INNOVATIVE ANALYSIS OF MUD VOLCANO PATTERNS IN WESTERN AND SOUTHWESTERN PAKISTAN THROUGH SATELLITE IMAGERY

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Abstract: Mud volcanoes are geological features formed due to pressurized mud, water, gases accompanied by rocks that are expelled to the surface from underground. In Pakistan, there are more than 80 mud volcanoes. However, there is a lack of extensive, thorough mapping and analysis of Pakistan's mud volcanoes in the West and Southwest utilizing satellite image technologies. The present study aims to locate various clusters in South Western and Western regions of Pakistan, and to make a laboratory scale and conceptual model of mud volcanoes in this region to understand the underlying geological and tectonic processes. Firstly, we have used high-resolution satellite images to demarcate and identify various clusters and individual mud volcanoes. Secondly, mud volcanoes of a lesser-known western segment of Pakistan are the unexplored Pishin Basin (Qila Saifullah, Babu Cheena, Zhob). These mud volcanoes occur in distinct patterns which is the regional trend of Makran subduction zone and Pishin Basin. These mud volcanoes occur in clusters (Hingol National Park), and follow the regional structural trend of lineaments. Tracing these lineaments can help in the identification of more mud volcanoes. These active mud volcanoes release methane and hydrocarbons along with mud and water and can be identified by changes in the tone, and texture (Ormara) of the satellite image. However, few fossil or extinct mud volcanoes still have eroded (Gwadar) craters and are relatively diminished in size (~50m). They exhibit a wide variety of surface structures extruding gas and sometimes with bubbles having viscous hot fluid of mud. It could signify the presence of hydrocarbons beneath the surface. Chandragup mud volcano is an attractive place for Hindus, as they consider it a holy place. They are also important as a geoheritage and tourist sight and can generate significant revenue. Hingol National Park is a captivating site for those all over the world who adore to grasp nature thoroughly. These are significant as similar settings in other countries like Azerbaijan, Romania and New Zealand hold immense petroleum, geoheritage, geotourism and geothermal potential.

Keywords: petroleum exploration, Methane, Makran accretionary wedge, geothermal, geotourism, Chandragup.

1. INTRODUCTION

Mud volcanoes are often associated with tectonically active regions. Their presence can indicate the movement of tectonic plates and the existence of subsurface geological processes (Lin et al., 2023). Monitoring mud volcanoes can provide valuable insights into the Earth's dynamic processes. They release various gases, including methane. Methane is a greenhouse gas, and its release from mud volcanoes adds to the carbon cycle worldwide (Kotelnikova, 2002). It offers scientists a window into the Earth's subsurface. Studying the materials ejected during mud volcano eruptions can reveal details regarding the

composition of the Earth, or fluids present beneath the surface (Salone et al., 2023). Mud volcanoes are not true volcanoes in the traditional sense, as they do not involve the eruption of molten rock (Mazzini & Etiope, 2017). Instead, they are associated with the discharge of gasses, water, and mud from beneath (800 m-1 km) the Earth's surface. These features are typically caused by subterranean gases, particularly methane, towards the surface. When the gas pressure builds up in the uncompacted / uncemented sediments, it forces mud and other materials to erupt, creating a distinctive landscape. The eruptions can be intermittent, and they often result in the formation of mud cones and craters (Mazzini et al., 2021).

The unique geological setting of the Makran region has attracted the attention of geologists and researchers to study active tectonics, rapid sedimentation processes, subduction zone dynamics, and migration of hydrocarbons (Figure 1; Burg, 2018; Delisle et al., 2002). Rapid sedimentation processes and substantial sedimentary influx are significant factors for understanding the phenomenon of mud volcanoes. They provide water-saturated fine-grained uncompacted / uncemented sediments needed as a source for mud volcanoes. Studying mud volcanoes in this area can provide deep structural, sedimentation and diagenetic insights which can lead to an understanding of the geological history of oil and gas basins, gas hydrates and degradation of organic matter (Hessler & Sharman, 2018).
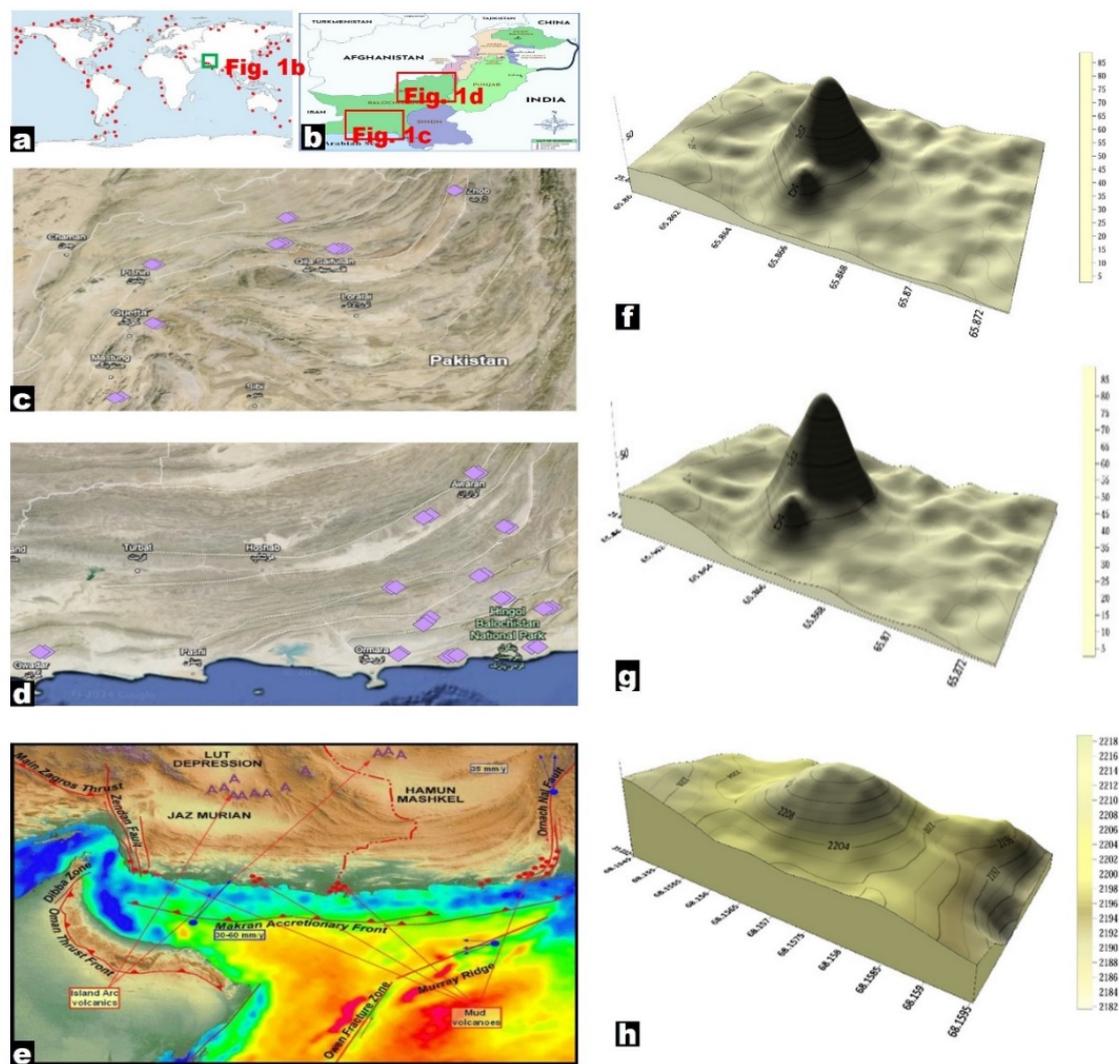

