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Gatan Mud Volcanoes, Oman Sea Coast in Southwestern Hormozgan, Iran

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Abstract

Iran's mud volcanoes are clearly visible on the coastal plains of the Oman and Caspian Seas. There are 30 Gatan Mud Volcanoes located in the southeast of Iran: 15 of which are located between Jask and Minab in Hormozgan province, nine are between Chabahar and Jask Ports, and another six are between Chabahar and the Iran-Pakistan border in Sistan and Balouchestan Province. After some studies and investigations, research was performed on some of the mud volcanoes in the western Jask city located in the west of lower Gatan village. Gatan is located in the eastern coast of Hormozgan Province between the counties of Jask and Minab and on the coastal region of Makran. Being located on the entrance of the Strait of Hormuz and due to marine currents, it has certain sedimentology circumstances. Formation of Gatan Mud Volcanoes is a result of rising muddy water along the faults and cracks in the crust to the earth's surface. Results of mineralogical studies indicate that clay and limestone samples contain fossils and abundant minerals include quartz, albite, illite, calcite and dolomite.

Keywords: *mud volcano, Oman Sea, Makran, Gatan, Iran*

1. Introduction

Mud volcanoes are landforms similar in appearance to volcanoes, but they are formed by extruded materials such as water, gas and mud that originate from sedimentary sequences from great depth. Often they are circular with a main crater in the middle and several smaller side craters. In some cases, mud volcanoes have no explosion, are not permanent, and operate intermittently and periodically.

According to geological and geophysical studies, distribution of mud volcanoes is reported in the Alps-Himalayan belt, the Pacific Ocean and Central Asia [1]. Approximately 1800 mud volcanoes have been found on earth and are abundant in Indonesia, Trinidad, Barbados, and Taiwan [2, 3, 4, and 5]. Mud volcanoes have been studied for over 200 years and mostly geologists from the USA, Russia, Italy, France, Japan, Taiwan, for instance, have studied the geologic setting of mud volcanoes, their seepages of natural gas, and their mechanisms of formation [6]. In addition, mud volcano eruptions may affect the drilling, piping, and erection of other structures in ongoing projects [6]. There are three main relationships between the mud volcanoes' development and geological environments [3]: 1- a close relationship between mud volcanoes and the tectonic position [7, 8 and 9] especially in compression settings [2], 2- the presence of deep potential source layers in sedimentary succession [10], and 3- in the location of mud volcanoes where the hydrocarbons are produced or are actively being produced [11, 12]. According to the following reasons it is important to study marine mud volcanoes [11, 12]:

1- To provide valuable information about the deeper, inaccessible parts of the sea,

2- To possible find sources of hydrocarbons, and

3- To study their possible contribute to climate change due to their releasing of greenhouse gases such as methane.

In Iran, most mud volcanoes are observed in the coastal plains of the Oman and the Caspian Seas (Fig. 1). Few studies have been conducted on mud volcanoes in Iran, especially in the studied area. Snead (1970), Negaresh (1997) and Nejad Afzali (2010) are among those who have studied mud volcanoes in Iran. Thirty mud volcanoes are located in the southeast of Iran: 15 are located between Jask and Minab [13], nine are between Chabahar and Jask Ports, and 6 are on the Chabahar and Iran-Pakistan border, mostly on the northern Gowater Gulf [14]. The current research was performed on some of the mud volcanoes in the western Jask County, located in the west of the lower Gatan Vllage (Fig. 2). Gatan is located in the eastern coast of Hormozgan province, between the counties of Jask and Minab and in the coastal region of Makran. Being located at the entrance of the Strait of Hormuz and due to marine currents, it has certain sedimentology circumstances. Published studies on Iran mud volcanoes have been mostly conduct with the

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purpose of studying their geotourism potentials and morphology, and little attention has been paid to their geochemistry and tectonic setting. This study reviews the geological, mineralogical and geochemical characteristics of the Gatan Mud Volcanoes on the coast of the Oman Sea [15].

