fig. 2) in the center and east of the southern Yemen (As-Saruri et al., 2010). The basins were then differentiated structurally into sub-basins, half-grabens and intra-basinal horsts. The distribution and thickness of sedimentary facies within these basins were controlled primarily by the major paleo-highs and arches within and between such basins. Mesozoic basins were episodically subsided by sporadic, localized and brief pulses of fault activity and erosion. The pre-rift sedimentary succession within these basins includes 1) the Paleozoic quartz rich pebbly sandstones, lateritic soil and the Gondwana glaciations related conglomerates and mudrocks, 2) the Middle to Upper Jurassic fluvial to coastal sandstones, conglomerate and carbonaceous shales of the Kuhlan Formation and the overlying carbonate-dominated Amran Limestone (Simmons and Al-Thour, 1994) and 3) the Cretaceous-Paleogene cliff forming shelf and platform limestones (Garzanti et al., 2001). The Upper Jurassic–Lower Cretaceous syn-rift sediments constitute the main hydrocarbon plays in Yemen. These sediments include the organic rich marine shales, debris flow gravel and breccias and well-bedded limestone of the Madbi Formation overlain by a thick evaporite succession of the Sab’atyan Formation (Leckie and Rumpel, 2003; King et al., 2003; As-Saruri et al., 2010).

The Cenozoic extensional tectonics in the Gulf of Aden have led to the development of the Aden-Abyan, Hawrah-Ahwar and Mukalla– Sayhut basins, which run parallel to the gulf along its northern coast. These basins are filled with thick fluvio-marine strata. The pre-rift sediments in these Cenozoic basins include the Jurassic (equivalent Kuhlan Formation and the Amran group), Cretaceous (equivalent Tawilah and Mahra groups) and Paleogene (equivalent Hadramawt group) sediments. The syn-rift sediments include the shale, sandstone and evaporites of the Ghaydah Formation, whereas the post-rift sediments are primarily represented by the prograding carbonate-dominated and the siliciclastic-dominated Hamian and Sarar formations, respectively (Bott et al., 1992; Brannan et al., 1997; Garzanti et al., 2001; As-Saruri et al., 2010). In the area of study, the surface geologic outcrops of the study area (Fig. 3) range in age from Pre-Cambrian to Quaternary. The Precambrian igneous and metamorphic rocks are unconformably overlain by the Lower-Middle Jurassic fluvial arkosic sandstones (Kohlan Formation), the Cretaceous continental sandstones (Tawilah Group) and the Upper Paleocene-Lower Eocene limestones (Umm Er Radhuma Formation) (As-Saruri et al., 2010; Al-Wosabi and Wasel, 2011). The cross section in the area of study shows a northward variation in the sediments. The detritus supplied by Wadi Fuwwah are derived mostly from the Cretaceous sandstones (Tawilah group), whereas the sediments supplied by the other two wadis include detritus of the Middle Jurassic Kuhlan Sandstone and the Lower Paleogene limestones (Fig. 3).
Fig. 2  Sedimentary basins and major structural highs surrounding Al-Mukalla area (after As-Saruri et al., 2010). a-a’ is a cross section shown in Figure 3.

Fig. 3  Cross-section showing the main structural and stratigraphic framework near Al-Mukalla, Yemen (modified after Beydoun, 1966; As-Saruri et al., 2010). The location of a-a’ line is shown in Figure 2.

The coastal plain of the Gulf of Aden is about 40 km wide and it is occupied by recent lava fields, rocky cliffs, raised beaches which are covered in dune sands and gravel terraces and bordered by continuous sandy shorelines (Garzanti et al., 2001). The raised beaches record continuous tectonic uplift during the Pliocene-Quaternary with a limited faulting affected the post rift section. The reactivation of old faults changes the composition of the detrital modes between adjacent drainage basins (Garzanti et al., 2001).

The sea level at the Gulf of Aden rises between September and May and falls during June-July to reach the minimum in August. The seasonal oscillations in the mean sea level is attributed to astronomical effects, effects of evaporation, very low to negligible precipitation and river discharge, atmospheric pressure, and steric sea-level effects. The effects of purely astronomical conditions (long-period tides) are not significant; they do not exceed 12 mm (Morcos and Abdallah, 2012).