Figure 1. a - Global map exhibiting active zones of mud volcanoes along different plates showing through red colors; b, c - Satellite Image of the Makran coastal belt displays the locations of both active mud volcanoes within the Makran Zone of Active Mud Volcanoes and the deposits of former mud volcanoes; d - Map of Pakistan representing sites of mud volcanoes presented using purple color. e-Makran Accretionary prism & zone of subduction in the Arabian Sea, Chaman/Ornach-Nal strike-slip fault, plate boundary between the Arabian Plate to the southwest and the Ormara microplate to the northeast, Murray Ridge and Oman Abyssal Plain (Pararas-Carayannis, 2006). f, g - Digital Elevation Model (DEM) of Chandragup -1, Chandragup-1 (back door) and Chandragup-3, h - DEM of Khatkandi mud volcano.

1.1. Geologic Setting

The Makran region, which encompasses parts of southeastern Iran and southwestern Pakistan, is known for its unique geological setting, including the presence of numerous mud volcanoes (Figure 1d, e; Naseem et al., 2023; Mir et al., 2023; Ghazi et al., 2020; Nezhadafzali, 2015; Ghazi et al., 2015; Faber et al., 2015; Bröcker et al., 2021; Babadi et al., 2019; Al-Lazki et al., 2014; Zhao et al., 2022; Rehman et al., 2023; Rohrman, 2007). The Makran coastal region is located on the confluence of Arabian and Eurasian Plates (Ali et al; 2022; Xi et al., 2023; Yasin et al., 2021; Qadri et al., 2023; Wahid et al., 2022; Malkani & Mehmood, 2017; Regard et al., 2004; Critelli et al., 1990; Platt et al., 1985; Farhoudi & Karig, 1977; Jacob et al., 1979). Complex geological processes, such as the uplift of mountain ranges and the creation of mud volcanoes, have been created as a byproduct of the collision and subduction of these plates (Javed et al., 2021; Ahmed et al., 2020; Stern, 2002).

Because the Makran Coastal Belt is closely associated with several plate boundaries, it is seismically active. The compressional region of Makran is located on the junction of Arabian and Eurasian Plates. The Chaman/Ornach-Nal strike-slip fault, which separates the Indian and Eurasian Plates, is another continental scale tectonic boundary situated along the eastern edge of the subduction zone (Ali et al., 2023; Mateen et al., 2022 Qadri et al., 2022; Rehman et al., 2022). The prominent left-lateral strike-slip fault Sonne, which is thought to be a plate boundary between the Arabian Plate to the southwest and the Ormara microplate to the northeast, cuts across the east-west trending Makran subduction zone (Figure 1e). A weak spreading zone is delineated by the Little Murray Ridge located in the Oman Abyssal Plain, situated beyond the Makran subduction zone. Near these plate boundaries, a sequence of imbricate thrust slices has severely damaged the accretionary wedge both onshore and offshore.

The aim of this article is:

- To demarcate the distribution of mud volcanoes in the Makran and Pishin Basins.
- To make a laboratory scale and conceptual model of mud volcanoes in this region.

1.2. Stratigraphy

The stratigraphy of the Makran region (Tassi et al., 2012), which spans parts of southwest Pakistan and southeast Iran, is characterized by a complex geological history, with a wide range of rock units spanning different geological periods (Burg, 2018). The study area has been under a complex system of folding and faulting that has made stratigraphy very diverse (Table 1; Burg, 2018).

Oligocene-Eocene Formations
Mainly consist of marl, shale and limestone rich in foraminifera (Potter et al., 2012).

Table 1. Generalized stratigraphy of Makran and surrounding areas (after Hunting Survey Corporation 1961; Kazmi & Abbasi, 2008).

Age		Group	Formation	Lithology
Quaternary	Holocene	Makran Group	Jiwani Formation	Littoral deposits of shelly limestone, sandstone and conglomerate
	Pleistocene			Unconformity
			Ormara Formation	Soft and poorly consolidated mudstone and minor sandstone
				Unconformity
			Chitti Formation	Greenish grey poorly bedded sandstone interbedded siltstone
Tertiary	Pliocene			Unconformity
			Talar / Hinglaj Formation	Sandstone, conglomerate, shale , shelly limestone
	Miocene	Turbat Group	Parkini Formation	Greenish grey, poorly bedded, mudstone interbedded thin sandstone
			Panjgur Formation	Grey sandstone and quartz arenite (basinal turbidite)
			Hoshab Shale	Bluish grey shale with thin section interaction
	Oligocene	Bathyal muds underlain by oceanic crust		

Miocene Formations

Limestone, sandstone and marl are the main rock types in the Miocene (McCall, 2002).

Pliocene-Pleistocene Formations

Sandstones, siltstones and clays are common rock types in the Pliocene-Pleistocene.

Quaternary Deposits

This includes alluvial deposits, sand dunes, and coastal sediments. Quaternary deposits are primarily unconsolidated sediments and soils found along river and coastal deposits (Table 1; Dill, 2022).

