Acta Geodyn. Geomater., Vol. 16, No. 1 (193), 55–69, 2019
DOI: 10.13168/AGG.2019.0005
journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

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

Ibrahim GHANDOUR [1, 2] *, Ali BASAHAM [1)], Rabea HAREDY [1)], Ammar MANAA [1)], Khaled AL-RABAKI [3)] and Khaled BAWAHIDI [3)]

[1)] *Marine Geology Department, Faculty of Marine Science, King Abdulaziz University, P.O. Box 80207, Jeddah 21589, Saudi Arabia*
[2)] *Geology Department, Faculty of Science, Tanta University, Tanta 31527, Egypt*
[3)] *Department of Environmental Sciences, Faculty of Environmental Sciences and Marine Biology, Hadhramout University, Al-Mukalla, Republic of Yemen*

**Corresponding author's e-mail:* ighandour@kau.edu.sa

ARTICLE INFO

Article history:
Received 6 August 2018
Accepted 15 January 2019
Available online 6 February 2019

Keywords:
Gulf of Aden
Al-Mukalla
Provenance
Sediment geochemistry
Weathering indices
Sediment maturity

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 mineralogical composition is dominated by quartz followed by calcite with traces of plagioclase, k-feldspars, dolomite, clay minerals and amphiboles. The chemical composition is consistent with the mineralogy where the SiO_2, CaO, Zr and Sr are the dominant oxides and trace elements, whereas other major and trace elements are strongly depleted. The sediments are compositionally mature and geochemically classified as quartz arenite to sublitharenite derived mainly from recycled sedimentary rocks that is consistent with the passive margin tectonic setting. The Chemical Index of Alteration (CIA) values suggest a low to moderate degree of weathering for the sediments of core I, whereas they show unweathered to poorly weathered source rocks of the sediments of cores II and III. Recycled sandstones mixed with carbonate sources and the hydraulic sorting minimized the effective usage of weathering indices in this study.

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).

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 (Garzanti et al., 2001). 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 continental rift margin of the Yemen is introduced relying solely on the detrital mode and framework compositional trends of the modern loose beach and bedload wadi sediments (Garzanti et al., 2001). Until now, the geochemistry of the Gulf of Aqaba beach sands and its provenance and tectonic implications have not been comprehensively investigated. The present study introduces the first attempt to interpret the provenance and tectonic

Cite this article as: Ghandour I, Basaham A, Haredy R, Manaa A, Al-Rabaki K, Bawahidi K: Geochemistry of the Gulf of Aden Beach Sands, Al-Mukalla, Yemen: Provenance and tectonic setting implications. Acta Geodyn. Geomater., 15, No. 1 (193), 55–69, 2019. DOI: 10.13168/AGG.2019.0005

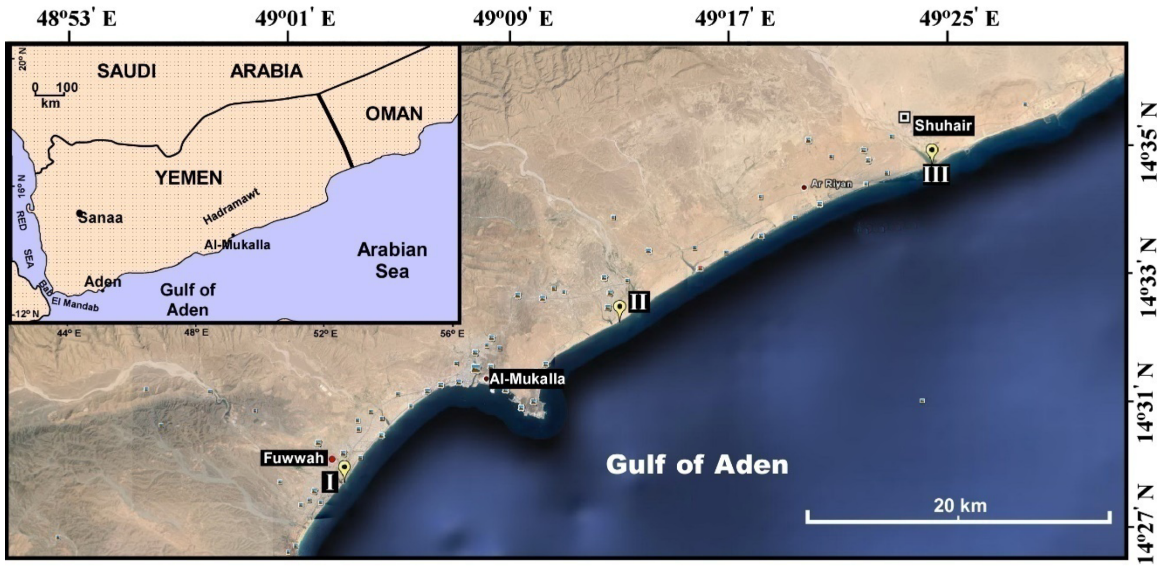

Fig. 1 Location map of the area of study showing the locations of collected cores.

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^{o}E, strikes obliquely (50^{o}) to the N25^{o}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 Hami 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).

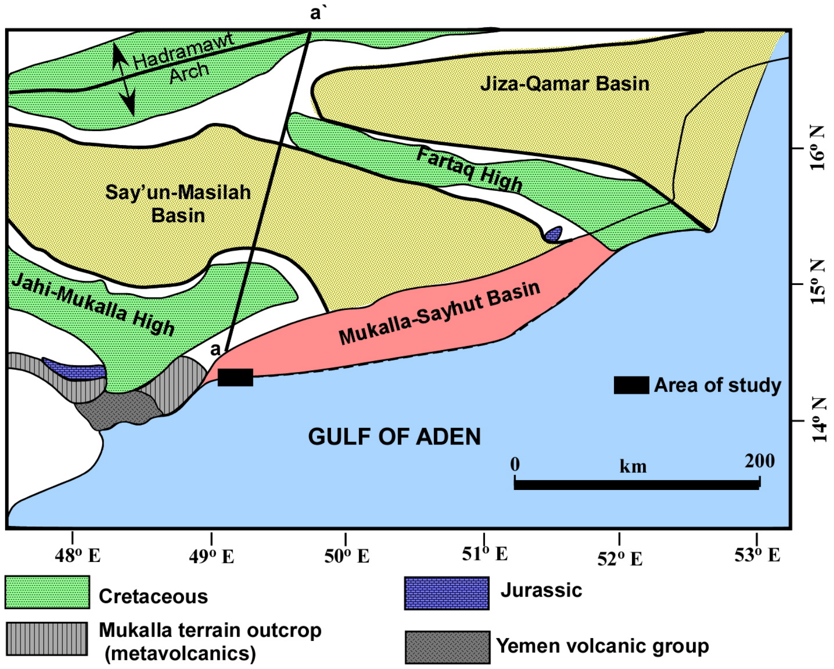

Fig. 2 Sedimentary basins and major structural highs surrounding Al-Mukalla area (after As-Saruri et al., 2010). a-a' is a cross section shown in Figure 3.

