Mud volcanoes in Sistan and Baluchestan Provinces, Makran Coast, Southeast Iran

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Abstract — Mud volcanoes are prevalent along the Makran coastal region and two of them are described here, Borborok and Pirgel. They form marked geomorphology rising several tens of metres above the surrounding plains and erupt mud of varying viscosities, colour and composition; associated gas, mainly carbon dioxide with some methane that causes bubbles to form. Their origin is attributed to a dewatering phenomenon associated with the subduction of the Oman Sea plate beneath Eurasia.

Keywords: SE Iran, mud volcano, geomorphology

INTRODUCTION

Most mud volcanoes in SE Iran occur in close proximity to the sea along the coastal region of the Oman Sea (Figure 1A). The mud volcanoes in SE Iran are of two types, hot and cold (Negaresh, 2001). The hot mud volcanoes, associated with the Taftan and Bazman igneous volcanoes located some distance inland, are the aftermath of volcanic activity and the temperature of the extruded water and mud varies from 70° to 90°C, much higher than the ambient temperature. The exuded gas is sulphurous and sulphur incrustation forms in their craters. Cold mud volcanoes are sedimentary-tectonic in origin and are entirely unconnected with the igneous activity with water and mud at the same or lower than ambient temperature. The exuded gas is mostly carbon dioxide and biological in origin. The Borborok and Pirgel mud volcanoes described here are of the cold, sedimentary-tectonic type. Amongst the twelve mud volcanoes in the province of Sistan and Balochistan, only the Pirgel mud volcano is located inland some 300 km from the coast in the mountains between Khaash and Bazmaan (Figure 1C). Most of the mud volcanoes possess one or more mud cones which rise several meters high above the ground. However, some mud volcanoes such as the Ayen, Sanad mir Suban and Kaashi do not have cones and are simply reservoirs containing water and mud with no topographic expression and cannot easily be distinguished from the adjoining ground. Each bears a distinctive morphology with no common shape or morphology. Variations in the erosion rates together with their size and thickness has developed new and spectacular land forms.

Little has been written about mud volcanoes in Iran. Accordingly, several visits were made to Borborok and Pirgel, to pinpoint their geographical locality using GPS, to study their geomorphology and to collect water, mud and gas samples.

BORBOROK

The Borborok mud volcano is located 15 km SW of Kahir village, two km N of Chegerdaan Laash village, nearly three km to the W of the Kahir-Zar Abad asphalted road, and about five km (direct distance) to the NE of Napag mud volcano (Figure 1B; Armed Forces, 1984). Borborok has been described as the best developed mud volcano on the coast of the Oman Sea and in the province of Sistan and Balochistan (Snead,1970). The distance between Borborok and the Napag mud volcanoes via earth-asphalted road is 14 km, whereas the distance between Borbork and Ayen mud volcanoes via the Malron route is only 16 km (Figure 1B). The geographical location of Borborok recorded using a GPS is 59° 59′ 46″ E and 25° 30′ 43” N.

Geology and geomorphology of the Borborok region

The bedrock geology of the Makran coast in the Chalabar region consists of Middle Miocene flysch sequences associated with post-Middle Miocene marls and limestones overlain by Quaternary unconsolidated sediments comprising eolian sand dunes, mud flat and marine terrace deposits in the coastal areas. Borborok is located in Tertiary sequences of the coastal region.

The geomorphology and degree of erosion at Borborok suggests that it is older than the other mud volcanoes in the province. It is multi-cone, contrary to most of the other mud volcanoes in the area which either have a single cone or none at all (Figures 2 and 3). The name Borborok is a Balochi term meaning gurgling and seething in Persian, and describes the bubbling of the relatively thin water and mud which issue from the vents there. According to Snead (1964), some attributes of the mud volcanoes in Iranian Balochistan appear analogous to Chandragup, Ormara and Kandawari mud volcanoes situated further east in Pakistani Baluchestan.

