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Original Research

Geological Characteristics and Geoheritage Significance of Mud Diapiric Provinces in Iran

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Abstract

Mud volcanoes are unique diapiric features located in southeastern Iran's Mokran region and the South Caspian area. This study aims to determine the geological settings of mud diapiric regions in Iran. Using tectonic analysis and remote sensing techniques, we identified and delineated the mud diapiric provinces of Iran. The mud diapirism in southeastern Iran, including the Khash-Bazman and Coastal Mokran provinces, is predominantly tectonically driven, while in northern Iran, including the South Caspian and North Gorgan provinces, buoyant mechanisms play a significant role. Additionally, the specialized water cycle associated with the subduction zones at the margins of Iran is integral to the development of these features. These geological phenomena contribute significantly to the geoheritage of Iran, emphasizing their importance for scientific research, ecological conservation, and sustainable tourism. It is also possible to raise people's awareness through promotion of scientific and cultural education and geoconservation, about the fact that lack of protection of natural resources leads to the depletion of geological resources and, on the other hand it is a serious threat to the geological heritage of the Earth. This is possible by providing information and training skills through which more forward-looking and correct decisions can be made.

Keywords: Mud Volcanoes, South Caspian, Geology, Iran, Geoheritage

1. Introduction

Mud volcanoes are distinctive geological features that expel mud through conical or circular structures. Often associated with tectonic activity, they provide valuable insights into Earth's tectonic and fluid migration processes. These features typically form along subduction zones and river deltas, with fluids sourced from meteoric waters, pore water expulsion, volcanic waters, or mineral dehydration reactions. Mud volcanoes serve not only as indicators of tectonic and sedimentary dynamics but also as significant geoheritage sites. Their preservation enhances our understanding of Earth's crust and contributes to biodiversity conservation. Also, these volcanoes have been fund in deltas of some rivers. Fluid for mud volcanism is supplied from various sources, including meteoric and volcanic waters, pore water expulsion, hot springs, mineral dehydration reactions, and gas hydrate destabilization. Gas may originate from as deep as the upper mantle (Kopf, 2002).

This study presents, for the first time, a comprehensive identification and classification of mud diapiric provinces in Iran using structural tectonic analysis combined with remote sensing data. The main innovation of the research lies in integrating structural geology approaches with modern remote sensing techniques to simultaneously examine the spatial distribution, formation mechanisms, and geoheritage significance of mud volcanoes across four distinct regions of Iran. Furthermore, the study offers a novel perspective on the relationship between mud diapirism and active tectonic processes, providing a solid foundation for developing geospatial strategies aimed at conserving these unique geological phenomena.

One of the significant milestones in the recognition of Iran's mud volcanoes as geoheritage sites is the official registration of the Tang Konarak mud volcano as a national natural monument in 2011. This registration highlights the unique scientific, educational, and ecological values of this feature and reflects growing national attention toward the preservation of geological phenomena. Tang Konarak, located along the coastal region of the Mokran Range, stands out not only for its geological characteristics (Feizi et al.,2015) but also for its aesthetic and touristic potential. Its designation as a national natural heritage site underscores the importance of integrating geoconservation strategies into environmental and cultural heritage planning, and it serves as a successful example of how mud volcanoes can be protected and promoted for both scientific and public appreciation.

2. Global distribution of Mud volcanos

Mud volcanos typically are located along active and convergent plate boundaries. However, they also occur along passive continental margins, within continents, and throughout the deep sea (Figure 1). About 2,000 mud volcanos have been confirmed, although this number is expected to increase significantly as deep sea exploration continues. Estimates for the number of mud volcanos in the world range from 7,000 to 1 million in total (Milkov 2000, Judd 2005). More than half of all known mud volcanos (about 650 onshore and at least 470 offshore) can be attributed to the active Alpine-Himalayan belt (Dimitrov 2003).

Starting from the Mediterranean ridge, this mud volcano belt extends through Romania and the Black Sea, the Caucasus/Caspian Sea region, Iran, Pakistan, India, and China to the Indonesian-Australian archipelago (Dimitrov 2003). The western flank of the Pacific Ocean hosts about 150 land-based mud volcanos. These mud volcanos range from Sakhalin Island/Sea of Okhotsk in the north through Japan, Taiwan, the Mariana Islands, Melanesia, Samoa, and Australia to New Zealand in the south (Kopf 2002, Dimitrov 2003). The total number of offshore mud volcanos along this belt is not yet fully determined, as this number is expected to grow.

The eastern Pacific Ocean is significantly less densely populated with mud volcanoes. Nevertheless, examples are known from the Aleutian Islands, Alaska, British Columbia, California, Costa Rica, Ecuador, and Peru inland (Kopf 2002, Dimitrov 2003).

The Atlantic Ocean hosts hundreds of terrestrial and marine mud volcanoes. In this respect, the vast majority are concentrated along the Caribbean thrust belts and the Barbados accretionary complex (Dimitrov 2003). Meanwhile, smaller/isolated clusters have been confirmed in association with the Amazon and Niger deltas in the southern Canary Basin (Müller et al. 2001) and offshore Portugal and Morocco in the Alboran Basin (Perez-Belzuz et al. 1997).
Smaller numbers of mud volcanoes have also been described from the Mississippi and Nile Delta (Hovland et al. 1997), Lake Michigan (Kopf 2002), Greenland (Kopf 2002), the North Sea (Vogt et al. 1997), and the Netherlands (Paine 1968 in Kopf 2002).

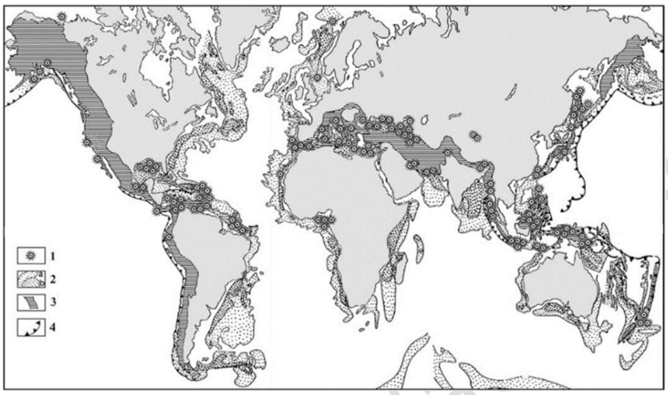


Figure 1. Global distribution of mud volcanos: 1) Individual mud volcanos, mud volcano belts, and isolated mud volcano zones; 2) Sediment thickness in areas outside the continental shelf: a) 1-4 km and b) > 4 km; 3) Active thrust zones; and 4) Subduction zones (Source: Dimitrov, 2003).