Fig 1. Geographical distribution of Iran mud volcanoes [15]

2. Description

2.1. Geological Setting

Gatan Mud Volcanoes are located in the southeastern part of Iran on the Makran zone. Active tectonic convergence of the India plate with the Arabian and Iranian microplates at a rate of about 30 to 50 mm/y [16] has created an extensive and complex tectonic plate margin in south central Asia along the Makran coasts of Iran and Pakistan (Fig. 3).

The east-west oriented complex is one of the largest accretionary wedges on earth. It is more than 800 km long and bounded to the east and west by large transform faults that define the plate boundaries. The present front, includes the Makran subduction zone (MSZ) and its associated topographic trench which, to a large extent, is buried by sediments. Also, the margin includes the Makran Accretionary Prism (MAP), the Makran Coastal Range (MCR), and the Chegai Volcanic Arc. To the west of the Accretionary Prism, continental collision has formed the Zagros fold and thrust belt [17]. Makran zone is an intercontinental drift dated from the late Jurassic and early Cretaceous periods [18]. It is located in an Iran platform in the southern Jazmouryan troughs and according to the behavior of sound waves in the bedrock, it was accompanied by ocean creation. It is limited to the Minab fault on the west, to the Gulf of Oman on the south, and to the Pakistan border on the east [19].

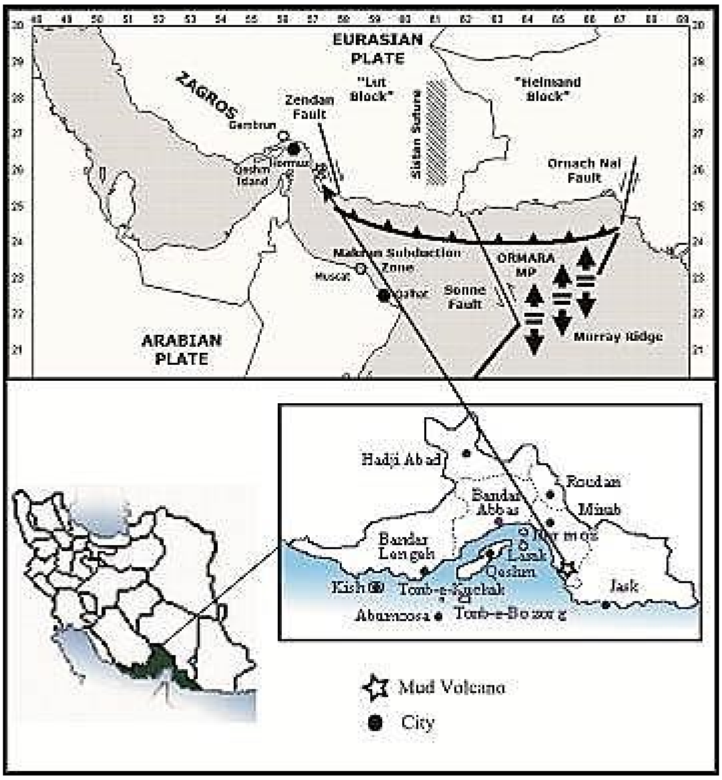

Fig 2. Location of the studied mud volcanoes on the map of Iran and the tectonic map of the western Makran [31]

About 70,000 square km of its 160,000 square km is in Iran and the rest is in Pakistan [19]. From the seismo-tectonic perspective, Makran is regarded as an active subduction zone. Existence of marine terraces and mud volcanoes shows the dynamism of this zone. The Makran area is divided into two parts: the outer Makran (offshore) and inner Makran according to the exposed constituting rocks and degree of deformation [19] in the coastal Makran; the folding and faulting intensity are less than the inner Makran. The studied area is located in the western part of the outer Makran structural zone on the coast of Oman and the area obeys all structural-sedimentary features of the outer Makran.

