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Makran continental margin sedimentation during Late Holocene

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Abstract

Sedimentation in the Makran active margin is governed by complex interaction of atmospheric, tectonics and hydrodynamic setting of northern flank of the Gulf of Oman. The mixed clastic carbonate sediments in tectonically and hydrodynamically active environment have complicated distribution pattern. The region is suffering from basic sedimentological data and specifically the sedimentation history of the Holocene deposits was rarely studied in Iranian coast. To deal with this deficiency, surface and core sediment samples from the Iranian continental shelf and upper slope of the Gulf of Oman have been studied using standard sedimentological techniques. The overall sediment distribution pattern demonstrates that the grain size gradually decreases from shoreline to the deeper zones. However, some medium to coarse grained sand patches can be found in deeper parts specially in the middle part of the studied area that can be related to sediment supply of ephemeral rivers discharging in to the sea in rainy seasons and/or high energy events i.e. turbidites and tsunamis during the Holocene. Several horizons of the coarse grained detrital sediments are detectable in upper slope sediment cores. The coarse grained materials are received from hinterland during flashfloods and could be accumulated due to mass wasting events. The elevated amount of organic materials in the upper slope indicates deficit of dissolved oxygen that leads to preservation of organic materials in the bottom sediments.

Keywords: Makran active margin, Gulf of Oman, sediment distribution, turbidite

1. Introduction

Active Makran continental margin stretches along Iranian and Pakistani shores in the Gulf of Oman (GO). Sedimentation in this oceanic basin is primarily controlled by the tectonic setting and geological background of the Makran subduction zone (Uchupi et al., 2002). However, climatic and hydrodynamic factors exert strong imprints on the sedimentary deposits of the basin (Miller et al., 2016).

According to the position of the GO at the border of Indian Ocean Monsoon (IOM) and Westerlies atmospheric systems as well as its position relative to Inter-tropical Convergence Zone (ITCZ) (Fig. 1), the sediment archives are admired to indicate climatic changes (Cullen et al., 2000; Prins et al., 2000; Ansari and Vink, 2007; Pourmand et al., 2004; 2007). Moreover, the potential of the area to receive the impacts of high energy events e.g. tsunami (Shah-hosseini et al., 2011; Hoffman et al., 2013) and tropical cyclones (Fritz et al., 2010) afford more studies to reveal the history of the marine hazards in this less studied area. Climatic changes could directly impact marine productivity and hydrochemical conditions that in turn are recorded in marine archives as biological and biochemical indicators (Miller et al., 2013, 2016). However, high energy events are more evident in marine bottom sediments as sharp textural changes (Bourget et al., 2010).

Insert Fig. 1

Bottom sediments of the GO and Makran coast have been introduced in sparse researches (Uchupi et al., 2002; Prins et al., 2000 a&b; Bourget et al., 2010), in which the west Makran (Iranian Makran) continental margin little touched yet. In this research we used a series of short sediment cores that have been taken in 2009 and 2012 in Iranian Makran continental margin. Some sediment cores of the first cruise were studied based on palynological proxies (Miller et al., 2013, 2016) and sedimentological approaches (Amjadi et al., 2012a & b; 2013). Here, we used sedimentological analysis of 24 short cores and 13 surface samples from Makran continental shelf and slope to get an insight of overall sedimentation pattern and downcore sedimentological changes that could be linked to both atmospheric and tectonic events.

2. Geographical Setting

The GO is a remnant oceanic basin of the Cretaceous ocean of Neotethys. The active tectonics of the basin is the result of converging of Arabian shortening, faulting and uplifting. (Platt et al., 1985; Nilforoushan et al., 2003; Vernant, et al., 2004) (Fig. 1). The GO is covered by thick sedimentary sequence (around 7 km) since Paleocene (Uchupi et al., 2002; Grando and McClay, 2007). A relatively thin layer of late Quaternary (Pleistocene-Holocene) sediments covers the older sediments consisting of fluvial detritus and biogenic sediments (Uchupi et al., 2002).

Coastal Makran comprise the main part of Makran subduction zone and most of which is above sea level (Uchupi et al., 2002). The Iranian Makran, known as western segment, stretches more than 800 km along the northern flank of the GO. The overall morphology of the coast is characterized by consequent arrangement of elevated headlands and Ω shaped lowlands (Uchupi et al., 2002). The coast has been uplifted during the late Quaternary with average rate of 1- 2.7 mm yr⁻¹ (Vita-Finzi, 1975).