2. METHODS AND MATERIALS

The tectonic and structural features were extracted from a single dataset. More than 100 Landsat photos were used to interpret these (Courtesy: Google Earth; Figure 1c, d). A base map of the Makran and Pishin areas was captured to obtain a complete map perspective of the study area. A comprehensive literature review was used for understanding the distribution of these mud volcanoes. Geo-referencing, fine-tuning, color balancing, and brightness matching (using Adobe Illustrator, CorelDraw and DaVinci Resolve) improved the image quality and made it easier to see lateral variations and structures (Huang et al., 2019; Zhu et al., 2022). Red, green, and blue bands were combined to create the image, accordingly. It was discovered that this process worked well for removing the study's relevant features from the Landsat images. A digital elevation model (DEM) of two mud volcanoes was also prepared (Figure 1f, g, h; Guan et al. 2023). The workflow is given here (Figure 2).

3. RESULTS

Arabian plate is subducting under the Eurasian plate and is the main tectonic control in this region. (Glennie, 2001). Mud volcanoes in the Makran region are the result of the subduction process. The rapid sedimentation and tectonics associated with the mud volcanoes results in the entrapment of formation water, gases and hydrocarbons in the sediments.

These gases accompany sediments and are expelled through conduits provided by fractures and faults (Hessler & Sharman, 2018; He et al., 2021). The mud volcanoes are composed of mud, gas (including methane), water and sporadically oil (Mazzini, 2017). These mud volcanoes may also emit sulfur compounds, creating unique chemical compositions at the surface (Lichtschlag, 2013; Yin et al., 2023).

3.1. Distribution of mud volcanoes

Mud volcanoes are scattered throughout the Makran region, with concentrations in areas such as Balochistan, Pakistan, and certain areas of southeast Iran (Yaseen et al., 2021).

The landscape is marked by more than 80 small to large mud volcanoes, some of which are highly active, while others are dormant (Dimitrov, 2002; Figure 1c, d; Table 2)

3.1.1. Hingol National Park

Hingol National Park is known for its numerous mud volcanoes (Figure 3), including the Chandragup and Kund Malir mud volcanoes. These unique geological features attract tourists and researchers interested in studying them.

3.1.2. Chandragup

The Chandragup Mud Volcano 25°26'29"N 65°52'19" E 6 m is indeed a specific geological feature located in Hingol National Park, situated in the southwestern province of Balochistan in Pakistan. In the Chandragup cluster, three groups of Chandragup I, II, and III mostly erupt viscous mud filled with hydrocarbons (Figure 4). High-resolution satellite photos clearly show mud flows. Several small mound-like objects that were once satellite vents but are now dormant are also visible. The viscous fluidized mud flooded the Chandragup-I. Hydrocarbon gasses are released when the mud bubbles up and occasionally explode violently. The Crater of the South Chandragup-II is a lake that is filled with water and has a weak extrusion of muddy water in the center and very little activity of gas bubbling. Part of the crater's circular walls have

1. Open Google Earth	2. Launch Google Earth	3. Search for desired location
4. Enable additional layers	5. Research and verification	6. Use the Historical Imagery feature
7. Explore the map	8. Check relevant layers	9. Geo-referencing, fine-tuning, color balancing, and brightness
10. Add custom placemark (optional)	11. Make a folder to save data of a project	12. Save or share your findings

Figure 2. Workflow for this research.

Table 2. List of major mega-clusters and clusters of mud volcanoes.

