The mud volcanoes of Pakistan

G. Delisle

Abstract Marine-geologic investigations on the Arabian Sea by Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in 1995 and 1998, and land expeditions in 1998 and 1999 to the coastal regions of the Makran Desert/Pakistan have extended the knowledge of the aerial distribution of mud volcanoes. These structures rise from under-compacted formations within the regional accretionary prism, which is built by the subduction of the oceanic crust of the Arabian Sea and its km-thick sedimentary load. The occurrence of mud volcanoes is limited to the abyssal plain near the accretionary front, to the coastal region of the Makran Desert and to a region in the interior of the Desert to the south to southeast of the so-called Hinglay Synform. The location of mud volcanoes in Pakistan is clearly tied to fault systems. Mud volcanoes are conspicuously absent on the lower slope of the accretionary prism, where thick gas hydrate layers have developed. The presence of large gas plumes emerging from the seafloor landward of the gas hydrate stability zone at water depths of less than 800 m points to a redirection of fluids from depth, which might explain the absence of mud volcanoes along the lower slope.

Keywords Mud volcanoes · Gas plumes · Makran · Pakistan

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Introduction

Mud volcanoes commonly occur in convergent margin settings and are expressions of the expulsion of under-compacted mud and fluids from formations in areas exposed to high sedimentation rates or to compressive tectonic forces. Mud volcanoes are known among other places from the coastal region of Pakistan (Makran Desert) and the upper slope and the abyssal plain seaward of the about 200-km-wide accretionary prism offshore the Pakistan coastline. These mud volcanoes show moderate variation in activity, only in some cases concurrent with earthquake activity (Snead 1964; Wiedicke and others 2001; Delisle and others 2002). This paper summarizes the knowledge on Pakistani mud volcanoes and limits itself to outlining the known key features. The reader is referred to the cited papers for more detailed information.

The setting

The oceanic crust of the Arabian Sea slowly subducts under the Eurasian land mass (Fig. 1) with a rate of approximately 4 cm per year (DeMets and others 1990). As the crust reaches the accretionary front, it is loaded by a sediment pile in excess of 6 km (White and Louden 1982; Minshull and White 1989; Gaedicke and others 2002) that has been built on it as a result of sedimentation rates in excess of 1 km per 1 million years. The ongoing subduction process, active at least since Cretaceous time (DeJong 1982), resulted in one of the world largest accretionary complexes, whose main part is exposed in the Makran Desert of Pakistan. The oldest parts are about 400 km inland from the Makran coast. Sediments of Plio- to Pleistocene age are exposed in the coastal zone (Hunting Survey Corporation Ltd. 1960). The coastal region of the Makran Desert is known for the existence of numerous mud volcanoes on the land side and the episodic appearance of mud volcanoes forming islands in the shallow, near-coastal waters, which are destroyed afterwards by wave action within months (Sondhi, 1947). The geologically youngest part of the accretionary prism is submerged under the waters of the Arabian Sea. The submerged accretionary prism exists along the lower slope of several upthrusted ridges (Kukowski and others, 2000). Sedimentation along the upper slope covers deeper thrust

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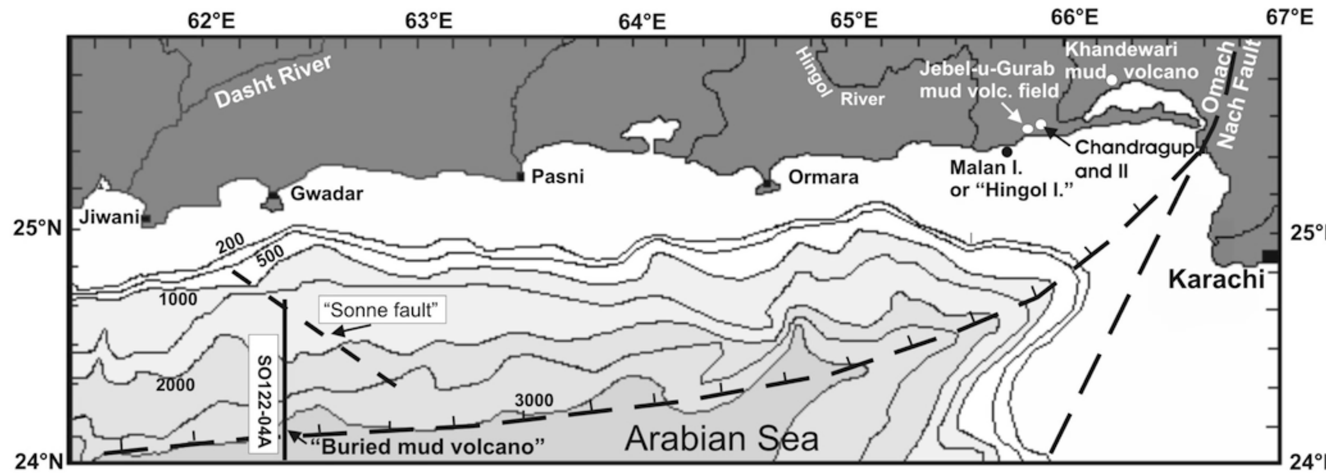

