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Geomorphologic Landform Analysis of the Hormuz Salt Dome from a Geotourism Perspective

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***Abstract*:** Salt domes are among the most intriguing geomorphological landforms, offering significant geotourism potential due to their unique geological features and striking landscapes. The Hormuz salt dome, located in southern Hormozgan Province, is an exceptional example of such formations, shaped by both internal and external geological processes over time. These domes originate beneath sedimentary rock layers, rising to the surface due to the lower density of salt compared to overlying rocks, tectonic activity, and the visco-plastic properties of salt. This study investigates the geomorphological evolution of the Hormuz salt dome using a combination of satellite imagery, topographic and geological analysis, and field surveys. The results reveal a diverse range of landforms, including salt creep, salt rivers, cauliflower-like formations, and dissolution-induced features, all of which enhance the geotouristic value of the region. These remarkable structures not only provide insight into salt tectonics but also serve as natural attractions for geotourists, researchers, and nature enthusiasts. By highlighting the unique geomorphological features of the Hormuz salt dome, this research underscores its significance as a key geotourism destination, promoting sustainable tourism and scientific exploration while fostering a deeper appreciation of Earth's dynamic processes.

Keywords: Geomorphology, Salt dome evolution, Hormuz Island, Geotourism, Landform analysis.

I. INTRODUCTION

Geotourism is a specialized branch of tourism that focuses on the appreciation and sustainable management of geological and geomorphological features, landscapes, and natural heritage (Ólafsdóttir & Tverijonaite, 2018). It integrates aspects of geology, geography, and environmental conservation to provide an educational and immersive experience for visitors (Ruban, 2015). Unlike traditional tourism, which often centers around cultural or recreational attractions, geotourism highlights the Earth's dynamic processes, including rock formations, fossils, caves, volcanoes, and other significant landforms (Chen et al., 2015). Geotourism is deeply rooted in geology, as it revolves around the study and appreciation of Earth's geological features, landscapes, and natural processes (Newsome et al., 2012) as persnted in Figure 1. Geological formations serve as primary attractions for geotourism, offering visitors a chance to understand the dynamic forces that have shaped the planet over millions of years (Dowling, 2013). The interpretation of rock formations, mineral deposits, and tectonic activity enhances public awareness of geological sciences while promoting conservation efforts (Hose, 2000). Additionally, geotourism supports geological education by providing hands-on experiences that bridge the gap between scientific research and public engagement (Herrera-Franco et al., 2020).

Geotourism also intersects with engineering geology, as many geosites showcase the relationship between geological stability and human infrastructure (Yazdi et al., 2014). Engineering geologists study rock mechanics, soil stability, and geohazards to ensure safe construction and land use planning (Lamich et al., 2016). Geotourism sites such as landslides, fault zones, and karst landscapes serve as natural laboratories where engineering geologists can analyze the impact of geological conditions on built environments (Doktor and Mayer, 2016). These sites also raise awareness of natural hazards, such as earthquakes and landslides, helping communities and policymakers make informed decisions about risk management and sustainable development (Ólafsdóttir & Tverijonaite, 2018). By integrating geology and engineering geology, geotourism provides a platform for scientific education, disaster risk reduction, and sustainable land management (Chen et al., 2015). Visitors to geosites not only appreciate the beauty of Earth's landscapes but also gain insights into the challenges of construction in geologically active regions (Desa, 1997). Educational geotourism initiatives can showcase engineering solutions for slope stabilization, tunnel construction, and dam safety, highlighting the importance of geological knowledge in infrastructure projects (Dowling, 2013). As a result, geotourism serves as an interdisciplinary field that connects geological sciences, engineering geology, and public awareness, ultimately fostering a greater appreciation for Earth's natural and engineered environments (Ólafsdóttir & Tverijonaite, 2018).

