Indian Journal of Geo Marine Sciences
Vol. 54 (07), July 2025, pp. 317-329
DOI: 10.56042/ijms.v54i07.15771

Research Article

A study of the sedimentary characteristics and geochemistry of Gorsuzan estuary deposits in the north of the Persian Gulf, Hormozgan Province, Iran

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Received 16 December 2024; revised 23 June 2025

The Gorsuzan estuary, located in central Bandar Abbas, southern Iran, was studied to understand its sedimentary characteristics. Eight surface sediment samples were collected and analysed for grain size, heavy minerals, XRD, XRF, petrography, and optical mineralogy. Results indicate that sediments are mainly sandy, with gravel found mostly in the northern part and minor silt and clay in the northern and middle parts. Particle size generally decreases from the estuary's origin towards the coast, reflecting the influence of marine processes and wave action. Sediments range from sandy gravel to mud-gravel sand, with gravel particles showing variable sphericity (low to high) and roundness (sub-angular to semi-rounded). Petrographic studies revealed three microfacies: limestone mudstone, bioclastic wackestone, and calcareous sandstone, all attributed to the Aghajari Formation (Middle Miocene to Middle Pliocene) based on fossil content and grain size. Fine sediments contain quartz, dolomite, and minor amounts of albite, orthoclase, muscovite, chlorite, and calcite. Autogenic minerals like calcite and dolomite, as well as transition minerals such as muscovite, originate from calcareous marl deposits of the Aghajari Formation. Heavy minerals identified include oligisto, garnet, and zircon, which likely derive from igneous and metamorphic rocks of the Hormuz series. Geochemical analysis shows SiO_2 and CaO as the dominant oxides. Source rock investigation classifies the deposits as litharenite, indicating immature to medium maturity under semi-arid climatic conditions with low to medium chemical weathering.

[**Keywords**: Bandar Abbas, Geochemistry, Gorsuzan estuary, Marine processes, Physical sedimentology, Textural characteristics]

Introduction

The coastal sedimentary environments of the north of the Persian Gulf mainly include deltas, bays, estuaries, tidal ranges, and various beaches. Generally, these environments are identified as the place of deposition of debris sediments drained from seasonal and permanent dry rivers. An estuary or bay is a part of the sea that has advanced on land. In the classification of estuary sedimentary environments, it falls into the intermediate sedimentary environments category, and more precisely, it is part of the coastal range. An estuary is formed at the end of a waterway or river leading to the sea[1-4]. In terms of sedimentation, estuaries are usually active areas. The speed and amount of sediment filling of estuaries depend on factors such as the area of the estuary, coastal erosion, the size of the mouth of the upstream rivers entering the estuary and their sediment load[5-6]. Rivers and watersheds upstream of estuaries, depending on the geological features of that area, transport sediments and feed the estuary[5,6]. Estuary consists of three main parts: the inner part, which is surrounded by incoming rivers, where river sediments are transferred to the estuary. The middle part of the estuary has relatively low energy, where marine energy (primarily tributary currents) is equal to that of river currents. The outer part contains high-energy material from marine processes (waves or tidal currents), where sediments transported by marine currents are deposited[6-8]. Examining the sedimentary characteristics of the estuary deposits will greatly contribute to the analysis of sedimentation conditions and processes governing the estuary's sedimentary environment[9-10]. On the other hand, the particle-size composition of sediments has a significant impact on the environmental indicators of sedimentary deposits, and the sediments in this sub-environment transport and absorb various types of pollution in the environmental cycles associated with beaches. Sedimentary characteristics include particle size, particle dispersion, elongation, swelling, roundness, sphericity, and the mineralogical composition of sedimentary deposits[11].

Sedimentary particles are mostly moved and transported by the weather. With the decrease in the intensity of the flow, they are gradually separated by size and deposited[13,14]. If the sediment originates from several sources, a mixture of sediment particles of different sizes accumulates, ranging from gravel to clay. Geochemical data from clastic sediments provide important information from the point of view of sedimentology and environmental geology. The chemical composition of sedimentary and debris deposits is the final product of various geological factors, such as tectonic setting, source rock composition, intensity of weathering, textural maturity, and mineralogy during transportation and deposition. These data are very important from theoretical and practical aspects. The purpose of this research is to investigate the sedimentary characteristics and geochemistry of Gorsuzan estuary deposits in the centre of Bandar Abbas city, which is located at the confluence of the Persian Gulf and the Oman Sea.

Numerous studies have been conducted on estuarine sediments, primarily focusing on their sedimentological and geochemical characteristics. In these studies, the analysis of sediment geochemistry is considered a crucial tool for understanding sedimentation processes and environmental changes. For instance, the research by Mishra *et al.*[9] on the Ashtamudi Estuary in India and by Gharib Reza[16] on the Reeg Estuary highlight the importance of geochemical analysis for identifying sediment provenance and sedimentary dynamics in such environments. In many of these studies, different approaches, such as the Folk classification and chemical composition analysis have been employed for sediment characterisation. In the study by Mishra *et al.*[9], sediments were classified using Folk's classification, a method also used in the current study. Geochemical analysis of the sediments in the Gorsuzan Estuary has been conducted in a similar manner, and this comparison provides a better understanding of the sedimentary processes and environmental changes in the region.

The analysis of chemical and mineralogical properties of sediments in estuaries and river mouths is another important area of focus in various studies. Research by Abad *et al.*[10] on paleoenvironmental changes in the Tinto River estuary (Spain) and by Michel *et al.*[21] on the Belon Estuary (France) shows that sediment geochemistry can provide valuable insights into environmental changes, sediment provenance, and dynamic processes. These studies also demonstrate that the geochemical characteristics of estuarine sediments are influenced by factors such as marine currents, sediment exchanges, and geographical features. Similarly, this research utilises geochemical analysis to examine the sediments of Gorsuzan Estuary, assessing the chemical changes in the sediments within this environment. In addition, studies such as those by Bulbul *et al.*[21] on the Mandovi Estuary in India and Selim & Baset[19] on the Nile Delta estuary (Egypt) emphasise the importance of geochemical analysis in evaluating sediment characteristics. These studies highlight that the geochemical analysis can provide critical information about sedimentary processes, sediment provenance, and environmental changes, which is also the focus of the current study. In conclusion, a comparison of this study's findings with those of other similar research shows that the sediments of the Gorsuzan Estuary share many characteristics with those of other estuaries. However, given the region's unique environmental features, the geochemical findings of this study may offer new perspectives on sedimentary processes and environmental transformations.

Materials and Methods

Geographical and geological location

The Persian Gulf is the most important water ecosystem in Western Asia and the Middle East, located along the Oman Sea and between Iran and the Arabian Peninsula. The coasts of this bay in the south of Iran generally have the most important ports. The coast of the Persian Gulf in the vicinity of Iran is of a longitudinal type, parallel to the axis of the nearby heights, and along the coast, rivers enter it, creating many estuaries. Gorsuzan estuary is located in the centre of Bandar Abbas city in Hormozgan province at the confluence of the Persian Gulf and the Oman Sea (Fig. 1). Gorsuzan estuary, also called Kamarbandi estuary or Shahnaz estuary, passes by the Hormoz Hotel in Shahrbandar Abbas, then passes through the Shah Hosseini and Shahid Modares