The area of study is a wild, barren region with high temperatures in summer reaching 54 °C and 35 °C in winter with a mean annual rainfall of 50–130 mm in coastal areas and may exceed 500 mm on the coastal mountain belt. Monsoon winds blow in winter westward and in summer northeastward, bringing violent storms up to 100 km/h with sporadic rains (Beydoun, 1964). Numerous occasionally active wadis run southeastward across major extensional
structures drain the adjoining mountainous and hilly hinterland and discharging freshwater and sediments into the Gulf of Aden mainly during heavy rains as flash floods. Rare perennial wadis such as Hajar and tracts of Wadi Hadhramaut occur (Greenwood and Bleackley, 1967).

3. MATERIALS AND METHODS

The database of the present study includes three shallow sediment cores (1–1.5 m long) collected from the Gulf of Aden sandy beach at the mouth of 3 wadis; Fuwwah (core I), Ar Rukayb (II) and Shuhair (III) near Al-Mukalla, Yemen (Fig. 1). All cores were sub-sampled at intervals of 5–10 cm apart. Laboratory techniques included sediment grain size, mineralogical and geochemical analyses.

The grain size analysis was performed on 69 samples (20, 22 and 27 samples from cores I, II and III, respectively) using the traditional mechanical sieving technique. The sediments were dried at 105 °C for a night. About 50 g of dry and homogeneous sediments were sieved for 20 minutes at one phi size interval using standard ASTM sieve set ranging from 2 to 0.063 mm. The size fraction retained in each sieve was carefully weighed and the weight percentage and cumulative weight percentage were computed. Mean size (Mz) and inclusive standard deviation (σi) were determined using the method of Folk and Ward (1957).

The mineralogical composition of 40 samples (13, 13 and 14 samples from cores I, II and III, respectively) was determined using X-ray powder diffraction (XRD) (SHIMAZU) with Ni-filtered Cu Ka radiation at 15 kV to 40 mA at the XRD laboratory, Faculty of Marine Science, King Abdullah University. The minerals were identified using the peak heights of basal reflections (Hardy and Tucker, 1988). The relative abundance of minerals is determined semi-quantitatively using the peak heights for basal reflections for the mineral. The identified minerals are grouped into abundant (A>40 %), moderate (M = 10 - 40 %) and trace (T<10 %). The bulk sediment geochemical composition of 40 samples was determined by conventional XRF technique at the department of Geosciences, Osaka City University, Japan. The analysis conditions were 50 kV and 50 mA accelerating voltage and tube current, respectively using a RIGAKU RIX 2100 X-ray fluorescence spectrometer (XRF), equipped with Rh/W dual-anode X-ray tube. Fused glass discs were prepared by mixing 1.8 g of powdered sample (dried at 110 °C for 4 hours), 3.6 g of spectrolux (Li2B4O7 20 %, LiBO2 80 %, dried at 450 °C for 4 hours), 0.54 g of oxidant LiNO3 and traces of LiI. The mixture is then fused at 800 °C for 120 s and 1200 °C for 200 s (Tawfik et al., 2017). The accuracy of the analysis was estimated to be ±2-3 % for major elements and ±10-15 % for trace elements. The total iron is introduced as Fe2O3. Loss on ignition (LOI) was determined by heating the dried samples for 2 h at 1000 °C (Tawfik et al., 2017). The results of geochemical analysis were employed to determine the provenance, tectonic setting and paleoweathering indices. Chemical weathering was evaluated using the chemical index of alteration (CIA). The CIA (Nesbitt and Young, 1982) is determined using the equation: CIA = [Al2O3/(Al2O3 + CaO* + Na2O + K2O)] x 100, where Al2O3, CaO*, Na2O and K2O are molecular concentrations, with CaO* representing Ca in silicate minerals only. To calculate the CaO* in silicate minerals, the formula: CaO* = mol CaO (10/ 3 x mol P2O5) is used. If the CaO* is < Na2O, then CaO* = CaO**, otherwise the CaO* = Na2O (McLennan, 1993). The CIA values <50 suggest unweathered fresh rocks and minerals, values from 50 to 60 indicate low chemical weathering, values between 60 and 80 suggest moderate chemical weathering and values >80 indicate intensive chemical weathering (Nesbitt and Young, 1982; Fedo et al., 1995).

4. RESULTS

4.1. GRAIN SIZE AND MINERALOGICAL COMPOSITION

Grain-size data show that most of the samples are dominantly fine and rarely very fine and medium sands with mean size values range from 2.08 to 2.44 (average 2.29φ), 1.65 to 3.03 (average, 2.43φ) and from 2.1 to 3φ (average, 2.49) in the sediments of cores I, II and III, respectively (Table 1 and Fig. 4). The sediments in the three cores display a slight lateral variation in the degree of sorting. The inclusive graphic standard deviation values range from 0.49 to 0.6 φ (well sorted to moderately well sorted), 0.6 to 1 φ (moderately well sorted to moderately sorted) and 0.31 to 0.73 φ (very well sorted to moderately sorted) in the sediments of cores I, II and II, respectively (Table 1 and Fig. 4).