Fig. 1
Map of the coastal region of Pakistan with location of mud volcanoes mentioned in text. The Makran Accretionary Prism is bounded by the accretionary front, which runs roughly parallel to 3,000 m waterline west of 65°E

structures. The existence of a well-developed gas hydrate layer over large areas of the prism is suggested by the presence of bottom simulating reflectors (BSR) (see e.g. Minshull and White 1989; Roeser and others 1997). The stability field of methane in sea water suggests that gas hydrates should be stable in the area at water depths in excess of about 800 m. No mud volcanoes are known to exist along the lower slope of the accretionary prism. However, mud volcanoes occur again on the abyssal plain seaward of the accretionary front.

The abyssal plain

High sedimentation rates on the abyssal plain seaward of the accretionary front result in under-compacted layers, from which mud diapirs and mud volcanoes rise. Marine geological cruises of BGR in 1995 and 1998 provided bathymetric surveys of the seafloor, which show a large number of circular elevations (Wiedicke and others 2001) near the foot and seaward of the front of the accretionary prism. High-resolution 4 kHz sediment echosounding has identified a series of conical, up to 65-m-high mounds with diameters of up to 1.5 km. In addition, the well-stratified sediments in the vicinity show repeatedly acoustically transparent zones with diameters of 100–300 m, rising to near the seafloor. These are interpreted (Wiedicke and others 2001) to be caused by the rise of gas-rich fluids and mud.

Seismic line SO122–04A of BGR (Roeser and others 1997) shows a slightly bulged seafloor representing the early nascent stage of a newly forming accretionary ridge. It contains a buried sediment mound covered and surrounded by flat-lying sediments (Wiedicke and others 2001, Fig. 2). This pile (or possibly a composite feature made up of two neighbouring mounds) is associated with a deep fracture imaged by the seismic record. The base of the approximately 120-m-high pile is approximately 420 m below seafloor. Its diameter is estimated to be $\leq$ 2.2 km. The most probable interpretation of this pile is given by