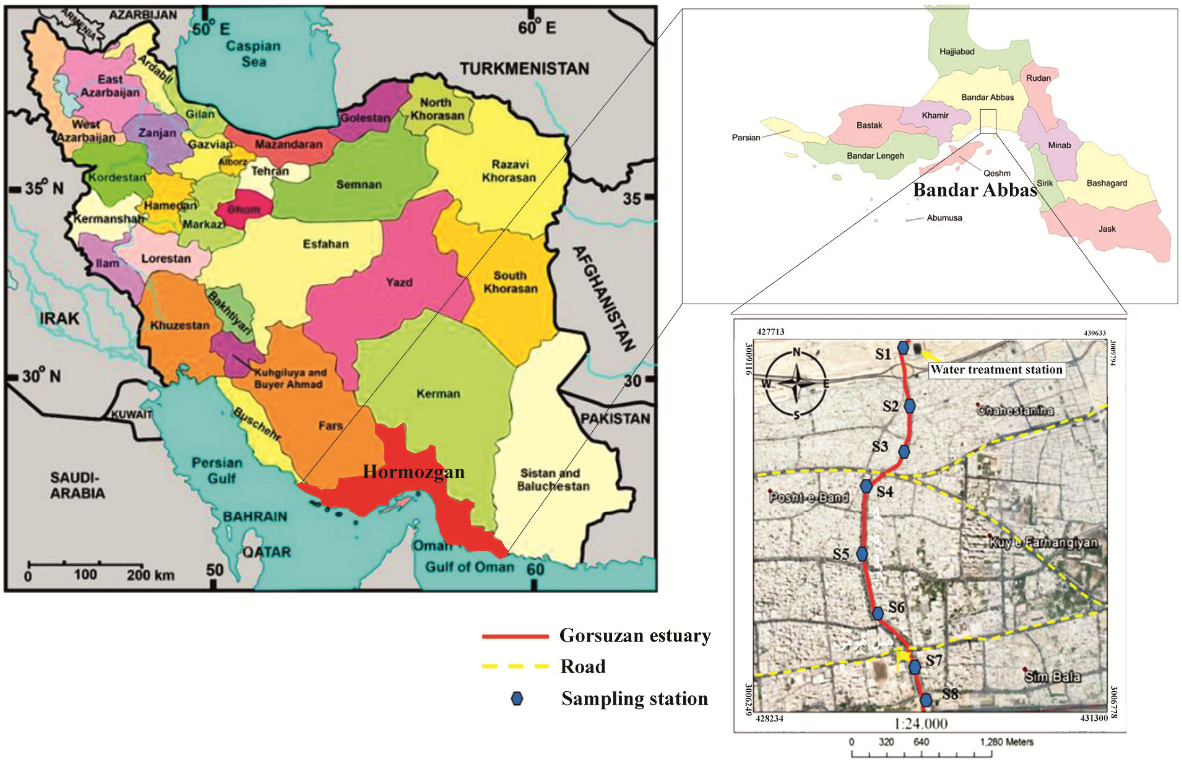

Fig. 1 — Aerial photo with a scale of 1:24000 with a defined square of Gorsuzan estuary using Google Earth

neighbourhoods (former Shahnaz neighbourhood), and then goes to the belt neighbourhood[22]. The run-off and floods of the districts of Belt, Shariati, Shir Som, Seyd Kamal, and Sim-Bala enter this estuary, which has made this estuary devoid of any fishing and port value and even a habitat for creatures[22]. The length of this estuary is about 4 kms and the average length of the tidal range is 50 cm.

Its width varies from 20 meters upstream to 31 meters downstream. The depth of this estuary is from 2.2 m in the upstream to 3 m in the middle part, and 2.3 m in the downstream[22]. The results of the latest research on the hydrodynamic behaviour of this estuary show that water only advances up to a length of 600 m from the opening into the estuary. Results from a tidal period indicated that the Gorsuzan estuary is affected only by tidal currents, with the dominant current being the tide.

Finally, due to the lack of amplitude damping at the mouth of the estuary and the existence of a phase difference caused by the constant change in the direction of the flow, it can be said that, in general, the behaviour of shallow and straight estuaries with medium length is rectangular in shape, and in the mouth, it shows the behaviour of a funnel-shaped estuary. The location of this estuary in the centre of Bandar Abbas city has caused more than 60,000 litres of domestic sewage to enter the sea through the Gorsuzan estuary, and the amount of physical and chemical pollution caused by the discharge of domestic sewage into this estuary is the highest compared to other estuaries in Hormozgan province[24].

Gorsuzan estuary is located on Quaternary deposits of fluvial, windy, and coastal origin. A view of the Gorsuzan estuary is presented in Figure 2. This range consists of Quaternary sediments, with an emphasis on the Holocene, and is characterised by significant thickness. Upstream of this area is the great Bandar Abbas anticline, where the deposits of Aghajari formation (alternation of calcareous sandstone and calcareous) form the most outcrops of this geological structure with a general east-west trend. These deposits are the main origin of the natural components of the studied sediments (Figure 2). The recent deposits on the shores of Bandar Abbas city, in addition to the estuary, are of the river type and the coastal plain. The faults of this range also have a west-east trend. The influence of the Hormuz series diapirism upstream of the target area is clearly visible in Figure 3.

Methodology

Based on common methods in field sedimentology, such as Tucker[25], Arzani[26], Khodabakhsh & Sahraro[27], 8 samples were taken from the Gorsuzan estuary at 500 m intervals (Fig. 1). These samples were collected using grabs, spatulas and zipped nylon bags. Due to the high sediment humidity, the samples were first placed in the open air for 24 h and then dried in the oven at 75 °C for 24 h. After completion of this process, the sediments were weighed and granulated using a sieving device. Granulation tests were performed using a shaker and hydrometry, heavy minerals with the help of bromoform solution and lithography, and optical mineralogy using a Blub Type G6 polarising microscope and a CS-5CAW binocular model in the laboratory of the Department of Geology, Hormozgan University. X-ray Diffraction (XRD) was performed using a Philips PW1730 XRD machine, and XRF analysis was carried out using a XRF Philips PW1730 in Zarazma, Persia. Folk[28], Dunham[29], and Petty John *et al.*[30] were used for classification and naming. In order to check the statistical parameters, the Folk[28] relations presented in Table 1 were used.

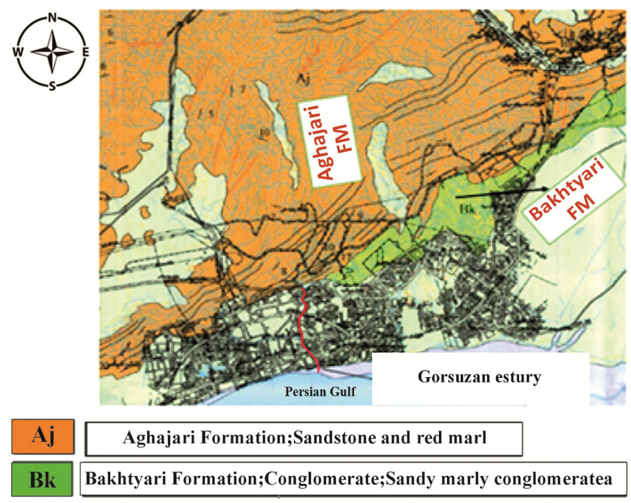

Fig. 2 — Summary of geological map - 1:100000 of Bandar Abbas (Adapted from geological map of Bandar Abbas 1:250000)[23]

Table 1 — Statistical relationships based on Folk[29] method for determining statistical parameters of Gorsuzan estuary sediments

Parameter	Mathematical equation
Mean	$MZ = \frac{\phi 84 + \phi 50 + \phi 16}{3}$
Sorting	$\sigma = \frac{\varphi 84 - \varphi 16}{4} + \frac{\varphi 95 - \varphi 5}{6.6}$
Skewedness	$\text{sk} = \frac{\varphi 84 + \varphi 16 - 2\varphi 50}{2(\varphi 84 - \varphi 16)} + \frac{\varphi 5 + \varphi 95 - 2\varphi 50}{2(\varphi 95 - \varphi 5)}$
Kurtosis	$k = \frac{\varphi 95 - \varphi 5}{2.44(\varphi 75 - \varphi 25)}$