Description of the Borborok Mud Volcano

Since 1989, the writer has monitored the activity of mud flowing from the Borborok vents where the process of mud extrusion differs from the other mud volcanoes. Sometimes the craters of some of the peripheral cones become filled with mud which then overflows down the side of the cone for a considerable distance from the crater (Figures 4 and 5). This mud rarely contains bubbles. Borborok had always been active since 1989 but on the last visit on February 5 2004, activity had ceased and the mud volcano had unexpectedly become dormant. The cause of the sudden extinction is as yet unknown.

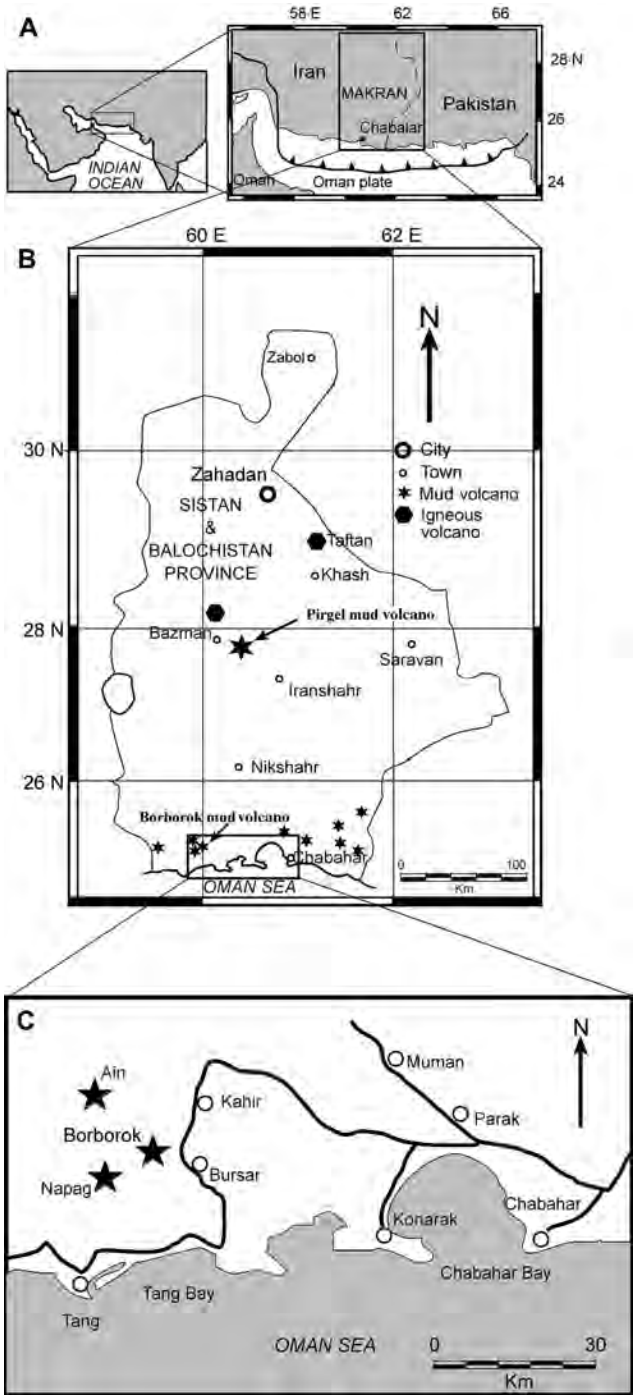

Figure 1: A– Location map of SE Iran with the position of a north-facing subduction zone off the Makran coast (adapted from Hosseini-Barzi & Talbot, 2003). B– Location of mud volcanoes in Sistan-Balochistan Province, SE Iran. Prigel mud volcano is in the central part of the province. C– Location of Boborok and nearby mud volcanoes in the coastal region, SE Iran.

When Borborok is at peak activity, the ejection of mud is accompanied by an unusual gurgling sound which is not heard at other mud volcanoes. If a stone is hurled into the mud reservoir, a weird and bizarre sound resounds through the atmosphere. Apart from the gurgling sound, the Borborok mud volcano has so far displayed no explosive state, unlike the Napag mud volcano which erupts violently, noisy effusion of mud. Borborok is capricious in temperament. Sometimes an inactive crater rejuvenates its activities and then at other times the crater suddenly becomes inactive.