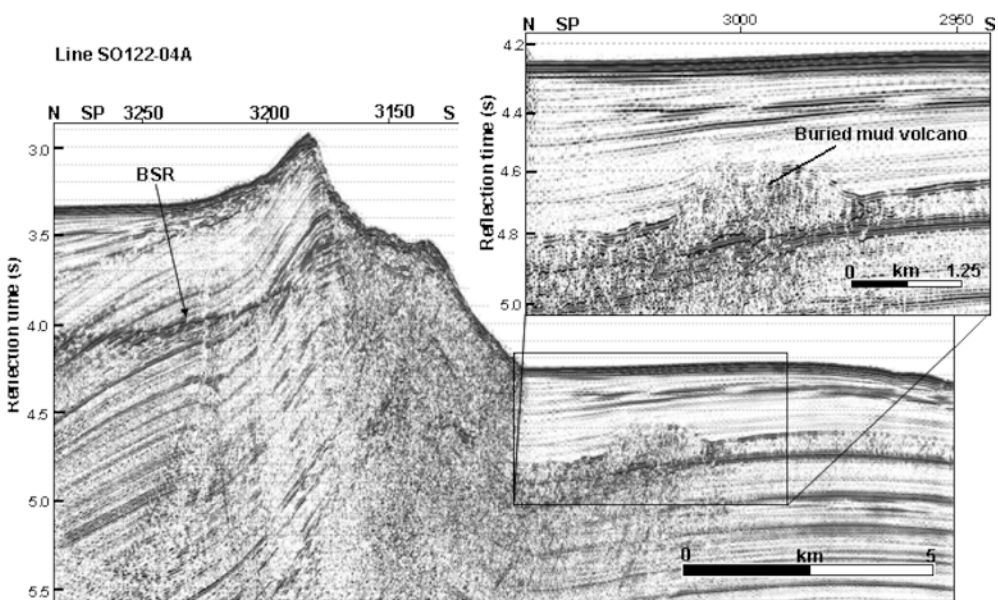

Fig. 2
The time-migrated seismic section of the multichannel reflection *seismic line* SO122–04a shows a structure between SP 2,960 and 3,020, which is interpreted as a buried mud volcano, approximately 0.3–0.55 s twt below seafloor (Modified after Wiedicke and others, 2001)

the assumption that a former mud volcano on the seafloor became inactive and was subsequently covered by further sedimentation. The regional sedimentation rate points to a burial age of about 460 ka BP. With all considered there is strong evidence for the existence of numerous mud diapirs on the abyssal plain of the Arabian Sea.

The accretionary prism

The accretionary prism is built by a succession of steep ridges (Kukowski and others 2001). The ridges are cut by erosive channels through which sediments are directly transported from the land and the upper slope area towards the deep sea. The accretionary prism has been postulated to be dissected by a strike-slip fault (named SONNE fault) that separates the western part of the Makran subduction zone with different intensities of plate boundary seismicity (Kukowski and others 2000). Reflection seismic profiles (see e.g. Minshull and White 1989; Roeser and others 1997) demonstrate the widespread occurrence of BSR indicative of the presence of gas hydrates. Given the regional water temperature gradient, gas hydrates should be stable in the area only in water depths of more than 800 m as derived from the gas hydrate stability field in a mixture of methane and sea water. Gas analyses of samples from different depth levels in the water column have revealed laterally drifting gas plumes that originate at water depths of less than 800 m (see Fig. 3a–d in Delisle and Berner, 2002). This limit closely correlates with the landward termination of the stability field of gas hydrates. This observation and the apparent lack of pathways for fluids through the lower slope accretionary prism has led to the interpretation of the gas hydrate layer that acts as a cap rock to migrating fluids at deeper levels.

Fig. 3
Malan Island shortly after emplacement (picture by courtesy of A. Tabrez, NIO, Karachi, Pakistan)

The upper slope

In addition to the observed gas plumes, numerous gas seeps were detected by surveys employing a TV-camera system, which was towed over the shallow seafloor. The gas seeps are indicated by white bacterial mats with sizes of typically one to several m^2 (von Rad and others 2000). For the near coastal region a history of periodically rising mud volcanoes forming temporary islands has been established. Well-documented events are the simultaneous emergence of three islands along the Makran coast during a strong earthquake in November 1945 (Sondhi 1947). The islands, placed apart from each other by more than 50 km were built by the discharge of typically several 100,000 m^3 of mud on the shallow seafloor. At the same time, a self-igniting plume of gas erupted on land near the mouth of the Hingol River "with such great force that the flames leaped thousands of feet high into the sky" according to Sondhi (1947).

Aerial photographs showed that the islands were made up of a series of parallel mud ridges, interpreted at that time (Sondhi 1947) as the result of the earthquake itself (frozen earth waves). It appears, however, to the author that these ridges are the result of mud extrusion from a fracture, whereby after reaching a certain height, the mud walls collapsed to the side only to give room for a second mud wall. This process eventually resulted in a series of mud ridges that were displaced sidewise from the central fracture. The islands were destroyed by wave action within months after emplacement (in early 1946).

New evidence for the emplacement of islands by extrusive flow mud through fractures emerged in 1999, when one island was apparently emplaced (Fig. 3) in the same position as one of the islands in 1945 (for details see Delisle and others, 2002).

The 1999 eruption was not accompanied by an earthquake that can be called upon as the initiating cause. This new island, called Malan Island, was apparently the result of destabilization of mud at depth and mud up welling driven by high gas content. Analysis of the gas discharged on Malan Island indicated methane of predominantly bacterial origin with only traces of admixed components of higher hydrocarbon components.

