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Sedimentological and Geomorphological Classification of Chabahar Coastal Area (Chabahar-Gawater)

Afarin, Mohammad*; Hamzeh, Mohammad Ali; Negarestan, Hossein

Iranian National Institute for Oceanography and Atmospheric Science, Tehran, IR Iran

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Abstract

In the present paper various transects perpendicular to Iranian Makran coasts (Chabahar-Gawater) were studied using satellite image processing, field observations, sandy shore profiling and grain size analysis to evaluate sedimentology and geomorphology of the area. Data revealed that the study area includes exposed rocky shores (52%), sandy shores (40%), and mud flats (8%) sheltered in estuaries. Forming spectacular landforms, coastal cliffs are the most frequent features in the area and have evolved by action of both coastal Makran uplift (1-6 $mm.yr^{-1}$) and wave induced erosion. Due to high tectonic activity and severe longshore drifting, sandy shores are narrow and less developed. The location and direction of backshore sand dunes observed by satellite images suggests that they are developed on top of cliffs and along paleoshorelines as a result of strong southwest monsoon winds. Estuaries formed by sedimentation of seasonal creeks are mostly sheltered by longshore associated sand barriers and spits. In some of estuaries, such as Bahukalat and Tiss, salt marshes are observed in mangrove forests. In general, the overall shape of Makran coastlines is governed by structural pattern of coasts. Other processes shaping coastal features include wind action, water runoff and weathering by physical, chemical or biological agents. Wave action, especially during summer monsoon has a fundamental role in coastal change.

Keywords*: Makran, Sedimentology, Coastal Landforms, Wave Action*

1. Introduction

Coastal areas occur at the interface between three major natural systems including atmosphere, ocean and land surface. Processes operating in all three of these systems are responsible for shaping the coastal zone (encompassing shoreline environments as well as adjacent coastal waters). Interactions among three variable sets of processes makes the coastal zone an extremely dynamic one. The coastal zone is also a zone of transfer of material from the land surface to the ocean system, with sediments eroded by rivers, glaciers, etc., being transported to the beach and nearshore, and ultimately to the ocean floor (Bird, 2011). However, in addition to its geomorphological significance, the coastal zone is particularly important from a human perspective.

A large proportion of the world population is concentrated in coastal areas, including almost all major cities. Man uses coastal areas for fishing, transportation, recreation, waste disposal, cooling and drinking water. It is also potentially a source of energy from tidal and wave power (Davidson-Arnott, 2010). Because of the threats to human life and activities imposed by both environmental impact and natural hazards, there is a strong economic incentive

* *E-mail: afarin.m@inio.ac.ir*

to improve our understanding of processes operating in the coastal area so that we can minimize their effects, and use this knowledge in developing comprehensive coastal management planning.

Investigations on coastal geomorphology have a long historical background. The past thirty years have seen a number of investigations that provide a variety of different perspectives. Many still provide good sources for information and insights on processes and coastal landforms (Carter and Woodroffe, 1994; Komar, 1998; Masselink et al., 2014; Short, 1999; Woodroffe, 2002). Finkl (2004) provided a thorough review of coastal classification in terms of their suitability for amphibious landings. Most of researches dealing with coastal classification in Iran are focused on Caspian Sea coasts (Gandomi et al., 2011; Ghodrati and Nazami, 2012; Kaplin and Selivanov, 1995) as well as Persian Gulf and its islands (Ansari et al., 2014; Nouri et al., 2008).

Coastal Makran offers an excellent opportunity to investigate geomorphological patterns and their elements in the context of convergent margins. Coastal Makran exhibits: (1) high convergence rates (Ellouz-Zimmermann et al., 2007) resulting in highly deformed coasts, composed accreted ridges; and (2) significant coastal erosion in an arid environment which has been controlled by Asian monsoon climate (Uchupi et al., 2002). Therefore, evolution of coastal morphology in the area has been affected by two major forcing processes, including climatic variations (being dominant on shorter geological time scales) and the tectonic evolution (over longer periods of time).

The present investigation deals with the study of coastal geomorphology of Iranian coast of Makran (from Chabahar Bay to Gawater Bay) and affecting processes, using: (1) coastal sedimentology; (2) sandy shore profiling; (3) coastal mapping by satellite image processing and field survey.

2. Material and Methods

2.1. Study area

The 170 km long study coastline (Iran's Oman Sea coasts between Chabahar and Gawater Bays) is the western part of ~1000 km long coastal Makran of Iran and Pakistan, extending from the Strait of Hormoz to near Karachi in Pakistan. Coastal Makran consists of series of accretionary prism resulted from the northward subduction of the Arabian Sea beneath the Iranian and Afghan continental blocks, now accreted to the Eurasian continent (Prins et al., 2000). Subduction (with an eastward increasing rate) started during Late Cretaceous times and fairly continued until present (Reyss et al., 1999) (Fig. 1).