Fig. 3 — Four views of the Gorsuzan estuary: a) Upstream of the estuary or the beginning of the Gorsuzan estuary, looking north; b) View of the middle part of the Gorsuzan estuary, looking south; c) End of the Gorsuzan estuary, the confluence of the estuary with the water of the Persian Gulf, looking south; and d) Sewer inlet to the end of Gorsuzan estuary, looking east

Results and Discussion

Sedimentology

Sediment particle size is a key parameter in analysing destructive sediments and their associated environment. The distribution of sand, silt, and clay ratios provides valuable insights into the environmental conditions of estuarine bays[11,20]. In the Gorsuzan estuary, the largest sediment fractions are sand, gravel, and mud (Fig. 4). Stations S1 and S2, located upstream, show less sand compared to downstream stations S7 and S8, suggesting the beach's role in increasing sand at the estuary mouth. Folk's triangular method[28] was used to classify sediments, which include sandy gravel (sG), gravelly muddy sand (gmS), gravelly sand (gS), sand with a little gravel (gS), and muddy sand (mS). Most sediments fall into the sand, gravelly sand, and muddy sand categories. The texture of Gorsuzan estuary sediments is similar to that of the Petrochemical and Jafari deposits from the Persian Gulf estuaries in Khuzestan province[31]. The particle-size distribution indicates that all studied samples contain coarse (gravel), medium (sand), and fine (silt and clay) particles, with sand being dominant across all stations. Furthermore, the average particle size decreases from upstream to downstream, primarily due to flow hydraulics. In the quantitative description of sediment texture, parameters such as mean, median, smoothness, skewness, tension, sphericity, and roundness are used[11,32]. Various definitions have been provided for each parameter. The mean represents the average particle size in sediment[11,28]. The median is the middle point in the particle size distribution, with 50 % of the samples smaller and 50 % larger[28,32,33]. Cohesiveness is the standard deviation of particle distribution and reflects the dispersion and proximity of the constituent particles[11,28]. The degree of dissolution in sediments depends on four key parameters: particle size range, deposit type, flow characteristics, and sediment supply rate[11,28,32,33]. All these characteristics were calculated using Folk's equations[28]. Table 2 presents the statistical characteristics and textural description of Gorsuzan estuary sediments. These findings show that from station 1 upstream (land) to station 8 downstream (sea), these characteristics improve with slight fluctuations, and the studied sediments become more uniform. In some stations and parameters, this uniformity is not observed, likely due to the entry of construction and human waste into the estuary.

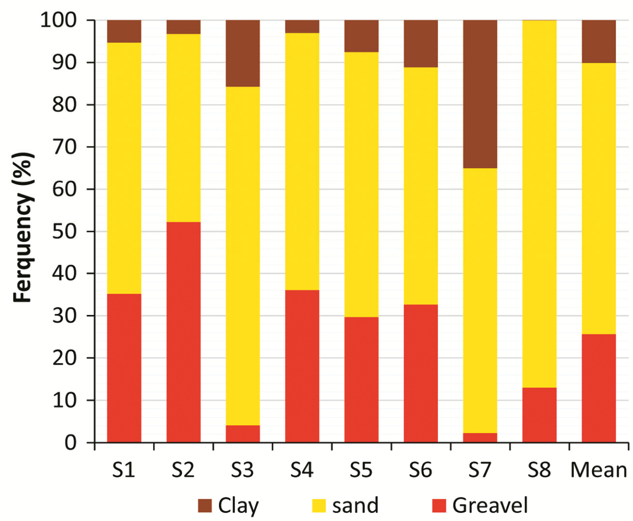

Fig. 4 — Size frequency of sediment particles in sampling stations

In the study of the physical sedimentology of coarse- and medium-grained deposits, roundness and sphericity are very important[35,36]. The roundness and sphericity of the gravel and sand samples from the Gorsuzan estuary deposits, based on the classifications presented by Tucker[25] and Folk[28] are shown in Table 2. Based on these data, it is clear that the sphericity of the studied sediments varies from low to high (Fig. 5). On the other hand, the degree of roundness also fluctuates from semi-angled to semi-rounded grains of sand (Fig. 6 and Table 3). The

Table 2 — Quantitative descriptive statistical and textural characteristics of surface sediment samples from the Gorsuzan estuary

Station	Sorting		Skewedness		Kurtosis		Mean	Mod
	Quantitative	Qualitative	Quantitative	Qualitative	Quantitative	Qualitative	ϕ́	ϕ́
1	0.9	Moderate	0.1 – 0.3	Very fine skewed	1 – 3.5	Very leptokurtic	1.3	1.5
2	0.6	Moderate	>0.1	Very fine skewed	>3	Very leptokurtic	0.2	-1.04
3	1.6	Poorly	-0.1 – -0.3	Coarse skewed	0.9	Platykurtic	2.6	2.5
4	0.5	Well	>1	Very fine skewed	>3	Very leptokurtic	-0.05	-1.2
5	1	Moderate	0.1 – -0.3	Symmetrical	1.9	Very leptokurtic	1.4	0.59
6	0.9	Moderate	0.1 – 0.3	fine skewed	2.7	Very leptokurtic	1.3	0.4
7	2.2	Very porly	-0.1 – -0.3	Coarse skewed	0.9	Platykurtic	3.5	3.4
8	0.8	Moderate	0.1 – 3	Very fine skewed	>3	Very leptokurtic	1	0.4

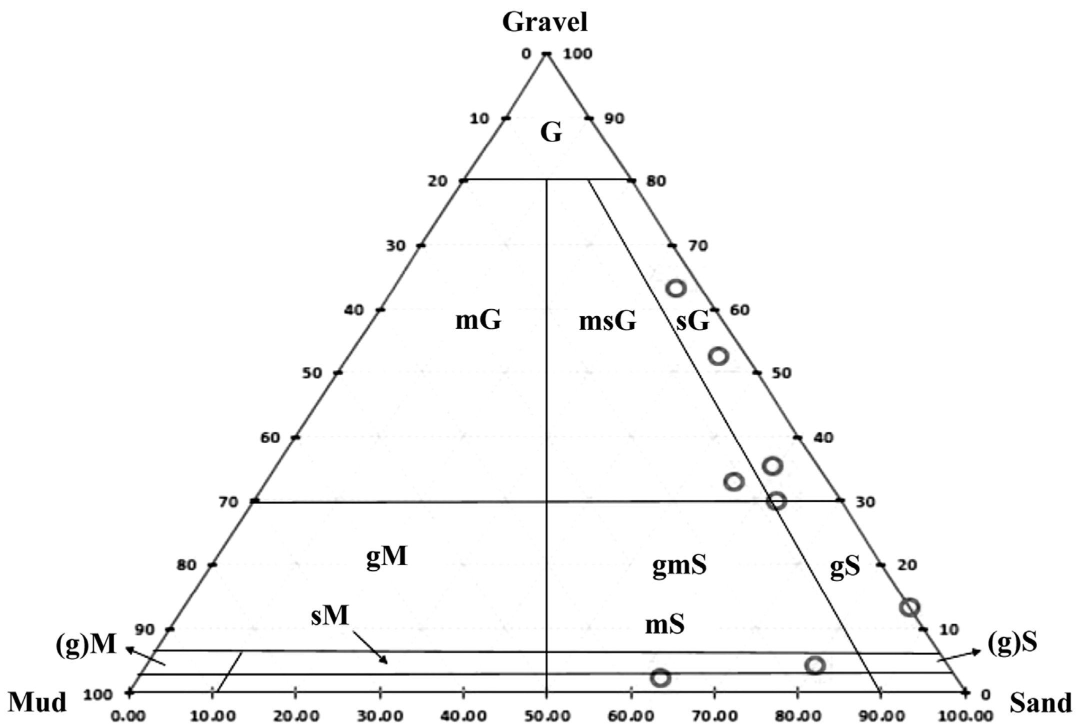

Fig. 5 — Classification of sediments based on the size of the sediment constituent particles[28]

Fig. 6 — Macroscopic images of gravel samples in stations 1, 2, 4, 6 and 8

amount of both mentioned characteristics improves from the land to the coast. The effects of marine processes, such as tides, on the improvement of these two sediment characteristics are evident downstream of the Gorsuzan estuary. On the other hand, this diversity and wide range are largely affected by the types of grains and the unnatural factors around this estuary. Having analysed the sedimentological characteristics of the Gorsuzan estuary, the focus now shifts to the petrographic features of the sediments, which provide further insight into their composition and origin.