The mineralogical composition of sediments determined by XRD technique is relatively homogeneous with very negligible variation among the three cores (Table 2). The mineral composition is overwhelmingly dominated by quartz followed by calcite with moderate relative abundance. In addition, traces of dolomite, plagioclase, K-feldspars, clay minerals and local occurrence of aragonite and amphiboles are recognized (Table 2). Though of low relative abundance, the sediments of core I show traces of clay minerals.

4.2. CHEMICAL COMPOSITION

4.2.1. MAJOR OXIDES

Ranges and mean values of major oxides and trace elements concentrations are listed in Table 3 and shown in Figures 5 and 6. The concentration of SiO2 varied in the sediments of core I from 61.83 to 79.51 (avg. 72.38 %), from 40.52 to 86.18 (avg. 64.82 %) in core II and 52.58 to 76.90 (avg. 66.67 %) in the sediments of cores III. CaO is the second abundant oxide showing average concentrations 12.73, 18.97 and 16.11 % in the sediments of cores I, II and III, respectively. The other oxides; Al2O3, Fe2O3, MgO, K2O, Na2O, TiO2, P2O5 and MnO surprisingly display low concentrations. The average concentrations of MgO, Al2O3 and Fe2O3 in the sediments of core I are
Table 1 Results of grain size analysis of the Gulf of Aden shallow subsurface beach sands.

<table>
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<tr>
<th>Sample</th>
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<th>Core II Mean (φ)</th>
<th>Core III Mean (φ)</th>
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1.31, 1.25 and 1.02, respectively, whereas their average concentrations in the sediments of cores II are 0.9, 0.58 and 0.41, respectively. In the sediments of core III, the average concentrations of MgO, Al₂O₃, MnO, MgO, Na₂O, K₂O and P₂O₅ are 1.15, 0.56 and 0.79, respectively (Table 3).

Comparing to the UCC values (Rudnick and Gao, 2003), the sediments of the three cores are strongly depleted in TiO₂, Al₂O₃, Fe₂O₃, MnO, MgO, Na₂O, K₂O and P₂O₅, whereas SiO₂ show values within the range of the UCC values. CaO is highly enriched compared to the UCC (Fig. 7).

4.2.2. TRACE ELEMENTS

The average concentrations of trace elements in the three cores normalized to average upper continental crust (UCC) (Taylor and McLennan, 1985) are shown in Figures 6 and 7. In comparison with UCC, sands from the three cores are highly depleted in trace elements except for Zr and Sr. However, the sediments of core I and III are highly enriched in Zr and the sediments of core II are highly enriched in Sr and slightly enriched in Zr with respect to the UCC (Fig. 7). The transitional trace elements like V, Cr, Co, Ni, Zn, Cu and Rb did not show much variation between the sediments in the three cores (Fig. 6). The concentrations of Sr varied between 205-495 µg/g (avg. 302 µg/g), 225 and 820 µg/g (avg. 485 µg/g) and 125 and 297 µg/g (avg. 200 µg/g) in the sediments of cores I-III, respectively (Table 3).

4.2.3. PROVENANCE, RECYCLING AND TECTONIC SETTING

The sediments are classified geochemically based on the biplot of log (SiO₂/Al₂O₃) vs. log (Fe₂O₃/K₂O) (Herron, 1988). This classification shows that the majority of samples are classified as quartz arenite, few samples from the sediments of core I are plotted in the field of Fe-sands and a single sample from core II is classified as sublitharenite (Fig. 8).