| Mega clusters	Clusters	Location	Remarks	Active / Dormant/Extinct
Hingol National Park	Chandragup Mud Volcano	Hingol National Park, Balochistan.	One of the largest mud volcanoes in the world, known for its large eruptions of mud and gas.	Active
	Salsal Mud Volcano	Hingol National Park, Balochistan	Famous for its consistent and regular eruptions, creating a dramatic landscape	Dormant
	Hinglaj Mud Volcano	Hingol National Park, Balochistan	This mud volcano is near the famous Hinglaj Mata temple and is considered sacred by Hindus.	Dormant
	Kund Malir	Hingol National Park, Balochistan		Active
	Jabel u Gurab	Hingol National Park, Balochistan		Active
	Jabal-e-Mehdi Mud Volcano	Hingol National Park, Balochistan.	A prominent mud volcano with a spectacular landscape, attracting tourists and researchers alike	Dormant
	Khandewari	Hingol National Park, Balochistan		Active
Malan island	Malan	Indus offshore		Extinct
Ormara	Ormara1 Ormara 2 Ormara 3	South of the Guard Hills the Balochistan		Active
Qila Saifullah	Babu Cheena	Kirthar Mountains in Balochistan	Highly active flow	Active
	Khatkandi	Gardab manda, North of Qila Saifullah	Highly active flow	Active
Pishin basin	Surkach	north west of the Surkach		Active
	Zhob	Quetta, Balochistan		Active
Gwadar Bay	Gwadar	Gwadar coastline	Dry to less viscous flow	Dormant
Zalzala Koh Mud Volcano		Lasbela District, Balochistan	Known for its intermittent eruptions and unique geological features, making it a popular attraction	Dormant
Kirthar Range Mud Volcanoes		Kirthar Range, Sindh	A cluster of mud volcanoes situated in the picturesque Kirthar Range, offering a stunning natural setting	Extinct
Koh-e-Sulaiman Mud Volcanoes		Koh-e-Sulaiman Range, Balochistan	A group of mud volcanoes located in a remote and rugged terrain, making it an adventurous destination for explorers	Extinct
Bela Mud Volcano		Bela, Balochistan	A relatively accessible mud volcano known for its unique formations and frequent eruptions.	Active
Jhudo Mud Volcano		Jhudo, Sindh	A smaller mud volcano that provides an opportunity for visitors to witness the geological wonders of the region.	Dormant
Pab Mountains Mud Volcanoes		Pab Mountains, Balochistan	A group of mud volcanoes within the Pab Mountains contributes to the diverse geological landscape of Balochistan.	Dormant.
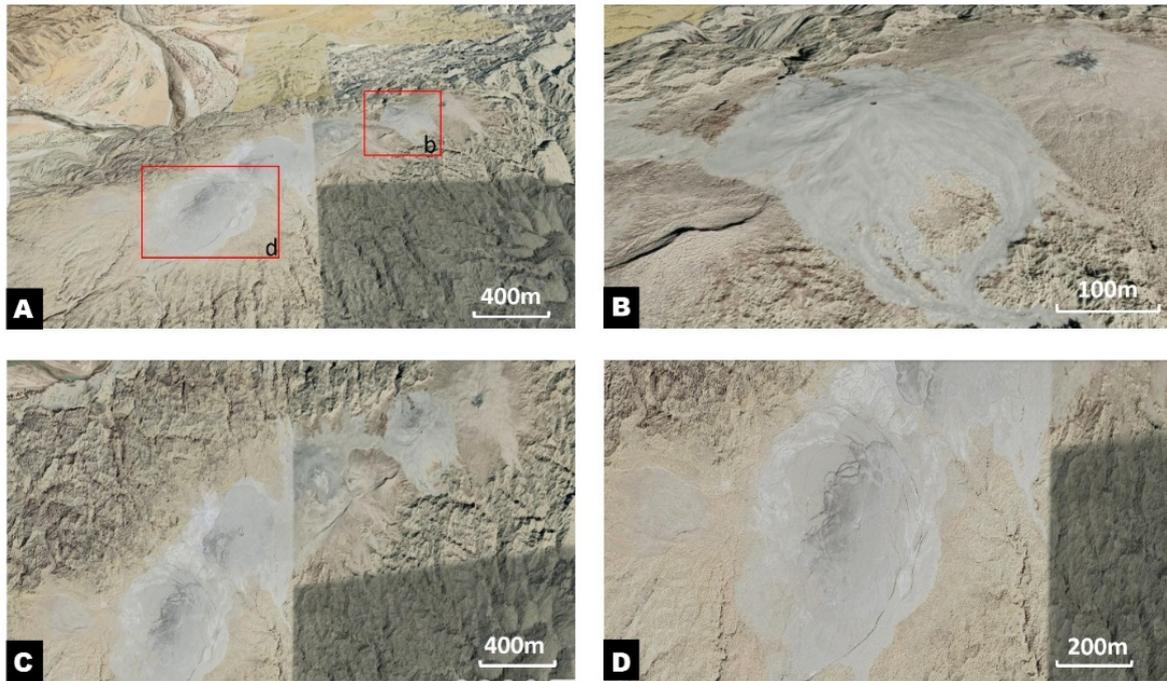
Figure 3. Google pictures on the Makran Coast, displaying groups of different mud volcanoes, a - A 3D view of mud volcanoes in Hngol National Park; b - A crater can be seen here, c- Aerial view of the Hingol National Park mud volcanoes; d – various colors of new and old mudflows can be seen.
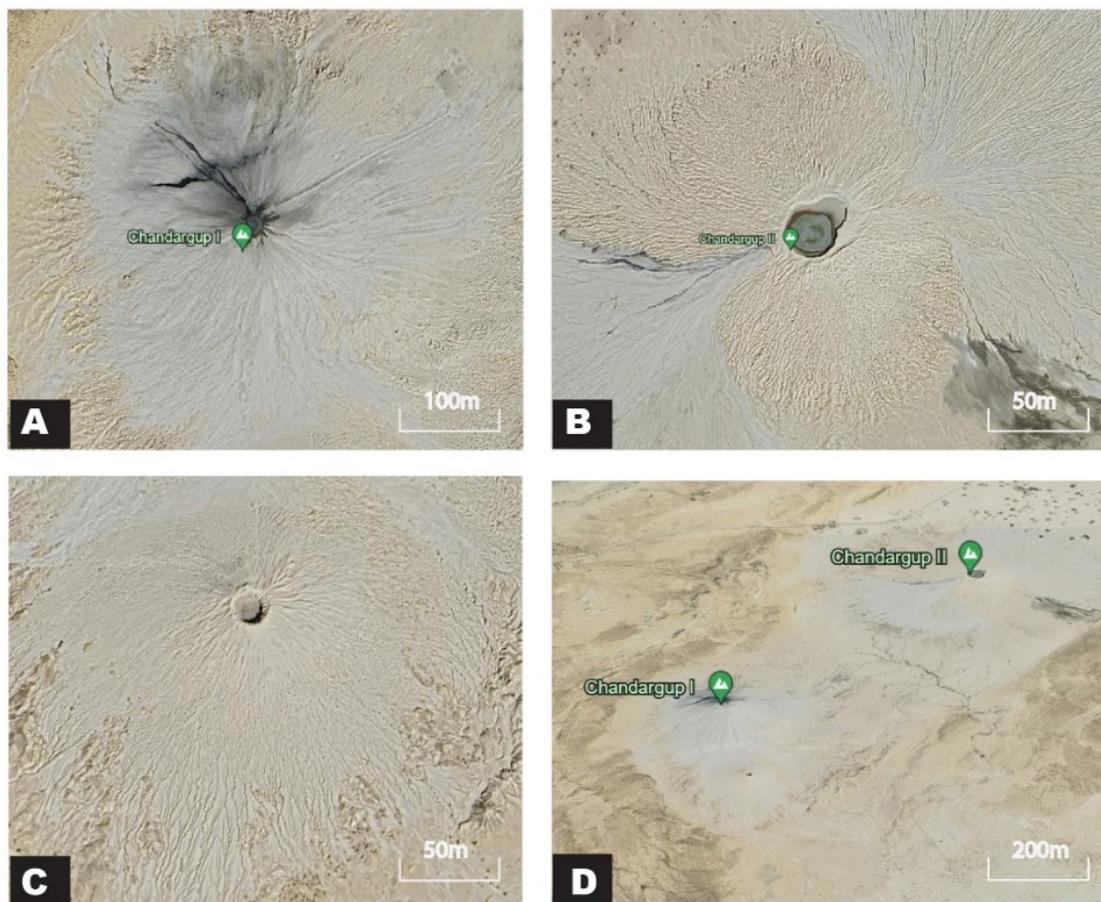

Figure 4. Google photos of the Makran Coast's several mud volcanoes, including; a - crater of Chandragup 1; b - Chandragup 2; c - Chandragup 3; d, 3D view of the Chandragup cluster.

crumbled due to erosion. The water level inside the crater dropped as a result of what appears to be a decrease in mud extrusion. The steep sides of the older deposits eroded and collapsed due to gravity (Kassi et al., 2014). The Chandragup-III appears to have dried up currently.