Petrography

Granulation tests on 10 samples show that most of the studied sediments are sand; and these sediments are accompanied by a little gravel (sand and rubble) and a small amount of mud (silt and clay). Based on

Table 3 — Description and classification of sphericity and roundness characteristics of sand and gravel grains from Gorsuzan estuary sediments

Station	Gravel		Sand	
	Sphericity	**Roundness**	**Sphericity**	**Roundness**
1	poorly	sub-angular	poorly	sub-angular
2	poorly	sub-angular	poorly	sub-angular
4	poorly	sub-angular	poorly	angular
6	well	sub-angular	poorly	sub-angular
8	well	semi-rounded	poorly	semi-rounded

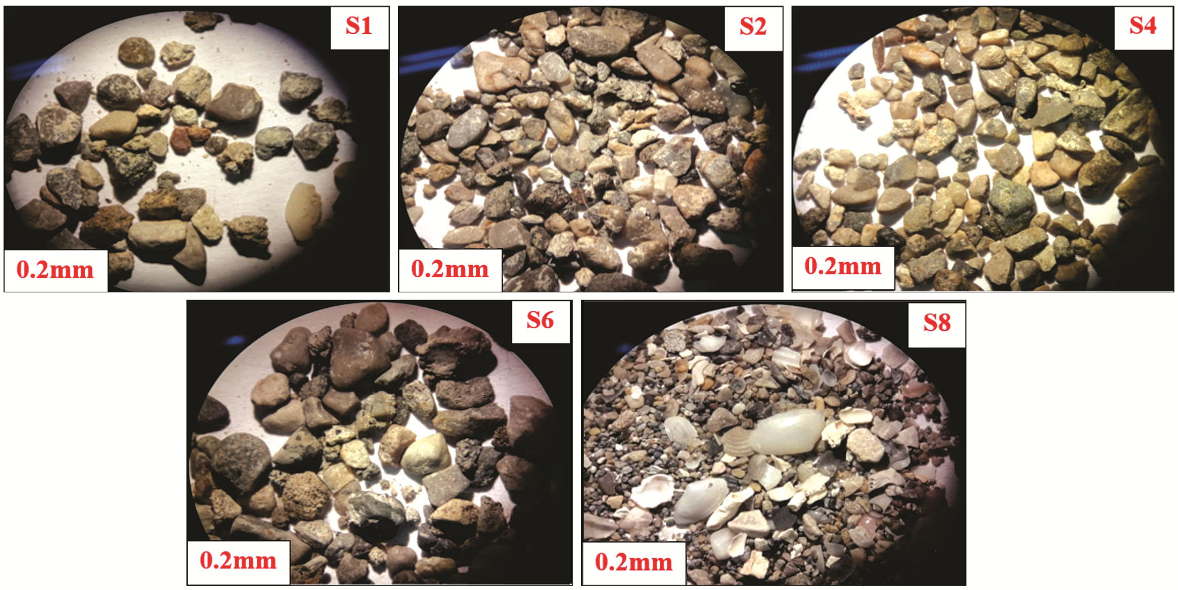

Fig. 7 — Macroscopic images of sand samples in stations 1, 2, 4, 6 and 8

this, the lithology and mineralogy of Gorsuzan estuary sediments are described in three categories: coarse-grained, medium-grained, and fine-grained.

Coarse-grained sediments

These grains range from gravel to gravel (between 2 and 6 mm) and are concentrated in the upper and middle parts of the estuary affected by river processes, waves and sediments. In addition, man-made gravels (bricks, concrete, etc.) were also present in the sediments of the Gorsuzan estuary, which are out of the scope of this article. The identified gravels (Fig. 6) are of three types, including limestone mud microfacies, bioclastic wackestone microfacies, and limestone sandstone petrofacies. These microfacies and petrofacies, with generally calcite-rich mineralogy, include small amounts of dolomite, quartz, hematite and dark minerals. The origin of all three formations is Aghajari (Middle Miocene – Middle Pliocene). The calcareous sandstone of this formation on the southern edge of the Bandar Abbas anticline is loose and detached and is easily affected by weathering, erosion and alteration. Bivalves and gastropods are also seen in these gravels (Fig. 7).

Medium-grained sediments

The highest concentration of these grains is in the middle and lower parts of the estuary, which is under the dominant influence of currents and waves. The lithological and mineralogical composition of the studied sands (Fig. 8) is completely similar to coarse-grained sediments, *i.e.*, gravel. In the two calcareous microfacies present in these sediments, there are types of foraminifera and bivalves related to Aghajari Formation. Quartz grains are monocrystalline with direct quenching. Bivalve fragments and modern gastropods are also seen in these grains.

Fine-grained sediments

Due to the effect of waves and sediments in the Gorsuzan estuary, the amount of these particles is very low, and the amount of silt and clay is very small. These particles are generally present in the upper and middle parts of the estuary. X-ray