The coastal region

A number of mud volcanoes are known from the near coastal region, the most spectacular being the Chandragup mud volcano complex, made up of four mud volcanoes. The 100-m-high mud volcano Chandragup I (unofficial term) has been repeatedly described in the literature since 1840. A summary of the available literature is given in Delisle and others (2002). The shape of the mud volcano and its level of activity over the last 160 years appear not to have changed to any significant degree. The 15-m diameter mud lake in its crater shows almost persistent discharge of methane of bacterial origin with modest fluctuation on a

Table 1
Gas analyses from the Chandragup mud volcanoes

Sample	Locality	Sample type	CH_4 (vol%)	C_2H_6 (ppmv)	C_3H_8 (ppmv)
MA99–4A	Chandragup I	Gas from mud volcano	95.3	1,509.8	73.3
MA99–4B	Chandragup I	Gas from mud volcano	97.5	1,703.3	118.4
HS 3	Chandragup II	Gas from mud volcano	99.9	1,311.7	
HS 4	Chandragup II	Gas from mud volcano	99.9	749.7	
HS 5	Chandragup II	Gas from mud volcano	99.8	2,434.3	274.6

daily basis. Periodically overflows of the mud lake occur, but seem not to add to the overall structure of the volcano. The overflowing mud is drying off along the flanks of the volcano into mud flakes, which eventually crumble to dust and are blown off by wind. Visual inspection of the main mass of the volcano suggests an initial episode of massive and very viscous mud flows in strong contrast to the mud of low viscosity discharged today from the mud crater lake.
An approximately 20-m-high circular and inactive mud volcano rises from the south-western flank of Chandragup I. Its former crater was apparently once filled by an approximately 10-m-deep lake that has dried out completely. This smaller volcano might well be regarded to have been fed by a parasitic feeder channel originating from the main mud conduit of Chandragup I. The mud volcano Chandragup II, 45 m high, rises about 1 km to the east of Chandragup I. The crater of Chandragup II forms a figure of eight, apparently developed from an initial twin volcano setting. The crater areas were then enlarged with time, until the figure of eight resulted from the collapse of the intermediate wall.
Chandragup II showed a low level of gas discharge during a first visit in May 1998 (Fig. 4, left). The discharged gas is of the same geochemical composition as at Chandragup I (personal communication, A. Lückge; Table 1). Surprisingly vigorous to violent gas discharge was observed during a second visit in November 1999 (Fig. 4, right). The periodicity or in more general terms the variability of gas discharge from this mud volcano complex is not well understood.
Finally to the north-east of Chandragup I a structure was found, which resembles the apparent deeply eroded remnants of a former mud volcano (Fig. 5). Visible today are basically two mud walls crossing themselves at near 90° angles. It appears that these walls were formed from solidified former feeder channels. This being true would again suggest that mud rises up along fractures and in this case apparently along the junction of two deep fractures.