A mud volcano requires thick layers of unconsolidated sediments or sheared sedimentary rocks with high pore pressures. Figure 2 provides a schematic illustration of the source of material and the subsurface hole structures associated with mud volcanos. They are, therefore, common in areas with high sedimentation rates, such as sedimentary basins and accretionary prisms. There may be about 103 mud volcanos on land (Etiope and Milkov 2004; Etiope 2015). The number of offshore mud volcanoes is not well known, and their location is not well mapped. Using extrapolating the data from mapped areas, Milkov (2000) estimated that there may be thousands to hundreds of thousands of submarine mud volcanos. Their eruptions occur under increased pore pressure and often form along the top of anticlines with the orientation of the feeder dike controlled by the regional stress field (e.g., Bonini 2012). Faults and fault intersections often help create pathways for fluid ascent (Mazzini et al. 2009). Since they are often associated with pressurized hydrocarbon reservoirs, they are sometimes targeted for hydrocarbon exploration.

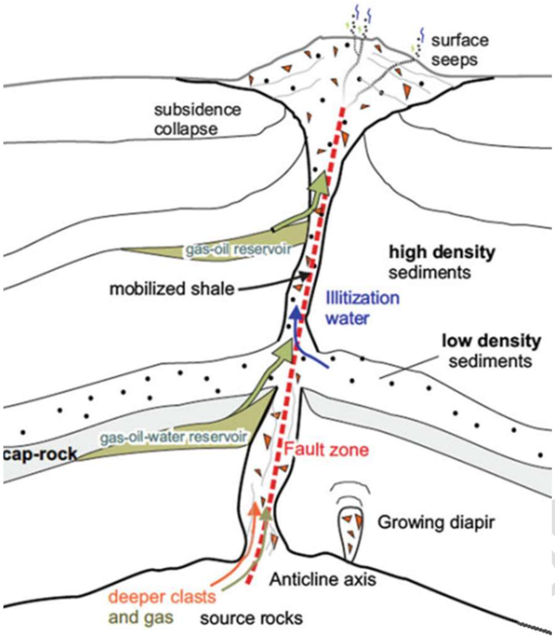


Figure 2: Schematic illustration of the subsurface "hole" structure of a mud volcano and the source of solids, fluids, and gas (from Mazzini and Etiope 2017)

Iran's tectonic framework comprises the Arabian plate (south and west), Cimmerian miniplate (north and east), and Eurasian plate (northeast). These plates form a complex convergent boundary system, hosting mud volcanoes in four primary regions (Figure 3):

1. Caspian Foreland Basin
2. South Caspian Remnant Basin
3. Mokran Range
4. Shahsavaran Mountain

Remote sensing and tectonic analysis were employed to delineate these provinces, identify structural trends, and explore their geoheritage potential.

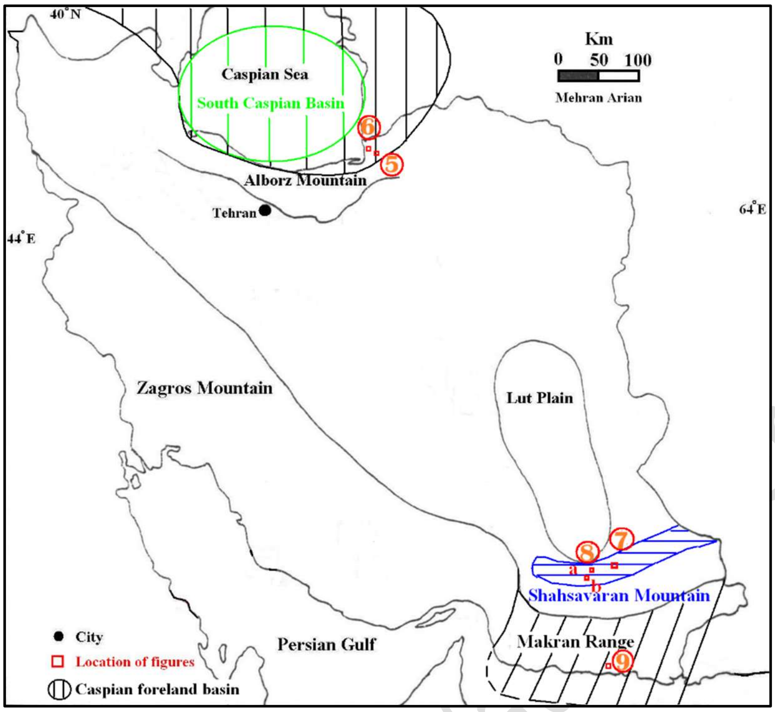


Figure 3. Geographical distribution of mud diapiric bearing physiographic-tectonic zones in Iran. Locations of figures 5 to 9 are shown by red rectangles.

3. Geologic Setting

3.1 Caspian Foreland Basin

This region exhibits NW-SE structural trends and hosts marine mud volcanoes. Some eruptions are powerful enough to form small islands. Gas hydrates associated with mud volcanism in this area provide critical insights into tectonic and sedimentary dynamics. The preservation of these features underscores their geoheritage value for education and research. On the other hand, gas hydrate processes are connected with mud volcanism (Soloviev and Ginsburg, 1994), possibly acting as a separate trigger (Kopf, 2002).

3.2 South Caspian Basin

The South Caspian Basin demonstrates NW-SE structural trends in the east and N-S trends in the west. This region features an active subduction zone and remnant oceanic basins (Berberian, 1983). Mud volcanoes here serve as dynamic markers of tectonic processes, enriching their geoheritage significance. This province is a part of Caspian foreland basin that, subducting beneath to Apsheron-Sill ridge (Jackson et al., 2002) on north boundary of South Caspian now (Allen et al, 2004). In the other hand, eruptions of mud volcanoes in Azerbaijan Country have investigated by Hovland et al. (1997), Milkov (2000) and Aliev et al. (2002).

3.3 Mokran Range

Located along the Oman Sea subduction trench, the Mokran Range includes an accretionary prism with E-W structural trends. Small mud volcanoes are closely associated with thrust and strike-slip faults. These features provide key insights into subduction and accretion processes, making them vital to Iran's geoheritage. A number of small mud volcanoes (>1 km in diameter) were found during seismic exploration by Wiedicke et al., (2001) in the Oman Sea along the Mokran range. Flueh et al., (1997) believe that position them are related to the location of thrust and strike-slip faults.

Based on DeMets et al. (1990) research, oceanic crust of the Oman Sea is subducting under the Cimmerian miniplate with a rate of approximately 4 cm per year. As the crust reaches the accretionary front, it is loaded by a sediment pile in excess of 6 km (Gaedicke et al. 2002) that has been built on it as a result of sedimentation rates in excess of 1 km per 1 million years (Deslisle, 2004).

In the Mokran region, especially around active mud volcanoes like the Tang Konarak mud volcano, the extracted mud is traditionally used for therapeutic purposes, commonly known as "mud therapy." Local communities believe that the mud possesses anti-inflammatory and soothing properties beneficial for skin ailments, joint pains, and muscular problems. Many residents and visitors apply the mud to their bodies or bathe in the mud volcano pools to take advantage of these natural healing effects. Although this practice is largely based on local experience and indigenous knowledge, scientific investigation into the mineral composition and bioactive properties of the mud could open pathways for future medical and therapeutic studies. Beyond its cultural and traditional significance, mud therapy in this area also holds potential as a health-based geotourism attraction.