In contrast to the smooth flow of mud at Borborok, the mud streams at Napag mud volcano lying five kilometers to the SW, are more viscous and appear as scaly and onion-skin-like shapes, visibly similar to volcanic aa-aa lava (Figures 6 to 9). The mud-streams appear to overlap each other, while covering a portion of mud layers lying underneath (Zomorrodian, 2002).

The Borborok mud volcano appears conical with one principal cone and several peripheral cones developed on its flanks (Figure 2). The mud volcano must formerly have been higher and a portion of the old cone can be seen as a higher mud parapet on the south eastern quadrant of the present cone (Negaresh, 2001). The highest of the remnants of the eroded cone is 32 m above sea level whereas the present cone is 21 m above sea level. Since a major portion of this mud volcano together with its old crater has been eroded modifying the original shape and Snead (1970) estimated that the height has fluctuated between 90 – 100 m above the sea level in the past.

The mud streams of the Borborok mud volcano have spread far from its crater forming a cone with an approximate diameter of 300 m to 350 m extending over an approximate area between 7.1 ha and 9.6 ha. Whereas at Pirgel located between Khash and Bazman, the mud volcano occupies an area of 50 ha.

The Borborok mud volcano has, at present, 14 dormant craters and one or two active craters on its eastern slope. The morphology of the various craters suggests that there was no permanent single crater in the past. Mud erupted from different sites and each crater erupted thick mud which formed higher and better-shaped cones. The craters changed configuration and resulted in several small satellite cones. Most of the crater of the original main cone has been removed by erosion but its remnants show that the diameter of the crater varied between 100 m and 150 m in the past whereas the present surrounding active craters measure from 20 m to 70 m.

Mud streams pouring from the peripheral craters tend to flow down the sides of the main cone with varying spread rates and dimensions. However, they have never exceeded 200 m to 300 m during the last 15 years. The quantity of mud issuing from the Borborok mud volcano remains

Figure 2: Principal cone and some of the peripheral cones at Borborok.

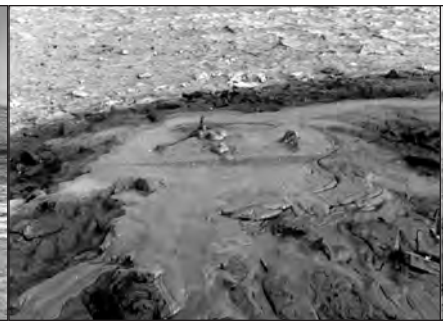

Figure 3: One of the active peripheral craters of the Borborok mud volcano.

Figure 4: Outpouring mud from the active cone of the Borborok mud volcano flows down to the foot of the mud volcano.

Figure 5: Reactivation of an old crater with fresh black-colored mud flowing across old white mud, Borborok (winter, 1996).

Figure 6: Coarsely vesicular mud flowing from Napag mud volcano.

Figure 7: Recent mud flow deposited over older, coarsely vesicular flow at Napag mud volcano.

constant when active even though it may be dormant for part of the time. Nevertheless, field observations show that the average quantity of mud does not exceed from three to six liters per second. There are few bubbles in the mud. The mud erupted from Borborok is usually thin (Figure 10) but variations in liquidity of the mud occur from time to time. For example, one of the active craters of this mud volcano contained unusually thin mud when examined on February 24 1996 but the same crater was spewing out relatively thicker mud after a lapse of 13 days (Negaresh, 1997). Sometimes the mud becomes very fluid and flows 200 m to 300 m to the foot of the mud volcano.

Snead (1970) estimated the temperature of the mud at 28°C while the ambient temperature was 35°C during his visit to the mud volcano. The last time the writer inspected the mud volcano at noon on the February 5 2004, the mud volcano was dormant and temperature measurements of the mud were not possible. However, the ambient temperature was 31°C. The mud temperature, like ambient temperature, to some extent, depends on season and time of assessment as well as the depth from where the mud originates.