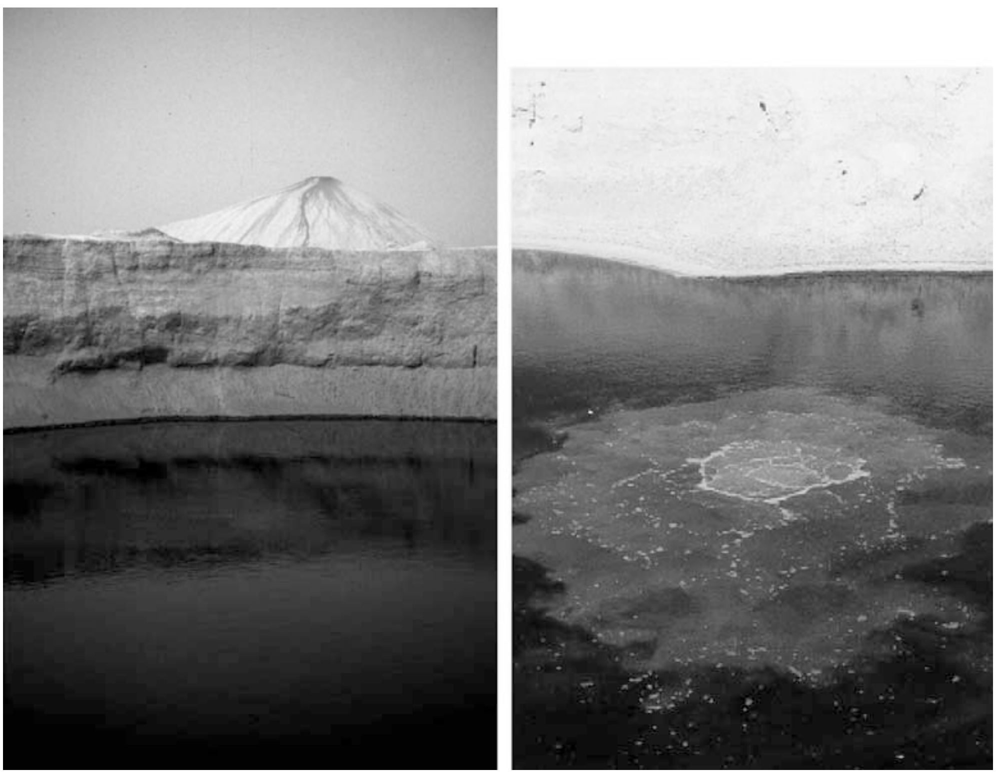

Fig. 4
Left: View across the water filled crater of Chandragup II toward Chandragup I. The *dark trace* from the top of Chandragup I is the result of mud overflow from the crater lake in May 1998. Right: Vigorous gas discharge from the lake of Chandragup II in November 1999

Fig. 5
Foreground: mud volcano ruin; note the two dyke-like walls in about perpendicular orientation. *Background*: northeast face of Chandragup I

More mud volcano complexes exist nearby in the wider vicinity in poorly accessible terrain.
One area is called the Jebel-u-Ghurab volcano field, which consists of a number of gryphons and salsas and only several m high mud volcanoes dispersed over an area of little more than about 0.5 km^2.
The Kandewari mud volcano is about 50 km to the east-north-east of Chandragup in mountainous terrain (Haro Range) and is reported to have discharged a fresh mud tongue in 2001 (personal communication, Ellouz 2001). All these reported mud volcano occurrences are along the long axis of the Dhak Anticline and attest to the role of tectonic lineaments in defining the ascend paths of the mud.
Additional mud volcanoes in Pakistan can be found along the coast near the city of Ormara.
Further inland, one formation, whose material composition is well comparable to the above described mud volcanoes, has been previously termed the "Extrusive Mud Formation" by the Hunting Survey (1960). The extent of this formation and the location of mud volcanoes have been mapped by Bannert and others (1992). This formation occurs over distances of tens of km along fault structures and would, if being extruded, represent the largest by far, but also in shape a very atypical extrusional mud volcano feature. Delisle and others (2002) have presented arguments in favour of this mass to be considered as a sedimentary unit of the Parkini Formation. Possibly, the "Extrusive Mud Formation" represents the exposed equivalent of the formation at depth, which acts today as the source formation for the now active mud volcanoes.
Other mud volcanoes in Pakistan have been reported from further inland to the southeast of the city of Quetta and south and southeast of the Hinglay Synform (see e.g. maps in Hunting Report, 1960; Bannert and others 1992). Earlier publications have not all differentiated between mud volcanoes *sensu strictu* and mud intrusions termed "Extrusive Mud Formation". Therefore, and as most of the inland occurrences are poorly documented (and difficult to reach for inspection), the true number of volcano occurrences in Pakistan is yet a matter of debate.

Conclusions

The activity of mud volcanoes in Pakistan is typically limited to an almost persistent discharge of small volumes of gas-rich fluids. The discharge rates appear to be influenced by periodicities of several hours (ocean tides?). Major eruptions are infrequent and occur decades apart. Self-igniting gas plumes in association with mud volcano activity are rare. The initial phase of emplacement of mud volcanoes in Pakistan appears to be followed by a long phase of low-level activity. The presence of mud volcanoes in the region can be demonstrated for the last 460 ka. The mud volcanoes of Pakistan are less active and spaced over a much larger area in comparison to the mud volcano system of Azerbaijan (Aliev and others 2002), for which violent eruptions on a decadal to sub-decadal basis are reported (Hovland and others 1997). This is surprising given the fact that both areas show geologically similar characteristics. Both are underlain by at least 10 km thick and partially under-compacted sediment layers. If the very extensive "Extrusive Mud Formation" in the Makran Desert is truly of extrusive nature, then the associated mass redistribution from depth might possibly explain the low concentration.

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