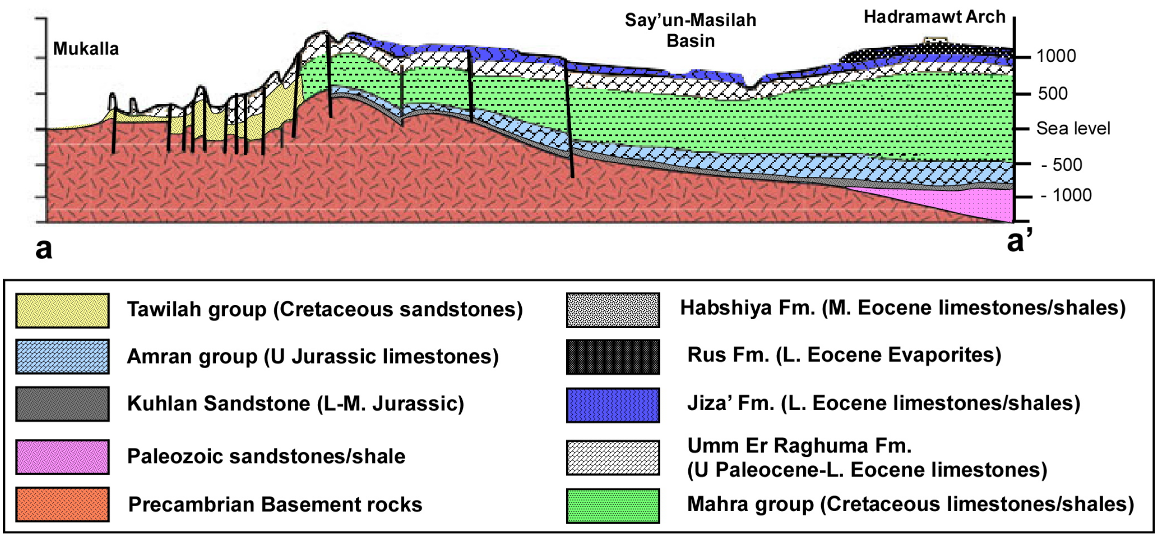

Fig. 3 Cross-section showing the main structural and stratigraphic framework near Al-Mukalla, Yemen (modified after Beydoun, 1966; As-Saruri et al., 2010). The location of a-a' line is shown in Figure 2.

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 (σ_I) 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 Kα radiation at 15 kV to 40 mA at the XRD laboratory, Faculty of Marine Science, King Abdulaziz 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 of 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 spectroflux ($Li_2B_4O_7$ 20 %, $LiBO_2$ 80 %, dried at 450 °C for 4 hours), 0.54 g of oxidant $LiNO_3$ 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 Fe_2O_3t. 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 = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \times 100$, where Al_2O_3, CaO^*, Na_2O and K_2O 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 P_2O_5) is used. If the CaO** is < Na_2O, then CaO* = CaO**, otherwise the CaO* = Na_2O (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 SiO_2 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; Al_2O_3, Fe_2O_3, MgO, K_2O, Na_2O, TiO_2, P_2O_5 and MnO surprisingly display low concentrations. The average concentrations of MgO, Al_2O_3 and Fe_2O_3 in the sediments of core I are

Table 1 Results of grain size analysis of the Gulf of Aden shallow subsurface beach sands.

Sample	Core I		Core II		Core III	
	Mean (ϕ)	σi (ϕ)	Mean (ϕ)	σi (ϕ)	Mean (ϕ)	σi (ϕ)
1	2.135	0.508	1.74	0.85	2.347	0.511
2	2.098	0.507	1.65	0.94	2.422	0.497
3	2.148	0.510	1.77	0.95	2.415	0.502
4	2.080	0.511	2.46	0.63	2.384	0.508
5	2.156	0.512	2.44	0.63	2.370	0.509
6	2.146	0.513	2.45	0.76	2.103	0.639
7	2.418	0.495	2.07	1.00	2.148	0.726
8	2.440	0.485	2.43	0.77	2.317	0.634
9	2.392	0.506	2.41	0.63	2.332	0.608
10	2.387	0.505	2.68	0.76	2.411	0.510
11	2.424	0.491	2.95	0.61	2.474	0.476
12	2.419	0.495	3.03	0.66	2.511	0.455
13	2.375	0.514	2.71	0.76	2.442	0.488
14	2.336	0.513	2.39	0.61	2.449	0.488
15	2.103	0.518	2.48	0.61	2.485	0.471
16	2.368	0.510	2.33	0.61	2.720	0.400
17	2.092	0.605	2.41	0.64	2.768	0.306
18	2.407	0.504	2.93	0.70	2.765	0.305
19	2.397	0.509	2.55	0.71	3.005	0.480
20	2.381	0.518	2.98	0.63	2.921	0.564
21			2.40	0.72	2.980	0.592
22			2.12	0.64	2.976	0.605
23					2.425	0.666
24					2.103	0.509
25					2.124	0.520
26					2.120	0.517
27					2.137	0.521
Min	2.08	0.49	1.65	0.61	2.10	0.31
Max	2.44	0.60	3.03	1.00	3.00	0.73
Average	2.29	0.51	2.43	0.72	2.49	0.52

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, Al_2O_3 and Fe_2O_3 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 TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, Na_2O, K_2O and P_2O_5, whereas SiO_2 show values within the range of the UCC values. CaO is highly enriched comparing 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 (SiO_2/Al_2O_3) vs. log (Fe_2O_3/K_2O) (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 SiO_2, Na_2O+K_2O and $TiO_2+MgO+Fe_2O_3$ is employed herein to identify the effect of recycling (Kroonenberg, 1990). Generally, the samples are clustered at high to moderate values of SiO_2 suggesting the major influence of recycling that led to increasing residual enrichment of quartz