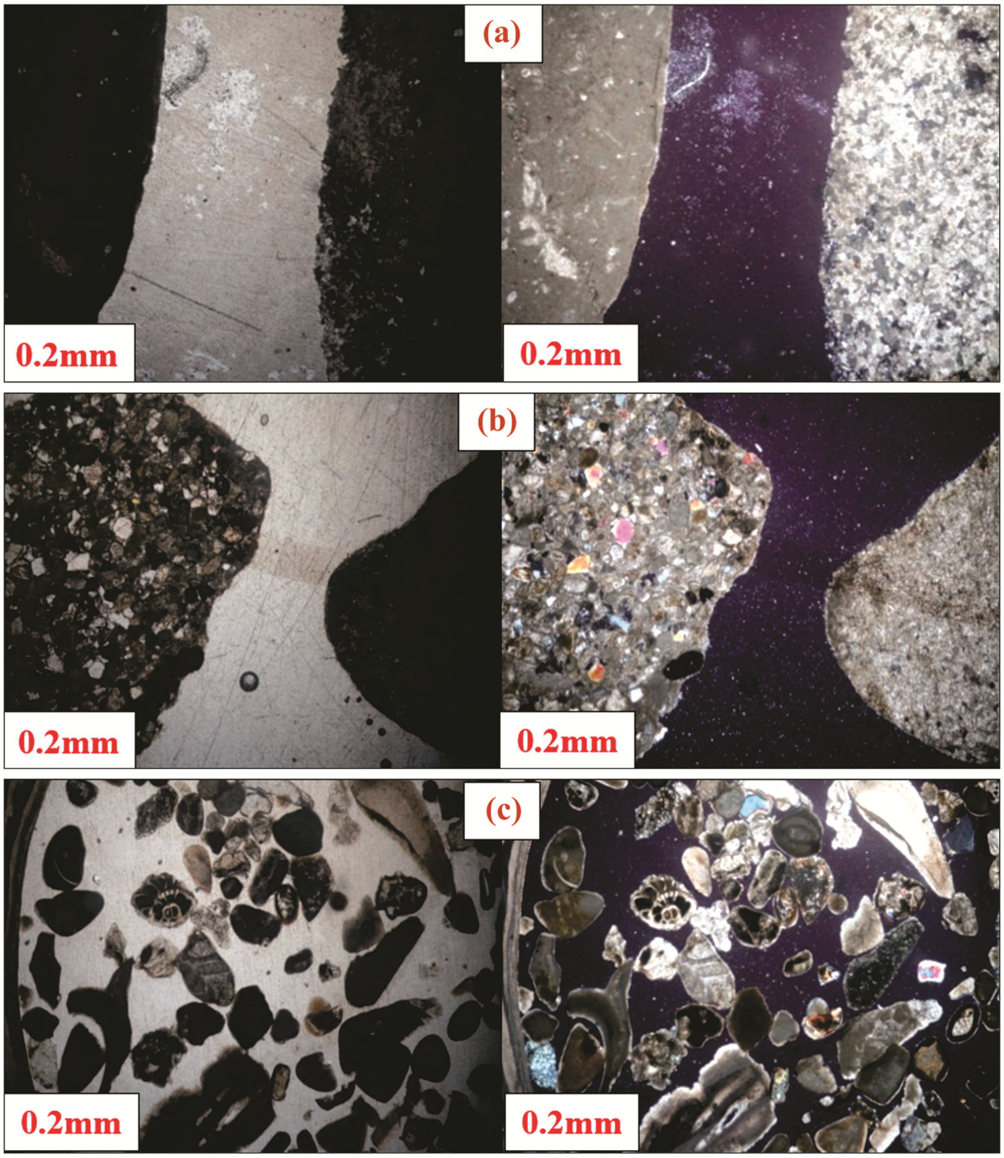

Fig. 8 — a) Calcareous marly microfacies; b) Calcareous sandstone petrofacies; and c) Bioclastic wackestone (natural and polarised light)

Diffraction (XRD) diagrams of 5 of them are presented in Figure 9. Based on this, in addition to the main mineral of these deposits, which is calcite, a small percentage of dolomite and quartz, and a small percentage of albite, anorthite, orthoclase, muscovite and chlorite are present in the composition of fine-grained sediments of the Gorsuzan estuary. This combination, along with the nature of the studied coarse- and medium-grained sediments was examined and is consistent with their origin, *i.e.*, the deposits of the Aghajari Formation. Calcite and detrital silicate minerals are the result of erosion of deposits of this formation, especially calcareous marls. The present dolomite and chlorite are in situ, and among them, chlorite is an indicator of water environments, especially at shallow depths[36]. Part of calcite of biological and biochemical origin, dark minerals, and feldspar and quartz minerals are of in situ type according to the peak points in these diagrams and the complete shapes in microscopic sections. This mineralogical composition is similar to that of the Persian Gulf coast[37-39].

Heavy minerals

These minerals, with a specific weight of more than 2.85 grams per cubic centimetre, have been widely used in identifying the origin of sediments[40] and based on their magnetic properties, they are

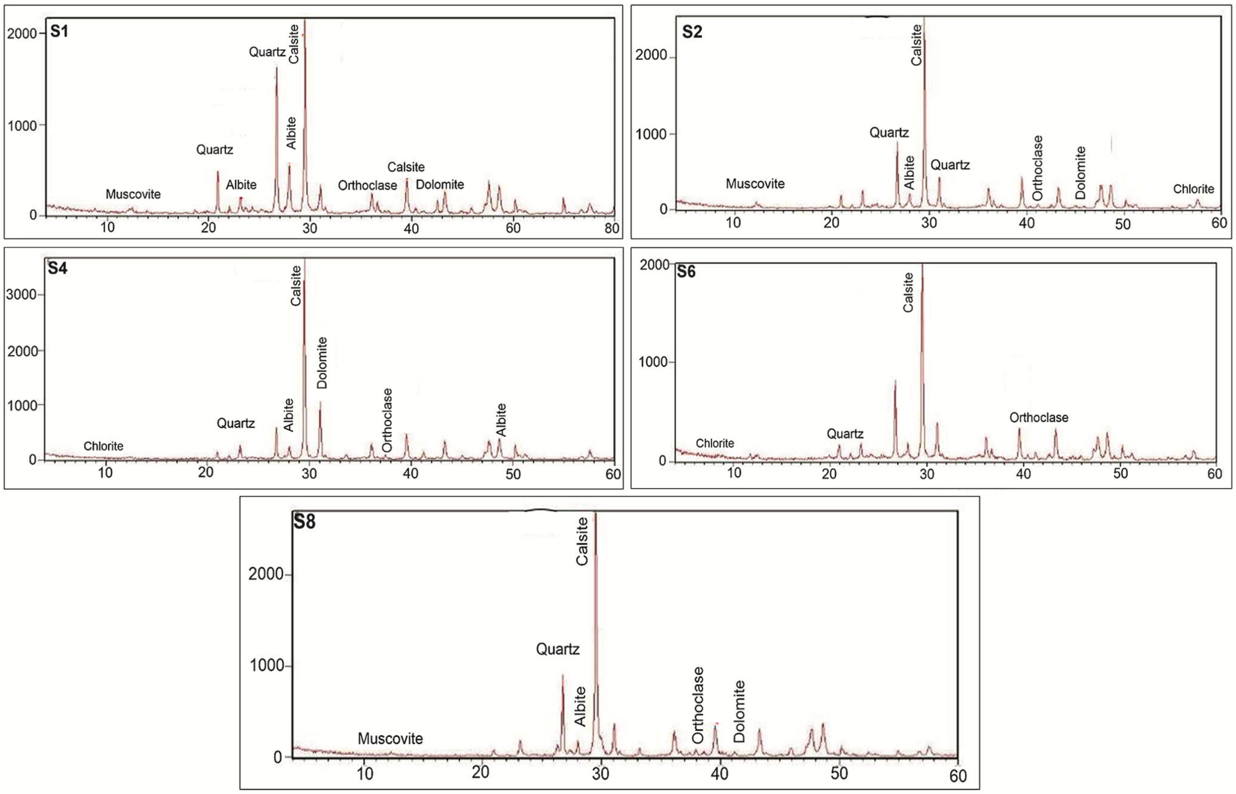

Fig. 9 — XRD patterns of fine-grained sediment samples collected from the Gorsuzan estuary, showing mineralogical composition

divided into three groups: strong, medium and weak[40-41] and are divided into transparent and opaque groups based on transparency. In all the samples collected from the upper, middle and lower parts of the Gorsuzan estuary, three heavy minerals, oligiso, garnet and zircon were identified (Fig. 10). Igneous and metamorphic rocks, and the Hormoz series, are the main origin of these heavy minerals. Previously, in a study by Gholamdokht Bandari *et al.*[37] on the deposits on the coast of Hormoz Island, the origin of these heavy minerals on the Persian Gulf coast was identified as the Hormoz series deposits. Building upon the petrographic analysis, the geochemical composition of the sediments is examined to better understand the environmental and geological processes influencing the estuary.

Geochemistry

The geochemical data of detrital sediments provide very important information from the point of view of sedimentology and environmental geology[42]. The chemical composition of sediments and detrital deposits is the final product of various geological factors such as tectonic location, source rock composition, weathering intensity, and textural and

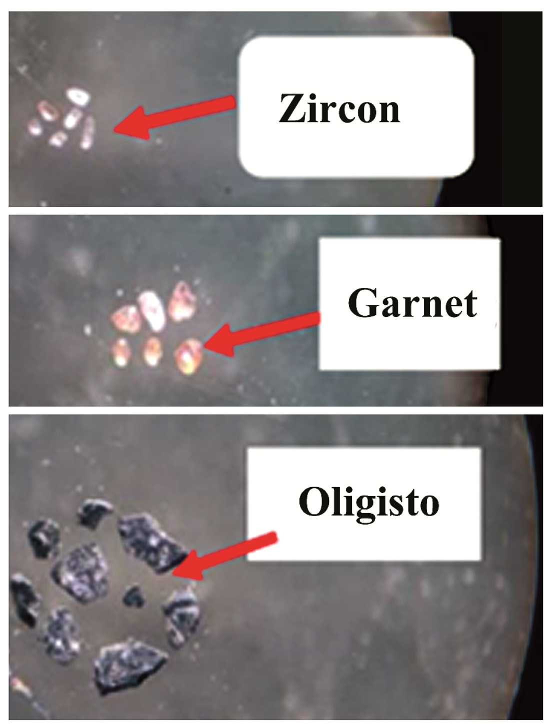

Fig. 10 — Identification of three heavy minerals (oligisto, garnet, and zircon) in sediment samples from the Gorsuzan estuary, Bandar Abbas, using polarised light microscopy