3.1.3. Jabel u Gurab

The Jebel-u-Gurab group of mud volcanoes is located one kilometer west of the Dhaka Anticline in the flat-lying Dhaka Desert, which is created by sediments resembling playas and is located at 25°19'07"N 65°07'44"E. Although other minor mound-like features have been recorded, only four mud volcanoes are apparent on the satellite image due to their modest sizes (Kassi et al., 2014). The reason for these mud volcanoes' existence in the anticline's core may be related to the tectonic feature that affects the concentration of gas close to the anticline's crest. About one kilometer west of the end of the Dhaka Anticline, in the completely flat Dhaka Desert produced by ancient lake sediments. Fractures along the axis of the anticline may have given passageways for the extrusion of mud and gas.

3.1.4. Kund Malir

Kund Malir Mud Volcano 25°25'33"N 65°26'54" E is another interesting geological feature located in the Hingol National Park (Figure 5e, f). Thick mu4. d volcano deposits are created when the mud flows from the majority of mud volcanoes collide with one another. The largest crater in the Kund Malir cluster has a diameter of 25 meters. In comparison to their new mud extrusions, the historical mud volcano deposits typically cover larger areas (Kassi et al., 2014). Every mud volcano in the group is active. The port city of Gwadar is situated in Pakistan's Balochistan province in the southwest, along the Arabian Sea. The city is known for its strategic location as a deep-water port, which makes it an essential hub for trade and commerce. In the surrounding areas of Gwadar, there are also several mud volcanoes (Figure 5a, b), similar to those found in other parts of Balochistan. These mud volcanoes exhibit types of eruptions common to such geological features (Kassi et al., 2014). Two mud volcanoes and a few mud mounds in the surrounding area can be observed on the high-resolution satellite image. Some small volcanoes are reported but cannot be observed on satellite images.

3.1.5. Khandewari

Six mud volcanoes make up the Khandewari cluster of mud volcanoes, which is situated 30–35 km northeast of the South Chandragup sub-cluster at the NNE–SSW-oriented Hero Range. Mud volcanoes within the cluster spew mud out of one or more primary vents and are positioned parallel to the range's strike (Kassi et al., 2014). Some consist of degraded and dried-up mudflows.

3.1.6. Qila Saifullah

Qila Saifullah is a small town situated in the northwestern part of Balochistan, Pakistan. It is part of the larger region of Balochistan, which is known for its rugged and arid landscapes. The town itself is characterized by its traditional architecture and the presence of a historical fort, after which it is named. The surrounding area features a desert-like terrain, with sparse vegetation and a dry climate. Mud volcanoes in the Qila Saifullah region are a geological phenomenon similar to those found in other parts of Balochistan. Most of the mud volcanoes erupt abundance of methane, some are dried up having little viscous mud.

3.1.7. Surkach

To the northwest of the Surkach Village lie mud volcanoes and related gas leaks at 31°23'02"N 69°12'58"E. This location has a group of mud volcanoes that span a radius of one kilometer (Figure. 6a, b). The greenish-grey shale strata of the Basal section of the Nisai Formation are home to mud volcanoes and related seepages. The crater mud slurry exhibits the unusual pale blue to ash-grey tint of the mud volcanoes (Iqbal, 2004; Yan et al., 2024). There are tiny layers of oil present in the mud volcano slurry. Three mud volcanoes stand out prominently at this location against the background's eroded and soft shale succession. Along the Surkach Thrust, it is thought that the gas seepages and mud have been transported to the surface.

3.1.8. Babu Cheena

Babu Cheena, is a well-known location in the Balochistan province of Pakistan. There are indeed mud volcanoes in the vicinity of Babu Cheena, and these geological features are part of the unique landscape of the region (Figure 5c, d). Babu Cheena is a small village located in the Kirthar Mountains in Balochistan, Pakistan. The region is known for its arid and rugged landscapes, and it is situated in a remote and sparsely populated area. The village itself is a gateway for visitors exploring the surrounding natural attractions, including mud volcanoes. The mud volcanoes near Babu Cheena, are highly fluidized and viscous, clearly observed through satellite images. Some vents erupt gas only.

3.1.9. Ormara

The Ormara Mud Volcanoes are a collection of geological formations situated close to the seaside town of Ormara in Pakistan's Balochistan region,
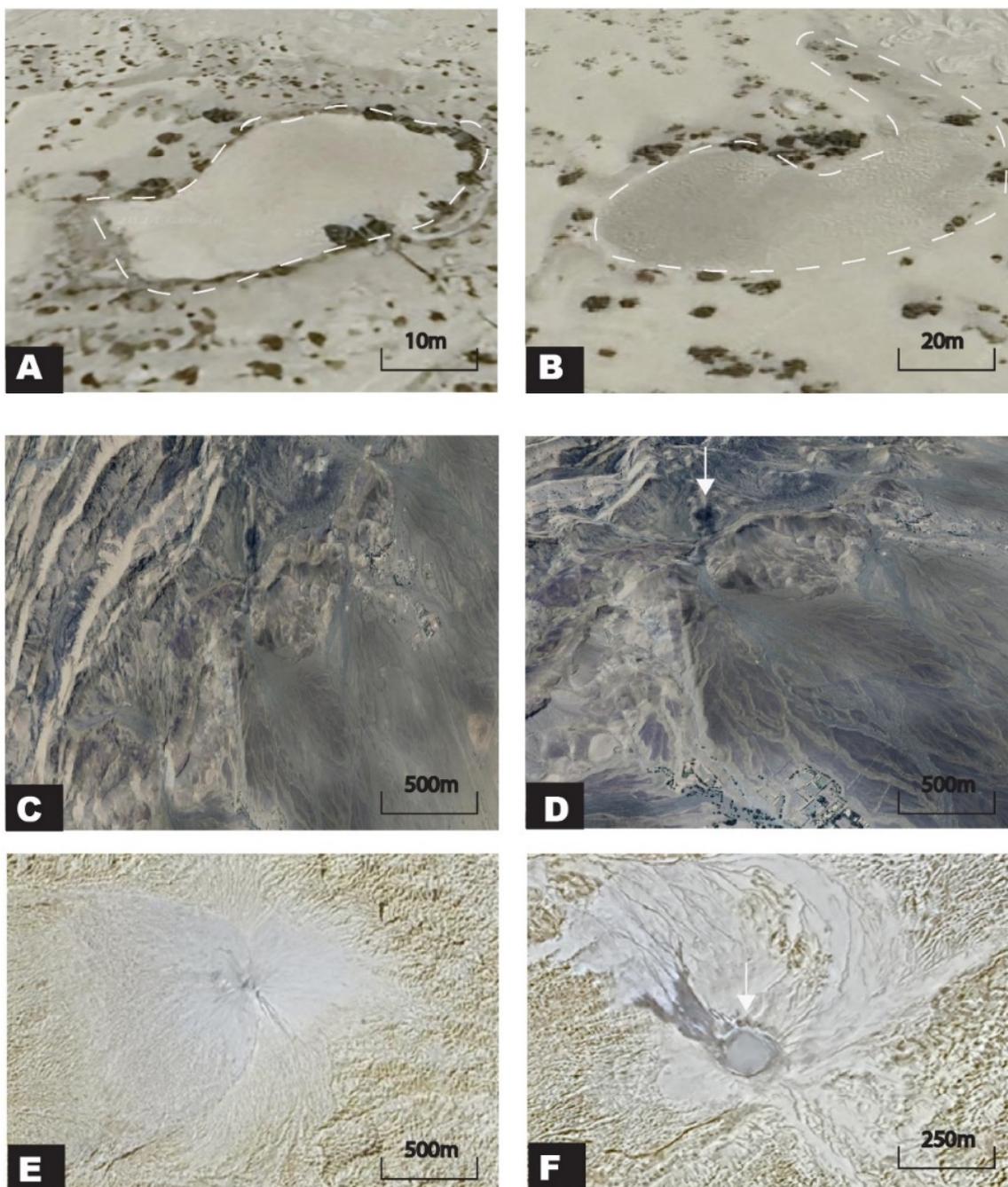
Figure 5. Satellite images showing mud volcano clusters; a, b - clusters of Gwadar coastline mud volcano, these are small size dormant eroded mud volcanoes, a crater can be seen, c, Babu Cheena mud volcano cluster; e- Kund Malir clusters; f- note the fresh mudflows in Kund Malir mud volcano (Courtesy: Google Earth).