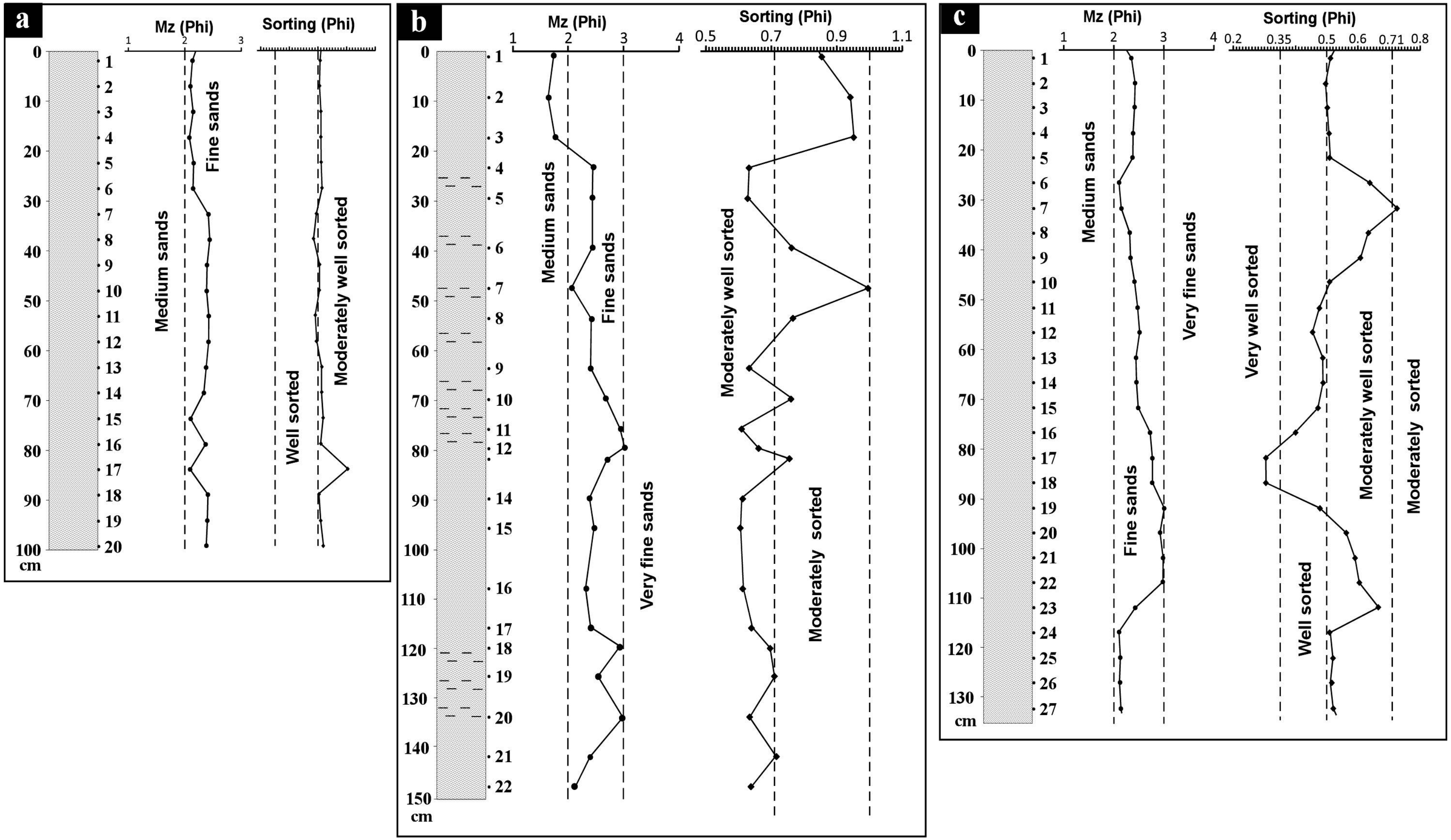

Fig. 4 Vertical variation of the grain size parameters mean size (M_z) and standard deviation (σ_I) in the Gulf of Aden shallow subsurface beach sands for core I (a), core II (b) and core III (c)

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

Core	Sample	Qz	Plag	K-fels	clays	hornb	calc	dolm	arag
CORE I	1	A	T		T	T	M	T	
	3	A	T				M	T	
	5	A	T		T		M	T	
	7	A	T		T		M	T	
	9	A	T		T		M	M	
	10	A	T		T		M	T	
	11	A	T		T		M	T	
	12	A	T		T		M	T	
	13	A	T	T			M	T	
	15	A	T		T	T	M	T	T
	17	A			T		M		
	19	A	T		T		M	T	
	20	A	T	T	T		M	T	
CORE II	1	A		T		T	M	T	
	2	A	T	T			M	T	T
	4	A		T			M	T	
	6	A					M	T	
	9	A					M	T	
	10	A					M	T	
	12	A		T			M	T	
	14	A		T			M	T	
	16	A					M	T	T
	18	A		T			M	T	
	20	A					M	T	T
	21	A		T			M	M	
	22	A					M	T	T
CORE III	1	A					M	T	
	3	A					M	T	
	5	A					M	T	
	7	A		T			M	T	
	9	A					M	T	
	11	A		T			M	T	
	13	A		T			M	T	
	15	A		T		T	M	T	
	17	A		T			M	T	
	19	A		T			M	T	
	21	A	T	T			M	T	
	23	A		T			M	T	
	25	A					M	T	
	27	A		T			M	T	

(Fig. 9B). Though the sediments of core II have the lowest average concentrations of SiO_2, the samples of core II are clustered near the $SiO_2/20$ apex comparing to the samples of cores I and III. The samples of core II show very low concentrations of TiO_2+MgO+Fe_2O_3 comparing to the other two cores. The linear correlation observed between K_2O vs. Rb and Ba (Fig. 10) 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 SiO_2/Al_2O_3 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 Al_2O_3 content

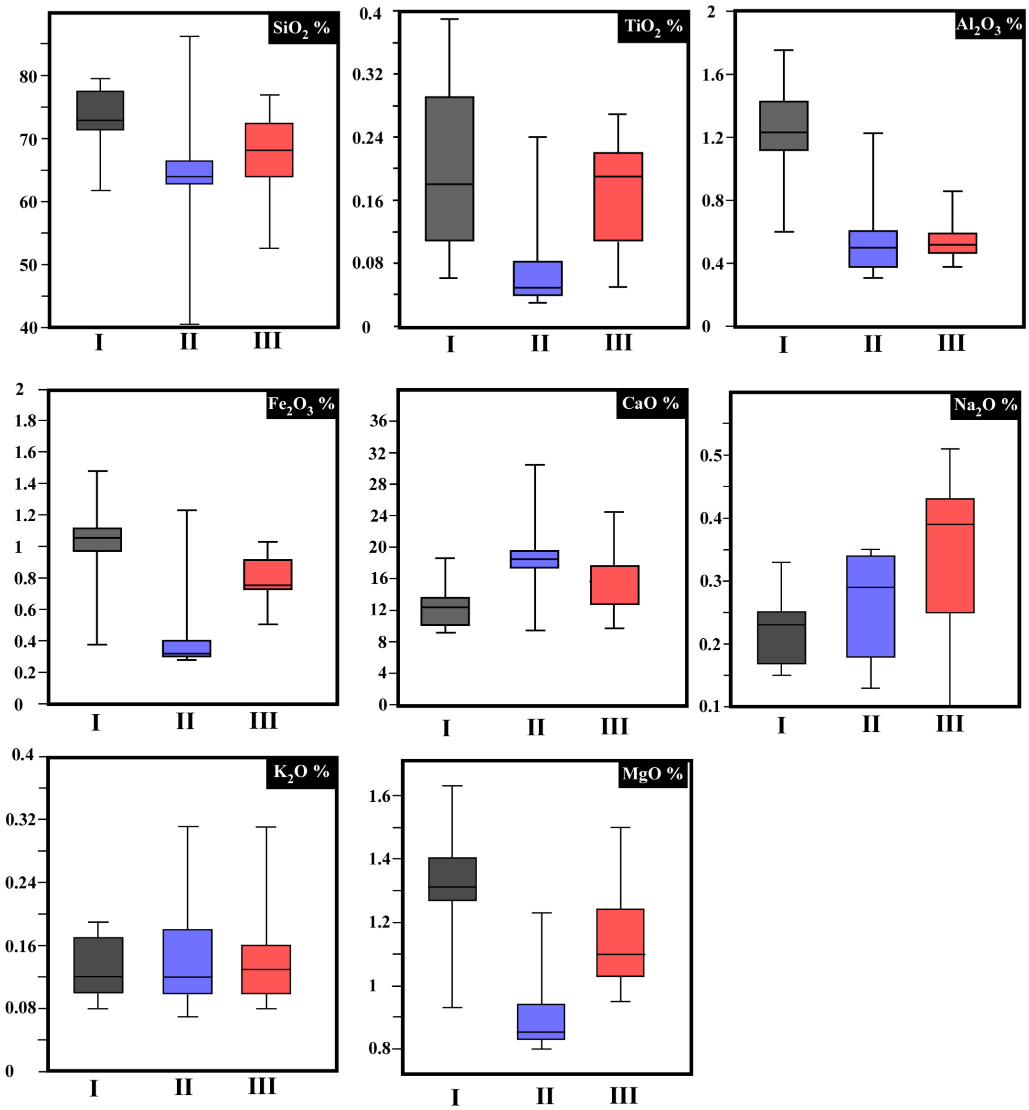

Fig. 5 Box chart showing the minimum, maximum and average concentrations of major oxides (wt%) for the Gulf of Aden shallow subsurface beach sands.