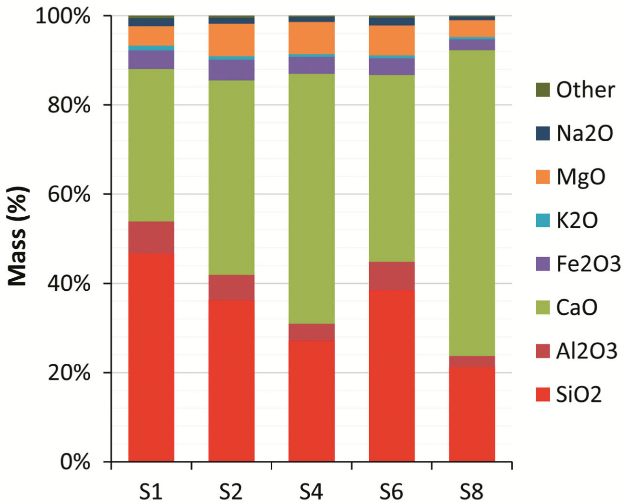

Fig. 11 — Relative abundance of the main oxides measured in surface sediments from the Gorsuzan estuary

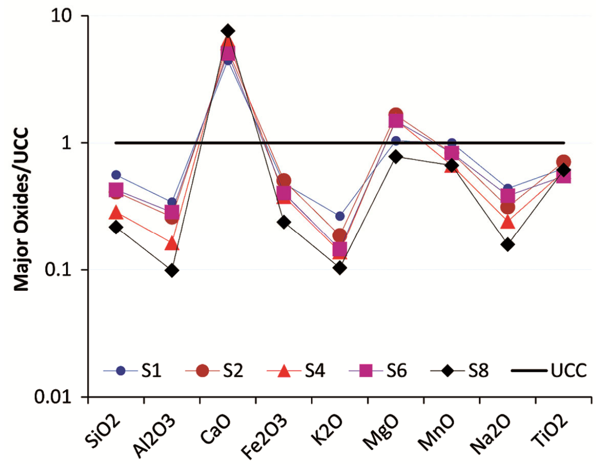

Fig. 12 — Normalisation diagram of major oxides in Gorsuzan estuary sediments compared to the average composition of the Upper Continental Crust (UCC)

mineralogical maturity during transportation and deposition[43,44]. The geochemistry of minor elements in detrital sediments, such as the surface deposits of the plain, is influenced by factors including source rock, watershed weathering, melting, and processes during transportation, deposition, and post-deposition reactions. Therefore, studying the geochemistry of these elements can help reveal the conditions of deposition and weathering of these deposits. Figure 11 shows the concentration of major and minor elements in the Gorsuzan estuary sediments. The highest concentrations of oxides in estuarine deposits belong to silicon and calcium oxide. Examining the change process of oxides (Fig. 11) from the upstream stations towards the mouth of the estuary and the sea shows a decrease in the amount of silica oxide and an increase in calcium oxide, which is related to marine deposits. The main concentration of silicon oxide in the studied deposits is directly related to the mineral quartz, and the concentration of calcium oxide is related to the mineral calcite and dolomite. The presence of TiO_2 oxide is related to the presence of phyllosilicate minerals, especially illite[44] and the presence of aluminium oxide and iron is related to clay minerals and feldspars. The concentration of Mg oxide is related to the presence of dolomite mineral in the deposits; and muscovite and chlorite clay minerals have magnesium in their structures. The concentration of K_2O oxide also indicates the presence of potassium phases in deposits such as muscovite[46]. To check the extent of changes in the main oxides relative to the average of the upper continental crust, the normalisation graph of the studied data is presented. Examining the process of changes of oxides in the sediments of the Gorsuzan estuary shows that enrichment is observed only in Ca and Mg oxides, and other oxides show depletion compared to the average of the upper crust. The highest depletion is in Al_2O_3, K_2O, SiO_2, Fe_2O_3, and TiO_2 oxides. The enrichment of CaO in the samples indicates the presence of calcite as the main mineral phase of the studied deposits (Fig. 12). The depletion of Na_2O oxide is related to the high mobility of this element during chemical weathering, diagenesis and secondary alteration processes[46,47]. MgO enrichment is also due to the presence of clay minerals[45], such as chlorite and dolomite, which are also present in the mineral phase of the Gorsuzan estuary deposits. The depletion in SiO_2, Al_2O_3, Fe_2O_3, and TiO_2 oxides indicates a low weathering rate in the studied deposits or proximity to the origin of these deposits[46]. Weather affects the weathering rate of the source area, hence the amount of weathering can be determined by using the composition of oxides. The intensity of chemical weathering of source rocks is mainly controlled by source rock composition, weathering duration, weather conditions and tectonic uplift rate of the source area[44,48]. Suttner & Dutt[49] presented a graph of the percentage of SiO_2 against the total percentage of Al_2O_3+K_2O+Na_2O to determine the climatic conditions during the deposition of clastic rocks (Fig. 13). The plot of the studied data on this diagram shows semi-arid weather conditions with low-to-medium chemical treatment. Considering the Persian Gulf's location in a dry climate region and its

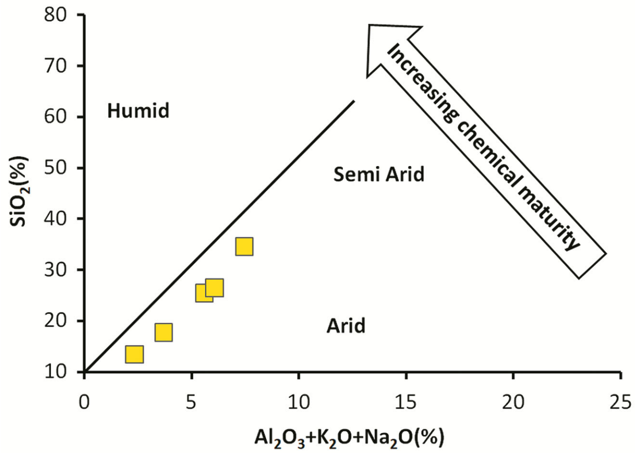

Fig. 13 — The graph of percentage of SiO_2 against the total percentage of $Al_2O_3+K_2O+Na_2O$ by Suttner & Dutta[49]

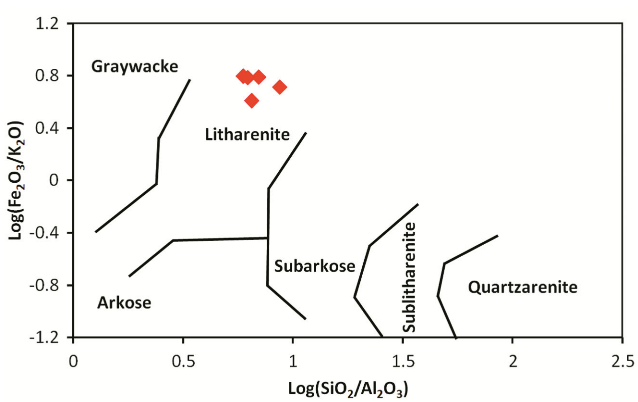

Fig. 14 — Herron[54] lithological composition diagram

surroundings, this result is confirmed[49]. Also, according to global climate change during the Holocene, in the middle Holocene (about 5500 years ago), arid and semi-arid weather conditions prevailed in the studied area, and sabkhas expanded along the coasts[12]. This issue is based on the results of Zarezadeh[52] in the sediments of Bandar Abbas beach and Jokar *et al.*[51] in the sediments of the southwest of Iran. The chemical composition of sediments is also affected by factors such as source rock[44,45]. The tectonic position, the sedimentary basin, and the source area are the main factors in controlling the composition of debris sediments[53]. To determine the lithological composition of the studied samples, Herron's diagram[54] was employed. The results indicate that the Gorsuzan estuary deposits fall within the litharenite field (Fig. 14). Similar findings have been reported by Zarezadeh[52] for the beach sediments of Bandar Abbas and by Jokar *et al.*[51] for the Quaternary sediments of southwestern Iran. This characteristic is closely related to the lithology and sediment supply derived from the upstream Bakhtiari and Aghajari Formations. Furthermore, the litharenitic nature of these sediments suggests that they have not reached a high degree of chemical maturity and therefore preserve valuable geochemical signatures inherited from their source rocks[51]. Overall, the integrated sedimentological, petrographic, and geochemical investigations provide a comprehensive understanding of the depositional environment and sediment provenance of the Gorsuzan estuary.