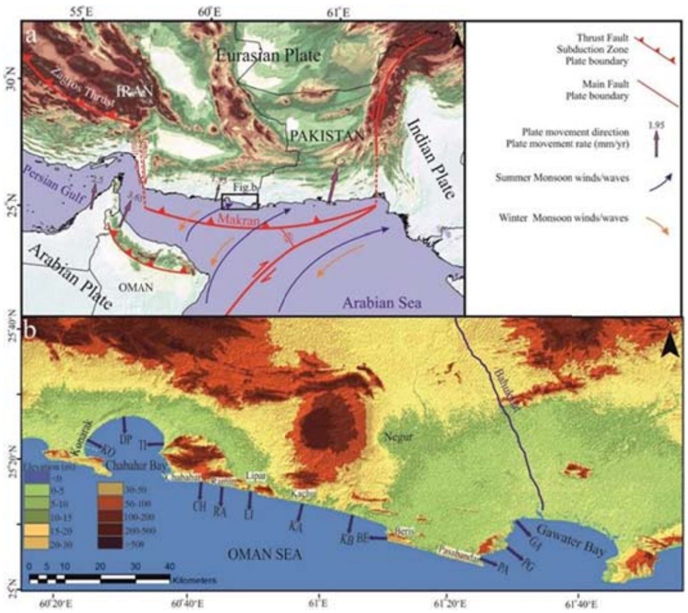

Fig 1: a) Tectonic and climatic setting of Makran in the northern Indian Ocean .b) Shuttle radar topography mission (SRTM) hill shade digital elevation model (DEM) map showing location of transects of sediment sampling in the study area

Coastal Makran is characterized by series of prominent sandstone- conglomerate headlands with narrow sandy shores separated by bays (such as Gurdim, Pozm, Chabahar and Gawater bays). Along the coast, outcrops are mainly sequences of calcareous mudstones (Snead, 1970). Uplifting Plio-Pleistocene mudstone and sandstone highlands show badland topography due to intensive erosion. Holocene episodic uplift of coastal fault blocks has caused coastal uplift rate between 0.1 and 0.6 m/ka along the coast (Prins et al., 2000). The coastline has been prograding since the mid- Holocene owing to both slight uplift and marine and alluvial sedimentation (Reyss et al., 1998).

Makran area corresponds to northern limits of summer Intertropical Convergence Zone (ITCZ). It is believed that during Early to mid-Holocene, due to northward migration of ITCZ, the area received much higher precipitations brought by summer monsoon (Fleitmann et al., 2007). The coastline of Iranian Makran is very hot and humid. Mean temperature in January is 20°C, and the maximum temperature in mid-summer is 40°C. Mean annual rainfall is less than 100 mm, and rainfall variability is extremely high. Tidal range is generally between 2 and 4 m (Saket and Etemad-Shahidi, 2012). Winds and currents are governed with monsoon circulation. The NE monsoon (winter monsoon) with moderate winds begins in October but is mainly peaking up between November and March. The longer and stronger SW monsoon begins in April and is very strong from June to September (Arz et al., 2003). During summer monsoon, the sea is very rough and SW winds and waves have severe effects on coastal processes. Coastal outlines are related to geology and processes of erosion and deposition.

Very low permeable formations of Iranian coastal Makran (marl) are covered by sparse vegetation, causing occurrence of many seasonal drainages flowing into the sea during springtime torrential rains. Bahukalat, is the only perennial long and major river in south-eastern Iran which flows into the Gawater Bay.

2.2. Sediment Sampling and Characterization

In order to evaluate effect of onshore-offshore currents in sedimentology of the coastal area, samples were taken from 12 transects (5-10 km long) perpendicular to the coastline from Chabahar to Gawater Bays (Fig. 1, Table 1). Three sediment sampling sites were chosen along each transect from onshore to offshore. Three samples were also collected from inside the Ramin, Beris and Pasabandar fishing Harbors. Sampling depth varied between zero (beach) to 17 m. The bottom sediments were sampled with a stainless steel Van–Veen grab with a sampling surface of 0.05 m2 and a sediment depth of 10 cm. Three replicate samples were collected from each site and the averaged data were reported as grain size distribution of corresponding sites. Beach samples were collected by a plastic snapper. Sediment sampling took place on February 2010 using research boat of Chabahar Oceanography Center. Samples were then stored in polyethylene bags at −18°C prior to undergoing laboratory analyses.

Subsamples of air-dried sediment samples were homogenized in order to normalize variations in grain size distribution. Wet sieving analysis separated five size fractions: >2 (gravel), 2-0.5 (coarse-very coarse sand), 0.5-0.25 (medium sand), 0.25-0.063 (fine-very fine sand), <0.063 mm (silt+clay). Grain-size of silt and clay fractions measured using FRITSCH laser grain-size analyzer (McCave et al., 1986). Some samples were chosen for replication measurements to confirm the reliability of the grain-size analysis results. Total organic matter (TOM) was determined using the weight of sediment lost in ignition method (Heiri et al., 2001) and %CaCO3 was measured by calcimetry method (Chaney et al., 1982). All above analyses were performed in Chabahar Marine Geology Laboratory of Iranian National Institute for Oceanography and Atmospheric Science (INIOAS).

Table 1: Samples depth and site description of sediment sampling transects along selected coastal area

Transect	Site depth (m below s.l)			Site description
	Site 1	Site 2	Site 3	
KO	0	4.6	10	West of Chabahar Bay, coast of Konarak town
DP	0	4.7	8	Northern coast of Chabahar bay, close to distillation plant
TI	0	3.1	8.2	East of Chabahar Bay, coast of Tiss town
CH	4.3	6.3	12.3	Rocky shore of Chabahar city
RA	6	11	17	Rocky shore of Ramin town
LI	2	7.4	9	Sandy shore close to Lipar estuary
KA	4	10	17	Long Sandy shore of Kachu area
KB	4.5	9	12	Sandy shores between Kachu area and Beris town
BE	4	8	11	Sandy shore of Beris town
PA	1.5	2.7	4.7	Sandy shore of Pasabandar town
PG	4.5	6.5	8	Rocky shore between Pasabandar and Gawater towns
GA	3.2	4.9	6	Sandy shore of Gawater town

2.3. Sandy Shore Profile Survey

A sandy shore profile survey is a topographic and bathymetric survey of a beach and adjacent regions. The present sandy shore profile survey was conducted along KO and DP transects that typically initiate at the dune and extend across the sandy shore to the minimum low tide level using a 5 meter rod and Nouveau device (Delgado and Lloyd, 2004). Distances between two consecutive height measurements were selected 5 meters. Sandy shore profiles were surveyed in July (during summer monsoon) and November (after summer monsoon), 2010.