Although no extensive badlands are found at the Borborok mud volcano as are found at the Napag and Drabole mud volcanoes, the eastern slope has, to some degree, developed badland features due to running water eroding ravines and channels. All the slopes are composed of identical material and have the same rainfall and the reason why there are badlands on the eastern slope of this mud volcano is not known. Perhaps it is due to the prevailing easterly wind.

The amount of solid material ejected from the Borborok mud volcano is comparatively low unlike at nearby Napag. Clasts of more than four to five cm are rarely seen. The component material is everywhere identical and the cause of the deficiency and small size of the clasts may be a function of the shallowness of the source.

Amongst all the mud volcanoes of the Sistan and Balochistan province, evidence of subsidence can be seen only at the Napag mud volcano where a semi-circular cliff two to three meters high indicates collapse. At Borborok a smaller subsidence feature can be seen on the NW slope where there is a shallow scarp seven to ten meters deep extending for about fifteen meters indicating that part of the cone has subsided. The subsidence appears to be reasonably fresh and recent as an old feature in relatively soft mud would have been removed by erosion.

PIRGEL

Whereas the rest of the mud volcanoes in the province are situated on the coastal plain, Pirgel is located in the central region of the province, almost 300 km from the Oman Sea coast. The Pirgel mud volcano lies to the east of Bazman volcano and to the SW of Khash town, in the mountain range of Seya Bandaan (Figure 1C). It is not marked on the geological map of Iran and no previous investigation has been made. The native people of the land attribute mud volcanoes to a holy person, a saint or a religiously devout mentor. They believe that the mud from this mud volcano belongs to a spiritual mentor and believe in the sanctity of

the mud and its location and they have named it "the mud of the religious mentor", that is a place where the mud belongs to a saintly devout (Negaresh, 2001).

The site was visited several times and the mud volcano is located at 60° 29′ E, 27° 59′ 5″ N. It is 78 km from Gohar Koh, 113 km from Noke Abad, 119 km from Eskal Abad and 224 km from Zahedan. The access route to Pirgel is partly asphalted as far as the inhabited district of Gohar Koh. Onward access to the mud volcano is by a foot track which is unsuitable for four-wheel drive vehicles.

Geology and geomorphology of the Pirgel region

The regional geology comprises highly folded Mesozoic mainly Cretaceous rocks overlain by Cenozoic and Quaternary less deformed strata (National Oil Company of Iran, 1977). The Pirgel mud volcano erupted onto marls exposed in the core of an anticline about one to four km across flanked, by two synclines, trending NW-SE (Figure 11). The rocks are predominantly sandstones with few conglomerates, shales, and siltstones, some dark-gray limestone (National Geological Organization of Iran, undated). On the eastern part of the mud volcano, the Karvandar fault with a NW-SW movement, separates folded, and metamorphosed flysch deposits in the east from colored-mélange lying to the west.

The geomorphology of the region around Pirgel is relatively rough and uneven. The interbedded shales and sandstones are deeply eroded. Vertical sandstone layers are eroded into scarps some 30 m to 40 m high. Extremely uneven animal dirt tracks pass through the eroded shale strata. The flanks of the mud volcano are covered by numerous rills and vast gullies with deep blind valleys. In the northern part of the mud volcano, deep ravines have formed, most probably by rapid underground streams fed by rainwater and which have created subsurface tunnels beneath the mud on the flanks of the mud volcano. Subsequent erosion has lead to the collapse of the tunnels.

The Pirgel mud volcano

The Pirgel mud volcano is located in a narrow anticlinal marl sequence between two elongated synclines clearly visible on satellite imagery and lies on a marl hill which has a length of about 1 km and a width of nearly 500 m (Figure 11). The mud volcano extends across an area of 50 ha. On the upper part of the hill, there are cones with craters of various sizes.The main cone rises 127 m above the surrounding countryside and is 1667 m above the sea level. There are seven active craters and four dormant cones at present (Figure 1C). The mud volcano extends over an area of nearly 50 ha.