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 SiO_2, 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 SiO_2 and

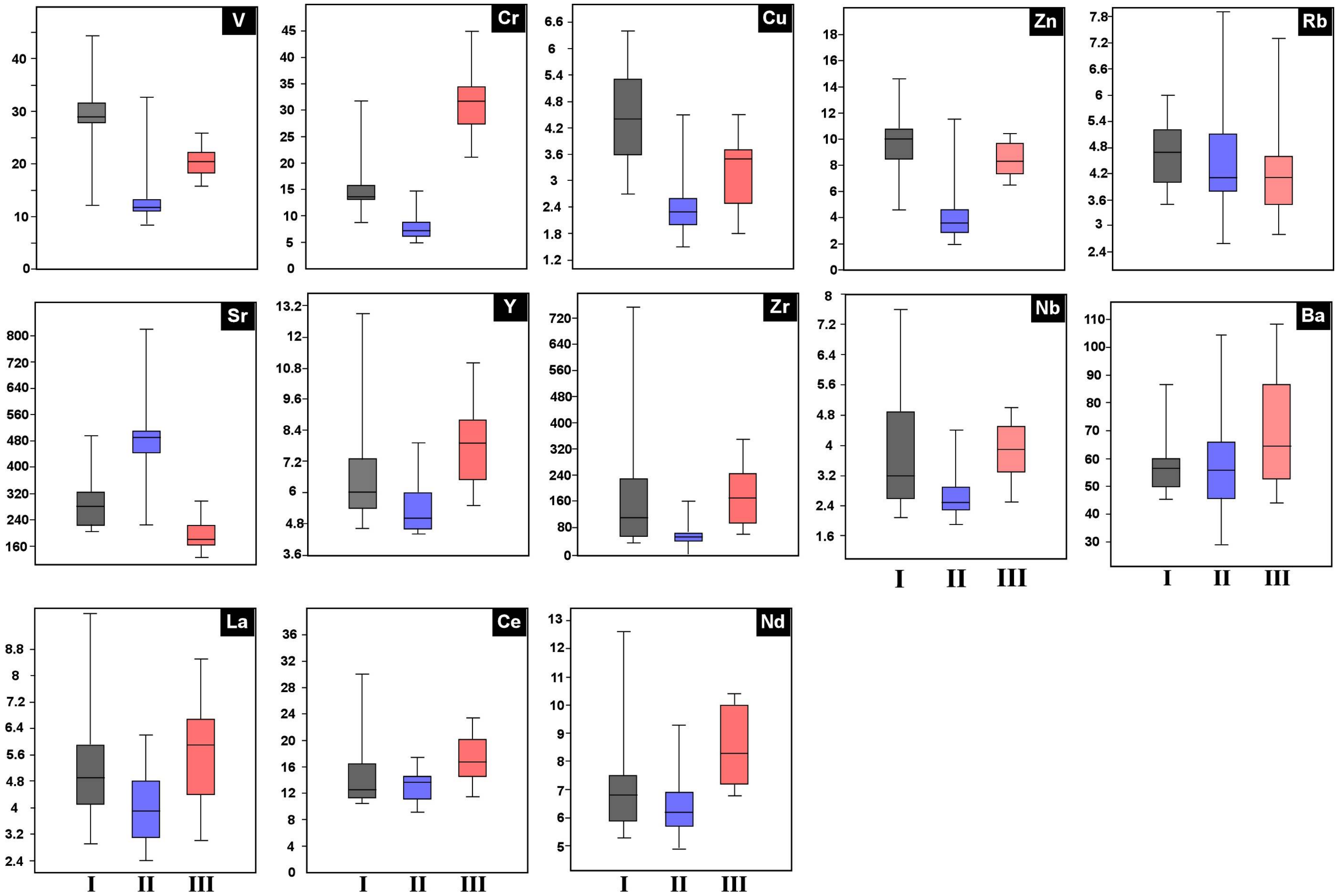

Fig. 6 Box chart showing the minimum, maximum and average concentrations of trace elements (μg/g) for the Gulf of Aden shallow subsurface beach sands.

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

Element	Core I			Core II			Core III		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
SiO_2	61.83	79.51	72.38	40.52	86.18	64.82	52.58	76.90	66.67
TiO_2	0.06	0.39	0.19	0.03	0.24	0.07	0.05	0.27	0.17
Al_2O_3	0.60	1.76	1.25	0.31	1.23	0.58	0.38	0.86	0.56
Fe_2O_3	0.38	1.48	1.02	0.28	1.23	0.41	0.51	1.03	0.79
MnO	0.01	0.03	0.02	0.01	0.02	0.01	0.01	0.02	0.02
MgO	0.93	1.63	1.31	0.80	1.23	0.90	0.95	1.50	1.15
CaO	9.15	18.61	12.73	9.49	30.53	18.97	9.72	24.4	16.11
Na_2O	0.15	0.33	0.23	0.13	0.35	0.26	0.10	0.51	0.34
K_2O	0.08	0.19	0.13	0.07	0.31	0.15	0.08	0.31	0.15
P_2O_5	0.04	0.16	0.05	0.04	0.26	0.12	0.01	0.02	0.01
LOI	6.50	13.87	9.58	0.70	22.42	12.95	8.62	18.70	12.62
V	12.20	44.40	28.94	8.40	32.60	13.78	15.80	25.80	20.59
Cr	8.80	31.90	15.86	5.00	14.80	8.27	21.10	45.00	31.51
Cu	2.70	6.40	4.46	1.50	4.50	2.58	1.80	4.50	3.21
Zn	4.60	14.60	9.78	2.00	11.50	4.21	6.50	10.40	8.36
Rb	3.50	6.00	4.71	2.60	7.90	4.63	2.80	7.30	4.37
Sr	205.00	495.00	302.08	225.00	820.00	485.46	125.00	297.00	199.50
Y	4.60	12.90	6.84	4.40	7.90	5.45	5.50	11.00	7.96
Zr	33.00	754.00	199.23	39.00	161.00	62.46	60.00	350.00	178.29
Nb	2.10	7.60	3.79	1.90	4.40	2.65	2.50	5.00	3.91
Ba	45.40	87.00	59.49	29.00	104.00	56.77	44.00	108.00	71.07
La	2.90	9.80	5.30	2.40	6.20	4.12	3.00	8.50	5.74
Ce	10.50	30.10	14.95	9.20	17.40	13.21	11.50	23.40	17.31
Nd	5.30	12.60	7.32	4.90	9.30	6.47	6.80	10.40	8.49
SiO_2/Al_2O_3	35.00	105.00	62.00	36.00	188.00	131.62	86.00	179.00	124.86
CIA	49.70	67.32	61.65	22.54	67.81	39.48	25.20	53.47	34.35