2.4. Spatial Data Analysis

For map compilation and providing the topographic map of the area, we used the data of Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2), 2011, with a resolution of 1 arc/second (30 meter) (http:// earthexplorer. usgs. gov). These digital elevation data were manually classified for selected elevations and were overlain by several prepared shape files. Satellite image of Landsat 7 was used to visualize coastal features of the study area. The coastal areas were also directly surveyed and photographed. Geographic Information System (GIS) techniques were applied to compile maps and spatial data processing.

3. Results

3.1. Sediment Distribution Patterns

Table 2 shows size characteristics of the samples of stations in transects and Harbors. Based on textural classification of clastic sediments (Folk, 1968), most transect stations along straight coastline were typified as sandy (Fig. 2). Sediments of Chabahar bay were mostly categorized as silty sand (DP and TI transects) and silt (transect KO). The TI transect had considerable gravel and coarse to very coarse sands (Fig. 2). Its grains were derived from physical erosion of rocky shore. Gawater Bay sediments were dominated by silty and muddy sand, while sediments in the calm environment close to Pasabandar Harbor (transect PA) were muddy, sandy mud and silty. Muddy sediments inside Beris and Pasabandar harbors, and sandy silt sediments in Ramin Harbor showed calm environments inside the Harbors.

Table 2: Granulometric data of sediment samples

	Sample	Gravel	Sand					Silt	Clay
			VC	C	M	F	VF		
Transects	KO1	0	3.4	3.3	4.6	7.1	19.8	52.9	8.9
	KO2	0	2.6	2.2	3.2	6.1	11.9	62.2	11.8
	KO3	0	1.4	1.5	1.8	3.1	10.2	46.6	35.4
	DP1	9.7	21.3	11.5	8.9	14.3	16.4	14.8	3.1
	DP2	5	20.1	17.2	10.5	6.7	10.5	25	5
	DP3	0	7.8	11.3	12.9	16.1	21.1	28.4	2.4
	TI1	17.8	20.5	14.7	13.2	9.8	16.3	5.4	2.3
	TI2	15	21.5	17.2	14.8	9.3	13.2	7	2
	TI3	11.2	18.1	18.3	17.4	11.4	9.6	9	5
	CH1	0	0	0.6	2.9	55.5	23.6	16	1.8
	CH2	0	1.6	1	22.9	60	10.2	3.7	0.7
	CH3	2.5	1.5	1.4	4.8	8.8	46.7	31.2	3.3
	RA1	0	0.3	2.3	7.7	39.6	45.3	4.3	0.5
	RA2	0.3	0.2	0.6	1.9	12.8	77.8	5.9	0.5
	RA3	0.2	0.3	0.8	1	11	61.6	21.3	4
	LI1	4.1	6.1	9.8	16	32.4	29.4	1.9	0.2
	LI2	0.1	0.5	1.9	13.9	29.3	49.8	3.9	0.6
	LI3	0	0.2	1.4	5.9	9.8	74.2	6.6	2
	KA1	1.2	7.7	28.1	29.7	8.3	23	1.7	0.4
	KA2	0	0.1	0.3	1.2	2.3	85.3	9	1.8
	KA3	15.2	4.7	5.8	5.8	0.2	35	28	5.5
	KB1	0	0.7	4	19.5	42.8	31.5	1.1	0.5
	KB2	0.1	0.1	0.1	0.2	5.5	74.7	16.9	2.5
	KB3	0	0.1	0	0.4	1.3	87	9.-6	1.7
	BE1	0	0	0.4	40.2	54.9	3.4	0.9	0.4
	BE2	0	0	0.1	0.2	1	92	5.7	0.9
	BE3	0	0	0.2	0.6	0.3	46.2	48	5.5
	PA1	0	0	0.1	0.2	0.7	2.9	65.8	30.1
	PA2	0.3	0	0.1	0.2	0.3	2.9	60.1	35.9
	PA3	0.5	0.3	0.5	0.6	0.4	15.3	46.9	35.4
	PG1	0.1	0	0	0.4	2.2	69.1	24.2	3.9
	PG2	0.1	0.2	6.3	15.9	15	30.8	19.9	11.7
	PG3	17.3	9.3	14.9	31.6	5.1	7.5	9.4	4.9
	GA1	0	0.2	1.1	5.8	49.3	39.7	3.2	0.7
	GA2	0.5	0.1	0.1	0.3	1.9	74.3	18.8	4.1
	GA3	0.2	0.5	1.1	4	5.8	44.7	25.9	17.9
Harbors	RA4	0.2	8	7.9	7.2	5.4	6.9	46.1	18.1
	BE4	0	0.9	0.3	0.3	1.6	7.6	52.2	37
	PA4	0	0	0.1	0.2	0.3	2.8	60.1	35.6