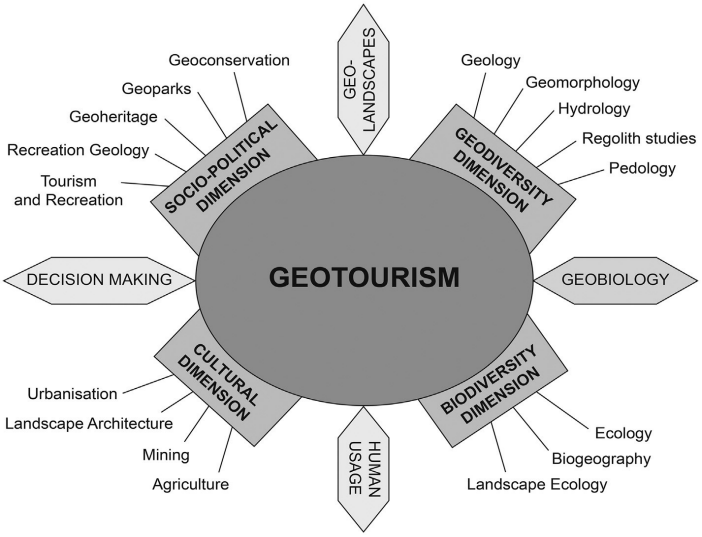


Fig. 1 A concept definition of geotourism (Newsome & Ladd, 2022)

The concept of geotourism has evolved over the years as a response to increasing interest in sustainable travel and environmental awareness (Drinia et al., 2023). Initially, geotourism was closely linked to nature-based tourism, but it has since developed into an independent discipline that merges scientific exploration with tourism (Ólafsdóttir & Tverijonaite, 2018). The Global Geotourism Charter and UNESCO Global Geoparks Network have played a significant role in promoting geotourism as a means of both education and conservation (Ruban, 2015). Geotourism encompasses several key elements, including geosites (unique geological locations), interpretative programs, geological trails, and visitor centers (Yazdi et al., 2014). These components are designed to enhance public awareness of geological heritage while fostering conservation efforts (Dowling, 2013). Successful geotourism initiatives often include guided tours, interactive exhibits, and local community involvement to ensure an enriching experience (Desa, 1997).

One of the major benefits of geotourism is its role in education and scientific literacy (Ólafsdóttir & Tverijonaite, 2018). It provides an opportunity for people to learn about Earth's history, natural hazards, and geological processes in an engaging manner. This increased awareness helps foster a sense of responsibility toward environmental conservation and climate change mitigation (Kubalíková, 2013). Geotourism has significant economic benefits, particularly for rural and underdeveloped regions. By attracting tourists to geosites, it generates revenue for local businesses, encourages job creation, and promotes sustainable economic growth (Ruban, 2015). Many communities that host geological attractions benefit from increased infrastructure development and improved living standards due to tourism-related investments (Dowling, 2013). In addition to its economic impact, geotourism supports cultural and environmental preservation (Drinia et al., 2023). Many geological sites are intertwined with local traditions, indigenous knowledge, and historical narratives. Through geotourism, these cultural elements are protected and shared with a broader audience, ensuring their survival for future generations (Mikhailenko et al., 2017). Moreover, responsible geotourism practices contribute to the conservation of fragile ecosystems and minimize environmental degradation.

Despite its many advantages, geotourism faces several challenges (Chen et al., 2015). One of the primary concerns is the potential for environmental damage due to excessive visitor traffic. Overcrowding at geosites can lead to habitat destruction, pollution, and erosion of fragile landforms (Ólafsdóttir & Tverijonaite, 2018). Additionally, unregulated tourism activities may compromise the integrity of geological features, reducing their scientific and aesthetic value (Newsome & Ladd, 2022). Another significant limitation is the lack of awareness and infrastructure in many geotourism destinations (Yazdi et al., 2014). Some geosites lack proper facilities, interpretative materials, and trained guides, which can diminish the visitor experience (Ruban, 2015). Furthermore, in many regions, geotourism is not adequately promoted or integrated into national tourism policies, resulting in missed opportunities for sustainable development (Lamich et al., 2016). Climate change poses an additional challenge to geotourism, as rising temperatures, extreme weather events, and natural disasters can threaten the stability of geological sites (Chen et al., 2015). Coastal erosion, desertification, and glacial melting are altering the landscape of many iconic geosites, requiring urgent adaptation and mitigation measures to ensure their long-term viability (Ólafsdóttir & Tverijonaite, 2018).