The water column of the GO is stratified due to interaction of different water masses i.e. Indian Ocean surface, intermediate and deep water masses and the Persian Gulf warm and saline outflow. Interaction of these water masses along with the climatic and tectonic drivers has significant imprint in the deep sedimentation as contourite and lead to changes in biogenic and chemical components (Rodriguez et al., 2016).

The arid to hyper-arid hot climate of the region is influenced by IOM and southern limit of Westerlies (Ansari and Vink, 2007) (Fig. 1). Mean annual rainfall is less than 100 mm and the rainfall variability is extremely high. Occasionally, tropical storms and cyclones occur almost during May–June and October–November and cross the west coast of the Arabian Sea but are fewer in the Gulf of Oman and the Iranian coast. Wave of 1% frequency has 3 m height and 7 s period. The wave height of 4.5 m has been measured during cyclone Gonu in June 8, 2007 in Chabahar (Hajivalie and Arabzadeh, 2017). The last strong tsunamigenic waves hit the coast in 1945 (Kakar et al., 2014), although more events were reported by Shah-hosseini et al. (2011) and Hoffmann et al. (2013) for the Holocene, based on their studies on coastal boulders.

Materials and Methods

1. Field campaign

Our study is based on the sediment samples taken during two expeditions in 2009 and 2012. In the first expedition 22 short gravity cores and 13 surface samples have been retrieved from the continental shelf up to 214 m of water depth (Fig. 1). In the second expedition two short cores have been retrieved from upper slope in depth of around 750m. Surface samples and cores were taken by Van Veen grab sampler and gravity corer, respectively (Fig. 1, Table 1). The physical and chemical properties of the water column were measured using Starmon CTD (Conductivity-Temperature, Depth) probes in both expeditions.

All sediment samples were transferred to Marine Geology Laboratory of INIOAS for further analysis. Results of some cores have been published previously by Amjadi et al., (2012 a & b; 2013) and Miller et al. (2013; 2016).

4.2. Laboratory analysis

Magnetic susceptibility (MS) of 2 intact sediment core samples from the upper slope has been measured using a Bartington MS2C Magnetic Susceptibility Meter with 2 cm increment. Core samples were split using a hand-made core splitter and subsampled systematically. The uppermost first centimeter of the core samples were separated to include them in surface sediment analysis. Core sediment subsamples were selected in every 2 cm along the cores and analyzed along with surface sediments for grain size analysis, organic matter and carbonate content. Organic matter content was measured based on outlined methods of Parker (1983) using Hydrogen Peroxide. Carbonate content was measured using a Barnard's calcimeter.

To evaluate the grain size changes, the samples were pretreated using the conventional chemical procedures (Konert and Vanderberghe, 1997). Samples were first treated with 5% hydrogen peroxide to remove organic matter, and then carbonate was removed using 10% HCl. Before the grain-size measurement, 10 ml of 0.05 M $(\text{NaPO}_3)_6$ was added to the solution to facilitate dispersion of sediment particles. LA-960 Horiba Laser Particle Size Analyzer was utilized for grain size analysis for fine grained sediments and sieve shaker was used for coarser grained sediments. Some samples were selected for repeated measurement to confirm the reliability of the grain-sizing. The results showed that those repeated measurements differ from each other generally less than 5%.

Insert Table 1

Results

5.1. Rate of sedimentation

Two cores were dated using Pb^{210} , Cs^{137} , and C^{14} at the east and west of Chabahar Bay by Miller et al. (2013; 2016) (Fig. 1C). Sedimentation rate in core OS55 (west of Chabahar Bay) is ~ 2.3 mm yr^{-1} using Pb^{210} , Cs^{137} . The rate of sedimentation in core OS73 (east of Chabahar Bay) using C^{14} shows that the lower part of the core was deposited by the rate of 0.21 mm yr^{-1} and then increased dramatically to 2.74 mm yr^{-1} in the middle part of the core. Finally the upper part of the core was deposited with the rate of 0.86 mm yr^{-1} .

5.2. Sedimentology

Based on textural nomenclature of clastic sediments (Shepard, 1954), surface sediments are mostly consist of silty sand to clayey silt (Fig. 2). The onshore sandy sediments in lowland areas change in to silty sand in shallow coastal waters. Surface sediments of the Chabahar Bay are mostly composed of sandy silt to silty sand. The shallow coastal waters in front of elevated headlands are typified as very fine sands that are coarsening landward to coarse sands, very coarse sand and gravel. In estuaries and harbors the sediments are finer grained and change to silt.