VC: very coarse, C: coarse, M: medium, F: fine, VF: very fine

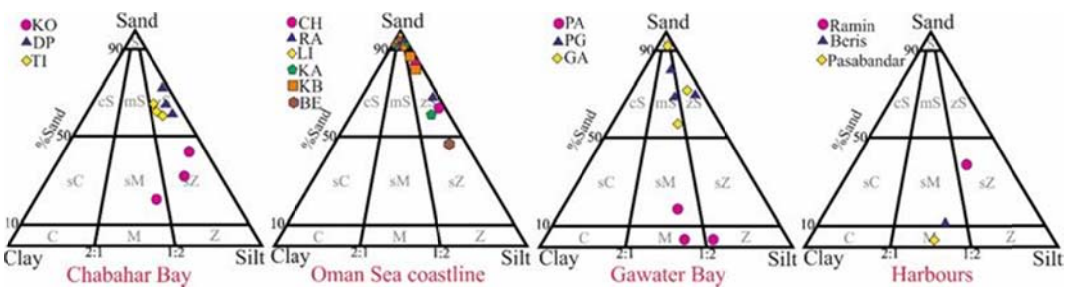

Figure 2: Size classification of clastic sediments (Folk 1968) in Chabahar and Gawater Bays, Iranian Oman Sea coastline and selected fishing Harbors

For better visualization of sediment type distribution along Iranian coasts of Makran, a GIS-based map of sediment distribution in the area was provided (Fig. 3). In general, by moving shoreward, sand fraction in sediments increased drastically. Nearshore (the area influenced by the nearshore or longshore currents) sediments were clearly dominant by sand, especially close to the cliffs. In coastal areas sheltered by headlands or man-made wave breakers such as Konarak (west of Chabahar Bay), Tiss (east of Chabahar Bay), and coastal areas of Beris, Pasabandar and Gawater towns, silty sand and sandy silt were observed (Fig. 3). Around 2 km seaward sandy silt sediments appeared gradually. Sandy silt sediments were also dominant in both bays. High TOM% and calcium carbonate content in sediments which are indicators of bioavailability in sediments are observed in stable environment in estuaries, lagoons and sheltered areas.

3.2. Sandy Shore Profile Changes

Figure 4 shows changes in sandy shore profile of two transects in Chabahar Bay during and after summer monsoon time. The sandy shore Profile corresponding to summer monsoon was convex and had lower elevation, while after monsoon profile had a concave and higher elevation confirming that strong waves of summer monsoon are destructive, withdrawing sand from the sandy shore (Bird, 2011).

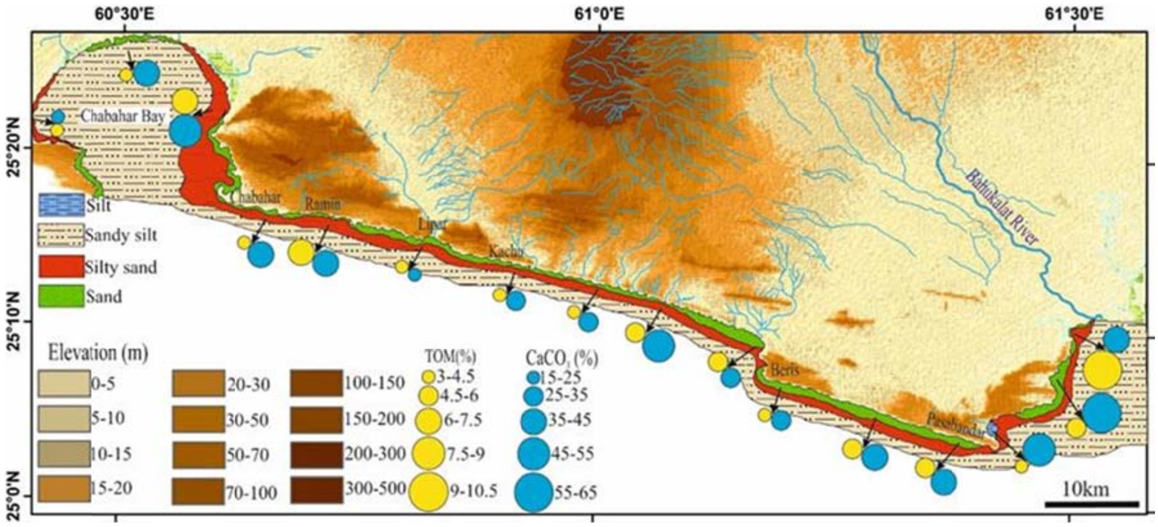

Fig 3: Distribution pattern of sediments along Iranian Makran coasts. TOM% and CaCO3% of sediments are also shown