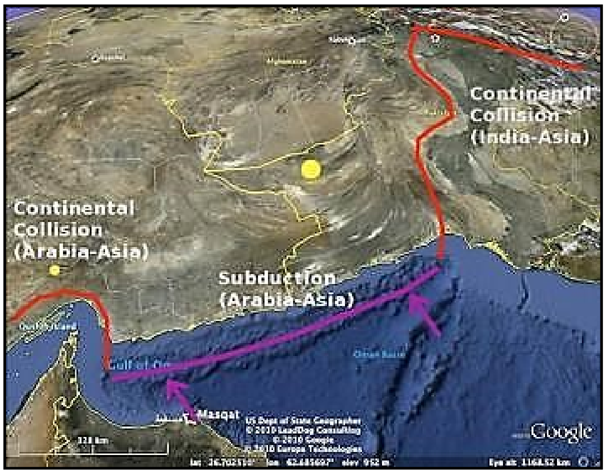

Fig 3. The Makran subduction zone, sandwiched between two areas of continental collision

The Oman sea crust has an oceanic nature and is about 6 km thick with dense deposits of approximately 7 km. The sediments of the lower section have a thickness of about 4 km known as the Himalaya turbidities and the upper section has a thickness of about 3 km known as the Makran sands. Upon the sediments known as the Makran sands, there is a thin layer of the present area deposits [19]. The source of alluvial sediments known as the Himalayan turbidity is the alluvial claw of the Indus River in the east [7], although Makran sands originated from the northern parts of the Makran accretion wedge. The Makran sands are placed uncomfortably on Himalayan turbidities (M in Fig. 4). Himalayan turbidities are composed of turbidity sediments and hemi-pelagic muds that are equivalent to the Panjgur formation belonging to the middle Oligocene-Miocene in Pakistan [16]. Much of the Makran sands are derived from the wedge erosion of the Makran accretion wedge. This unit probably belongs to the late Miocene to Pliocene and is equivalent to the Parkini formation in Pakistan. Gatan mud volcanoes include Pliocene deposits of Makran and the region's largest deposits and rocks consist of Giushi marl, which is also referred to as marl of the

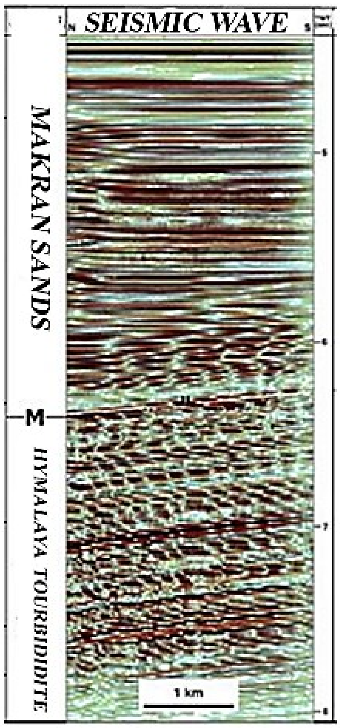

Fig 4. Seismic stratigraphy showing the deep zone characteristics of the Oman Sea [32]

central Makran group or Makran marl [20]. This marl is a sequence of gray gypsum-bearing mudstone, marl, and shale with thin layers of sandstone, siltstone and sometimes conglomerate. Giushi marl is deposited in shallow coastal waters with intense evaporation. Probably, the limited basin was in the pool form and its open part was in the sabkha form, because the Giushi unit is located between two bio-zones of *Globorotalia Acostaensis* and *Globorotalia Humerosa* and belongs to the late Miocene era [19]. Gatan mud volcanoes are located near the Bonji anticline.