Insert Fig. 2

The content of organic materials (OM) in surface nearshore sediments ranges between 3 to 10.5% and the percentage of calcium carbonate in the sediments oscillates dramatically between 16 to 64%. Highest amount of OM is observed at the mouth of estuaries and harbors. Calcium carbonate content of sediments is positively correlated with silt and clay fraction of sediments. Both carbonate and organic materials indicate generally increasing trend in lower energy areas, i.e., embayments and estuaries. The upper slope has been covered mainly by fine sediment fraction (core OM 26 and OM 31). The silt content changes from 48% to 60%, where clay varies from 31% to 50%. Sand sized sediments occur up to 3% in deep cores.

5.3. Sediment core composition

Sediments of the Makran continental margin have both detrital and biogenic carbonate components. The carbonate content of the samples ranges from 68% in the upper shelf to 18% in the upper slope (Fig 3). The biogenic carbonate content of the upper shelf sediments is mainly provided by benthos fauna while pelagic organisms are mainly responsible for biogenic carbonate content of upper slope sediments.

Insert Fig. 3

Detrital carbonate of the marine sediments in Makran continental shelf is provided by the hinterland's sediments that are composed of marlstone, siltstone, sandstone and limestone.

Most of the sediment core samples are composed homogeneously of clayey silt and silty clay that do not change considerably along the cores (Fig. 3). Core 62 (in front of Chabahar Bay) is an exception in terms of sediment composition where it contains alternative layers of sandy silt and sandy silty clay. The sand content layers are also observed in core 72 and 92 (Fig. 3). All of these cores are limited to the eastern part of the study area.

Two deep cores (around 750 m) in front of Chabahar Bay (Fig. 4 and 5) contain lamination of detrital coarse grained sediments. The core OM31 (east of Chabahar Bay; Fig. 1) has more coarse grained laminae compared to core OM26.

Insert Fig. 4

Insert Fig. 5

The OM content of the OM26 core sample ranges between 11.5% and 5.6% and decreases downcore (Fig. 4). The OM content of the OM31 core sample ranges between 4.2% and 16.8% and shows increasing trend downcore (Fig. 5).

The carbonate content of the OM26 core sample is negatively correlated with OM content and ranges between 4% at the top to more than 18% to the bottom of the core (Fig. 4). A distinctive difference could be distinguished in carbonate content of the core OM31 relative to the other

core; the carbonate content of OM31 core drops from around 14% at the top to around 3.6% at the depth of 47cm and then the carbonate content does not change considerably.

The calcium carbonate content of deep sediment ranges from 8% to 18%. Organic materials have elevated amount up to around 18%. Magnetic susceptibility of two cores did not display significant trend compared to grain size and composition (Fig. 4 and 5).

6. Discussion

Radiocarbon dating of lower slope (depth ~ 1800 m) at the eastern Makran indicates that the rate of sedimentation is around 0.5 mmy^{-1} (Prins et al., 2000). They reported that the rate of sedimentation in continental margin of the Makran varies from 0.34 to 0.83 mmy^{-1} . However, Miller et al. (2013; 2016) showed that the sedimentation rate in the study area and at the upper slope is high and reaches up to 2.48 mmy^{-1} during middle to late Holocene. The Holocene sedimentation rate sharply decreased in middle and lower slope (Von Rad et al., 1999; Von Rad et al., 2002). In lower slope of the GO where sediments are not disturbed due to slumping (depth 2732 m), sedimentation rate is around 0.15 to 0.23 mm y^{-1} during the Holocene (Collen et al., 2014). According to the available age dating of the region and the length of the cores in this study, we expect that these cores represent the late Holocene in the Makran.

Insert Fig. 6

The sediment distribution pattern of the Makran continental margin demonstrates that generally the grain size decreases by the water depth. However, some medium to coarse grained sand patches can be found in deeper parts (Fig. 4). The sediment distribution pattern in upper continental shelf of Makran is highly influenced by coastal morphology, the climate of the region and water column characteristics. In front of elevated headlands (rocky shores) the sediments are coarser than low lying areas. Wave action is responsible for eroding the uplifted headlands and providing coarser grained sediments. High energy events of tropical cyclones and tsunamis could lead to deposition of onshore coastal boulders (Shah-hosseini et al., 2011) and offshore reworked sediments (Bourget et al., 2010). The presence of heavy minerals in the sediments of Makran continental shelf (e.g. zircon, garnet, apatite, hornblende and tourmaline) shows the role of reworked sediments in the deposits (Amjadi et al., 2012a & b; 2013). In areas with gentle topography, fine sediment appears in the coastal and upper shelf area. The distribution pattern of

organic matter and clay fraction are concordant that could be attributed to the absorption of organic matter by clay fraction. Well ventilated water column in shelf area decomposes organic materials, while the deeper parts of the continental shelf towards the slope are dominated by stagnant water with lower dissolved oxygen. The water column characteristics lead to changes of organic materials content in bottom sediments from around 1.5% in upper shelf to around 17% in deeper parts. The same condition was reported from continental margin of the eastern Makran where elevated amount of organic materials in sediment attributed to the oxygen minimum zone of the water column and sedimentation with negligible disturbances (Schulte et al., 2000).