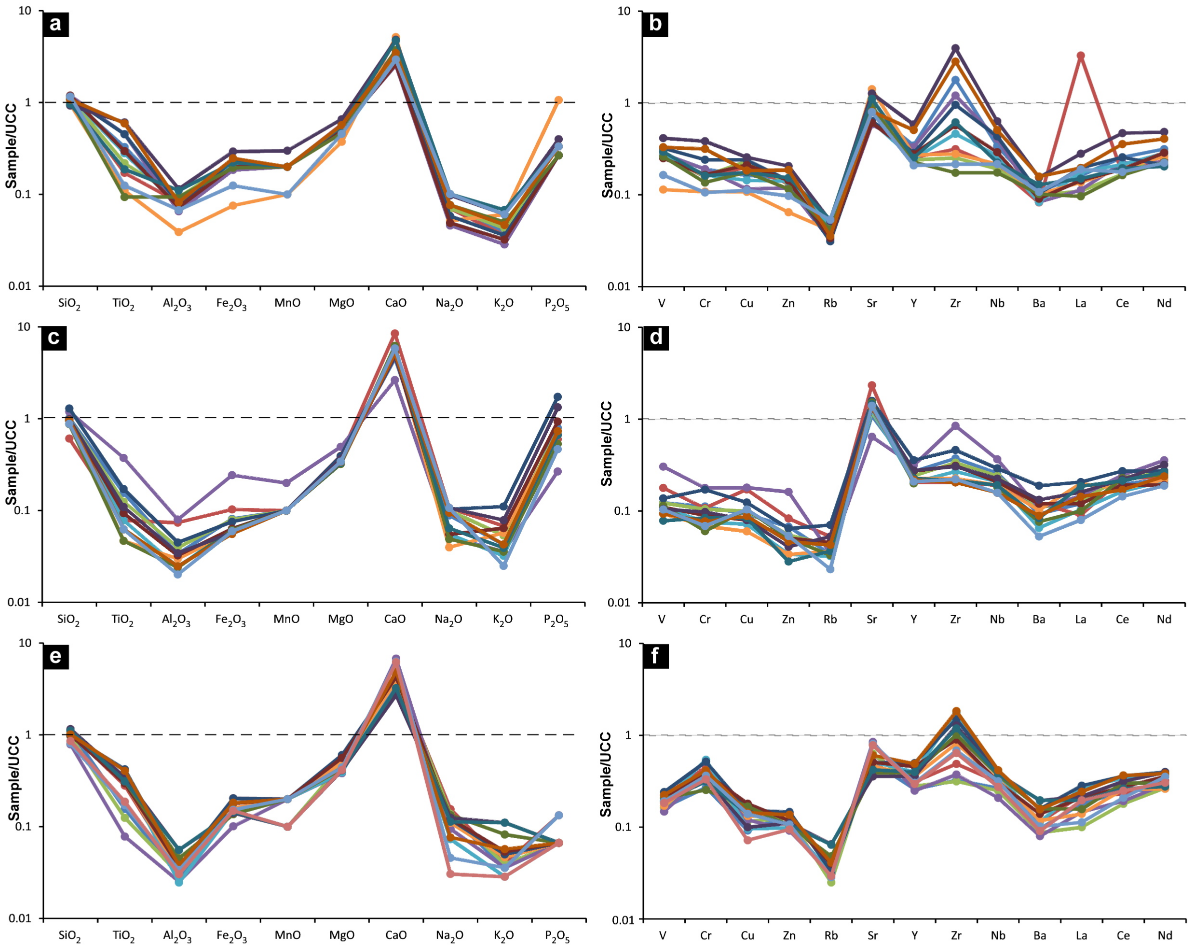

Fig. 7 Diagram for the normalization of samples against the upper continental crust for major oxides (Rudnick and Gao, 2003) and trace elements (Taylor and McLennan, 1985), a and b for major and trace elements in core I, c and d for core II and e and f for core III.

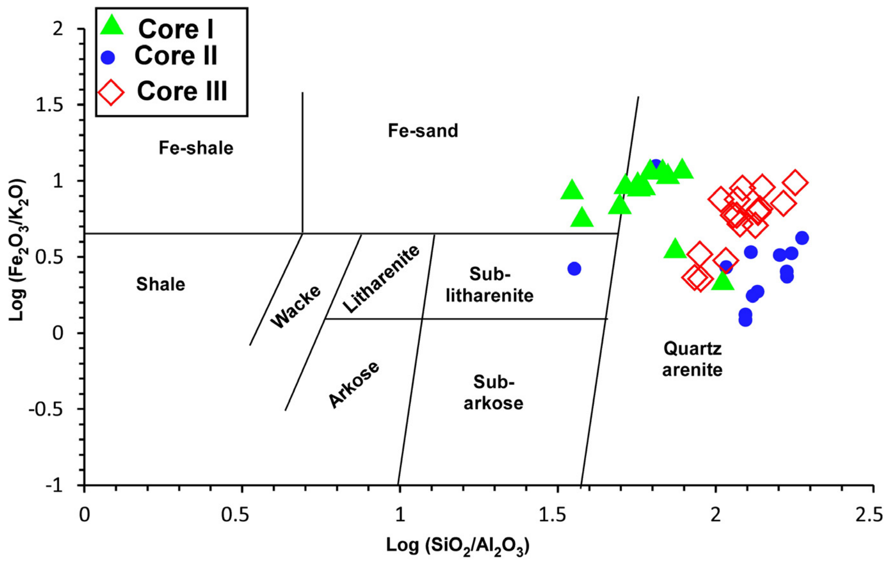

Fig. 8 Geochemical classification of the Gulf of Aden shallow subsurface beach sands (after Herron, 1988).

the relatively low CaO content in the sediments of core I indicates a dominantly sandstone source possibly detritus from the Cretaceous sandstones of the Tawilah group. On the other hand, the relatively low to moderate SiO_2 and higher CaO concentrations in the sediments of cores II and III suggest a mixture of siliciclastic and carbonate source rocks possibly the Lower to Middle Jurassic sandstones of the Kuhlan Formation and carbonates of the Jurassic to Eocene limestones of the Amran group, Umm Er Rhadhuma, Marha and Jiza' formations. Increasing sediment recycling preferentially increases the proportion of quartz, whereas less stable minerals such as feldspar and mafic minerals decrease; this leads to a progressive increase in the SiO_2/Al_2O_3 ratio (Chen et al., 2014). Passive margin sands are quartz rich relative to other unstable (liable) minerals, where weathering leads to residual enrichment of quartz (SiO_2) and depletion of feldspars and micas (Kroonenberg, 1990).