2.2. Characteristics the main mud volcanoes

The studied mud volcanoes include four craters of G1, G2, G2a and G2b (Table 1, Fig. 5). In the 1:100,000 scale geological map of Jask-Gatan [21], the G1 mud volcano is placed near the Bonji anticline and three other mud volcanoes are located near the beach in the 1:250,000 scale Taherouei map [22]. In terms of geology, the G1 mud volcano is in the Giushi marl unit, but three other mud volcanoes are located in the risen coastal sediments. The morphology of the mud volcanoes is largely controlled by the viscosity of the extruded mud. Based on the variable viscosity and eruption intensity, the shapes of the mud volcanoes can be divided into five types, i.e. mud cone, mud dome, mud pie, mud pool, and mud pore [6]. The studied mud volcanoes have two types of pool-shaped mud volcanos (G1) and cone-shaped mud volcanos (G2) (Fig. 5a and b).

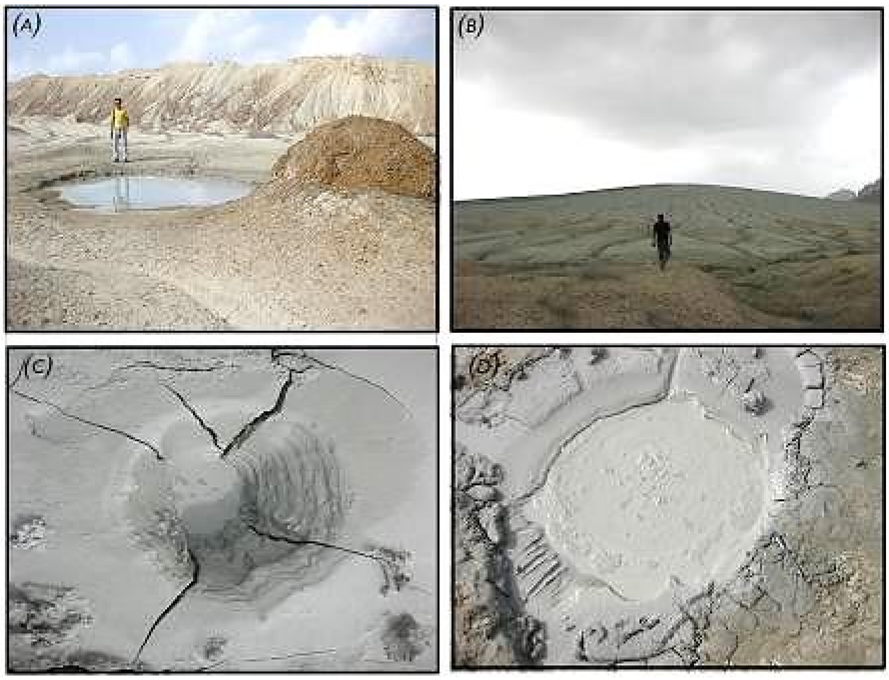

Fig 5. The morphology of the Gatan Mud Volcanoes. A) Mud pool B) mud cone C) mud pie and D) mud pool with abundant gas.

Table 1. Characters of the studied Gatan Mud Volcanoes

Name	Type of mud volcano	Location (UTM)	Result of XRD analysis	
			Major minerals	Minor minerals
G1	Pool-shaped	524809 , 2875160	Calcite, Quartz, Albite, Ilitte	Halite, Chlorite, Dolomite
G2	Cone-shaped	524015 , 2876955	Calcite, Quartz, Albite, Ilitte	Dolomite, Ankerite, Halite
G2a	Pie	523956 , 2877083	Not determine	
G2b	Pool	523993 , 2877120		