Geotourism plays a crucial role in advancing sustainable development goals by promoting responsible travel, conservation, and community engagement (Ruban, 2015). UNESCO Global Geoparks serve as models for integrating geotourism with environmental stewardship, scientific research, and local economic development (Drinia et al., 2023). By emphasizing sustainability, geotourism contributes to preserving Earth's geological heritage while providing long-term benefits to host communities (Chen et al., 2015). To maximize the benefits of geotourism while mitigating its challenges, effective policies and management strategies are essential (Doktor & Mayer, 2016). Governments, conservation organizations, and tourism stakeholders must collaborate to establish guidelines for visitor management, infrastructure development, and environmental protection (Hose, 2000). Educational programs and public awareness campaigns can further enhance geotourism's impact by fostering a sense of appreciation and responsibility among tourists (Newsome et al., 2012).

This study aims to analyze the geomorphological landforms associated with the evolution of the Hormuz salt dome from a geotourism perspective. By integrating satellite imagery, topographic and geological data, and field surveys, the research seeks to identify and classify the unique landforms resulting from salt tectonics, including salt creep, salt rivers, and dissolution features. Additionally, the study aims to assess the geotouristic potential of these formations, highlighting their significance for sustainable tourism and scientific education. Through a detailed investigation of the geomorphological processes shaping the Hormuz salt dome, this research contributes to a deeper understanding of salt dome dynamics and their role in landscape evolution. The necessity of this study lies in its contribution to both geological research and geotourism development. The Hormuz Salt Dome represents a rare and scientifically valuable geological structure, yet its geotouristic potential remains underexplored. By documenting and promoting these unique geomorphological features, this research supports sustainable

tourism initiatives that can boost local economies while preserving natural heritage. Furthermore, understanding the processes governing salt dome evolution is essential for hazard assessment, land-use planning, and environmental conservation. This study not only enhances scientific knowledge of salt dome geomorphology but also raises awareness of the importance of geotourism in promoting geological education and conservation.

II. Geology of Salt Domes

Salt domes, also known as diapirs, are geological structures formed by the upward movement of salt through overlying rock layers (Jackson & Hudec, 2017) are illustrated in Figure 2. These structures result from the buoyancy of salt, which has a lower density compared to surrounding sediments (Duffy et al., 2023). Over millions of years, salt deposits buried under thick layers of rock begin to rise due to their plasticity and the pressure exerted by overlying sediments (Xue et al., 2024). This process leads to the formation of dome-like structures that pierce through the Earth's crust, creating unique geomorphological landforms (Ellison et al., 2022). The salt forming these domes originates from ancient evaporite basins, where seawater evaporated and left behind thick salt layers (Gutiérrez et al., 2023). Over time, these deposits were buried by additional sedimentary layers, preserving them deep within the Earth's crust (Schuba & Moscardelli, 2023). Geological movements, such as tectonic activity, trigger the rise of salt toward the surface, leading to the formation of salt domes (Duffy et al., 2023). The age of salt deposits can range from a few million to over 500 million years, depending on the geological history of the region (Xue et al., 2024). The primary driving force behind salt dome formation is the difference in density between salt and the surrounding rock layers (Vera-Arroyo & Bedle 2023). Since salt is less dense and has viscoelastic properties, it behaves like a highly viscous fluid over geological timescales (Islam & Wali, 2024). When subjected to tectonic forces or differential loading, salt starts to flow and move upward, pushing through weaker zones in the overlying rock (Gutiérrez et al., 2023). This process, known as diapirism, results in the formation of salt structures that can extend several kilometers above their original depositional layers (Jackson & Hudec, 2017).

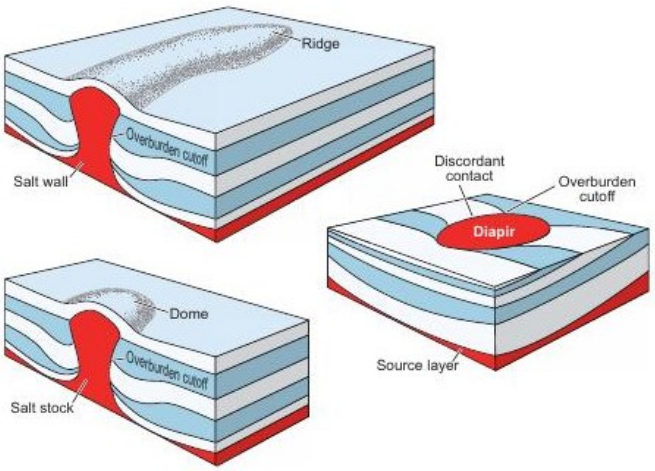


Fig. 2 A schematics of salt dome (Jackson & Hudec, 2017)