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).

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.

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

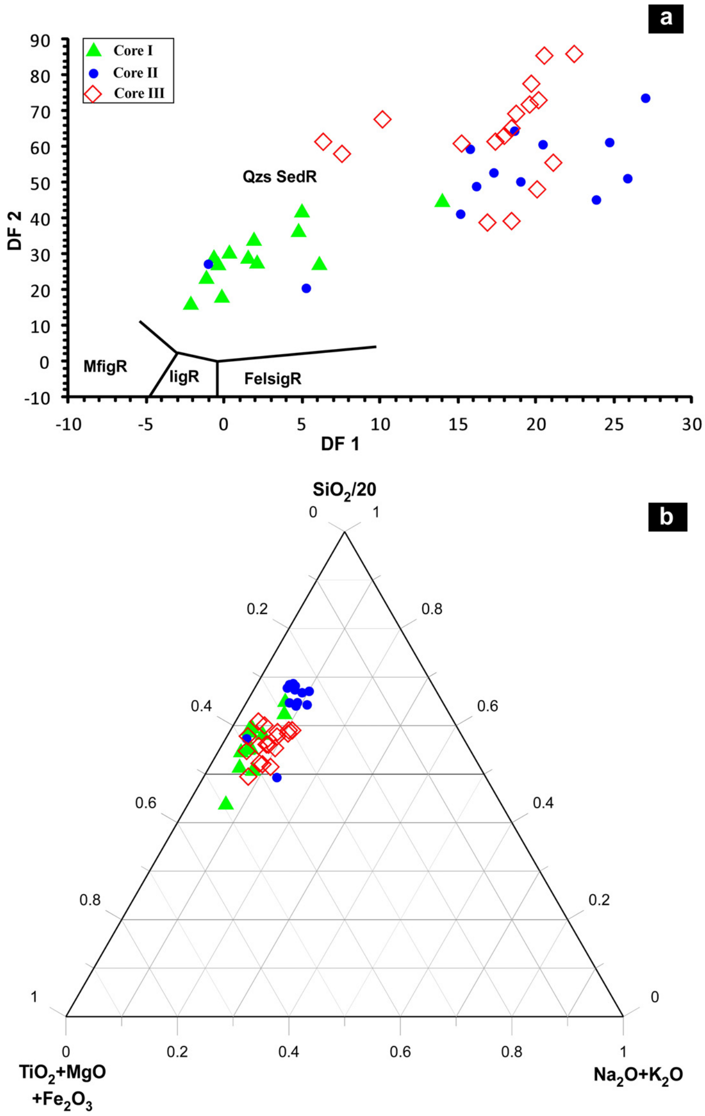

Fig. 9 Provenance and the impact of sediment recycling on the chemical composition of the Gulf of Aden shallow subsurface beach sands a) Discriminant function diagram for the provenance signatures of the Gulf of Aden beach sands (after Roser and Korsch, 1988); Discriminant function 1 (DF1) = –1.773 TiO_2 + 0.607 Al_2O_3 + 0.76 $Fe_2O_{3(total)}$ – 1.5 MgO + 0.616 CaO + 0.509 Na_2O – 1.224 K_2O – 9.09; Discriminant function 2 (DF2) = 0.445 TiO_2 + 0.07 Al_2O_3 – 0.25 $Fe_2O_{3(total)}$ – 1.142 MgO + 0.438 CaO + 1.475 Na_2O + 1.426 K_2O – 6.861., b) Ternary plot diagram showing quartz (SiO_2), feldspars and micas Na_2O, K_2O) and ferromagnesians (TiO_2, MgO and, Fe_2O_3) (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 Al_2O_3, Na_2O, K_2O and CaO that are involved in the equations used to calculate weathering indices. Under dominantly arid climate, the Jurassic and Cretaceous Kuhlan 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 Al_2O_3 and

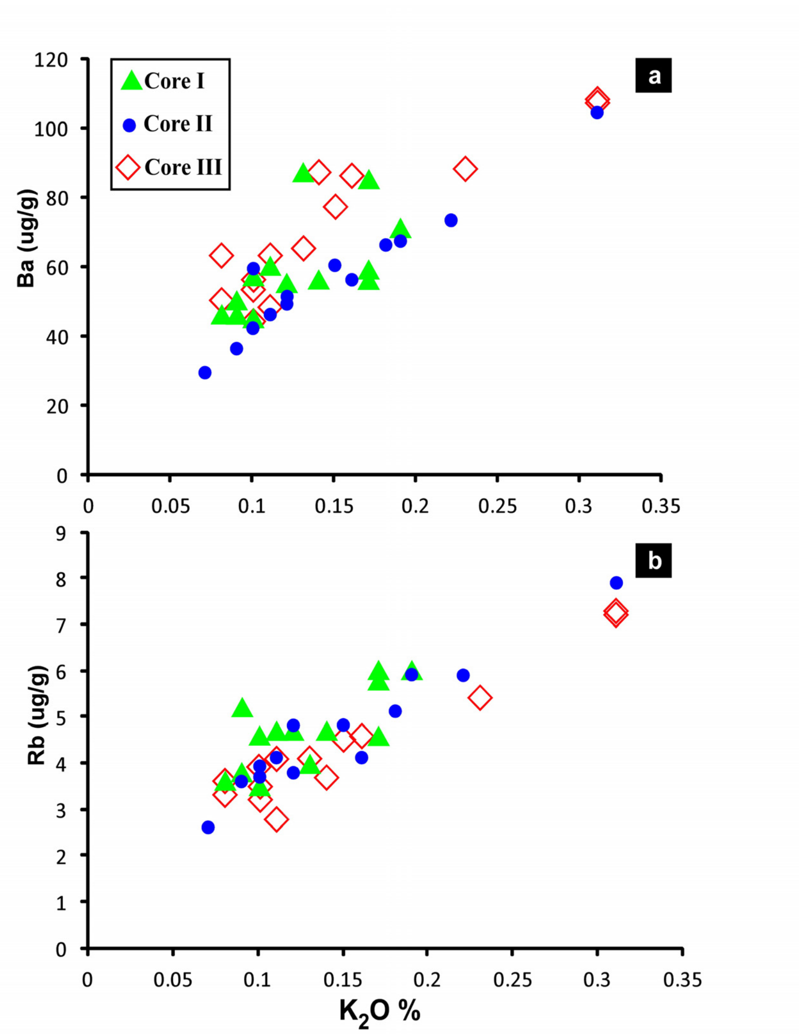

Fig. 10 Bivariate plot between K_2O and Ba (a) and Rb (b).