3.4 Shahsavaran Mountain

The Shahsavaran region is part of an active magmatic arc with E-W structural trends. It contains Quaternary eruptive centers extending into Pakistan. Mud diapirism here reflects magmatic-tectonic interactions, further highlighting its geological and geoheritage significance. Shahsavaran magmatic arc has formed on south margin of East-Central Iran microcontinent and it contains 16 Quaternary eruptive centers with 450 km length.

4. Diapiric Provinces of Iran

Mud diapirs in Iran exhibit diverse shapes and elevations, influenced by tectonic activity, erosion rates, and emergence times. Based on structural and geological investigations, four provinces have been identified (Figure 4):

These provinces provide valuable data for understanding tectonic processes and serve as important geoheritage sites that demand preservation.

4.1. South Caspian Province:

This province is located at South Caspian basin (Figure 4). There are more than 400 submarine mud volcanoes. They have formed on a thick old oceanic crust that overlies by 10 to 18 Km sedimentary cover.

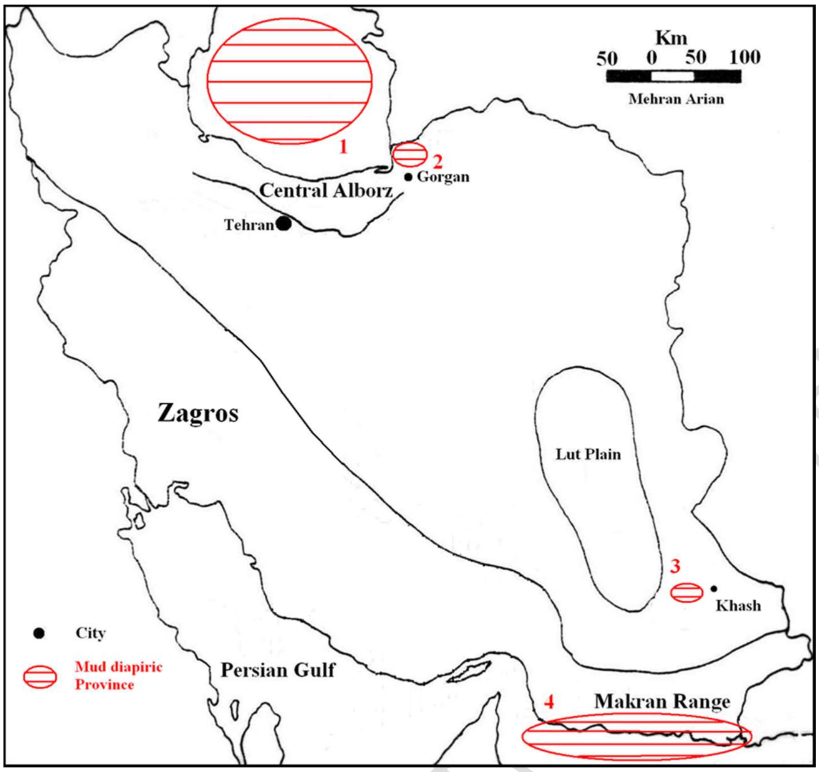


Figure 4. Geographical distribution of mud diapiric provinces in Iran.

4.2. North Gorgan Province:

This province is located at North Gorgan (Figure 4). There are 3 big mud volcanoes around Gomish-Tapeh that one of them (Gharniarigh-Tapeh) is very big and clear (Figure 5). The second one is Naft-Lije that fund at north of Gomish-Tapeh (Figure 6). They have formed on a thick old oceanic crust that overlies by 10 Km sedimentary cover in Caspian foreland basin. Also, it seems that, the former Abaskon island in Gorgan River delta has been formed in this province.

4.3. Khash-Bazman Province:

This province is located at east Khash (Figure 4) to east of Bazman. There are a few old mud volcanoes. The biggest one is Pirgel mud volcano (Figure 7) with up to 50 meters elevation. They (Figure 8) have formed on a thick continental crust of Shahsavaran magmatic arc.

4.4. Coastal Mokran Province:

This province is located at Coastal Mokran (Figure 4). The implemented studies indicate that the up to 20 mud volcanoes have formed along Coast line of Mokran range. Also, there are several submarine mud volcanoes in offshore of Oman Sea, especially along the main faults such as Zendan or Minab fault. Mud volcanoes originate from the clastic rocks located on a platform similar to the carbonate platform, as described by Khalili et al. (2021). The biggest one is Tang (or Napag) mud volcano (Figure 9) with up to 20 meters elevation at west of Konarak.