Salt domes exhibit a variety of geomorphological features, including salt glaciers, dissolution sinkholes, salt karsts, and salt springs (Zanganehasadi et al., 2023). As salt reaches the surface, it interacts with weathering processes, forming distinctive landforms such as ridges, valleys, and isolated hills (Sahraei et al., 2023). The dissolution of salt by groundwater leads to the creation of salt caves and sinkholes, further enhancing the complexity of these geological structures (Bland et al., 2019). In some regions, salt domes contribute to the formation of salt flats and playas, adding to their geomorphological diversity (Al-Zoubi & Brink, 2001). Tectonic forces play a crucial role in the evolution of salt domes. In many cases, salt domes form along fault zones or in compressional tectonic settings where rock layers are subjected to intense pressure (Jallouli et al., 2005). The presence of salt structures can also influence regional deformation patterns, leading to the formation of anticlines, synclines, and fault-related features. Salt movement can create structural traps that are important for hydrocarbon accumulation, making salt domes significant in petroleum geology (Zanganehasadi et al., 2023).

Salt domes have considerable economic significance due to their association with natural resources (Hudec & Jackson, 2012). Many salt domes contain valuable deposits of minerals such as halite (rock salt), potash, sulfur, and gypsum (Bland et al., 2019). Additionally, salt domes serve as structural traps for oil and gas reservoirs, making them prime targets for hydrocarbon exploration (Zanganehasadi et al., 2023; Derakhshani et al., 2024). The impermeable nature of salt helps in sealing oil and gas accumulations, leading to the formation of some of the world's most productive petroleum fields (Xue et al., 2024). While salt domes have economic benefits, they also pose environmental and geohazard risks (Schuba & Moscardelli, 2023). The dissolution of salt by groundwater can lead to ground subsidence, sinkhole formation, and land instability (Gutiérrez et al., 2023). Additionally, excessive mining and drilling in salt dome regions can cause structural collapses and contamination of groundwater sources (Jackson & Hudec, 2017). Understanding the geological processes controlling salt dome formation is crucial for mitigating these risks and ensuring sustainable resource extraction (Duffy et al., 2023).

Salt domes offer unique opportunities for geotourism, attracting visitors with their striking landscapes and rare geological formations (Vera-Arroyo & Bedle 2023). Features such as salt caves, salt waterfalls, and colorful mineral deposits create visually stunning environments that appeal to both scientists and tourists (Jackson & Hudec, 2017). Many salt domes are located in geologically significant regions, where they are incorporated into geoparks and conservation areas (Drinia et al., 2023). Promoting geotourism in salt dome regions can enhance scientific awareness and support local economies through sustainable tourism initiatives (Toma et al., 2022). Salt domes are found in various parts of the world, with notable examples including the Hormuz Salt Dome in Iran, the Gulf Coast salt domes in the United States, and the Zechstein salt structures in Europe. Each of these regions showcases different aspects of salt dome geology, from massive subsurface diapirs to exposed salt karst landscapes. The study of these salt domes provides valuable insights into the geological history of evaporite basins and the long-term processes driving salt tectonics. So, salt

domes are fascinating geological structures that play a significant role in Earth's geological, economic, and environmental systems. Their formation involves complex interactions between density contrasts, tectonic forces, and subsurface fluid dynamics. Beyond their scientific importance, salt domes contribute to resource exploration, geotourism, and environmental conservation.

III. Studied Location

The Hormuz salt dome is one of the most fascinating and unique salt structures in Iran and globally (Talbot, 1998). Geographically, it is part of Qeshm County, located in the southern region of Hormozgan Province, approximately 17 km south of Bandar Abbas via a maritime route (Stewart, 2018). Positioned 20 km east of Qeshm Island, the salt dome is accessible by sea from the Shahid Haghani Port in Bandar Abbas (Talbot, 1998) as presented in Figure 3. It is situated at 27°04′N latitude and 56°28′E longitude, occupying a significant geological and geomorphological position in the Persian Gulf (Geng et al., 2022). The Hormuz Salt Dome is a striking geological feature formed through the upward movement of ancient evaporite deposits. These deposits, originating from the Hormuz Series, date back to the Precambrian to Cambrian periods (over 540 million years old). The dome's structure is the result of salt tectonics, where the low-density salt mass rises through overlying rock layers due to buoyancy and tectonic forces (Kent, 1979). This process, known as diapirism, has led to the formation of an extensive and exposed salt dome, rich in various evaporite minerals such as halite, gypsum, and anhydrite (Khodabakhshnezhad & Arian, 2016).