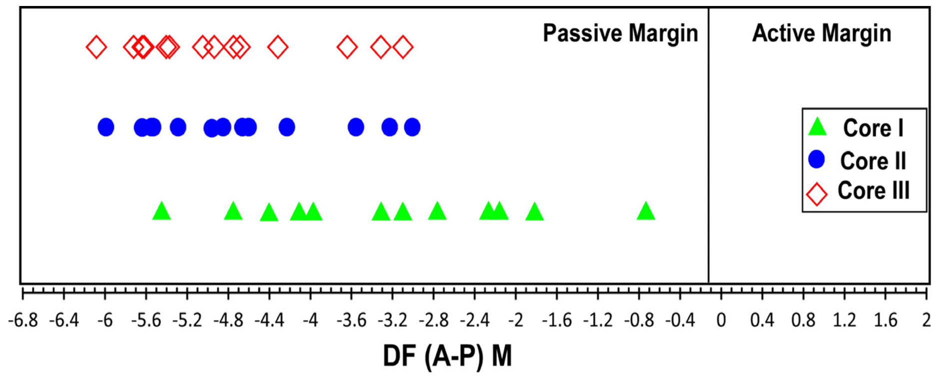

Fig. 11 Major element based multidimensional discriminant function diagram showing that the Gulf of Aden shallow subsurface beach sand plot in the field of passive margin settings (Verma and Armstrong-Altrine, 2016).

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 Al_2O_3 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 Shihr (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 mineralogy where SiO_2 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 polycylic 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.

ACKNOWLEDGMENTS

This project was funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, under grant no. G-543-150-1436. The authors, therefore, acknowledge with thanks DSR for technical and financial support. We are very grateful for the reviewers for their careful reading and constructive comments that surely improved the quality of the manuscript. Great thanks go to the editor for his editorial handling.

REFERENCES

Al-Wosabi, M.A. and Wasel, S.: 2011, Lithostratigraphic subdivision of the Kuhlan Formation in Yemen. Arabian J. Geosciences, 4, 1323–1335.

Armstrong-Altrin, J.S.: 2009, Provenance of Sands from Cazones, Acapulco, and Bahía Kino Beaches, Mexico. Revista Mexicana De Ciencias Geológicas*,* 26, 764–782

Armstrong-Altrin, J.S., Nagarajan, R., Balaram, V. and Natalhy-Pineda, O.: 2015, Petrography and geochemistry of sands from the Chachalacas and Veracruz Beach Areas, Western Gulf of Mexico, Mexico: Constraints on provenance and tectonic setting. J. South American Earth Sci., 64, 199–216. DOI: 10.1016/j.jsames.2015.10.012

Armstrong-Altrin, J.S., Lee, Y.I., Kasper-Zubillaga, J.J. et al.: 2012, Geochemistry of Beach Sands Along the Western Gulf of Mexico, Mexico: Implication for Provenance. Chemie Der Erde Geochemistry, 72, 345–362. DOI: 10.1016/j.chemer.2012.07.003

Armstrong-Altrin, J.S., Nagarajan, R., Lee, Y.I., Kasper-Zubillaga, J.J., Carranza-Edwards, A., Garcia, D., Eby, N., Balaram, V. and Cruz-Ortiz, N.L.: 2014, Geochemistry of sands along the San Nicolás and San Carlos Beaches, Gulf of California, Mexico: Implications for provenance and tectonic setting. Turkish J. Earth Sci., 23, 533–558. DOI: 10.3906/yer-1309-21

As-Saruri, M.A., Sorkhabi, R. and Baraba, R.: 2010, Sedimentary basins of Yemen: their tectonic developmentand lithostratigraphic cover. Arab J Geosci., 3, 515–527, DOI: 10.1007/s12517-010-0189-z

Avigad, D., Sandler, A., Kolodner, K., Stern, T.J., McWilliams, M., Miller, N. and Beyth, M.: 2005, Mass-production of Cambro-ordovician quartz-rich sandstone as a consequence of chemical weathering of Pan-African Terranes: Environmental implications. Earth and Planetary Sci. Letters, 240, 818–826. DOI: 10.1016/j.epsl.2005.09.021

Beydoun, Z.R.: 1964, The stratigraphy and structure of the eastern Aden Protectorate. In: Overseas Geol. and Mineral Resources, Bull Supp 5, HMSO, London, 1–107.

Beydoun, Z.R.: 1966, Eastern Aden Protectorate and part of Dhufar. USGS Prof Pap 560-H, 1–49.

Beydoun, Z.R., As-Saruri, M.L. and Baraba, R.S.: 1996, Sedimentary basins of the Republic of Yemen: their structural evolution and geological characteristics. Rev. Inst. Fr. Petrol., 51, 763–775. DOI: 10.2516/ogst:1996049

Bosence, D.W.J.: 1997, Mesozoic rift basins of Yemen. Mar. Pet. Geol., 14, No. 6, 611–616. DOI: 10.1016/S0264-8172(97)00039-1

Bott, W.F., Smith, B.A., Oakes, G., Sikander, A.H. and Ibraham, A.I.: 1992, The tectonic framework and regional hydrocarbon prospectivity of the Gulf of Aden. J. Petrol. Geol., 15, 211–243. DOI: 10.1111/j.1747-5457.1992.tb00963.x

Brannan, J., Gerdes, K.D. and Newth, I.R.: 1997, Tectono-stratigraphic development of the Qamar basin, Eastern Yemen. Mar. Pet. Geol., 14, No. 6,701–730. DOI: 10.1016/S0264-8172(96)00048-7

Carranza‐Edwards, A., Kasper‐Zubillaga, J.J., Rosales‐Hoz, L., Morales de la Garza, E. and Lozano Santa‐Cruz, R.: 2009, Beach sand composition and provenance in a sector of the Southwestern Mexican Pacific. Revista Mexicana De Ciencias Geológicas, 26, No. 2, 433–447.

Chen, M., Sun, M, Cai, K., Buslov, M.M. and Rubanova, E.S.: 2014, Geochemical study of the Cambrian-Ordovician metasedimentary rocks from the Northern Altai-Mongolian Terrane, Northwestern Central Asian Orogenic Belt: Implications on the provenance and tectonic setting. J Asian Earth Sciences, 96, 69–83. DOI: 10.1016/j.jseaes.2014.08.028

D'Acremont, E, Leroy S., Beslier M-O., Bellahsen, N., Fournier, M., Robin, C., Maia, M. and Gente, P.: 2005, Structure and evolution of the eastern Gulf of Aden conjugate margins from seismic reflection data. Geophys. J. Int., 160, 869–890. DOI: 10.1111/j.1365-246X.2005.02524.x

Fedo, C.M., Nesbitt, H.W. and Young, G.M.: 1995, Unraveling the effects of potassium metasomatism in sedimentary rocks and paleosols, with implications for paleoweathering conditions and provenance. Geology, 23, 921–924. DOI: 10.1130/0091-7613(1995)023<0921:UTEOPM>2.3.CO;2

Folk, R.L. and Ward, W.C.: 1957, Brazos River Bar: A Study in the significance of grain size parameters. J. Sedim. Petrol. 27, 3-26.

Garzanti E., Vezzoli G., Ando`S. and Castiglioni, G.: 2001, Petrology of rifted-margin sand (Red Sea and Gulf of

Aden,Yemen). J. Geol., 109,277–297. DOI: 10.1086/319973

Garzanti, E. and Resentini, A.: 2016, Provenance control on chemical indices of weathering (Taiwan river sands). Sedim. Geol., 336, 81–95. DOI: 10.1016/j.sedgeo.2015.06.013

Greenwood, J.E.G.W. and Bleackley, D.: 1967, Geology of the Arabian Peninsula: Aden protectorate. U.S.G.S Professional Paper 560-C, 1–96.