Thin, watery mud erupting from the mud volcano is saline and is dark gray in color, with nominal exudation of carbon dioxide (CO_2) gas (Figures 12 and 13). Samples of gas, water, and mud were collected and sent to Chemistry Department University of Sistan and Balochistan. Dr. Maysum Nourozifar performed the laboratory analyses to identify the mineral composition.

The activity at various craters varies throughout the year or even in different years. Sometimes, an active crater completely dormant and then a dormant crater starts erupting afresh.

Seven of the craters were active or semi-active at the time of the last visit on May 22 2003 (Figure 14). Four craters were dormant. The distinguishing feature of this mud volcano compared to the other mud volcanoes in the province is its greater height. The maximum height is 1667 m above the sea level and the minimum height is 1540 m so the height of the mud volcano is 127 m above the surrounding plain and is the highest mud volcano not only in the province as well as in Iran.

Although the height of the hill is 127 m none of the active or inactive cones of exceeds seven meters and most of them are from two to four meters high. Pirgel mud volcano covers about 50 ha compared to the others which barely cover two hectares.

Although there are active igneous volcanoes in the region, the Pirgel mud volcano belongs to the cold, sedimentary type. The mud volcano formation mechanism depends on the origin of pressure applied to spew out from below. Diverse hypotheses and theories, in this regard, have so far been expounded. Formation water is trapped within the sediments which leads to excess fluidity and mobility in clays, resulting in intrusion of liquid mud along faults and fractures. If the pressure is sufficient, liquid clay is forced to the surface where it gushes out, along with gas. Seismic factors may also contribute to the ejection of water and mud from a mud volcano. Thus, the main factor of mud volcanism (whether the mud volcano is of the cold or hot, small or big type or having a cone or a reservoir) is high pore water pressure.

The mud of the Pirgel mud volcano is more saline than that of the other mud volcanoes in the province, and the exuding gas is solely carbon dioxide whereas the other mud volcanoes of the province contain minor quantities of methane. Pirgel has numerous craters and cones unlike the other mud volcanoes of the province, such as Napag, Sesad, or Dorabole, which have single cones. Furthermore, Pirgel has a number of fresh water-springs, whereas none of the mud volcanoes elsewhere in the province have fresh springs. The color of the ejecting mud from other mud volcanoes is usually dark or light gray, whereas at Pirgel, the mud is yellowish or cream colored.

The Pirgel mud volcano lies between the igneous volcanoes Taftan and Bazman in the NE and SW respectively and whereas Taftan and Bazman volcanoes are hot, Pirgel mud volcano is cold. This mud volcano contains no noticeable amount of gas and the mud contains mostly small bubbles 10 to 20 cm, rarely 30 cm in diameter unlike that at Napag mud volcano near the coast.

The characteristics of bubble formation at the seven active craters of the mud volcano recorded on May 22 2003 are shown in Table 1. The period of bubble-formation process, on the average, ranges between 15 to 600 seconds and the life-span of successive bubbles fluctuates between

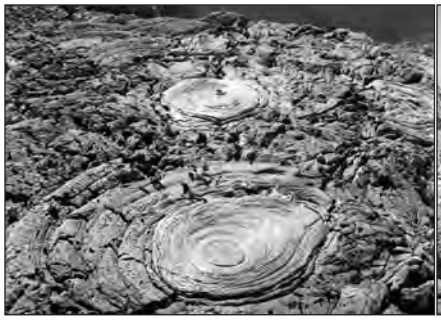

Figure 8: Viscous mud forming concentric patterns in a small vent at Napag mud volcano.

Figure 9: Large viscous mud bubble at maximum development, Napag mud volcano.

Figure 10: Very fluid mud flowing like a stream from the crater. The fluid mud flows to the foot of the Borborok mud volcano.

Figure 11: A partial view of the marl hill on which lie the craters (indicated by arrows) of the Pirgel mud volcano.

Figure 12: Slackening of the mud cone activities at Pirgel and deposition of salt in crater No.2, situated on the SW side of the Pirgel mud volcano.

Figure 13: Mud-exudation manner from the crater No.6, situated on the north and northwest of the Pirgel mud volcano.