The Hormuz Salt Dome has a nearly symmetrical, fig-shaped appearance, with its major axis oriented in an east-west direction (Talbot, 1998). The larger diameter extends approximately 8 km, while the smaller, irregular diameter averages around 7 km, covering an area of nearly 56 km^2. The dome's topography can be divided into two primary zones (Kent, 1979):

- *Elevated Zone*: This area rises from an elevation of approximately 30m above sea level and reaches a maximum height of 182m at the dome's peak. This peak is likely the original point of emergence for the salt diapir.
- *Lower Zone*: Surrounding the elevated core, this region consists of salt flats, dissolution features, and various erosional landforms, shaped by wind, water, and tectonic activity.

The geomorphological diversity of the Hormuz Salt Dome is evident in its salt glaciers, dissolution sinkholes, salt rivers, and intricate karst-like formations (Rostami et al., 2020). These features result from ongoing weathering and erosion processes, influenced by the high humidity and marine environment of the Persian Gulf (Ranjbaran et al., 2020). The combination of vibrant red, white, and purple salt deposits, along with iron-rich sediments, creates a visually stunning landscape, making the area a prime destination for geotourism and scientific research (Arian & Noroozpour, 2015). This exceptional salt dome not only provides insights into regional tectonics and salt dynamics but also serves as a valuable natural heritage site with immense educational, ecological, and geotouristic potential (Khodabakhshnezhad & Arian, 2016).