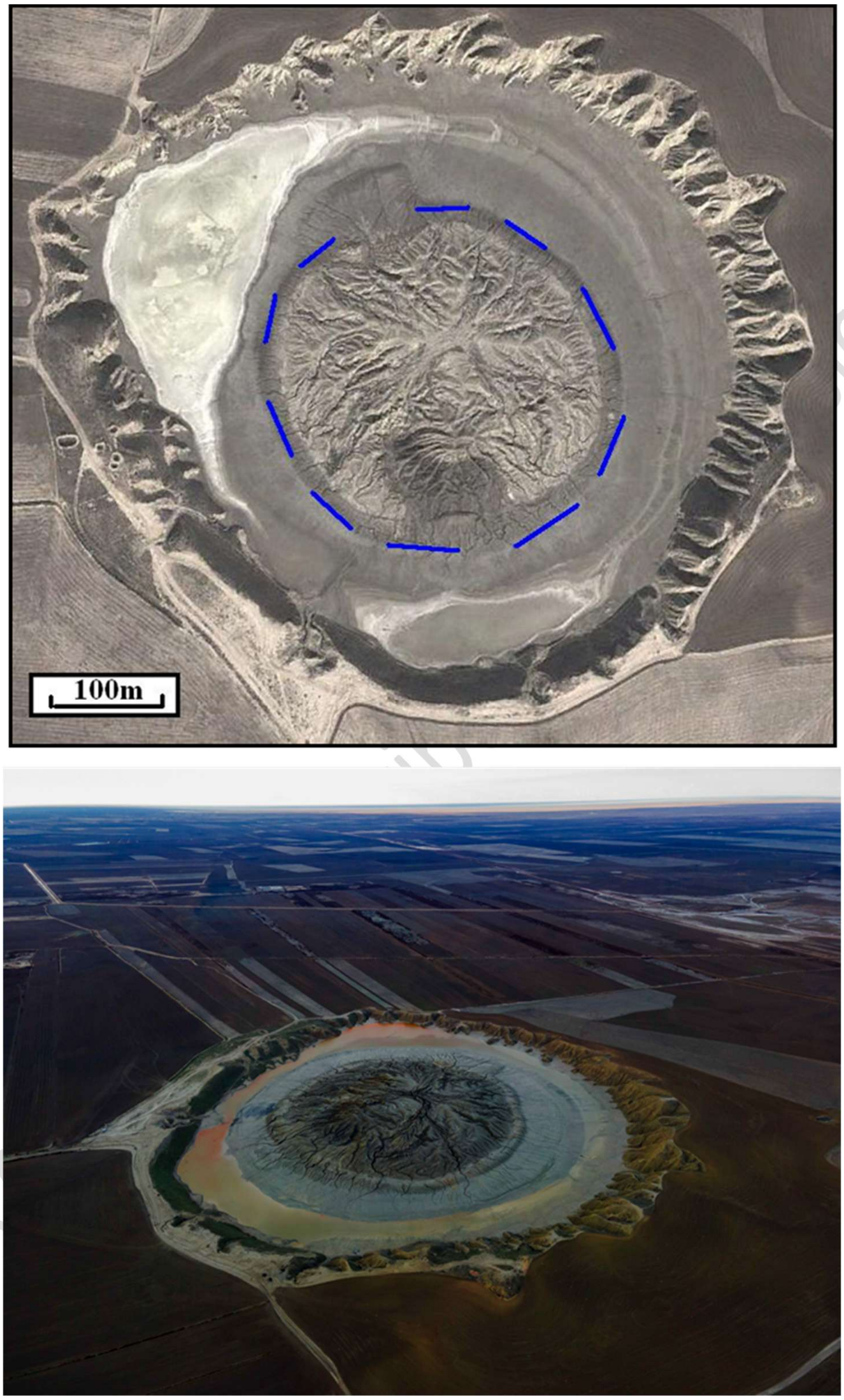


Figure 5. Interpreted ETM+ Satellite image of Garniarig-Tapeh mud volcano at North Gorgan province (up, from Arian and Sistanipour 2015) and oblique aerial photo with a quadcopter drone(down). The location of the photograph is shown in Figure 3.

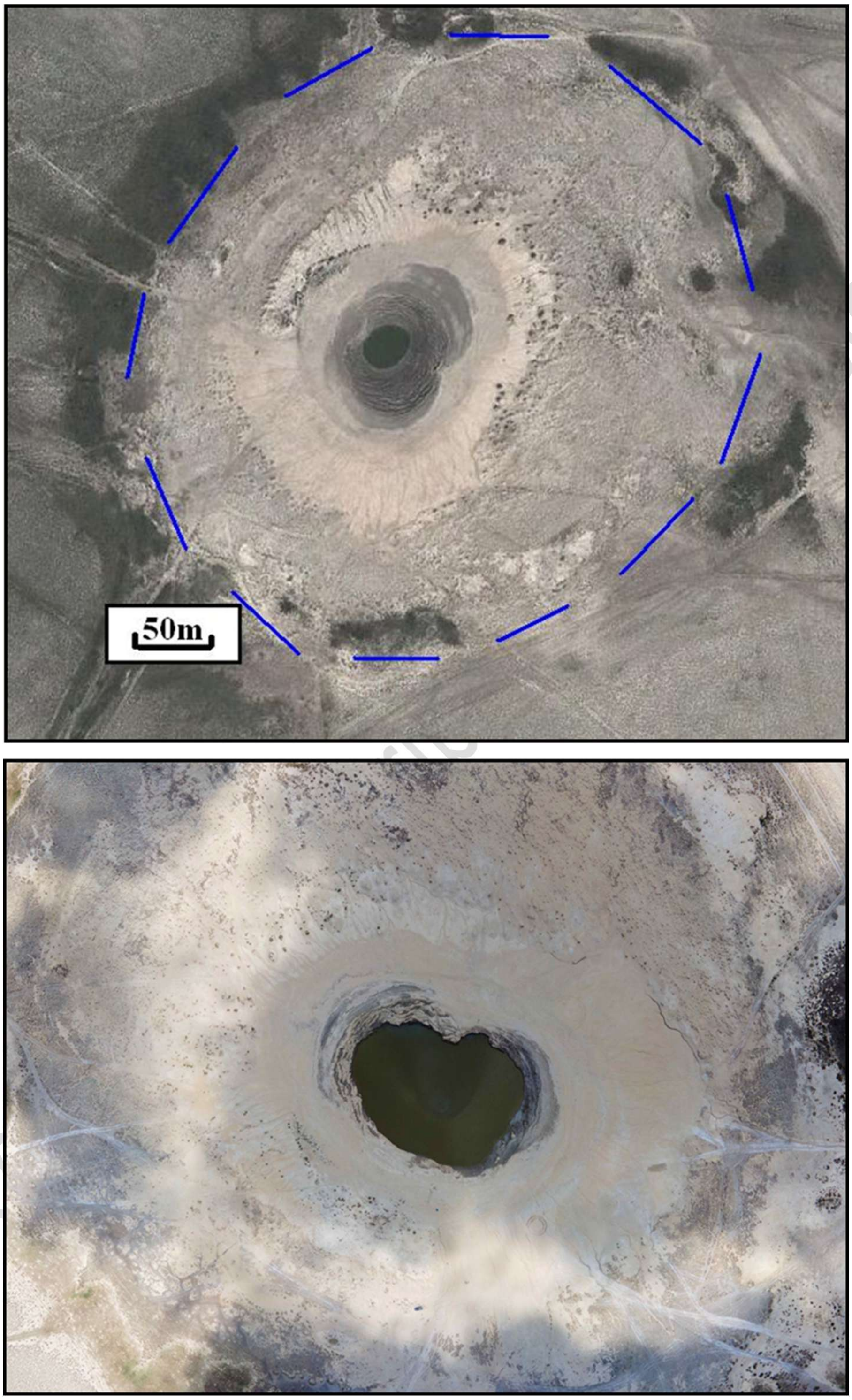


Figure 6. Interpreted ETM+ Satellite image (up from Arian and Sistanipour 2015) and oblique aerial photo with a quadcopter drone(down). The location of the photograph is shown in Figure 3.