Table 1: Characteristics of bubble at the seven active craters of the mud volcano at Pirgel.

No. of craters of mud volcano	Crater's location on the mud volcano	Bubble exudation period in seconds	Exudation life-span in seconds*
Crater No.1	SW of the mud cone	15	5
Crater No.2	SW of the mud cone	15	5
Crater No.3	Middle of the mud cone	**	**
Crater No.4	N and NW of the mud cone	**	**
Crater No.5	N and NW of the mud cone	600	29.5
Crater No.6	N and NW of the mud cone	270	201
Crater No.7	N and NW of the mud cone	8	3-5

Note: Measured by engineer M'ashallah Rahmani, Chemistry Department and Dr.Maysam Nourozi, Chemistry Department, University of Sistan & Balochistan. * Period between bubbles appearance and collapse. This process continues so incessantly that there exists no time space between each bubble. At certain times and at certain craters, bubbles explode while the new ones come into existence. The aforesaid time is the time-period when the bubbles take shape continuously and incessantly one after the other (the said time is the mean of a three-phased measurement). ** Bubbles absent on May 22 2003.

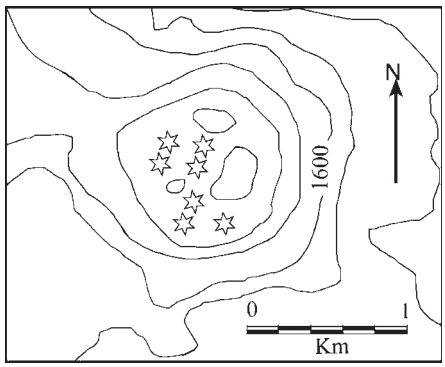

Figure 14: A topographic sketch of the summit of Pirgel mud volcano showing the distribution of seven active vents. Contours at 20 m intervals.

3.5 seconds and at the most 201 seconds.

The mud viscosity of the Pirgel mud volcano is low compared to other mud volcanoes at Ayen, Kaashi, Sind Mir Soban, Borbor where the mud is more viscous but more dilute than the mud of the Napag mud volcano (Negaresh, 1997).

The ejected mud from most of the mud volcanoes is gray and dark gray and the mud at Pirgel is the same except crater No.5 located on the NW side of the mud volcano where the mud is yellow or creamy derived from cream coloured sediments. Due to the highly salinity salt is deposited on the rims of the mud volcano when the mud volcano activities slacken and the evaporation rate rises (Figure 6). The temperature and pH of the mud from seven craters at Pirgel are given in Table 2.

The temperature of ejected mud fluctuates between 20.5 to 30°C whereas the pH varies between7 to 9.5. The ambient

temperature at 2:00 pm ranged between 37 to 39°C, lower than that of the the mud. Laboratory analysis indicates the gas is carbon dioxide rather than methane confirming the field test carried that the gas extinguishes a burning match-stick. The water of this mud volcano is highly saline compared with the other mud volcanoes in the province.

Table 3 shows the chemistry of two samples of ejected water from the mud volcano. Water sample No.1 is cream-coloured, was taken from the crater No.5 on the March 28 2003, while water sample No.2, is gray, was taken from the crater No.7, situated on the NW flank of the mud volcano, on the May 22 2003.

The sodium content in both samples is very high and the content of sodium, potassium, lithium, magnesium and lead in water sample No.1 is greater than water sample No.2. Iron and calcium are higher in water sample No.2.

Mineral composition of the extruded mud from the Pirgel mud volcano collected from craters No.5 and 7 were analyzed by XRD equipment. Quartz is common in both the samples, but the composition of these two samples, despite the fact that their craters are only seven meters apart, is different. The cream color taken of the sample from crater No. 5 is probably related to the calcite, calcium and potassium, while the gray color of the sample from crater No. 7 by the presence of iron and magnesium minerals.

Table 2: Temperature and pH of mud at Pirgel.