south of the Guard Hills (Figure 7a-d). These mud volcanoes are part of the Makran Coastal region and are notable for their unique and otherworldly landscapes (Kassi et al., 2014). They are distributed in three sub-clusters. The majority of the Ormara cluster's mud volcanoes are active.

3.1.10. Pishin Basin
The western edge of the Indo-Pakistan Plate is located in Pakistan and is known as the Pishin Basin. The Pishin Basin spans the districts of KhuzdarQuetta and Zhob-Kabul, spanning around 800 km in length and 40 to 175 km in width. The left lateral Chaman and Ghazaband transform faults, respectively, encircle it on the west and east. It reaches the Makran area in the south and the Main Karakorum Thrust (MKT) in the north (Iqbal et al., 2013)
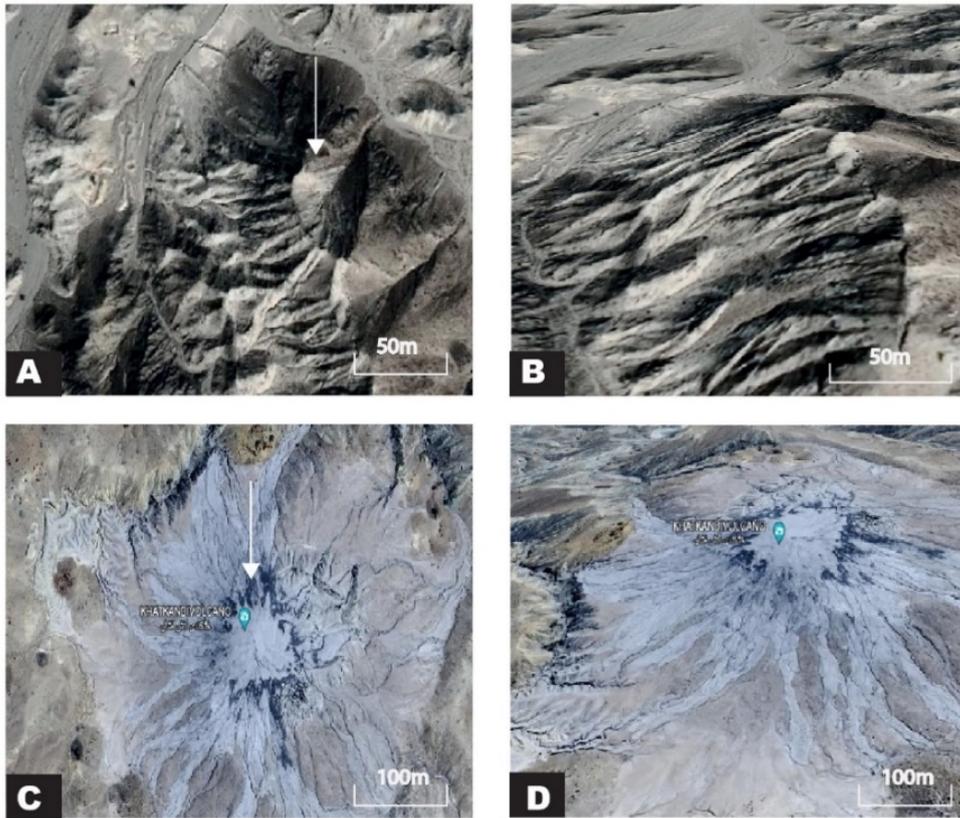
Figure 6. Satellite images showing mud clusters; a, b – crater of Mud volcano at Surkach; c, d - clusters of Khatkandi mud volcano with eruption of gaseous–viscous mud (Courtesy: Google Earth).
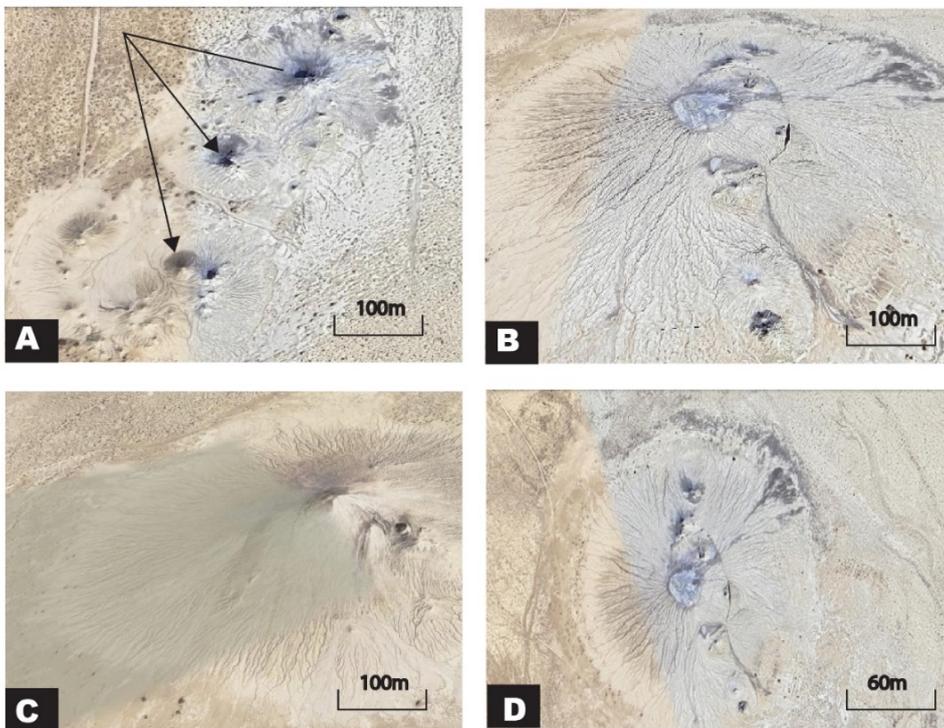