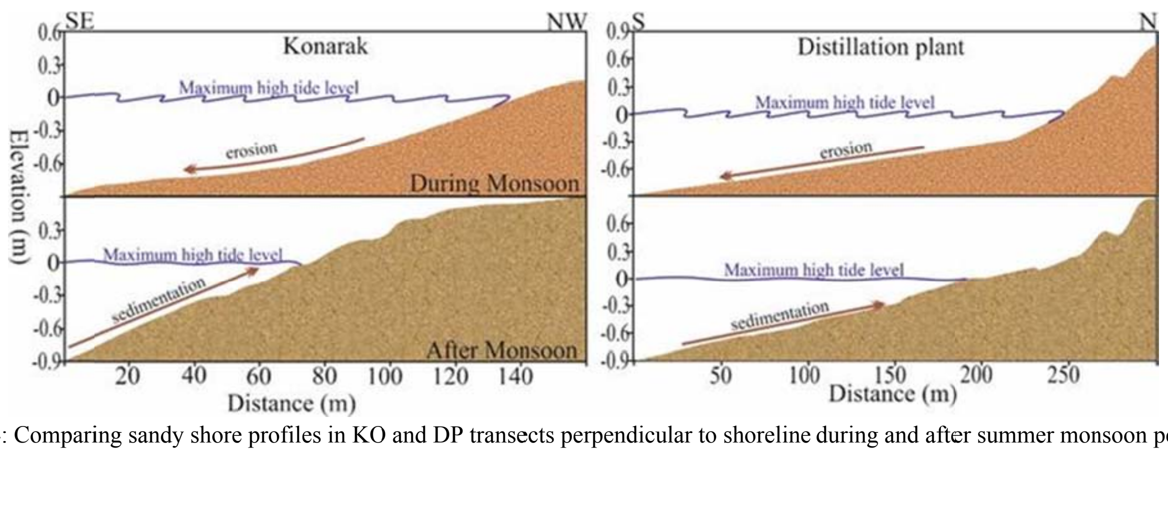

Fig 4: Comparing sandy shore profiles in KO and DP transects perpendicular to shoreline during and after summer monsoon period

4. Discussion

4.1. Coastal Classification

Shores vary depending on their sediments composition and their exposure to the sea. Based on sedimentology, image analysis and field survey, we classified Iranian Makran coasts (Chabahar to Gawater Bays) into three categories as below (Figs 5, 6):

4.1.1. Rocky Shores

Rocky shores of the area form coasts where high, rocky landforms are in direct contact with the Oman Sea's exposed coastlines. They comprise 52% of shores and are characterized by cliffs and a flat, wave cut platform that is likely to be strewn with fallen rock (Figs. 6, 7c). These landforms are influenced by geology (lithology and structure), and their profiles and rates of recession are determined by rock resistance and exposure to weathering and erosion (Masselink et al., 2014). They are dissected along zones of weakness, particularly bedding, joint and fault planes.

Boulders comprise typical particles of the Rocky shores formed from the breakdown of fallen rock from the cliff face. Narrow sandy shores with slopes greater than ten degrees are observed in front of some rocky shores in Kachu and a limited area between Beris and Pasabandar (Fig. 7c, g). Processes at work on rocky shores are largely erosional, dominated by abrasion by waves armed with sand and gravel. Rates of cliff retreat depend on several factors, including lithology and structure, exposure to strong wave action, presence of a protective sandy shores and sea level changes (Jackson et al., 2005). These can cut grooves, clefts and potholes, as well as sloping ramps at the base of a receding cliff and deposit rock fragments. These kinds of shores are extended in: 1) west of Chabahr Bay; 2) east of Chabahar Bay including coasts of Tis, Chabahar, Ramin and Lipar; 3) east of Lipar; and 4) coasts of Beris, Pasabandar and Gawater (Fig. 6).

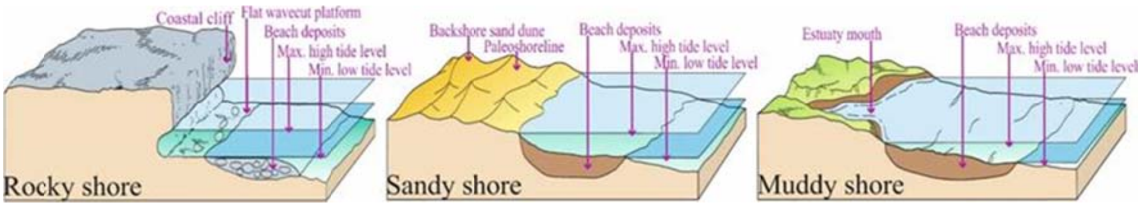

Fig 5: Schematic figure showing three types of shores in the Iranian Makran coasts (after Finkl, 2004)

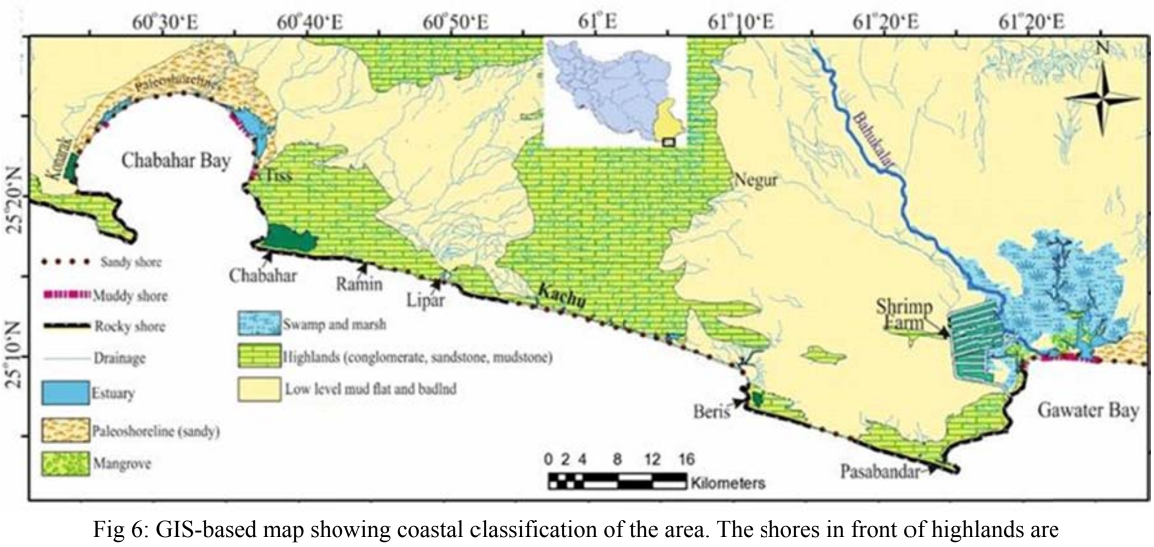

Fig 6: GIS-based map showing coastal classification of the area. The shores in front of highlands are mostly rocky. whiles in some areas a narrow Sandy shores has been formed in front of rocky shores.