The G1 mud volcano is located farther from the sea at a height of 10 meters above the sea level. It has a circular crater with a diameter of 5 meters, covering an area of approximately 20 square meters and with a pool full of muddy water and low viscosity. This mud volcano is surrounded by small mountains and hills of Giushi marls. The muddy water is mostly constituted of clay silt with the sediment color being dark greenish gray. The G2 mud volcano is the largest and main mud volcano in the Gatan area. It has a cone shape and elliptical crater of 20 meters in diameter and covers an area of approximately 300 square meters and is located 15 km off the coast of the Oman Gulf on the risen marl sediments of the sea. This mud volcano has two minor craters (G2a and G2b). The G2a mud volcano is pie-type and the G2b mud volcano is mud-pool type with abandoned gas (Fig. 5c and d). Domains of the G2 mud volcano are influenced by recent processes and other activities like erosion. The silt around the mud volcano is fresh, which represents their constant activity. This mud volcano has a pool full of water and mud. Based on the mud volcano activity, which is on an average rate of once every 6 to 10 seconds, some water and mud erupt out (Fig. 6a). Besides the central part of the basin, eruption can be seen in other parts as well. In addition to dark greenish gray clay-silt sediments in the water, some muddy water of brown to black is observed in the marginal parts of this mud volcano, which are oily and are probably evidence of hydrocarbon material erupting out and due to their lighter weight, are driven toward the mud volcano crater wall and float on water (Fig. 6b). In addition to the main crater, there are two small mud volcanoes nearby that always have activity and are mud pie and mud pool type. In areas adjacent to the mud volcanoes, there is a thick sequence of sandstone and marl with large shells, such as bivalves and *Gastropods* (Fig. 7). Large amounts of shells on the marls of the region show a sign of rising coasts.

Fig 6. a) Methane emission and bubble formation in the G2 mud volcano, b) Crater of the G1 mud volcano

Fig 7. Bivalvia and Gastropoda fossils on the marl

3. Methods and Materials

In this study, after collecting topographic and geologic data and satellite images, the geographical location of the mud volcanoes was recorded and then geological and morphological studies were performed through field investigations. Then the outlet muddy water and the surrounding mud were sampled. Dried mud samples were sent to the Kansaran Binaloud laboratory to prepare a thin microscopic section. The whole-rock major, minor, and trace element contents of the samples were also determined by ICP-OES and all the other elements were determined by XRF. The major and trace element analyses were performed on glass discs (fusion beads) and powder pellets, respectively. The powder pellets and fusion beads were run through a Philips Pw 1480 XRF spectrometer equipped with either a 3-kW rhodium anode tube or a tungsten anode tube. Minerals were determined by XRD with the Philips Pw 1800 in the laboratory of Clausthal University in Germany. Finally, the obtained data were analyzed and evaluated.

4. Result and interpretation

4.1. Petrography

The thin microscopic section of G1 sediment samples shows a powdered limestone, a major part of which is made of a fine-grained context of particulate carbonate mud in mudstone size (Fig. 8a). Particles of metallic minerals (iron oxide) with very fine clastic quartz of particulates and size plus silt can be seen scattered throughout the sample (Fig. 8b). A thin microscopic section of sediment samples of G2 mud volcano shows necrotic peloid particles created by the activity of microorganisms with algae coatings. Non-skeletal carbonate components are also observed in a fine-grained carbonate context (Fig. 8c and d).

4.2. Geochemical analysis of extruded materials

The muddy sediments, water, oil, and gas from the mud volcanoes are significant in the study of processes occurring at depth, including assessment of hydrocarbon accumulations and originated material and formation mechanism of the mud volcanoes [2, 3, 4, 7, and 23]. In our study, we collected samples of muddy sediments and water to perform geochemical analyses.

4.2.1. Mineral phases of muddy sediment

In order to identify mineral phases and determine the chemical composition of the area's mud volcanoes, four samples were taken from inside and outside of the two mud volcanoes and they were analyzed after preparation with XRD analysis. Phase analysis of the samples shows that although the relative peak intensity of the different phases is slightly different, the mineral composition of the samples is almost the same. In the G1 sediment samples among the marl hills, the highest constituents are calcite and quartz minerals respectively. However, in G2 sediment samples near the coast of Oman, the largest constituents are the minerals quartz and calcite respectively (Table 1, Fig. 9).