Figure 7. Satellite images showing clusters of mud Volcano; a, - highly gaseous erupted clusters of Ormara mud volcano; b – 3D view of the major volcano in the Ormara cluster; c- another mud volcano in Ormara cluster, note old crater near the new one; d- Plane view of b, showing fresh mud in the center crater.

3.1.11. Zhob

Zhob is situated along the Zhob River's banks. The distance from Quetta, the capital of Balochistan, is 337 kilometers at 31°15'41"N 69°29'49"E. Many mud volcanoes filled with pressurized gases are present here and can be seen through satellite images. One mud volcano covered with fluid mud was also observed through satellite images.

3.1.12. Global outlook

Geological formations known as "mud volcanoes" spew forth a mixture of mud, water, gases—especially methane—and occasionally hydrocarbons from deep under the Earth. On the surface, they frequently display conical or dome-like features (Mazzini & Etiope, 2017; Table 3).

Mud volcanoes are found in tectonically active areas where tectonic plates collide, such as subduction zones. Fluids and sediments are released from the subducting plate as a result of the subduction process (Stern, 2002).

Mud and clay-rich deposits are the primary components of mud volcanoes, and ascending fluids carry these elements to the surface.

Mud volcanoes can range in age from recent to millions of years old. The relative age of a mud volcano can be calculated based on the record of its eruptions. The other information can come from the contact relationship of the mud volcano ejecta with the surrounding rocks (Dembicki, 2022; Dai et al., 2023). An understanding of a mud volcano's age requires an understanding of the region's tectonic activity and

geological past. Mud volcanoes are present all over the world with major concentrations in areas like the Caspian Sea (Azerbaijan), Indonesia, Italy, the Makran Coastal region (Pakistan/ Iran), and the Black Sea, among others.

3.2. Significance in Petroleum Exploration

Mud volcanoes have a vital role in petroleum exploration due to various reasons. Although they do not serve as direct reservoirs for conventional oil and gas, but they provide invaluable insights and data that assist the exploration and understanding of subsurface hydrocarbon reservoirs (Tinivella & Giustiniani, 2012). Here are some key roles of mud volcanoes in petroleum exploration:

1. Hydrocarbon Emissions: Mud volcanoes are often associated with the emission of hydrocarbons, predominantly methane, to the surface (Etiope et al., 2009). The presence of these hydrocarbons signifies the potential existence of underground reserves, thus attracting the attention of petroleum geologists and exploration entities.

2. Material Extrusion: Mud volcanoes extrude subsurface materials, encompassing sediments and hydrocarbons, to the surface. Analysis of these materials by geologists facilitates a comprehensive understanding of the geological history, composition, and organic content of subterranean layers (Huuse et al., 2010). Such insights are indispensable for evaluating the prospective nature of oil and gas reservoirs.