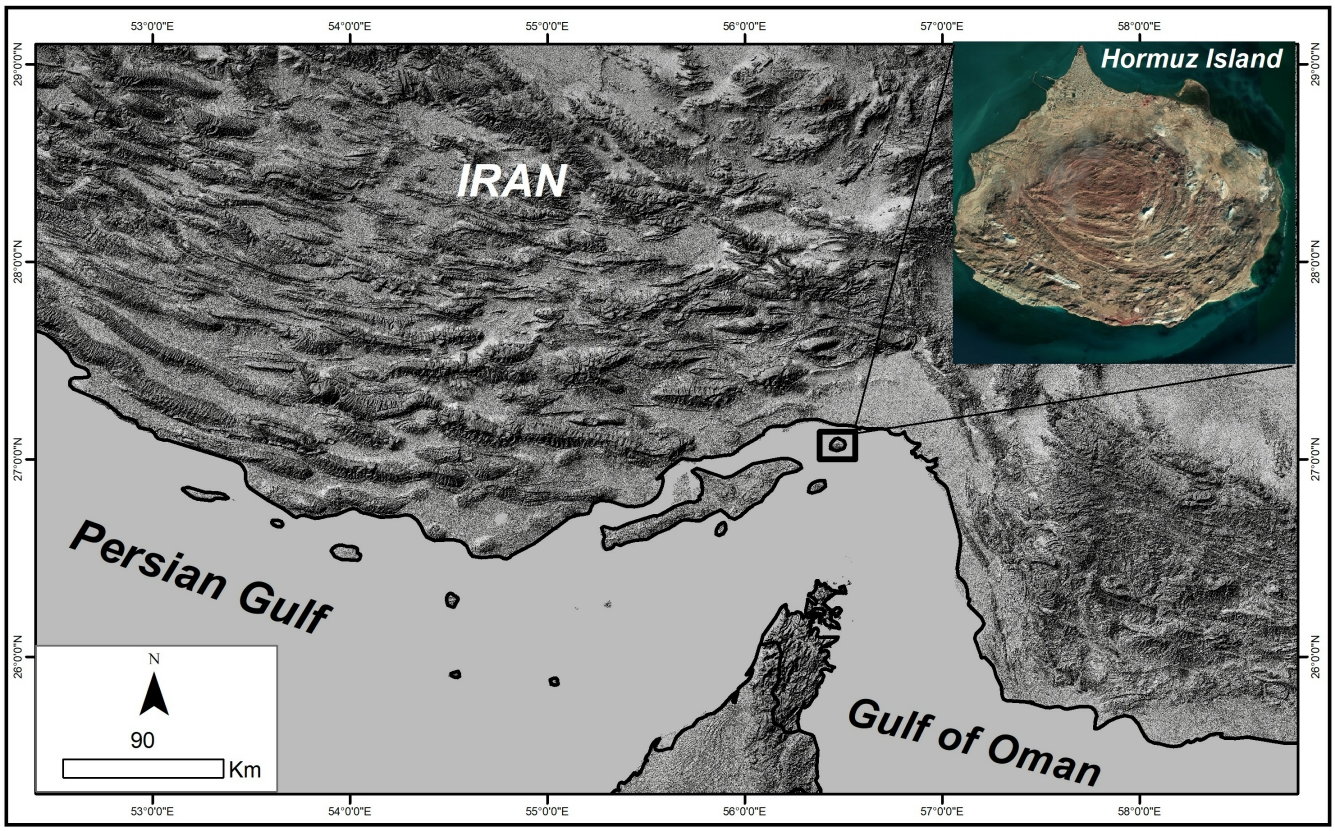
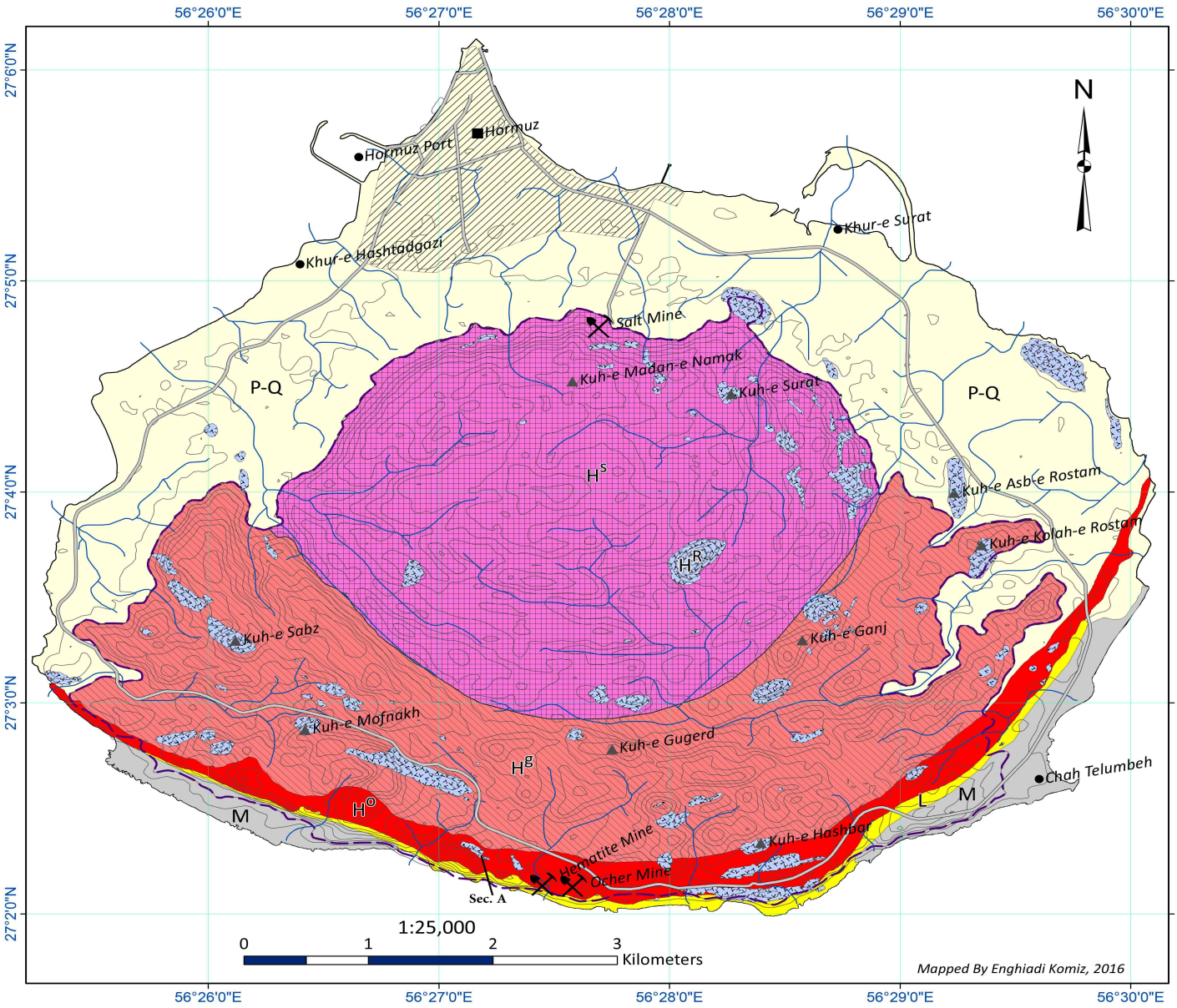