Discriminant function diagram (Roser and Korsch, 1988) indicated that the beach sediments of the Gulf of Aden were derived mainly from a recycled sedimentary source rocks (Fig. 9A). The sediments of core I cluster in the field of recycled sedimentary source rock at a position lower than the samples of cores II and III, suggesting possibly different sedimentary source rock composition. The sediments of core I were derived mainly from a sand-dominated source with possible slight mixing with other carbonate sediments. The clustering of samples of the cores II and III in a higher position suggests a mixing of carbonate and siliciclastic source rocks, with a higher siliciclastics contribution than carbonates in the sediments of core III. The ternary plot (Fig. 9B) portraying weight percentages SiO₂, Na₂O+K₂O and TiO₂+MgO+Fe₂O₃ is employed herein to identify the effect of recycling (Kroonenberg, 1990). Generally, the samples are clustered at high to moderate values of SiO₂ suggesting the major influence of recycling that led to increasing residual enrichment of quartz.
Fig. 4  Vertical variation of the grain size parameters mean size ($M_z$) and standard deviation ($\sigma_I$) in the Gulf of Aden shallow subsurface beach sands for core I (a), core II (b) and core III (c)
Table 2 The relative abundance of the different minerals in the shallow subsurface beach sands of the Gulf of Aden that recognized by XRD analysis.

Qz = quartz, Plag= plagioclase, K-fels= K-feldspars, hornb= hornblende, calc= calcite, dolm= dolomite, arag= aragonite, A=abundant, M=moderate and T= traces

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</table>

The sediments of core II have the lowest average concentrations of SiO₂, the samples of core II are clustered near the SiO₂/20 apex comparing to the samples of cores I and III. The samples of core II show very low concentrations of TiO₂+MgO+Fe₂O₃ comparing to the other two cores. The linear correlation observed between K₂O vs. Rb and Ba (Fig. 9B) indicates the effect of multiple cycling (Tao et al., 2014). Both Rb and Ba have low solubility and remain in the residual constituents and K are easily moved during the recycling and chemical weathering.

The tectonic setting of the Gulf of Aden beach sediments is determined using the major element based diagram (Active Passive Margin Discriminant) using APMDISC; online software (Verma and Armstrong-Altrin, 2016). The diagram showed that all the samples of the three cores without exception plotted in the field of passive margin setting (Fig. 11). The compositionally mature Gulf of Aden beach sands are well correlated with the passive margin tectonic setting. The SiO₂/Al₂O₃ ratios vary in the sediments of core I from 35 to 105 (avg. 62) and varied in the sediments of cores II and III from 36 to 188 (avg. 132) and 86 to 179 (avg. 125), respectively. These extremely high ratios are consistent with continentally derived recycled sedimentary source consistent with the passive margin setting.

4.2.4. PALEOWEATHERING

The estimated average values of CIA (Table 3) show wide ranges varying in the sediments of core I from 50 to 67 (average, 62), core II from 23 to 68 (average, 40) and core III from 25 to 54 (average, 34) suggesting lateral variations in the degree of chemical weathering. The CIA values of core I suggest low to moderate degree of chemical weathering, whereas the sediments of cores II and III are generally unweathered to poorly weathered with a bulk composition similar to their source material. The variations in the CIA values among cores are possibly attributed to the variation in the source rock composition and the relatively higher Al₂O₃ content.
and clay minerals in the sediments of core I than the sediments of the other two cores. The source of the sediments in core I possibly has older weathered components.

5. DISCUSSION

The Gulf of Aden shallow subsurface beach sediments at the mouths of wadis Fuwwah, Ar Rukayb and Shuhair near Al-Mukalla, Yemen are dominantly moderately to well-sorted fine-grained sands, classified geochemically in general as quartz arenite. Texturally, the sediments show a relatively similar average mean size. However, they show slightly different degree of sorting with the sediments of core I are generally well sorted relative to the sediments of the other two cores. This is possibly attributed to different grain composition. The relatively homogeneous quartz rich sand grains are more sorted than a mixture of carbonate and quartz grains. Though they have same size, both grain types behave differently during transportation and deposition. Mineralogically, the sediments are overwhelmingly dominated by quartz followed by calcite. In contrast to the sediments of core II and III, the sediments of core I contain traces of clay minerals. The depletion of trace elements in the sediments of cores II and III comparing to the sediments of core I could be attributed to the scarcity and absence of clay minerals. Trace elements preferentially concentrated in clay minerals during hydraulic sorting. Hydraulic sorting is an important process that controls textural and compositional maturity of sediments (Singh, 2009; Wu et al., 2013). Hydraulic sorting preferentially enriches specific grain size fraction and minerals and therefore, controlling the chemical composition of bulk sediments. The chemical composition shows enrichment of SiO₂, CaO, Zr and Sr with a noticeable depletion of other major and trace elements. The relatively high content of Ca and Sr is attributed to the mixing with sand sized carbonate grains. The geochemical information held in the sediments characterizes a sedimentary source rock that is compatible with the passive margin tectonic setting. The higher average concentrations of SiO₂ and
Fig. 6  Box chart showing the minimum, maximum and average concentrations of trace elements (µg/g) for the Gulf of Aden shallow subsurface beach sands.
Table 3: The average and ranges of the concentrations of major oxides (%) and trace elements (µg/g) in the Gulf of Aden shallow subsurface beach sands. LOI = Loss on ignition; CIA = Chemical index of alteration