Conclusion

Gorsuzan estuary in the centre of Bandar Abbas city is a place of accumulation of natural and man-made sediments transported and deposited by seasonal floods. Sedimentological investigations of Gorsuzan estuary deposits show three main types of sediments, including gravel, sand, silt, and clay, and the average superiority of these sediments in all stations is sand. Gorsuzan estuary sediments are classified as gravel, sand, gravelly sand, clay-gravel sand, and sand with low gravel. The sphericity of gravel particles in the mentioned deposits changes from low to high. The circulation also fluctuates from semi-rounded to rounded. The degree of sphericity and circulation of sediments improves from the upstream (land) to the downstream (sea) side. The petrographic and mineralogical studies show that the deposits of calcareous sandstone and limestone (two microfacies of limestone mudstone and bioclastic wackestone) are the main sources of these sediments. In addition to the fossil fragments of the current era, it is important to mention the special in situ minerals of shallow-water sedimentary environments. The heavy minerals found in these deposits confirm that the Hormuz series (Late Precambrian-Early Cambrian) is the bedrock of the folded Zagros and the main source of the components of these sediments, which have endured several sedimentary cycles. In addition, the textural characteristics of these sediments are highly influential on their geochemical behaviour, with an emphasis on environmental evaluations. Geochemical investigations indicate a high concentration of calcium and silicon oxides in these deposits, which are directly related to their mineral phases. Investigating the source rock of the estuary sediments indicates a litharenite source rock in a semi-arid climate with low textural maturity, suggesting active tectonics in the Zagros upstream of the estuary.

Funding

This research received no external funding.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author Contribution

PR: Conceptualization, methodology, supervision, validation; SAJ: Software, data curation, writing-original draft preparation; MMN: Software, data curation; SR: Writing- reviewing and editing; MK: Writing- original draft preparation; and SD: Methodology.

References

1 Pritchard D W, What is an estuary? Physical viewpoint, In: *Estuaries*, edited by Lauff G D, (American Association for the Advancement of Science, Washington, DC), 1967, pp. 3-5. http://hdl.handle.net/1969.3/24383

2 Seibold E & Berger W, *The sea floor: An introduction to marine geology*, (Springer), 2017, pp. 201-214.

3 Szary W, *Principles of Sedimentation*, (Amazon Digital Services LLC - KDP Print US), 2019, pp. 184.

4 ness Media), 2012, pp. 272.

5 Gill D & MeThrush S, Hewitt J, Pilditch C & Norkko A, *Ecology of coastal marine sediments: form, function, and change in the anthropocene*, (Oxford University Press), 2021, pp. 458.

6 Braat L, *Morphodynamics and Sedimentology of Estuaries with Sand and Mud*, Doctoral dissertation, University Utrecht, 2019, pp. 26-38.

7 Isla F I & Bujalesky G G, Coastal geology and morphology of Patagonia and the Fuegian Archipelago, *Dev Quat Sci*, 11 (2008) 227-239. https://doi.org/10.1016/S1571-0866(07)10010-5

8 Wolanski E & McLusky D S (Eds), *Treatise on estuarine and coastal science*, (Academic Press), 2011, pp. 25-37

9 Gao S, Energy partitioning in global marine sedimentation: tidal, geothermal, and solar radiation contributions, *Geo-Mar Lett*, 44 (2) (2024) 1-7. https://doi.org/10.1007/s00367-024-00769-2

10 Mishra P K, Shah P, Yadav A, Sunil Kumar, Ambili V, *et al*., Geochemical and sedimentological characteristics of surface sediments from Ashtamudi Estuary, Southern India: implications for provenance and modern sedimentary dynamics, *Environ Earth Sci*, 78 (2019) 1-11. https://doi.org/10.1007/s12665-019-8376-z

11 Abad M, Arroyo M, Ruiz F, González-Regalado M L, Rodríguez Vidal J, *et al*., Miocene-Holocene paleo-environmental changes in the Tinto River estuary (SW Spain) evidenced by sedimentology, geochemistry and fauna, *Carnets Geol*, 22 (20) (2022) 847-855. https://doi.org/10.2110/carnets.2022.2219

12 Cojan I & Renard M, *Sedimentology*, (CRC Press), 2020, pp. 492.

13 Jones M, Morteza J, Lora S, Vanessa H, Hajar A, *et al*., Mid Holocene environmental and climatic change in Iran, In: *Ancient Iran and its Neighbours: Local Developments and Long-Range Interactions in the Fourth Millennium BC*, edited by Petrie C A, (Oxbow Books, Oxford, United Kingdom), 2013, pp. 25-34.

14 Wu W, *Sediment transport dynamics*, (CRC Press), 2023, pp. 562.

15 Hedayatzadeh F, Ildoromi A, Hassanzadeh N & Bahramifar N, A systematic and meta-analysis review of heavy metals pollution, toxicity potential, ecological and biological risk in surface sediments of Mahshahr and Imam Khomeini port estuaries (Coastal areas of Khuzestan province), *J Mar Biol*, 12 (2) (2020) 55-80. http://jmb.ahvaz.iau.ir/article-1-823-fa.html

16 Mori Bazofti H, Safahieh A, Nabavi S M B & Ghanemi K, The evaluation of mercury contamination in the sediments of intertidal creeks of Mahshahr, *J Nat Environ*, 70 (3) (2017) 699-708. https://doi.org/10.22059/jne.2017.207693.1163

17 Gharibreza M, Sedimentary facies and origin of carbonate deposits of the Reeg estuary (northern of the Persian Gulf), *Sci Semiann J Sed Facies*, 8 (2) (2016) 216-235. https://doi.org/10.22067/sed.facies.v8i2.35764

18 Behbahani R, Lak R, Chanani N & Hosseinyar G, Organic Geochemistry of Khowr-e-Mussa's Sediments and its Adjacent Marine Areas, Northwest of the Persian Gulf, *J Geosci*, 23 (92) (2014) 55-67. https://doi.org/10./2271/gsj.2014.43652

19 RanjbariKeloi M & Rahbani, Investigation of Tiab estuary sedimentation, In: *4th International conference on environmental engineering with a focus on sustainable development, Tehran*, 2017.

20 Selim S S & Baset A A, Sedimentological analysis and reservoir characterisation of an estuarine bar: An example from the El-Basant Gas field, Nile Delta, Egypt, *J Nat Gas Sci Eng*, 84 (2020) p. 103548. https://doi.org/10.1016/j.jngse.2020.103548

21 Michel G, Le B S, Lesourd S & Lafite R, Morpho-sedimentological and dynamic patterns in a ria type estuary: the Belon estuary (South Brittany, France), *J Maps*, 17 (2) (2021) 389-400. https://doi.org/10.1080/17445647.2021.1925170

22 Bulbul M, Ankit Y, Basu S & Anoop A, Characterisation of sedimentary organic matter and depositional processes in the Mandovi estuary, western India: an integrated lipid biomarker, sedimentological and stable isotope approach, *Appl Geochem*, 131 (2021) p. 105041. https://doi.org/10.1016/j.apgeochem.2021.105041

23 Hamzeh M, *Environmental study of the estuaries of Bandar Abbas city*, Master's thesis, Field of Environmental Management, Hormozgan University, 2008, pp. 145.