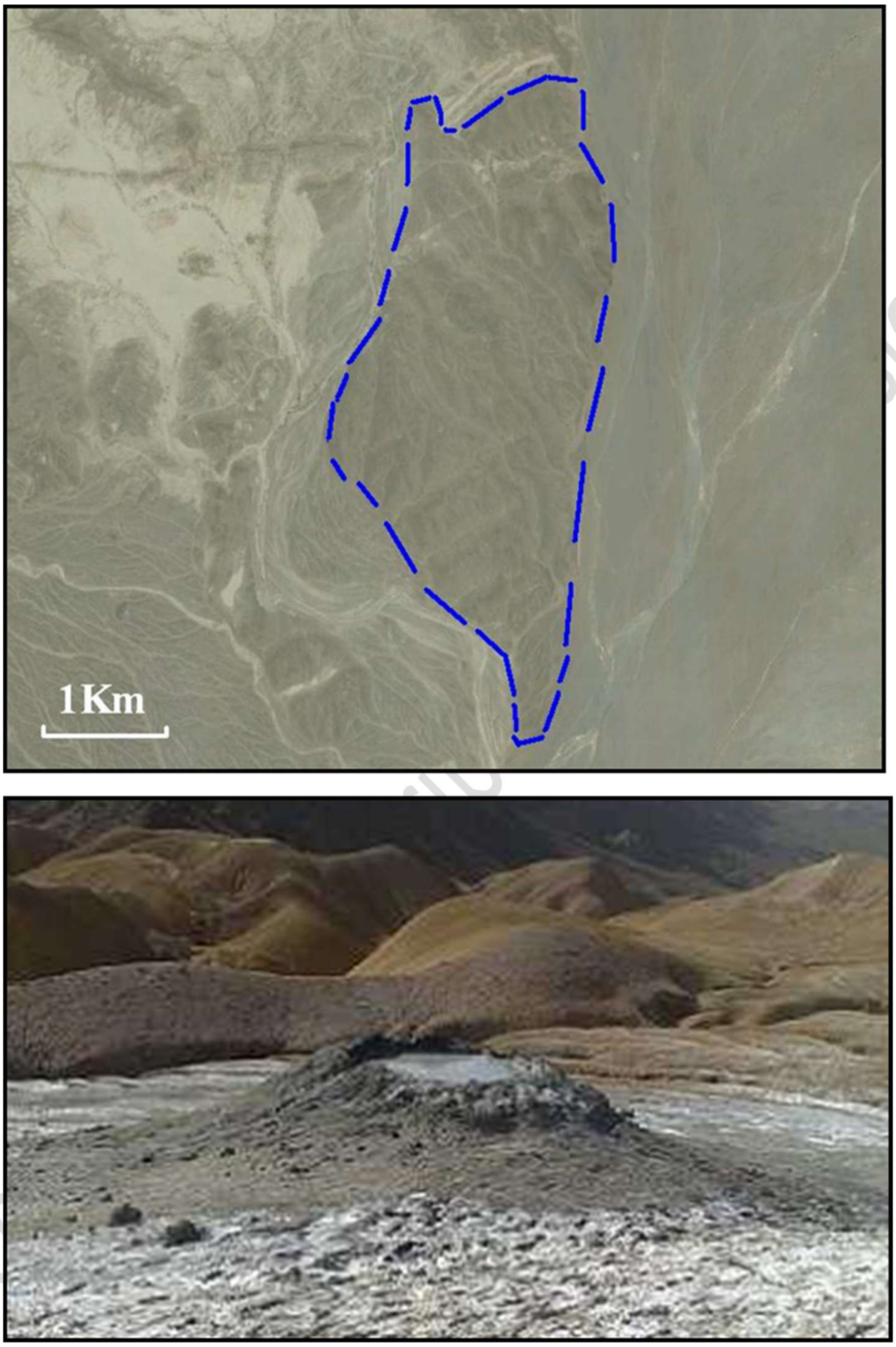
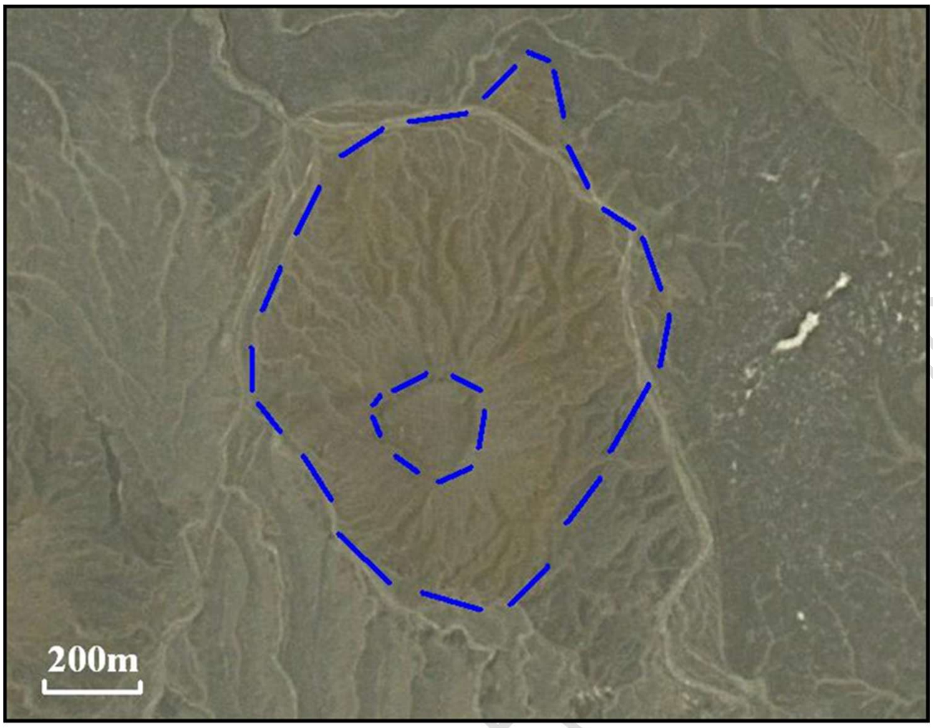


Figure 7. Interpreted ETM+ Satellite image (up) and a photo from a one of its small craters (down) of Pirgel mud volcano at Khash-Bazman province. The location of the photograph is shown in Figure 3.



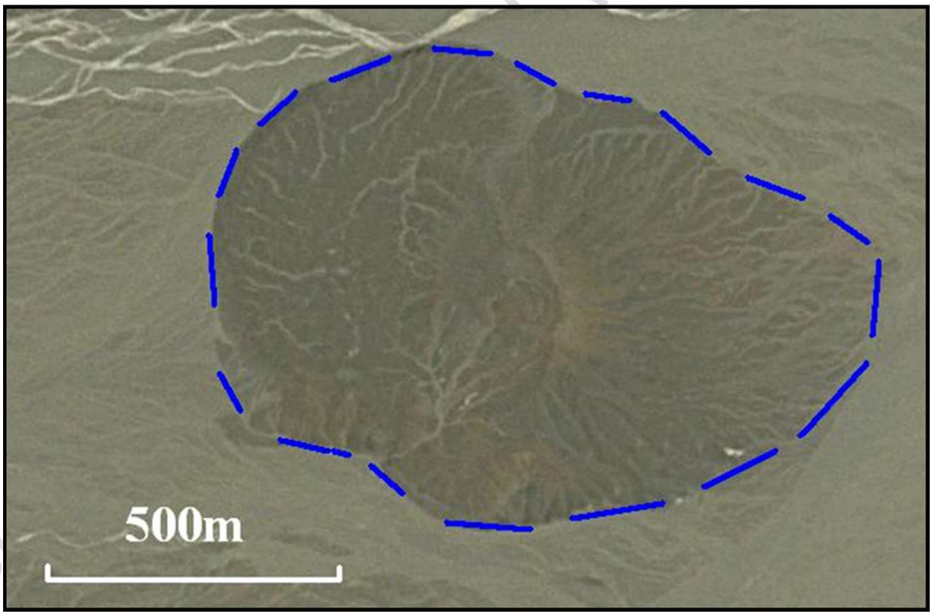


Figure 8. Interpreted ETM+ Satellite image of two old mud volcanoes at Khash-Bazman province. Map located in Figure 3.