<table>
<thead>
<tr>
<th>Element</th>
<th>Core I</th>
<th>Core II</th>
<th>Core III</th>
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<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
</tr>
<tr>
<td>SiO₂</td>
<td>61.83</td>
<td>79.51</td>
<td>72.38</td>
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<tr>
<td>TiO₂</td>
<td>0.06</td>
<td>0.39</td>
<td>0.19</td>
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<tr>
<td>Al₂O₃</td>
<td>0.60</td>
<td>1.76</td>
<td>1.25</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.38</td>
<td>1.48</td>
<td>1.02</td>
</tr>
<tr>
<td>MnO</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
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<tr>
<td>MgO</td>
<td>0.93</td>
<td>1.63</td>
<td>1.31</td>
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<tr>
<td>CaO</td>
<td>9.15</td>
<td>18.61</td>
<td>12.73</td>
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<tr>
<td>Na₂O</td>
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<td>K₂O</td>
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<tr>
<td>P₂O₅</td>
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<tr>
<td>LOI</td>
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<td>V</td>
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<tr>
<td>CIA</td>
<td>49.70</td>
<td>67.32</td>
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Fig. 7: Diagram for the normalization of samples against the upper continental crust for major oxides (Rudnick and Gao, 2003) and trace elements (Taylor and McLennan, 1985), a and b for major and trace elements in core I, c and d for core II and e and f for core III.
5.1. APPLICABILITY OF WEATHERING INDICES

Various geochemical proxies and indices have been employed to quantitatively estimate the intensity of chemical weathering; the chemical index of alteration (CIA; Nesbitt and Zouny, 1982) is the most widely used. The calculation of the CIA depends on the ratio between elements that display different mobilities during chemical weathering. Larger cations (e.g. Al$^{3+}$ largely concentrated in phyllosilicates) are immobile and remain fixed in the weathering profile, whereas smaller cations (e.g. Ca$^{2+}$, Na$^{+}$ and K$^{+}$; largely hosted in plagioclase and feldspars) are selectively leached (Nesbitt and Zouny, 1982; von Eynatten et al., 2003). In some cases, the use of CIA may yield an incorrect interpretation for weathering and climatic conditions (Garzanti and Resentini, 2016). Overall, the average compositional data and the CIA values suggest low to moderate weathering in the source area. This is possibly related to the complex mixing detritus of different lithologies that may contain older weathered components. The low to moderate weathering values are consistent with the prevailing hot and arid climate and the scarcity of land vegetation, where physical weathering is the dominant. Variations in the source rock composition, recycling, mixing of siliciclastic and carbonate lithologies and hydraulic sorting hampered the successful use of these indices for the Gulf of Aden beach sands.

The interpreted recycled sedimentary source rocks are compatible with previous petrographic and detrital mode studies of the Gulf of Aden beach sands near Al-Mukalla (Garzanti et al., 2001). Sedimentary detritus from pre-rift successions is more abundant toward the Marib-Balhaf graben and its eastern flank (Rudum, Hajar and Mukalla Provinces) and exclusive farther east (Riyan and Hadramaut Provinces). In the Rudum Province, beach sands are dominated by monocrystalline and largely recycled quartz is mostly with more abundant plagioclase than K-feldspars. The beach sands at the mouth of Wadi Hajar consists dominantly of monocrystalline recycled quartz from the Cretaceous quartz arenites and limestone to dolomite grains from the Paleogene carbonates. In the Mukalla province, the beach sands consist mainly of recycled monocrystalline quartz and abundant carbonate grains (Garzanti et al., 2001), whereas the beach sands to the east near the Riyan Province, consist dominantly of monocrystalline quartz and carbonate grains from sedimentary sources are exclusively derived from recycled pre-rift sandstones (Garzanti et al., 2001).