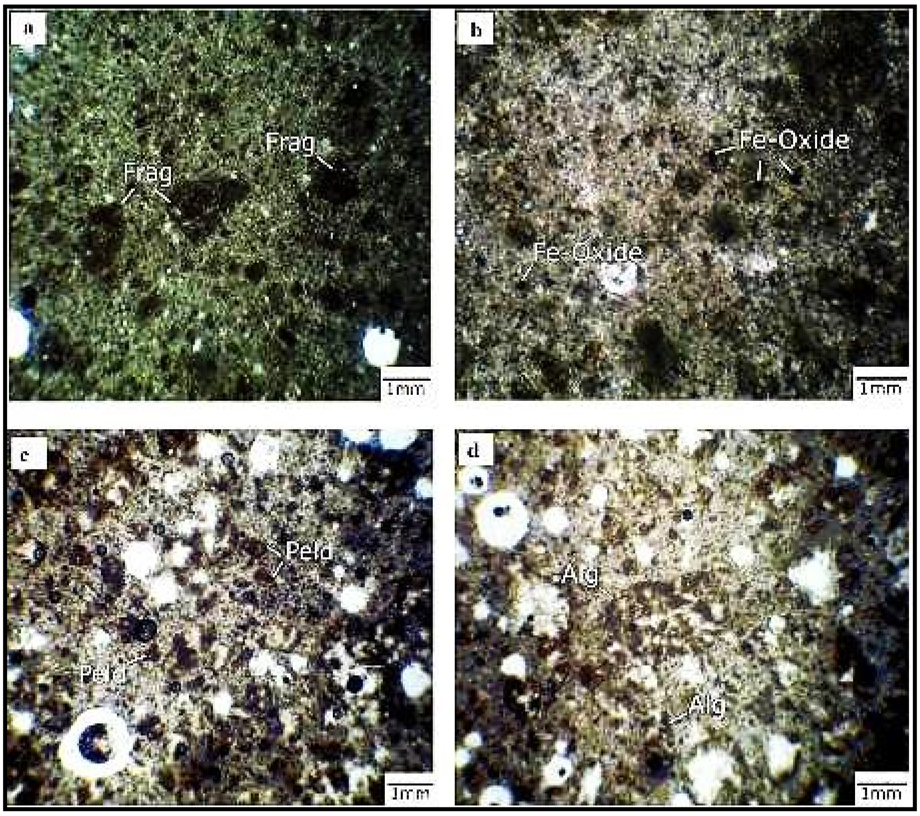

Fig 8. a) Particles carbonate mud in mudstone, b) Particles of metallic minerals (iron oxide) with very fine clastic quartz, c & d) necrotic peloid particles created by the activity of microorganisms with algae coatings.

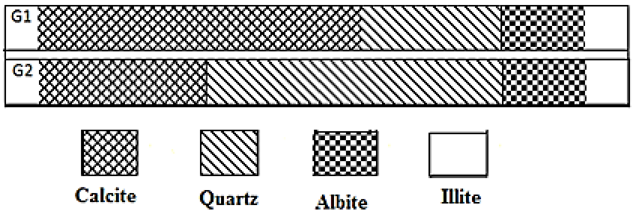

Fig 9. Comparison of mineral phases in G1 and G2 sediments

In addition to these two minerals, other minerals such as illite, albite and orthoclase, dolomite, and polygorskite were detected in the samples. Halite mineral is reported as a minor mineral and in low amounts in the samples. The phase analysis results also confirm the study of thin microscopic sections, because the major percentage of constituent minerals of thin sections in the phase analysis appears as the main minerals. Formation of polygorskite, a magnesium-rich mineral, represents an alkaline and silicon-rich environment.
According to aggregation studies performed on the deposits from Gatan [24], constituent particles are smaller than 2 microns in diameter and are mainly clay minerals, and the coarse particles have sizes of sand and gravel. Detrital particles such as quartz, clastic carbonate, and clay and biochemical minerals are mainly composed of bivalve shells, gastropods, and so on. In this study, different types of bed sediments of Gatan were classified using the triangular diagram of Folk [25] into the many varieties of mud, sand, sandy mud, and muddy sand.