Fig. 3 Location of studied area



GEOLOGICAL LEGEND

Upper Fars Series
- P-Qt / P-Q — Recent clastics, dunes and beach deposits (Pliocene-Quaternary)
- Miocene — M — Steeply dipping rim of transgressive marls
- Miocene — L — Steeply dipping rim of transgressive limestones

Hormuz Formation
- PrecamB-Cambrian — H^R_v — Rhyolitic and trachytic plugs and irregular masses (tuffs)
- H^o — Concentrated red oxide, forming a rough hematitic and limonitic surface (locally mined).
- H^g — Ferruginous gypsum and salt
- H^s — Salt, partly reddish banded

SYMBOLS
- Drainage
- Asphalt Road
- Holocene marine cliff-line at 30 m asl
- Contour Line (15m intervals)
- Urban area

Fig. 4 Geological map for studied region (Geological Survey of Iran 2009)

Hormuz Island is part of the folded Zagros Belt, a geologically significant region shaped by complex tectonic forces and salt diapirism (Ranjbaran et al., 2020; Ghanbarian et al., 2021). The island's structural framework is primarily characterized by west-east trending fold structures, which align with the broader deformation patterns of the Zagros Orogenic Belt (Faramarzi et al., 2015). This orientation plays a crucial role in the formation of major fault systems and fractures in the region, influencing both the island's geomorphology and geological evolution (Nasir et al., 2008). The present structure of the island is the result of intense tectonic activity during the Alpine orogeny, particularly in the Neogene and Quaternary periods (Kent, 1987). These movements have contributed to the development of thrust faults, large-scale fractures, and uplifted salt formations. The evidence of structural disturbances and deformations in the folded units suggests a significant influence of thrusting mechanisms and strike-slip faulting, which have further intensified the complexity of the island's geodynamic behavior (Khodabakhshnezhad & Arian, 2016; Ghanbarian & Derakhshani, 2022). Additionally, the presence of the Hormuz Salt Formation has played a crucial role in shaping the island's landscape through diapiric movements and salt tectonics (Ranjbaran et al., 2020). The combination of tectonic compression, salt buoyancy, and viscoplastic deformation has resulted in unique landforms, including salt domes, fault-controlled ridges, and eroded karstic features (Kent, 1979). These geological characteristics not only provide valuable insights into the regional stress regime and tectonic evolution but also make Hormuz Island a key site for studying salt-related deformation processes in active orogenic settings (Kent, 1987).

IV. Geotourism of Hormuz Salt Dome

The Hormuz salt dome, located in the Persian Gulf, is one of the most remarkable geological attractions in Iran and globally. Known for its vibrant landscapes, unique geomorphological formations, and mineral diversity, the island has become a key site for geotourism. Its extraordinary features, including salt glaciers, colorful soil, salt caves, and karstic formations, provide a visually stunning environment that attracts both researchers and nature enthusiasts. The Hormuz salt dome is part of the Zagros Fold Belt and has been shaped by diapiric movements, where deep-seated salt has risen due to its low density and plasticity. This geological phenomenon, occurring over millions of years, has resulted in varied rock formations, including salt flows, gypsum deposits, and anhydrite layers. The exposure of these ancient rocks makes the region a natural laboratory for geologists and visitors interested in Earth's dynamic processes.

One of the most fascinating aspects of the Hormuz salt dome is its diverse geomorphological formations. Features such as salt rivers, mushroom-shaped rock formations, and cauliflower-like salt structures create a landscape that appears almost otherworldly. Additionally, the presence of colorful soil layers has earned Hormuz the nickname "Rainbow Island", making it a prime destination for nature photography and eco-tourism. Figures 5 to 11 present several geological and geomorphological features for the Hormuz salt dome.