The Indian Ocean Surface Waters (IOSW) reach to the Makran continental shelf (Pous et al., 2004) and along with subtropical climate of the region lead to higher productivity that is reflected in biogenic carbonate content of the deposits (Fig. 6). On the other hand, detrital and biogenic carbonate could be transported from the Persian Gulf into the GO (Callen, 1984; Prins et al., 2000; Uchupi et al, 2002) and elevate the carbonate content as well (Fig. 6). Generally, the westernmost samples of this study show higher amounts of carbonate content than the eastern ones that could be linked to the impacts of the Persian Gulf outflow.

Although the deposits of the continental margin of Makran could be disturbed by tectonic and atmospheric events (e.g. earthquake, tsunami, flash flood and tropical cyclone), indeed the main governor of high sedimentation rate in the upper slope is climatic. Comparing to analogue active margins (e.g. Cascadia in North America; Gutiérrez-Pastor et al., 2013), this region is arid, without permanent river and the vegetation is poor. The ephemeral rivers of the Makran can carry large amounts of alluvium to the GO during flash floods in rainy season due to low vegetation cover of the coast (Fig. 6). It is assumed that these kinds of rivers are 400 times more effective in transporting coarse detritus to deeper parts of the basin (Reid et al., 1994; Laronne and Reid, 1993). This condition leads to high sedimentation rate in the slope that could result mass wasting and submarine landslides (Bourget et al., 2010). The imprints of mass wasting are evident in OM31 core sample as frequent laminas of coarser grained materials. The disordered sample shows inverse trend of OM and strange behavior of carbonate content along the core (Fig. 5). More studies are needed to reveal the age and cause of the disturbances. Governance of oxygen minimum zone (OMZ) significantly changes the preservation and degradation of OM. The OMZ itself related to the ocean circulation and Monsoon intensity. High productivity during intensified Monsoon condition correspond to the stronger OMZ, however penetration of the

Antarctic water with high dissolved oxygen into the northwest Indian Ocean cause weakening of the OMZ (Das et al., 2017). Our data represent oxygen depletion from mid shelf in front of Chabahar where it deepens toward the southern part of the GO and western Makran. Cyclic variation of coarse grained deep sediments and organic materials could correspond high energy events and marine bioproductivity both triggered by climatic forcing, Monsoon intensification and ocean circulation.

7. Conclusions

Sedimentation in the Makran continental margin is complicatedly controlled by the regional geology, oceanography and climate of the region. This study shows the potential of the continental margin sediments of the Gulf of Oman to study the role of different governors of sedimentation in this less touched marine environment.

The main suppliers of coarse grained sediments at the offshore of the study area are flashfloods in the hinterland during tropical storms and/or torrential rains that in turn are distributed by oceanographic and/or tectonic events. The Makran continental margin favors turbidite events that deciphered by coarse grain lamina in the core samples. Well oxygenated water column accelerated degradation of the organic materials mainly in the shelf area. Deficit of dissolved oxygen in the intermediate water column is responsible for the elevated amount of the organic materials in the sediments.

Aknowledgement

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380 Table Caption

381 Table 1. The sediment samples used in this study and their attributed information

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Figure Caption

Fig. 1 The study area and the sampling position. A) The geographic position of the study area is shown by rectangle in relief map of the West Asia (<https://maps-for-free.com>). The main atmospheric systems influencing the study area are illustrated by flashes. The modern summer position of inter-tropical convergence zone is sketched as yellow dashed line. The major faults of the study area are represented by red lines. B) The lithology map of the study area (GSI, 1996). C) The positions of sediment samples that are used in this study. The age dated cores (OSC-73 and OSC-55) are indicated by red color.

Fig. 2 A) Sediment types of the analyzed samples based on Shepard (1954) nomenclature. B) Sediment distribution pattern of the study based on surficial sediment analysis of this study. C) Dissolved Oxygen (ppm) of the water column in the Gulf of Oman in front of Chabahar Bay.