Cliff dissection resulted in formation of caves, blowholes (Chabahar coast), gorges (Ramin), natural arches (Pasabandar), stacks (Pasabandar) and truncated valleys (Ramin). Chabahar blowhole is a passageway connecting the roof of a sea cave with the surface of the land above. At high tide, especially in summer monsoon time, strong waves force water up into a blowhole causing a geyser of water and pressurized air to erupt from the top of the blowhole (Fig. 7f). In most of the area (mostly in Ramin), SW winds cause forming of cliff-top dunes (Fig. 7e).

At the landward areas, erodible and impermeable calcareous marl cliffs (McCall, 2002) are weathered and subjected to erosion by torrential rains falling over a barren area, forming a unique and spectacular mountain landform locally known as “Mars Mountains” (Fig. 7a). Extensive further erosion of these geological units is characterized by typical badland topography in Kachu and Beris Coastal areas (Figs, 6 and 7b).

4.1.2. Sandy Shores

Sandy shores, comprising about 40% of the coastline, form sheltered coastlines, where eroded coastal landforms are deposited. Some narrow sandy shores are formed in front of cliffs in Tiss, Ramin, Kachu and Gawater (Fig. 7c, g). Their typical slopes are in a range of 1–9 degrees. Studied shores consisted of sediments ranging from medium sand to boulders. They have derived from various sources including eroding cliffs, seasonal rivers, and the sea floor. The CaCO3 and TOM content in these sediments range between 15-45% and 3-6%, respectively, which are lesser than those of muddy shores with stagnant environment. Frequent sand size shell fragments, originated from shelly organisms of more stable subtidal zone and erosion of high calcium carbonate content cliffs, are responsible for relatively high CaCO3 content of sandy shore sediments.

Sandy shores are shaped largely by wave action which generates longshore, onshore and offshore currents in different parts of the year. Sandy shores in erosional periods (summer) generally have concave profiles (Figs. 4, 7g), whereas in winter, accreting Sandy shores with typically convex in profile are observed. Sandy shores compartments, typically delimited by headlands or breakwaters, containing sediment cells.

Sandy shores are observed at the middle parts of Chabahar and Gawater Bays, and narrow Sandy shores in east of Ramin and between Kachu and Beris (Fig. 6).

4.1.3. Muddy Shores

Muddy shores are formed in very sheltered coastlines along estuaries or bays. They consist only 8% of studied coastline and their typical particle sizes are less than 0.063 mm. Muddy shores slopes are less than one degree. Due to the stagnant and productive environment, their CaCO3 and TOM contents reach up to 65% and 10.5% respectively. Muddy shores of the study area were located at mouth of estuaries sheltered from strong wave actions, and were host of mangrove forests (Tiss and Gawater) (Fig. 6). These forests trap sediments to form salt marshes. There are often distinct threshold bars at the marine entrance and, therefore, they are partly or wholly enclosed by longshore barriers. As they are subject to interactions between fluvial and marine processes, the estuaries are generally filled with sediment. Salt marshes have formed in relatively vast Bahukalat estuary and influence patterns of sedimentation. Lipar as a bar-built estuary separated from the sea by a sand bar or barrier that has been deposited by wave action (Fig. 7d). Extended estuaries are located at both Chabahar and Gawater Bays. However, about 10 little bar-built estuaries as well as moderate size Lipar lagoons are distinct in the straight coastlines between the two Bays (Fig. 6).