Hardy, R. and Tucker, M.: 1988, X-ray powder diffraction of sediments. In: Tucker, M., (ed.) Techniques in Sedimentology, New York: Blackwell Scientific Publication, Oxford, 191–228.

Herron, M.M.: 1988, Geochemical classification of terrigenous sands and shales from core or log data. J. Sedimentary Petrology, 58, No. 5, 820–829. DOI: 10.1306/212F8E77-2B24-11D7-8648000102C1865D

Hossain, H.M.Z., Roser, B.P. and Kimura, J-I.: 2010, Petrography and whole-rock geochemistry of the Tertiary Sylhet succession, northeastern Bengal Basin, Bangladesh: Provenance and source area weathering. Sediment. Geol., 228, 171–183. DOI: 10.1016/j.sedgeo.2010.04.009

King, W.A., Mills, B.R., Scoot, G. and Abdillah, A.A.:2003, The Masilah Fields, Republic of Yemen. In: Halbouty, MT. (eds), Giant oiland gas fields of the decade 1990–1999. AAPG Spec Publ., 17, 1–24.

Kroonenberg, S.B.: 1990, Geochemistry of Quaternary Fluvial Sands From Different Tectonic Regimes. Geochemistry of the Earth' Surface and of Mineral Formation. 2nd International Symposium, Aix en Provence, France, 88–91.

Lacassie, J.P., Roser, B., Ruiz del Solar, J. and Hervé, F.: 2004, Discovering geochemical patterns using self-organizing neural networks: a new perspective for sedimentary provenance analysis. Sediment. Geol., 165, 175–191. DOI: 10.1016/j.sedgeo.2003.12.001

Leckie, D.A. and Rumpel, T.: 2003, Tide-influenced sedimentation in a rift basin—Cretaceous Qishn formation, Masila Block, Yemen: A billion barrel oil field. AAPG Bull., 87, No. 6, 987–1013. DOI: 10.1306/01220301116

McLennan, S.M.: 1993, Weathering and global denudation. Journal of Geology, 101, 2, 295–303. DOI: 10.1086/648222

McLennan, S.M., Hemming, S., McDaniel, D.K. and Hanson, G.N.: 1993, Geochemical approaches to sedimentation, provenance, and tectonics. In: Johnsson, M.J. and Basu, A. (Eds.) Processes Controlling the Composition of Clastic Sediments, Geological Society of America, Special Paper, No. 284, 120, 21–40.

Morcos, S.A. and Abdallah, A.M.: 2012, Oceanography of the Gulf of Aden John Murray–Mabahiss Expedition 1933–1934 Revisited. Egypt. J. Aquatic Res., 38, 77–91.

Nesbitt, H.W. and Young, G.M.: 1982, Early proterozoic climates and plate motions inferred from major element chemistry of Lutites. Nature, 299, 715–717. DOI: 10.1038/299715a0

Ohta, T. and Arai, H.: 2007, Statistical empirical index of chemical weathering in igneous rocks: A new tool for evaluating the degree of weathering. Chem. Geol., 240, 280–297. DOI: 10.1016/j.chemgeo.2007.02.017

Ramachandran, A., Madhavaraju, J., Ramasamy, S., Lee, Y.I., Rao, S., Chawngthu, D.L. and Velmurugan, K.: 2016, Geochemistry of Proterozoic clastic rocks of the Kerur Formation of Kaladgi-Badami Basin, North Karnataka, South India: Implications for Paleoweathering and Provenance. Turkish J. Earth Sciences, 25, 126–144. DOI: 10.3906/yer-1503-4

Roser, B.P. and Korsch, R.J.:1988, Provenance signatures of sandstone mudstone suites determined using discrimination function analysis of major element data. Chemical Geology, 67, 119–139. DOI: 10.1016/0009-2541(88)90010-1

Rudnick, R.L. and Gao, S.: 2003, Composition of the continental crust. Treatise on Geochemistry, 3. Editor Roberta L. Rudnick. Executive Editors: Heinrich D. Holland and Karl, K. Turekian, 1–64. DOI: 10.1016/B0-08-043751-6/03016-4

Simmons, M. and Al-Thour, K.: 1994, Micropaleontological and biozonation of the Amran Series (Jurassic) in the Sana'a region, Yemen Republic. In: Simmons, M. (ed.): Micropaleontology and hydrocarbon exploration in the Middle East. British Micropaleontological Society Publication Series, Chapman & Hall, London, 43–80.

Singh, P.: 2009, Major, Trace and REE Geochemistry of the Ganga River sediments: Influence of Provenance and Sedimentary Processes. Chemical Geology, 266, 242–255. DOI: 10.1016/j.chemgeo.2009.06.013

Suttner, L.G., Basu, A. and Mack, G.H.: 1981, Climate and the Origin of Quartz Arenites. J. Sedim. Petrol. 51, 1235–1246.

Tao, H., Sun S, Wang, Q., Yang, X. and Jiang, L.: 2014, Petrography and geochemistry of lower carboniferous greywacke and mudstones in Northeast Junggar, China: Implications for provenance, source weathering, and tectonic setting. J. Asian Earth Sci., 87, 11–25. DOI: 10.1016/j.jseaes.2014.02.007

Taylor, S.R. and McLennan, S.M.: 1985, The continental crust: Its Composition and Evolution. Oxford, Uk: Blackwell, 312 .

Tawfik, H.A., Ghandour, I.M., Maejima, W., Armstrong-Altrin, J.S. and Abdel Hameed, A.T.: 2017, Petrography and geochemistry of the siliciclastic Araba Formation (Cambrian), east Sinai, Egypt: Implications for provenance, tectonic setting and source weathering. Geol. Mag., 154, No.1, 1–23. DOI: 10.1017/S0016756815000771

Verma, S.P. and Armstrong-Altrin, J.S.: 2016, Geochemical discrimination of siliciclastic sediments from active and passive margin settings. Sediment. Geol., 332, 1–12. DOI: 10.1016/j.sedgeo.2015.11.011

von Eynatten, H., Barceló-Vidal, C. and Pawlowsky-Glahn, V.: 2003, Modeling compositional change: The example of chemical weathering of granitoid rocks. Mathemat. Geol., 35, 231–251. DOI: 10.1023/A:1023835513705

Wu, W., Zheng, H., Xu, S., Yang, J. and Liu, W.: 2013, Trace element geochemistry of riverbed and suspended sediments in the upper Yangtze River. J. Geochem. Explor., 124, 67–78. DOI: 10.1016/j.gexplo.2012.08.005

Zaid, S.M.: 2015, Geochemistry of sands along the Ain Soukhna and Ras Gharib Beaches, Gulf of Suez, Egypt: Implications for provenance and tectonic setting. Arab. J. Geosciences, 8, 10481–10496. DOI: 10.1007/s12517-015-1982-5

Zhang, Z., Pe-piper, G. and Piper, D.J.W.: 2014, Sediment geochemistry as a provenance indicator: Unravelling the cryptic signatures of polycyclic sources, climate change, tectonism and volcanism. Sedimentology, 61, 383–410. DOI: 10.1111/sed.12066