3. Geophysical methods e.g. Electrical (Zeyen et al., 2011; Ping-Yu et al., 2011) and seismic (Evans

Table 3. Global distribution of mud volcanos

| Name of mud volcano	Age	Group	Formation	Lithology
Gobustan Mud Volcanoes (Azerbaijan) (Aghayeva et al., 2021)	Various ages, some dating back thousands of years	N/A	Associated with the ongoing tectonic activity in the Caspian region (Aghayeva et al., 2021).	Mud and sedimentary rocks. Often associated with the release of natural gas and oil (Tucker & Jones, 2023).
Yellowstone Mud Volcano (USA)	Various ages, with ongoing activity	Hydrothermal system component of Yellowstone National Park	The outcome of steam and hot water mixing with surface sediments (Lowenstern & Hunt, 2015. Menapace et al., 2019)	Mud and hydrothermal minerals. Primarily associated with hot water and steam, not hydrocarbons
Sidoarjo Mud Flow (Indonesia)	Active since 2006.	N/A	Caused by a drilling accident, not a natural mud volcano (Blouin, 2019). However, some researchers have contended the opinion and suggested its origin by a distant earthquake (Abidin et al., 2009).	Mud and sediment.
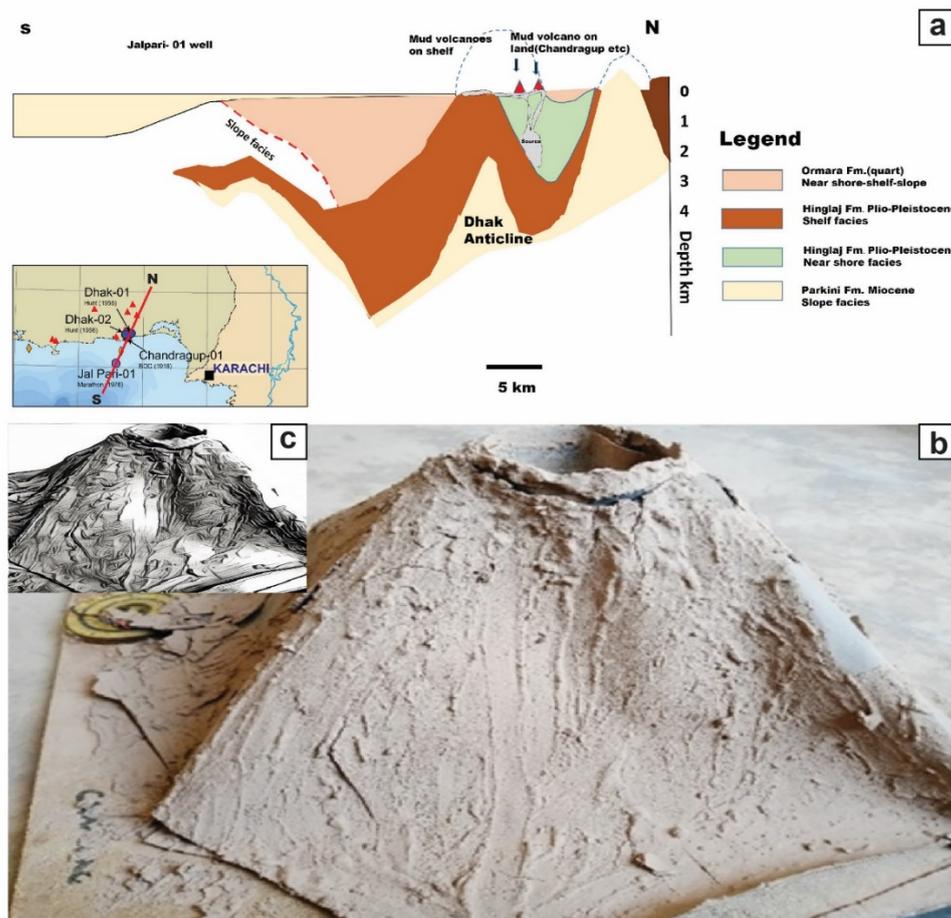
Figure 8. Lab scale and Conceptual Model showing: a – the NS line on the inset map shows the location of the geological cross section, presenting the various lithological units from Miocene to Quaternary (Campbell et al., 2008), with the main source of mud volcanoes in the Plio-Pleistocene sediments. b, c - Chandragup Mud Volcano, Laboratory model and its sketch.

et al., 2006; Cuffaro et al., 2019) can help monitor a mud volcano. A subsurface movement of fluids can provide us with evidence of hydrocarbon migration.

3.3. Field Scale - Conceptual Models

The field scale and lab scale model help in the visualization of the mechanism of mud volcanoes (Figure 8a). In the vicinity of the Makran prism, sediment accumulation rates vary between 110 cm/ka and 200 cm/ka (Abbasi et al., 2016), leading to rapid burial of fine-grained sediments that have been both under and over-compacted. The phenomena of mud fluidization are likely initiated by the compaction-driven dewatering of sediments during this process. Along the Makran Coast, all mud volcanoes and mud islands emit flammable methane gas, which is associated with mud extrusion. Research utilizing bottom simulating reflectors (BSR) indicates extensive methane hydrates within the Makran accretionary prism, originating either from microbial sources (anaerobic decomposition of organic matter) or being biogenic (by thermal breakdown of organic matter in earth crust due to high temperature and pressure) (Delisle et al., 2002)

Delisle et al., (2002) reported on the discharge of gases from offshore Malan Island. During the development of islands following the 1945 earthquake, self-igniting gas flames erupted near the entrance of the Hingol River, projecting thousands of feet into the sky with remarkable force. No reports indicate such intense ignition coinciding with subsequent island emergence. Local pressure release, induced by subsurface slumping, seismic activity, or decompaction, may destabilize solid clathrates, transitioning them into a gaseous phase that ascends as gas and mud bubbles until the local clathrate supply is depleted (MacDonald, 1990; Max et al., 2005). The presence of methane within the rising mud plume effectively reduces the mean sediment density, facilitating their upward movement. Delisle et al., (2002) argued that the rapid formation of islands is likely attributed to the release of dissolved gases or over-pressured liquids, indicating a swift energy release mechanism.

The field-scale model represents the interaction of tectonic forces, fluid migration and sedimentary loading.

3.4. A Laboratory-Scale Model

The lab scale model helps in visualization, predictive capability, educational and communicational tools for understanding mud volcanoes (Figure 8b). A model of mud volcanoes gives new details on how Chandra Gup formed. Based on literature the fluids and sediments as deep as 3-5 kilometers, along with gas, usually make mud volcanoes. Over time, these parts build up and harden to create its unique shape. Mud volcanoes show there are active processes underground, like those that likely made Chandra Gup. These processes include overpressure, fluid migration, mud eruption, tectonic activity and geochemical development (Blouin, 2019; Bayramova et al., 2023; Abbasi et al., 2016). Understanding mud volcanoes can help us learn about Chandra Gup's past and future exploration in the area.

4. CONCLUSIONS

In conclusion, Mud volcanoes are valuable markers and information sources for oil and gas exploration. They help geologists and exploration companies identify potential hydrocarbon-rich areas, map geological structures and understand the migration of hydrocarbon through the Earth's crust. Studying mud volcanoes can significantly enhance the success of petroleum exploration efforts. Pakistan has more than 80 active mud volcanoes spreading over the whole Balochistan Basin and some over the Pishin Basin, actively erupting along the Indus offshore Basin. Six mega-clusters hold many sub-clusters. Chandragup and Jabel u Gurab are actively set onshore while the Malan is an offshore extinct mud volcano. The large mud-volcano clusters in the region are Chandragup, Kandewari, and Awaran, which are all situated along important fold axes and faults. This implies that mud upwelling has an upward route provided by tectonic lineaments. Except for Malan Island, which emerged in 1999, all of the mud islands built after 1945 surfaced following a significant earthquake in the area. The Ornach Nal fault zone was near the 1945 islands of Ormara and Hingol and the 1999 island of Malan. Nonetheless, aside from the Makran Subduction Zone, neither Zalzala Jazeera (2013) nor Gwadar Bay Island (1945) were situated adjacent to any recognized fault structure experiencing significant seismic activity. This suggests that sediments that have been over- and under-compressed have mobilized in response to seismic activity and tectonics.

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