24 Fakhari M, *Geological map 1:250000 of Bandar Abbas*, Iran National Oil Company, 1995, p. 1.

25 Rouhanian H, *Preliminary study of the estuaries of Hormozgan province*, Department of Fisheries of Hormozgan province, 1981.

26 Tucker M E & Fielding C R, Sedimentary rocks in the field, *Sediment Geol*, 109 (1) (1997) p. 207.

27 Arzani N, *Sedimentology Laboratory*, Payam Noor University Publications, 1997, pp. 129 (in Persian).

28 Khodabakhsh S & Sahraro N, *Sedimentology Experiments*, Bo Ali Sina University Press, 2014, pp. 119.

29 Folk R L, *Petrology of sedimentary rocks*, (Hemphill publishing company), 1980, pp. 605.

30 Dunham R J, Classification of carbonate rocks according to depositional texture, In: *Classification of Carbonate Rocks - A Symposium*, edited by Ham W E, (The American Association of Petroleum Geologists), 1962, pp. 108-121.
31 Pettijohn F J, *Sedimentary rocks*, 3rd edn, (Harper & Row, New York), 1975, pp. 628.
32 Ghazanfarishabankareh M, *Coastal sediments zoning of petrochemical and Jafari Creeks based on the effective factors on the accumulation and transfer of heavy metals*, Master's thesis in Environmental Geology, Khorramshahr University of Marine Sciences and Technology, 2016, pp. 150.
33 Allen J R L, *Principles of Physical Sedimentology*, (Springer Science & Busirriam D F (Eds), *Geomathematical and Petrophysical Studies in Sedimentology: An International Symposium*, 1st edn, (Pergamon), 2015, pp. 267.
34 Scholle P A, *A color illustrated guide to constituents, textures, cements and porosities of sandstones and associated rocks*, (American Association of Petroleum Geologists (AAPG)), 1979, pp. 215.
35 Cepeda H S G, da Silva Junior J B C, Nogueira A C R, Gomez-Neita J S, do Espírito Santo Quadros M L, *et al*., West Gondwana paleoenvironmental and diagenetic history of Cambrian alluvial deposits in the Jaibaras Basin, Northern Brazil, *J South Am Earth Sci*, 146 (2024) p. 105068. https://doi.org/10.1016/j.jsames.2024.105068
36 Okrusch M & Frimmel H E, Sediments and sedimentary rocks, In: *Mineralogy: An Introduction to Minerals, Rocks, and Mineral Deposits*, (Springer Berlin, Heidelberg), 2020, pp. 417-452. https://doi.org/10.1007/978-3-662-57316-7_25
37 Gholamdokht Bandari M, Rezaie P & Ghorbani M, Sedimentary and geochemical characteristics of coastal deposits in Hormoz Island in the south of Iran, *J Stratigr Sedimentol Res*, 36 (2) (2020) 105–124. https://doi.org/10.22108/jssr.2020.118294.1111
38 Zarehzadeh R & Rezaee P, Geochemical and mineralogical study of calcareous marine terraces of the Quaternary in Qeshm Island, *J Stratigr Sedimentol Res*, 27 (3) (2011) 121–138. https://dorl.net/dor/20.1001.1.20087888.1390.27.3.7.7
39 Kaveh F A, Mohammadi A & Lak R, Makran coastal plain deposits (SE Iran), a potential source of aeolian sediments; insights from sedimentology and geochemistry, In: *2nd International Conference on Oceanography for West Asia*, Tehran, Iran, 2020, pp. 98–101.
40 Sergio A (Ed), *Heavy Minerals: Methods & Case Histories*, (MDPI Books), 2021, pp. 312.
41 Andò S, Gravimetric separation of heavy minerals in sediments and rocks, *Minerals*, 10 (3) (2020) Art No 273. https://doi.org/10.3390/min10030273
42 Rollinson H R, Rollinson H & Pease V, *Using geochemical data: to understand geological processes*, (Cambridge Univ Press), 2021, pp. 159.
43 Babu S S, Rao V P, Satyasree N, Ramana R V, Mohan M R, *et al.*, Mineralogy and geochemistry of the sediments in rivers along the east coast of India: Inferences on weathering and provenance, *J Earth Syst Sci*, 130 (2021) 1–24. https://doi.org/10.1007/s12040-020-01551-5
44 Rezaee P, Khanehbad M, Ezatifar M, Jooybari S A & Hosseini K, Facies analysis, sedimentation conditions and geochemistry of clastic deposits of Ashin formation (Late Ladinian–Early Carnian), Northeast of Nain, East of Central Iran, *Iran J Earth Sci*, 14 (3) (2020) 221–240. https://doi.org/10.30495/ijes.2021.685396
45 Fedo C M & Babechuk M G, Petrogenesis of siliciclastic sediments and sedimentary rocks explored in three-dimensional Al2O3–CaO*+ Na2O–K2O–FeO+ MgO (A–CN–K–FM) compositional space, *Can J Earth Sci*, 60 (7) (2022) 818–838. https://doi.org/10.1139/cjes-2022-0051
46 Babechuk M G & Fedo C M, Analysis of chemical weathering trends across three compositional dimensions: applications to modern and ancient mafic-rock weathering profiles, *Can J Earth Sci*, 60 (7) (2022) 839–864. https://doi.org/10.1139/cjes-2022-0053
47 Jimoh M T, Bolarinwa A T & To K, Mobility and redistribution of major elements in weathered profile developed on pegmatite at Kitibi-Iwoye, Southwestern Nigeria, *Malaysian J Geosci*, 4 (2) (2020) 59–64. http://doi.org/10.26480/mjg.02.2020.37.42
48 Malekzadeh M, Hosseini-Barzi M, Sadeghi A & Critelli S, Geochemistry of Asara Shale member of Karaj Formation, Central Alborz, Iran: provenance, source weathering and tectonic setting, *Mar Pet Geol*, 121 (2020) p. 104584. https://doi.org/10.1016/j.marpetgeo.2020.104584
49 Suttner L J & Dutta P K, Alluvial sandstone composition and paleoclimate; I, Framework mineralogy, *J Sediment Res*, 56 (3) (1986) 329–345. https://doi.org/10.1306/212F8909-2B24-11D7-8648000102C1865D
50 Purser B H (Ed), *The Persian Gulf: Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea*, (Springer Science & Business Media), 2012, pp. 456.
51 Jokar A, Kohansal Ghadimvand N, Jahani D & Meshal M, Origin and study of geochemical properties of detrital sediments in southwestern Iran, *Quat J Iran*, 7 (3,4) (2022) 872–888. https://doi.org/10.22034/irqua.2022.702436
52 Zarezadeh Z, *Sedimentology, mineralogy and geochemistry of the Persian Gulf mangrove forest deposits, west of Bandarabbas*, Ph.D. Thesis, Hormozgan University, 2017.
53 Wang L, Lyu Q, Li L, Liu J, Luo S, *et al*., Sedimentary characteristics of mixed source fine-grained gravity-flow and its significance for shale oil exploration in a lacustrine depression basin: A case study of the Chang 73 Sub-member of the Triassic Yanchang Formation in Ordos Basin, NW China, *Sediment Geol*, 464 (2024) p. 106629. https://doi.org/10.1016/j.sedgeo.2024.106629
54 Herron M M, Geochemical classification of terrigenous sands and shales from core or log data, *J Sediment Res*, 58 (5) (1988) 820–829. https://doi.org/10.1306/212F8E77-2B24-11D7-8648000102C1865D