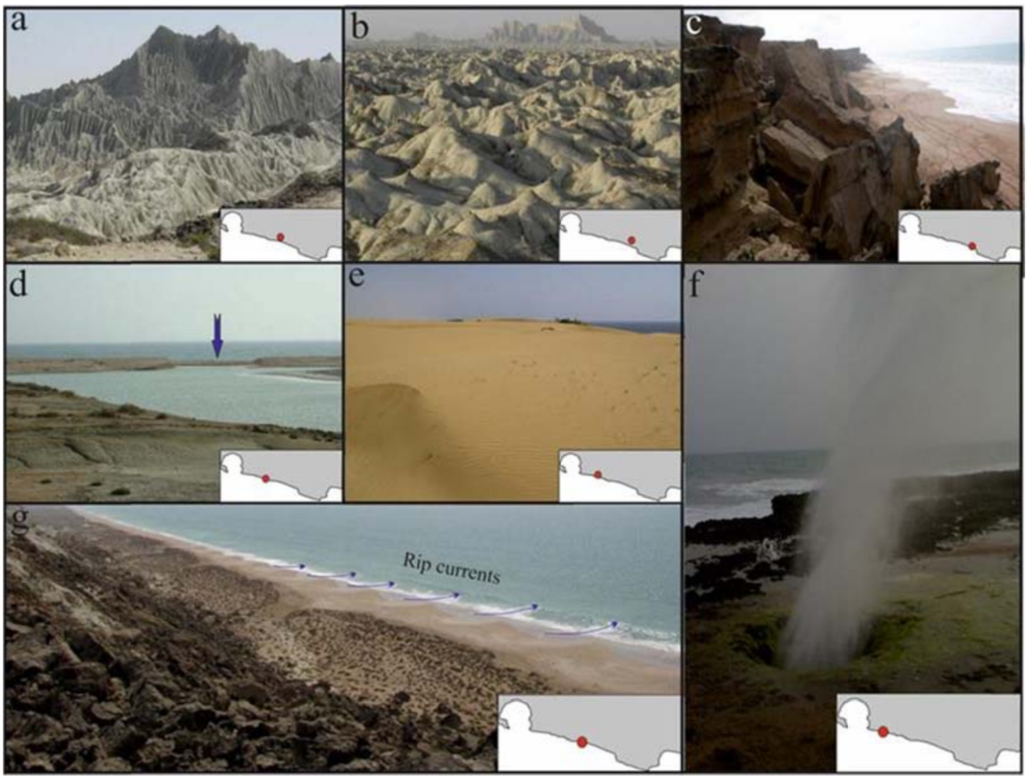

Fig. 7: Image showing some coastal landforms and features in the area. a) Erodible Plio-Pleistocene calcareous marls representing strange and picturesque landforms, locally known as "Mars Mountains". b) Highly eroded above mentioned marls forming typical badland. c) Coastal cliff, which has partially fallen. A narrow sandy shore is also observed at the front of cliffs. d) Lipar lagoon, a bar-built estuary with highly saline water due to high evaporation rate. The arrow shows sand bar separating lagoon from the sea. e) Backshore sand dune formed on top of cliffs in Ramin. f) A blowhole on top of cliffs in Chabahar. g) Narrow and long sandy shore of Kachu area forming in front of cliffs. Rip currents are shown by arrows. At the head of each rip current the sandy shore has been lowered and cut back Location of images are shown in their right corner.

4.2. Controlling Factors

Three groups of factors are recognized that influence coastal development, termed 1) physical factors of the land; (2) physical factors of the sea; and (3) biological factors (Davies, 1972). Biological factors incorporate into micromorphology of coasts and are ignorable in tectonically active coasts with strong waves. Therefore, local geology (tectonics, petrology, sedimentology, relief and sediment supply) and physical oceanography parameters (winds and waves characters) are dominant factors affecting coastal geomorphology of the area.

4.2.1. Local Geology

There are often simple relationships between coastal outlines and the geology and topography of coastal areas (Masselink et al., 2014). As mentioned earlier, coastal Makran belongs to an active subduction margin. Hence, the overall shape of coastlines is related to faulted accretionary prisms (Uchupi et al., 2002). The accretional ridges are composed of soft marls and hard sandstones (McCall, 2002), which their relative erodibility forms major coastal landforms. Headlands and promontories generally occur where there are outcrops of resistant rock at, above or below sea level, or where higher ground comes to the coast, while a bay forms when less-resistant strata are eroded quicker than surrounding strata (Jackson et al., 2005).

Headlands are composed of more resistant strata (sandstone and conglomerate) and are left protruding into Oman Sea as less-resistant strata (marls) around them are eroded. Major headlands of studied coasts are Konarak, Chabahar, Beris, Pasabandar and Gawater (Figs. 6, 8).

Bays have been excavated where softer marl outcrops are bordered by more resistant formations of sandstone and conglomerate, particularly where lowlands have formed. Where there have been relatively recent tectonic movements (upward or downward, tilting or folding) it is likely that uplifted sectors protrude seaward and that subsided areas have become bays. There are several bays along Iranian Makran coasts such as Gurdim, Pozm, Chabahar and Gawater, which the last two are located in the study area (Figs. 6, 8).

Frequent paleoshorelines (mostly at the northern parts of bays), and paleo-terraces on the land are symptoms of uplift associated coastline progradation (Shah-hosseini et al., 2011).

4.2.2. Wave Action

Coastal outlines of the study area are produced largely by waves, which also generate longshore drifting of sediment (Saket and Etemad-Shahidi, 2012). Breaking waves may be constructive (moving sediment shoreward) or destructive (causing erosion). Processes in coastal waters include waves generated by wind action locally (including storm waves) and remotely (ocean swell transmitted from distant storms), tides related to coastal and nearshore configuration, disturbance by storm surges and tsunamis, and associated currents (Davidson-Arnott, 2010). They act in combination, but are conveniently treated separately.

Coastal Makran of Iran shows seasonal alternations of onshore and offshore waves leading to strengthening or weakening of ocean swell. In stormy periods waves locally generated by SW winds (onshore winds) blowing over coastal waters are typically much steeper than ocean swell of distant derivation (Davidson-Arnott, 2010) (Fig. 8). They are superimposed on ocean swell arriving in coastal waters. In contrast, offshore NE winds blowing in winter, flatten swell to produce relatively calm conditions in the nearshore zone (Moon, 2005) (Fig. 8). At other times of the year, however, ocean swell is usually strong enough to produce waves that shape the coastline. The waves generated in coastal waters by onshore winds also break on the shore with sufficient energy to erode coastal rock formations and transport sediments along shore.

Where waves approach the shoreline with high angle, a portion of the momentum flux is directed alongshore and results in the generation of a longshore current that typically can have speeds of 0.2-1.0m s-1 (Bird, 2011). Seasonal alternations of longshore drifting in the area consisting of westward in winter (NE winds and waves dominant) and eastward in summer (SW winds and waves dominant) has formed many coastal features such as spits and sand barriers (Fig. 8). SW winds and their associated currents are dominant cross shore currents generating eastward longshore drift. These currents in turn cause accretion at the west and sedimentation at the east of natural and man-made barriers (Fig. 8f).