4.2.2. Major and trace elements of muddy sediment

In addition to phase analysis of the samples, they were also tested by XRF in order to study the changes in major oxides and some elements that constitute the mud of the volcanoes and to match them with the mineral phases.
The results of the chemical analysis are shown in Table 2. According to the results, the most abundant oxides are silica (37.72 - 40.01%), calcium (12.12 - 15.45), aluminum (9.21 - 10.45) (Fig. 10) and slightly low K_2O/Na_2O ratios, which conform to the most abundant main mineral phases (quartz, clay minerals, and calcite). Due to the pass of time, salt in the sediment will increase with evaporation. Salinity of the mud samples in the outer part of the mud volcano has risen, and thus, the amount of its chlorine is higher. In the ternary diagram (Fig. 11), SiO_2 (representing the amount of quartz or opal), Al_2O_3 (representing clay of the minerals), and CaO (representing carbonate)

deposits of the region show a combination of carbonate and alumina-silicate that suggests that the amount of its Al_2O_3 is a little higher than shale average. Sediments and soils consisting of highly weathered material predominantly found in tropical regions are known for their high Al contents [15].

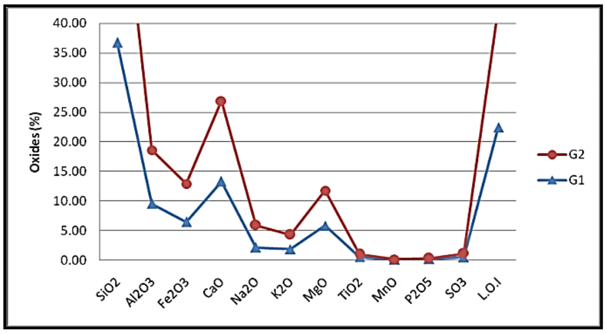

Fig 10. Comparison of major oxides in the G1 and G2 mud volcano sediments

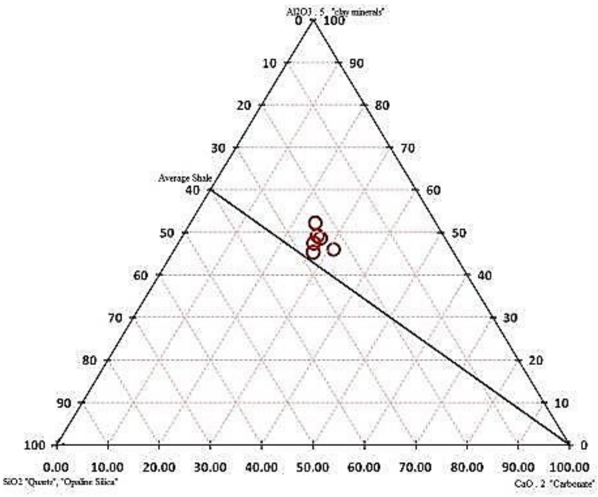

Fig 11. Composition of Gatan Mud Volcano sediments on Al_2O_3- SiO_2- CaO

Table 2. XRF analysis results of the studied samples

Major Oxide (wt %)	G1	G2
SiO_2	37.72	40.01
Al_2O_3	9.21	10.45
Fe_2O_3	6.06	6.40
CaO	15.45	12.12
Na_2O	1.95	2.55
K_2O	2.12	2.17
MgO	6.95	6.45
TiO_2	0.538	0.560
MnO	0.076	0.069
P_2O_5	0.183	0.148
SO_3	1.220	0.828
L.O.I	18.74	18.19
Minor Elements (ppm)		
Cl	9851	10021
Ba	71	92

Because there are no samples plotting toward higher SiO2 contents in the ternary plot, quartz and biogenic silica fractions are rather low or negligible. These samples contain high amounts of Ti, but are depleted in La, Ce and Y. The sediments presented here are characterized by relatively low TiO_2/ Al_2O_3 ratios.