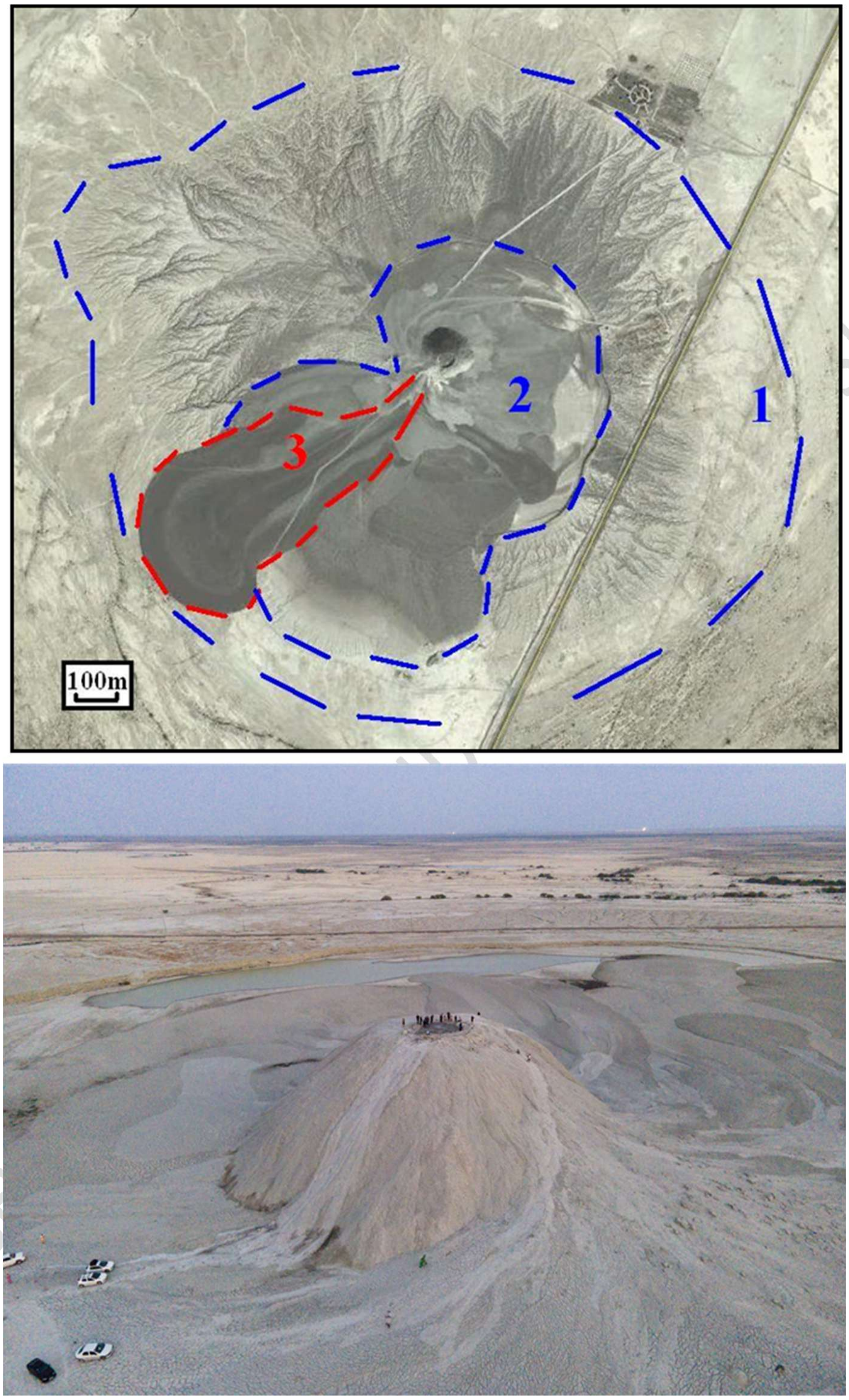


Figure 9. Interpreted ETM+ Satellite image (up) and oblique aerial photo with a quadcopter drone of Tang mud volcano at Coastal Mokran province (down). The location of the photograph is shown in Figure 3.

5. The Importance of Protecting Geological Phenomena and Mud volcano

Places that have a beautiful, interesting, and impressive geological form or process can be converted into geosites by creating accommodation facilities, tourist routes, and management related to preserving that attraction.

Geoconservation is necessary because we see that geosites are at risk of several types of threats such as destruction by visitors, misuse of these beautiful geological sites, inappropriate legislation, etc. If geosites are protected and managed, they will provide an opportunity to develop scientific research, educate students and the general public, and develop geotourism activities and generate income for local residents.

Such geological heritage is related to its spatial importance (from small and local, to regional, national and international), its uses (educational, scientific, recreational) and the need for its protection (Barettino et al. 2000; Osborne, 2000). The importance of protecting geological heritage has already been recognized by several international organizations such as UNESCO and the International Geosciences Union. Also in Europe, the European Association for the Protection of Geological Heritage (ProGEO) has presented an integrated strategy of geoconservation.

Despite this recognition by the international community, and many efforts to protect geological attractions, we see that geological diversity is still at risk and threatened (Yazdi et al. 2024). Therefore, serious measures should be taken to protect all geosites, especially the mud volcanoes that are the subject of this article.

One important aspect of mud volcano geotourism is the perceived therapeutic properties of the mud, which play a significant role in attracting tourists and strengthening the cultural-natural connection of these areas. In many local communities around mud volcanoes, people still believe in the positive effects of mud therapy on various ailments and physical and mental health. They use the mud and sediments from mud volcanoes to treat skin diseases, rheumatism, inflammation, and muscle pain. These traditional beliefs, besides their cultural value, also have the potential to create health tourism opportunities in these regions. Therefore, paying attention to this therapeutic aspect in the sustainable development of mud volcano geotourism can help preserve the natural and cultural heritage of the area and foster local economic development. Further scientific studies are needed to examine the validity of these therapeutic claims and to manage related tourism activities appropriately.

6. Methods of protecting geological diversity

Different elements of geological diversity need to be protected and managed in different ways. Murray Gray (2005) proposed geoconservation objectives for eight themes of geological diversity, including rocks, minerals, fossils, landforms, landscapes, processes, soils and other earth resources. This plan is based on rare and common occurrences and phenomena, as it is argued that geological diversity and the environment in general, should be respected both within and outside protected areas.