Sandy shore profiles are lowered and cut back by strong wave action, especially during stormy periods of summer when plunging and surging waves, with limited swash and stronger backwash, withdraw sand and shingle to the nearshore zone, leaving a concave profile (Fig. 4). In calmer weather spilling waves, with a strong swash and lesser backwash, move sand and shingle up the sandy shore and rebuild a convex profile. Alternations of sandy shore erosion by plunging or surging waves and sandy shore accretion by spilling waves are known as cut and fill, and are associated with alternations of seaward and shoreward drifting of sediment. Generally the erosion takes place rapidly during summer and the shoreward drifting is a slower process that extends over longer periods. On these sandy shores the offshore return flow occurs as part of a complex three dimensional system termed a rip cell. They are also described as horizontal circulation patterns in contrast to the vertical pattern associated with undertow (Fig. 7g).

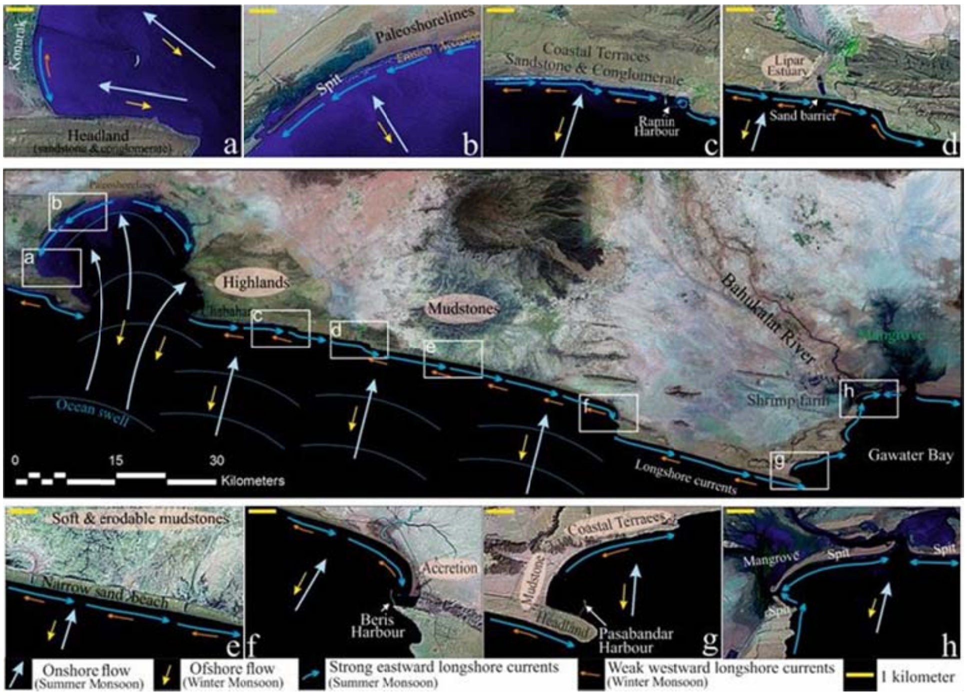

Fig. 8: Landsat 7 satellite image showing some coastal features formed as a result of wave action. a) Coast of Konark town sheltered by a headland causing dominance of a calm environment with a relatively high sedimentation rate b) Refraction of waves moving into Chabahar Bay leading to strong westward longshore current at the western part of the bay. A lagoon impounded by a spit on the coast is observed. Location of recurve at the western end of spit confirms westward movement of longshore currents. c) Strong eastward longshore currents along rocky shore of Ramin area preventing sandy shore formation. d) A barrier which formed by the deposition of beach material across mouths of Lipar estuary, above the level of normal high tides, enclosing the lagoon. The barriers have evolved by longshore currents. e) A narrow sandy shore evolved in front of cliffs due to limited net sedimentation. f) Eastward longshore drifting of sand in such a way as to cause extensive accretion updrift on NW side of Beris Harbor and erosion downdrift on south of Harbor. g) Coast of Pasabandar Harbor sheltered by a headland causing beach extension. g) Bahukalat, a lagoon of branched outline impounded by pa ired spits along Gawater coast.

5. Conclusion

The sedimentology and geomorphology of Iranian Makran coasts provide new insights about coastal landform evolution and effects of geology and climate as two main controlling factors affecting the area. Influence of high energy SW winds of summer monsoon and low energy NE winds of winter monsoon on tectonically active coastline of Makran have governed dynamic coastal features in the area. Rocky shores, sandy shores and muddy shores are formed as a result of interaction of different geological units with various wave actions.

Overall shape of Makran coastlines is controlled by faulted accretionary prisms. Active tectonics of Makran forms straight coastlines, headland and bays, while climate induced waves modifies the coasts and controls sedimentation/erosion patterns. Coastal Makran of Iran shows seasonal alternations in strength and direction of nearshore waves. In summer time waves generated locally by SW monsoon winds (onshore winds) blow over coastal waters and cause strong backwash. Refraction of these waves in turn generates strong eastward longshore currents preventing extended sandy shore formation. In contrast, weak offshore NE winds are together with swash and limited westward longshore current during winter. However, spits and location of sediment accretion on the sides of harbors confirm that eastward longshore drift is predominant along Makran coasts of Iran.

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