Fig. 3 Sedimentological properties of core samples. For each core: A) sediment lithology, B) percentage of total organic material and C) percentage of Carbonate content.

Fig. 4 Sedimentological properties of upper slope sediment core OM26. OM represents organic material and MS is magnetic susceptibility.

Fig. 5 Sedimentological properties of upper slope sediment core OM31. OM represents organic material and MS is magnetic susceptibility

Fig. 6 Schematic block diagram of the study area. The bottom morphology is drawn based on Uchupi et al. (2002). The water masses of Indian Ocean including Surface Water (IOSW), Intermediate Water (IOIW) and Deep Water (IOSW) are indicated based on Tomczak and

433 Godfrey (2003). The Persian Gulf outflow is abbreviated as PGW and is shown based on the
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Table 1 The Makran sediment core samples and their attributed information used in this study

Sample ID	Long	Lat	Depth (m)	Sampeling Method	Core Length (cm)
OSC-11	59.28333	25.36667		Grab	-
OSC-12	59.28353	25.28865	34	Corer	72
OSC-13	59.28333	25.217	113	Corer	43
OSC-15	59.28918	25.1845	198	Corer	57
OSC-21	59.6	25.36667		Grab	-
OSC-22	59.60033	25.31883	57	Corer	81
OSC-23	59.59867	25.2815	105	Corer	85
OSC-24	59.60067	25.239	187	Grab	-
OSC-31	59.8	25.36667		Grab	-
OSC-32	59.80067	25.29833	61	Corer	35
OSC-33	59.79933	25.26783	100	Grab	-
OSC-34	59.81617	25.23783	185	Corer	89
OSC-41	60	25.35		Grab	-
OSC-42	60.00067	25.285	54	Corer	61
OSC-43	60.00017	25.25	100	Corer	80
OSC-44	60.00183	25.20133	205	Corer	47
OSC-51	60.24628	25.33333		Grab	-
OSC-52	60.25083	25.217	48	Corer	77
OSC-53	60.25083	25.16717	102	Grab	-
OSC-55	60.2506	25.1235	170	Corer	85
OSC-61	60.50344	25.36667		Grab	-
OSC-62	60.5	25.25	20	Corer	33
OSC-63	60.49917	25.21167	50	Corer	105
OSC-65	60.50167	25.06883	200	Corer	28
OSC-71	60.83333	25.23333		Grab	-
OSC-72	60.83367	25.18917	50	Corer	85
OSC-73	60.8325	25.13667	100	Corer	141
OSC-74	60.83633	25.0995	190	Corer	30
OSC-81	61	25.2		Grab	-
OSC-82	61.00167	25.11667	55	Corer	77
OSC-83	61.004	25.0515	112	Grab	-
OSC-84	61.001	25.02	200	Corer	61
OSC-91	61.25	25.08333		Grab	-
OSC-92	61.25	24.91767	55	Corer	66
OSC-93	61.25567	24.889	100	Grab	-
OSC-94	61.25067	24.86683	214	Corer	33
OM-26	60.52537	25.04495	763	Corer	46
OM-31	60.68112	24.99885	720	Corer	158

Fig. 1 The study area and the sampling position. A) The geographic position of the study area is shown by rectangle in relief map of the West Asia (<https://maps-for-free.com>). The main atmospheric systems influencing the study area are illustrated by flashes. The modern summer position of inter-tropical convergence zone is sketched as yellow dashed line. The major faults of the study area are represented by red lines. B) The lithology map of the study area (GSI, 1996). C) The positions of sediment samples that are used in this study. The age dated cores (OSC-73 and OSC-55) are indicated by red color.

229x202mm (300 x 300 DPI)

Fig. 2 A) Sediment types of the analyzed samples based on Shepard (1954) nomenclature. B) Sediment distribution pattern of the study based on surficial sediment analysis of this study. C) Dissolved Oxygen (ppm) of the water column in the Gulf of Oman in front of Chabahar Bay.

272x91mm (300 x 300 DPI)

Fig. 3 Sedimentological properties of core samples. For each core: A) sediment lithology, B) percentage of total organic material and C) percentage of Carbonate content.

296x209mm (300 x 300 DPI)

Fig. 4 Sedimentological properties of upper slope sediment core OM26. OM represents organic material and MS is magnetic susceptibility.

196x192mm (300 x 300 DPI)

Fig. 5 Sedimentological properties of upper slope sediment core OM31. OM represents organic material and MS is magnetic susceptibility.

241x199mm (300 x 300 DPI)

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