The goal of geoconservation is to protect geosites as fundamental and important units of the Earth's geological heritage (Henriques, 2010), which is achieved through specific methods such as geosite cataloging, assessment, protection, valuation, and monitoring (Brilha, 2005). Based on the above classification, in order to protect mud volcanoes, attention should be paid to issues such as maintaining the completeness of the landforms and restoring them (if necessary), encouraging authentic contouring within the boundaries of mud volcanoes, maintaining the topography intact, trying to maintain the active processes of mud volcanoes intact for their beautiful views and restoring them (if necessary).

Certainly, creating a protected area by passing a protective law and enforcing fines is one way, but this is not a guaranteed protection, due to violations of the law or changes in political or investment trends. Fines are rarely enough to deter commercial collectors or visitors. One of the surest ways is to deter visitors from reaching mud volcanoes by fencing them off and visiting them from a distance, or under certain conditions.

In order to preserve mud volcanoes as a geological heritage, the following points must be observed.

1 Legal Protection: Establishing legal frameworks to classify mud volcanoes as protected natural monuments is essential. These regulations should ensure their preservation against industrial and urban encroachment.

2 Monitoring Programs: Implementing continuous monitoring systems, including remote sensing and field surveys, can help detect changes in mud volcano activity and assess their structural integrity.

3 Public Awareness and Education: Promoting awareness among local communities and stakeholders about the ecological and geological importance of mud volcanoes is crucial. Educational programs and materials can play a significant role in fostering sustainable tourism and conservation efforts.

4 Sustainable Tourism Development: Developing eco-tourism initiatives around mud volcano sites can contribute to local economies while preserving their natural state. Infrastructure planning should prioritize minimal environmental impact and include designated viewing areas and information centers.

5 Research and Collaboration: Encouraging interdisciplinary research on mud volcanoes can provide deeper insights into their dynamics and conservation needs. Collaborations between geologists, ecologists, and policymakers can lead to more effective management strategies.

6 Habitat Restoration: Where necessary, habitat restoration programs should be implemented to rehabilitate areas affected by erosion or human activities, ensuring the ecological sustainability of mud volcanoes.

However, these have not been given serious attention in Iran so far, although Yazdi (2013) studied the geotourism potential of Iran's mud volcanoes. Therefore, in this paper, as the first phase, the process of their formation has been investigated.

Visitor education plays an important role in helping to conserve geological attractions. Part of conservation should also include providing adequate scientific documentation of the geological attractions of the protected areas, promoting and advancing further research as necessary, and a conservation management plan that should be updated regularly. The latter should include a program for monitoring and surveillance of the condition of geological heritage assets within the protected areas and a program for upgrading and restoration to improve facilities and repair damage.

7. Results and Discussion

Mud volcanism in southeastern Iran, particularly the Mokran region, spans a larger area but exhibits less activity compared to the South Caspian region. Key differences between these regions are summarized below (table 1):

Table1. main characteristics of mud diapirism in the Southeastern and Northern Iran provinces.

Characteristics of mud diapirs	Southeastern Iran provinces	Northern Iran provinces
Time of mud diapirism	Early Pliocene	Early Miocene
Age of diapiric Formations	Paleocene to Late Miocene Turbidities	Jurassic to Late Oligocene Shales
Index Structures	Thrust Faults	Folds
Tectonic Setting	Semi-active subduction zone	Inactive subduction zone
Setting of mud diapirs Evolution	Accretionary Prism and Magmatic Arc	Abyssal Plain and Foreland Basin
Diapir Size	Small to Moderate	Big and very big
Regional Shortening	Pre -Diapirism	Syn -Post-Diapirism
Diapirism as result of	Tectonic Forces	Buoyant driving mechanisms
Depth of diapirs	Less	More
Distance of diapirs	More	Less
Common shape of Mud Volcanoes	Cone-shaped domes	Caldera-type craters
Mud Volcanoes Activity	Less	More
Overburden Behavior	More Brittle	More Ductile
Recent deformational rate	19 mm per year	14 mm per year
Seismicity frequency	High	Low
Trend of diapirs	West-East	Dispersed
Eruption Rate	Less	More
Weather and Water Temperature	More	Less
Diapirs Position	Controlled by faults	Determined the shape and of folds
Number of Diapirs	50 at least	130 at least
Thickness of Overburden	Down to 1000 Km	Up to 1000 Km
Seismicity Frequency	Less	More
Rate of Sediment Accumulation	Low	High

- Southeastern Iran: Tectonically driven processes dominate, with mud diapirs associated with fault systems.
- Northern Iran: Buoyancy-driven mechanisms prevail, resulting in large, dispersed domes.

Mud volcanoes offer natural laboratories for studying fluid migration and sedimentary dynamics. Their geoheritage value lies in their ability to demonstrate Earth's tectonic processes while supporting ecological diversity. Additionally, their visual appeal and scientific importance make them attractive for sustainable tourism, promoting geological conservation. To ensure their protection, integrated conservation strategies should be implemented, including:

1.Legal protection and monitoring frameworks to prevent damage from urbanization, mining, and industrial activities.
2.Community engagement and education initiatives to raise awareness of their significance and promote local stewardship.
3.Sustainable tourism practices that balance public access with preservation efforts, such as controlled visitor pathways and eco-friendly infrastructure.
4.Scientific collaboration for regular monitoring and research, including assessing impacts of climate change and tectonic activity on these fragile features.
5.Preservation of ecological habitats surrounding mud volcanoes to maintain biodiversity and their natural processes.

Such strategies emphasize the importance of these features not only as geological phenomena but also as vital components of Iran's natural heritage that require careful and sustained conservation efforts.

Comparative analysis of mud volcanoes in Iran with those in other regions of Western Asia and the broader Middle East reveals both commonalities and distinctive characteristics shaped by local tectonic settings. For example, mud volcanoes in Azerbaijan, situated along the South Caspian Basin adjacent to northern Iran, display similar buoyancy-driven mechanisms and are associated with active subduction and sedimentary basin dynamics (Milkov, 2000; Hovland et al., 1997). In contrast, mud volcanoes in eastern Turkey and the Levant region tend to form in more compressional tectonic regimes linked to the collision of the Arabian and Eurasian plates, showing prominent fault-controlled diapirism. Furthermore, the unique tectonic setting of southeastern Iran's Mokran region, influenced by the Oman Sea subduction zone, results in tectonically driven mud diapirs associated with accretionary prisms, which differ from the primarily buoyancy-driven mud volcanoes observed in northern Iran (Wiedicke et al., 2001). This comparative perspective highlights how regional tectonics, sediment supply, and fluid sources interact to control the formation, morphology, and activity of mud volcanoes across Western Asia, underscoring the geoheritage significance of Iran's mud diapiric provinces within a wider geological framework.