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Generally, the Gulf of Aden beach sands are compositionally mature, enriched in quartz and strongly depleted in both mobile and immobile elements reflecting the possible multicyclic origin of the source rock. The compositional maturity and the dominance of quartz are incompatible with the low to moderate values of weathering indices because these
Fig. 9 Provenance and the impact of sediment recycling on the chemical composition of the Gulf of Aden shallow subsurface beach sands 
a) Discriminant function diagram for the provenance signatures of the Gulf of Aden beach sands (after Roser and Korsch, 1988); Discriminant function 1 (DF1) = –1.773 TiO₂ + 0.607 Al₂O₃ + 0.76 Fe₂O₃(normal) – 1.5 MgO + 0.616 CaO + 0.509 Na₂O – 1.224 K₂O – 9.09; Discriminant function 2 (DF2) = 0.445 TiO₂ + 0.07 Al₂O₃ – 0.25 Fe₂O₃(normal) – 1.142 MgO + 0.438 CaO + 1.475 Na₂O + 1.426 K₂O – 6.861., b) Ternary plot diagram showing quartz (SiO₂), feldspars and micas (Na₂O, K₂O) and ferromagnesians (TiO₂, MgO and, Fe₂O₃) (after Kroonenberg, 1990).

features require severely weathered source rock under humid climate. This interpretation is applicable only for the first cycle sands, whereas sands derived from recycled quartzose sedimentary rocks and preferentially sorted during transportation and deposition provide no information on the weathering history of the source rock (Tawfik et al., 2017). The late Neoproterozoic–Ordovician compositionally mature first cycle quartz arenites cropping out in northern Africa and Arabia were produced under intensive chemical weathering (Avigad et al., 2005). Suttner et al. (1981) argued that most of these compositionally mature sands must be of polycyclic origin excluding the impact of chemical weathering. The recycled quartzose sedimentary source rocks formed probably after several sedimentary cycles through which, less resistant rock forming minerals such as feldspars were degraded and leached leaving behind quartz and ultrastable heavy minerals. The source rocks are therefore depleted in elements such as Al₂O₃, Na₂O, K₂O and CaO that are involved in the equations used to calculate weathering indices. Under dominantly arid climate, the Jurassic and Cretaceous Kuhl Formation and Tawilah group sandstones were eroded and transported by sporadically active wadis into the Gulf of Aden coastal area. Weathering indices can be a reliable indicator for the degree of chemical weathering for sands of first cycle origin (e.g. Armstrong-Altrin, 2009; Armstrong-Altrin et al., 2012).

Recycling and mixing with calcareous remains disturbed several weathering indicator ratios such as the Rb/Sr ratio. High Rb/Sr ratios indicate intense chemical weathering and recycling (McLennan et al., 1993). Both elements have different behavior during weathering. Rb behaves in a similar way as Al₂O₃ and
Ba, whereas Sr is an easily leached element. The close association of Sr with CaO disturbs this relationship and in the present study therefore, the Rb/Sr is not applicable for weathering interpretation.

The depletion of Al₂O₃ and other clay related major and trace elements may be attributed to the absence of phyllosilicates and mica possibly due to the scarcity of clay minerals in the source and the hydraulic segregation during transportation and deposition by shoreline processes and basinward drift of clay and fine grained sediments. Sediment recycling and hydraulic sorting result in the depletion of feldspar- and clay minerals-related major and trace elements.

6. CONCLUSIONS

The study of mineralogical and geochemical composition of the Gulf of Aden shallow subsurface beach sands at the mouth of Wadi Fuwwah (core I), Wadi Ar Rukayb (II) and Wadi As Shihir (III) near Al-
Mukalla, Yemen led to the following conclusions:
1. The sediments are dominantly well to moderately sorted fine grained sands.
2. Mineralogical composition is dominated by quartz followed by calcite with low quantities of k-feldspars, plagioclase, dolomite, clay minerals and local occurrences of traces of aragonite and hornblende.
3. The geochemical composition is compatible with minerology where SiO₂ was the dominant major oxide followed by CaO. Other elements are strongly depleted such as elements related to clay minerals (Al and Rb) and feldspars (K and Na).
4. The sediments are compositionally mature to submature and classified as quartz arenite to sub-litharenite. They were derived mainly from recycled sedimentary rocks of the Jurassic Kohlan Formation and the Cretaceous Tawilah group and consistent with a passive (rift) continental margin.
5. The relatively low values of CIA are inconsistent with the sediment compositional maturity the recent arid climate. This suggests that the polycyclic origin, hydraulic sorting by active coastal processes and mixing with carbonate grains hindered the applicability of weathering indices for the Gulf of Aden beach sands. Therefore, weathering indices must be used with utmost care particularly for sands derived from quartz rich polycyclic quartzose sedimentary provenance.

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