4.3. The mechanism and formation of mud volcanoes in the Makran Coasts

Formation of mud volcanoes as a consequence of geological, geochemical, and hydrology factors are believed to play a major role in the formation of mud volcanoes [1]. From the tectonic setting, mud volcanoes are principally formed into one of these two positions: (1) areas of convergent plates and their marginal movements and (2) areas of divergent geological plates and high rates of sedimentation in deep parts. Gatan region's mud volcanoes in the Makran coasts are similar to the first case regarding the tectonic setting. The Oman oceanic crust has been subsiding under the Eurasian land since the Cretaceous, and today this subsidence rate has raised to about 400 km. Thickness of the sedimentary cover near the reflow plates exceeds 6 km; the subsidence angle is about 2° and the subsidence amount of the oceanic plate is about 4 cm per year. With the advancement of the subduction since the Paleocene era, the oceanic basin has moved in stages to the south [26].

At each stage of the shift and during the over-thrust phenomenon, a beam of the sedimentary prism is added to the continental plate in the north. Based on surface structures, a shortening of 25 to 30 percent is estimated in Makran [26].

5. Discussion and Conclusions

Abundant sediments as a source of material, high pore fluid pressure (overpressure) as the driving force, and certain trigger mechanisms are the conditions necessary for the formation of the mud volcanoes [7, 13, 27, 28, 29 and 30].

The developmental characteristics, geochemical analysis of extruded materials, and regional geology of mud volcanoes were analyzed at the Makran coast, southeastern Iran. Comparing the study of Gatan mud volcanoes [15] and these demonology studies of the Gatan [24] shows that the G1 mud volcano, located farther from the sea, mostly consists of primary carbonate minerals of less than microns, but the particles forming the G2, G3, and G4 located near the coast of the Oman Sea are often quartz, clastic carbonate, and clay minerals, and their particle sizes are larger than the sediments of the G1 mud volcano.

From the seismotectonic perspective, Makran has very poor seismicity power as an active subduction zone. This is for two reasons: 1) a low slope subduction and 2) because Makran is an accretionary set in water. Due to the presence of water in the pores of rocks, they show a plastic behavior rather than a brittle one. In other words, the water presence reduces effective forces. However, marine terraces and mud volcanoes are a sign of the dynamism of this area. Formation of Gatan mud volcanoes is the result of rising muddy water along the faults and cracks in the crust to the earth's surface (Fig. 12).

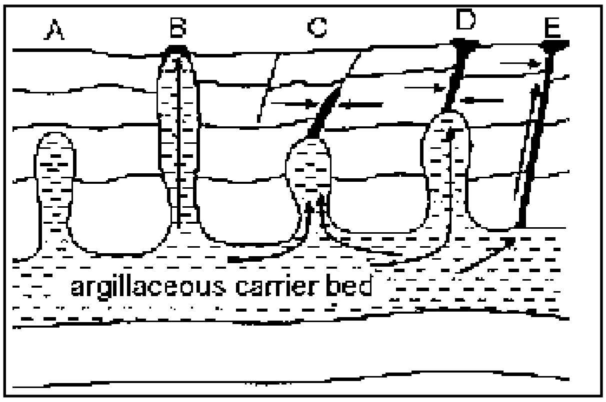

Fig 12. Picture showing submarine mud volcanoes. a) Seafloor/ surface – piercing shale diaper without a mud volcano, b) Mud volcano formed on top of a seafloor/ surface – piercing shale diaper, c)Seep, and d & e) Mud volcanoes formed due to the rise of fluidized sediments along fault [2].

The mechanism is as follows: subduction of the oceanic crust of the Oman Sea beneath the Makran continental crust that fills the clay and marl layers with gas and water, and the high pressure caused by the subduction that causes buckling in the upper layers; if the pressure is too high, it cuts them to the ground level and creates a conic mud volcano. The above mechanism applies entirely to mud volcanoes in the Makran coasts.

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