Despite its harsh and saline environment, the island hosts unique ecosystems, including salt-tolerant vegetation and diverse marine life. The proximity of the salt dome to the Persian Gulf contributes to its rich coastal biodiversity, where mangrove forests and coral reefs thrive. Geotourism in the area promotes environmental awareness and conservation by highlighting the delicate balance between geology and ecology. Beyond its geological significance, Hormuz Island has a rich cultural heritage. The island has been a historical trade hub, and its soil has been used for traditional dyeing and artwork. The famous "Red Soil of Hormuz", rich in iron oxides, is not only a geological wonder but also an integral part of the local artistic and culinary traditions. Combining cultural tourism with geotourism enhances the visitor experience and supports local communities.

Geotourism can be a sustainable economic driver for Hormuz Island. By attracting tourists, it promotes local businesses, handicrafts, and eco-friendly accommodations. Investments in geotourism infrastructure, such as educational centers, guided tours, and nature trails, can create job opportunities and boost the regional economy. Proper management ensures that tourism benefits both the environment and the local population. Despite its potential, geotourism in the Hormuz salt dome faces several challenges. Lack of infrastructure, environmental degradation, and uncontrolled tourism activities pose threats to the delicate ecosystem. Over-tourism can lead to erosion of fragile rock formations, pollution, and habitat destruction. Sustainable tourism strategies, including visitor limits, eco-friendly transportation, and waste management systems, are essential to minimize negative impacts.

The harsh climatic conditions of Hormuz Island, including extreme heat and humidity, make tourism challenging during certain seasons. Additionally, limited accessibility, as the island is only reachable by boat from Bandar Abbas, restricts the flow of visitors. Improving transportation facilities and promoting seasonal tourism planning can help overcome these limitations. To preserve the unique geological heritage of the Hormuz Salt Dome, a sustainable geotourism framework must be implemented. This includes geoconservation initiatives, environmental education programs, and responsible visitor behavior. Establishing protected areas and UNESCO Geopark status could further enhance conservation efforts while promoting responsible tourism. The Hormuz Salt Dome is a natural treasure that holds immense potential for geotourism, scientific research, and sustainable development. By balancing economic benefits with environmental preservation, geotourism can ensure that this unique landscape remains intact for future generations. With proper management, infrastructure development, and awareness programs, Hormuz Island can emerge as a leading global geotourism destination, offering an unparalleled experience in Earth's geological history.

Fig. 5 An example of salt springs

Fig. 6 An example of existing salt river

Fig. 7 An example of cauliflower-shaped formations observed in the salt diapir

Fig. 8 An example of salt cliffs

Fig. 9 An example of interior view of a salt cave in the region

Fig. 10 An example of mushroom-shaped formations

Fig. 11 An example of stepped slopes within the diapir

V. Conclusion

The Hormuz salt dome is a unique geological and geomorphological phenomenon that holds significant importance in both geotourism and engineering geology. Its striking landscapes, including salt caves, salt rivers, cauliflower-shaped formations, and stepped slopes, create a visually stunning natural attraction. These features not only enhance the geotourism potential of the region but also provide valuable insights into salt diapirism, tectonic activities, and surface processes. The geomorphological diversity of the salt dome reflects the dynamic geological history of the area, influenced by diapirism, erosion, and tectonic forces. From an engineering geology perspective, the structural complexity of the Hormuz salt dome presents both challenges and opportunities. The presence of highly soluble salt formations, potential instability, and variable mechanical properties of salt rocks must be considered in construction and infrastructure planning. Additionally, understanding the geotechnical behavior of salt domes can aid in resource extraction and hazard assessment. Despite its immense scientific and touristic value, the preservation of the Hormuz salt dome is crucial. Sustainable geotourism initiatives should be promoted to protect the fragile salt formations while allowing visitors to appreciate its natural beauty. Proper management strategies can help balance conservation efforts with tourism development, ensuring that this remarkable geological site remains a valuable resource for future generations.

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Authors' contributions

Yasaman Parvar conducted the main data analysis, contributed to the data collection, preprocessing, interpretation, and was responsible for drafting the initial manuscript. She performed conceptual and critical revision of the manuscript, final approval of the version to be published. All authors read and approved the final manuscript.

Conflict of interest

The authors have not disclosed any competing interests.

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