8. Conclusions

This study identified four distinct mud diapiric provinces in Iran. The South Caspian and North Gorgan provinces in northern Iran are primarily buoyancy-driven, whereas the Khash-Bazman and Coastal Mokran provinces in southeastern Iran are tectonically driven. These unique features highlight the dynamic geological processes shaping Iran's crust and underscore their significance as geoheritage sites. Preservation and further study of these regions are essential for advancing geological knowledge and promoting sustainable tourism.

9. Acknowledgements

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10. Competing interests

We have no conflict of interest to declare. This statement is to certify that all Authors have seen and approved the manuscript being submitted. We warrant that the article is the Authors' original work. We warrant that the article has not received prior publication and is not under consideration for publication elsewhere.

11. Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

References

Aliev, A.A.A., Guliev, I.S., Belov, I.S., 2002. Catalogue of recorded eruptions of mud volcanoes of Azerbaijan. Publishing House ‘‘Nafta-Press’’, Baku, pp 88.

Allen, M., Jackson, J., Walker, R., 2004. late Cenozoic reorganization of the Arabia-Eurasia Collision and the Comparison of Short-term and long-term deformation rates, Tectonics, 23,16P.

Arian, M. and Sistanipour, A.,2015. Mud Diapirism on the Gorgan, North Iran. Open Journal of Geology, 5, 442-450. http://dx.doi.org/10.4236/ojg.2015.56041.

Berberian, M., 1983. Southern Caspian: A compressional depression floored by a trapped, modified oceanic crust, Can. J. Earth Sci., 20, 163-183.

Bonini, M. 2012. Mud volcanoes: indicators of stress orientation and tectonic controls. Earth Sci Rev, 115:121–152.

Delisle, G., 2004. The Mud Volcanoes of Pakistan, Environmental Geology, 46, 1024-1029.

DeMets, C., Gordon, R.G., Argus, D.F., Stein, S. 1990. Current plate motions. Geophysical Journal International 101,425–478, 1990.

Dimitrov, L. I., 2003. Mud volcanoes – a significant source of atmospheric methane. Geo-Marine Letters 23, 155-161.

Etiope, G. 2015. Natural gas seepage. The Earth’s hydrocarbon degassing. Springer, https://doi.org/10.1007/978-3-319-14601-0

Feizi, F., Arian, M., Arian, A. .2015. Mud Diapirism on the Makran, Iran: Case Study on the Napag Mud Volcano. Open Journal of Geology, 5, 300-308. doi: 10.4236/ojg.2015.55027.

Flueh, E. R., N., Kukowski, Reichert, C., 1997.Cruise Report SO 123, MAMUT, Rep. 62,292 pp., GEOMAR Res. Cent., Kiel, Germany.

Gaedicke, Ch., Prexl, A., Schluter, H. U., Meyer, H., Roeser, H., Clift, P., 2002. Seismic stratigraphy and correlation of major regional unconformities in the north Arabian Sea? In: Clift, P.D., Kroon, D., Gaedicke, C., Craig. J., (Eds.). The tectonic and climatic evolution of the Arabian Sea Region. Geol Society, London, Special Publications 195:137–146.

Graue, K., 2000. Mud volcanoes in deep water Nigeria. Marine and Petroleum Geology 17, 959-974.

Hovland, M., Hill, A. Stokes, D., 1997. The structure and geomorphology of the Dashgil mud volcano, Azerbaijan, Geomorphology, 21, 1–15.

Hovland, M., Hill, A., Stokes, D., 1997. The structure and geomorphology of the Dashgil mud volcano, Azerbaijan. *Geomorphology 21*, 1-15.

Jackson, J.A., Priestley, K., Allen, M., Berberian, M., 2002. Active Tectonics of the South Caspian Basin, Geophysical Journal International. 148, 214-242.

Judd, A., 2005. Gas emissions from mud volcanoes. In Mud Volcanoes, Geodynamics and Seismicity. Proceedings of the NATO Advanced Research Workshop on Mud Volcanism, Geodynamics and Seismicity. Baku, Azerbaijan 20-22 May 2003. The Netherlands: Springer.
Khalili, A., Vaziri-Moghaddam,H., Arian,M., Seyrafian,A. 2021.Carbonate platform evolution of the Asmari Formation in the east of Dezful Embayment, Zagros Basin, SW Iran,Journal of African Earth Sciences, 181,104229,https://doi.org/10.1016/j.jafrearsci.2021.104229.
Kopf, A. J., 2002. Significance of mud volcanism. Reviews of Geophysics 40 (2).
Kopf, A., J., 2002.Significance of mid volcanism, Reviews of Geophysics, 40, 52p.
Mazzini, A., Etiope, G. 2017. Mud volcanism: an updated review. Earth Sci Rev 168:81–112.
Milkov, A. V., 2000. Worldwide distribution of submarine mud volcanoes and associated gas hydrates. Marine Geology 167, 29-42
Milkov, A.V. 2004. Global estimates of hydrate-bound gas in marine sediments: how much is really out there? Earth-Sci Rev 66:183–197.
Milkov, A.V., 2000.Worldwide distribution of Submarine mud Volcanoes and associated gas hydrates, Marine Geology, 167, 29-42.
Müller, C., Theilen, F., Milkereit, B., 2001. Large gasprospective areas indicated by bright spots. *World oil 222 (1)*.
Perez-Belzuz, F., Alonso, B., Ercilla, G., 1997. History of mud diapirism & triggering mechanisms in the Western Alboran Sea. *Tectonophysics 282 (1-4)*, 399-422.
Perez-Belzuz, F., Alonso, B., Ercilla, G., 1997. History of mud diapirism & triggering mechanisms in the Western Alboran Sea. *Tectonophysics 282 (1-4)*, 399-422.
Soloviev, V., Ginsburg, G. D., 1994. Formation of submarine gas hydrates, Bull. Geol. Soc. Den., 41, 86–94.
Vogt, P. R., Cherkashev, G., Ginsburg, G., Ivanov, G., Milkov, A., Crane, K., Lein, A., Sundvor, E., Pimenov, N., Egorov, A., 1997. Haakon Mosby mud volcano provides unusual example of venting. *Eos, Transactions, American Geophysical Union 78 (48)*, 549; 556-557.
Wiedicke, M., Neben, S. Spiess, V., 2001. Mud volcanoes at the front of the Mokran accretionary complex, Pakistan, Mar. Geol., 172,57–73.
Yazdi, A., Dabiri, R., Mollai, H. 2024. Protection of Geological Heritage by a New Phenomenon in Earth Sciences: Geoconservation, Journal of Mining and Environment, 15(1): 365-379, https://doi.org/10.22044/jme.2023.13434.2478
Yazdi, A. 2013. Potentials of Iran's geotourism and structure of mud volcanoes. Appl. Sci. Res 3.1, 350-358.