No. of mud cone craters	Crater's location on the mud cone	Exuding mud temperature in °C	Exuding mud pH
Crater No.1	SW of the mud cone	25	8.5
Crater No.2	SW of the mud cone	24	8
Crater No.3	Center of the mud cone	28	9
Crater No.4	N and NW of the mud cone	*	*
Crater No.5	N and NW of the mud cone	24.5	8
Crater No.6	N and NW of the mud cone	20.5	7
Crater No.7	N and NW of the mud cone	30	9.5

Note: Measured by Dr. Maysam Nourozi and Ma'shallah Rahmani at 2 pm on May 22 2003. *The crater was quiescent making measurements of temperature and pH impractical.

Table 3: Elemental chemistry of mud samples taken from Pirgel.

Element		Water sample No.1 with creamy color mud, crater No. 5 (ppm)	Water sample No.2 with gray color mud, crater No. 7 (ppm)
Copper	Cu	—	—
Manganese	Mn	—	—
Lead	Pb	1.4	0.56
Iron	Fe	0.4	3.1
Lithium	Li	22	17
Calcium	Ca	14	18
Magnesium	Mg	164	124
Potassium	K	250	210
Sodium	Na	15200	13600

ECONOMIC AND SOCIAL PROSPECTS

The mud from the mud volcanoes could be utilized in a number of useful applications in the ceramics, pottery, gas utilization, tourism and mud therapy industries. If the mud from the mud volcano is thin, mud therapeutic activities are feasible, either smearing the mud on their bodies or by total immersion into the thin mud. The indigenous people strongly believe that the mud of this mud volcano, in addition to having the therapeutic qualities, has also the healing properties. The therapeutic use of mud is not an exclusive phenomenon of the mud volcanoes in Sistan and Balochistan. Mud theraputic remedies are in vogue in Azerbaijan and generates a substantial amount of foreign exchange as nearly 40% mud volcanoes of the world are found there (Dinets, 2000). Mud is not only used as an treatment for skin complaints, but it is also used in the treatment of backache and rheumatoid arthritis. (Guliyev, 1998).

The Pirgel mud volcano is in many aspects, noticeably different compared with other mud volcanoes in the province and it is one of the outstanding and unique mud volcanoes of Iran.

ORIGIN OF THE MUD VOLCANOES IN SE IRAN

Mud volcanoes occur both in shallow water offshore and up to 300 km inland. Eocene to Miocene flysch sequences forming part of an accretionary prism related to the convergent margin are exposed further inland towards the Lut block. The present magmatic arc formed by collision of the Arabian (Oman) plate with Eurasia lies onshore some 450 – 500 km behind a deformational front 100-150 km offshore in the Oman Sea (Figure 1A), (Hosseini-Barzai & Talbot, 2003). This convergent margin in the Oman Sea offshore of the Makran coast has caused uplift of Holocene to Recent coastal deposits to the extent that some beach deposits are upwards of 100 m above current sea level (Vita-Finzi, 1987). Two beach terraces occur at Jask, the highest 12 m a.s.l. and nine terraces have been identified at various levels on the Konarak peninsula (Page *et al*., 1979).

Mud volcanoes occur above a subcreted zone comprising 3 km of Makran sands overlying turbidites (Hosseini-Barzai & Talbot, 2003; Kopp *et al*., 2000; Harms *et al*., 1984; Platt *et al*., 1985). The 'subcreted' zone is where strata are transferred from the downgoing slab upwards onto the base of the overlying Eurasian plate, recognised by the northwards sequence of basin-plain sediments passing into slope and then shelf strata concordantly (Leggett, 1987).

Mud volcanoes (Fowler *et al*., 1985; Schluter *et al*., 2002) are the result of expelled formation water where dewatering stiffens the subducted sediments (Hosseini-Barzai & Talbot, 2003). Their activity is often triggered by earthquakes.

It seems likely that mud volcanoes are sourced from depths of up to 3 km and probably located along fault weakness planes aligned on a NE and NW system and caused by the regional convergent tectonics. In the case of Pirgel, its location in the core of an anticline is similar to the mud volcanoes at Jerudong, Brunei Darusalam and in the lower Baram valley in Sarawak, East Malaysia Wilford, (1961).

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