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RESEARCH PAPER

Halokinetic sequences as indicators of Cenozoic diapiric growth: The Handun Salt Diapir (SE Zagros, Bandar Abbas)

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Abstract
Sedimentary successions in the eastern part of the Zagros Fold-Thrust Belt were episodically influenced by halokinetic events. The positive and negative accommodation spaces created by salt-induced uplifting and downbuilding processes caused variable sedimentation rates followed by stratal geometry variations and forming the halokinetic sequences. The Handun passive salt diapir, located in the north of the Bandar Abbas area is one of the best examples in which the evolution of the salt diapir could be analysed by the halokinetic sequences. These sequences are studied in four outcrop sections in the core of Handun anticline within the uppermost part of the Cretaceous to Lower Cenozoic successions (Tarbur Formation to Guri Member of the Mishan Formation). The succession flanking of salt diapir displays various halokinetic sequences with hook and wedge types growth strata. These geometries are mainly developed in the Paleocene-Eocene Pabdeh and Jahrum Formations. The Middle-Upper Eocene Jahrum Formation shows the maximum facies, geometry, and thickness variations and is truncated by a regional unconformity at the Eocene-Oligocene boundary. This stratigraphic unit is also interrupted by an allochthonous salt sheet as a result of lateral extrusion of the Hormuz salt. In addition, withdrawal and uplifting of the salt diapir caused strong lateral changes in accommodation spaces and sedimentation rates during this time interval. These variations could be documented by hook geometries in the halokinetic sequences around the Handun salt diapir. During the Oligocene to Lower Miocene times, in the Razak Formation and lower parts of the Guri Member, hook types growth strata can be observed in the N flank of the Handun salt diapir, while in other flanks, geometries of the sequence/growth strata become wedge-shaped more tabular far from the salt diapir. Based on these variations three halokinetic phases have been recognised which include nine halokinetic sequences showing the temporal and spatial effects of the halokinesis on the sedimentation systems.

Keywords: Halokinetic Sequences, Handun Salt Diapir, Hormuz Salt, Halokinesis, Bandar Abbas, Eocene, Growth Strata.

Introduction

Halokinetic sequences (HS) is a kind of sequences in which accommodation, sediment supply, and types of bounding surfaces are strongly controlled by salt movements. Therefore the interpretation of the halokinetic sequences not only defines the various episodes and evolution of the salt diapir but also determines the temporal and spatial effects of the salt movement on the sedimentation systems. Halokinetic sequences are usually bounded at the top and bottom by salt-related angular unconformities adjacent to the salt diapir and by conformable surfaces far from the diapir (e.g. Giles & Lawton, 2002; Rowan et al., 2003; Giles et al., 2004; Giles &

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Rowan, 2012; Rowan et al., 2012a). These types of sequences are dominantly recognized by their growth stratal geometries adjacent to salt diapirs. Depends on the rate of salt withdrawal and exhumation and associated subsided and uplifted settings, growth strata could have hook and wedge geometries. In addition rate of sediment supply including allochthonous (salt debris) and autochthonous sediments play important roles in the configuration of the stratal patterns. The drape folding of growth strata due to upward salt movement produces high dips and even overturned layers adjacent to salt structures. The intensity of drape folding is controlled by the rates of salt rising and sediment accumulation, as a result of which halokinetic sequences form into two hook and wedge-shaped geometries. In the hook type halokinetic sequences, the rate of net salt rise is relatively higher than the rate of sediment accumulation. In addition, fast doming in the crest of the diapir is followed by shedding mass-wasted deposits or diapir-derived debris at the beginning of each hook halokinetic sequence. The stack of hook halokinetic sequences is called tabular composite halokinetic sequences (CHS). Wedge halokinetic sequences are formed when the rate of sediment accumulation is higher than the rate of salt rising, in which the diapir is covered or overlapped by growth strata. The stack of wedge halokinetic sequences is called tapered composite halokinetic sequences (e.g. Giles & Lawton, 2002; Rowan et al., 2003; Giles & Rowan, 2012; Rowan et al., 2012a).

The halokinetic growth strata are a critical factor for hydrocarbon exploration and have been examined in the halokinetic salt basins throughout the world. Some examples include terrestrial, mixed clastic-carbonate, and carbonate systems, according to outcrop data, such as the Gulf of Mexico (e.g. Wu et al., 1990a,b; Rowan et al., 2012a; Hearon et al., 2014a), the Basque-Cantabrian basin in Spain (e.g. Arbués et al., 2012; Rowan et al., 2012b; Roca et al., 2020), the Central High Atlas in Morocco (e.g. Vergés et al., 2013; Martín-Martín et al., 2017), the Sivas basin in Turkey (e.g. Ribes et al., 2015; Ringenbach et al., 2016). Most of the exploration activities in the eastern parts of the Zagros and Persian Gulf are were also concentrated around the salt-induced structures (e.g. at Siri fields).

Halokinesis played an important role in the tectonic style and sedimentation during the evolution of the Zagros foreland and fold-thrust belt (e.g. Ala, 1974; Talbot & Alavi, 1996; Jahani et al., 2009, 2017; Snidero et al., 2019, 2020). Although in the past 25 years, researchers have studied the Hormuz salt in the context of diapirism, regional tectonics, Hormuz salt tectonics, tectono-sedimentary insights, hydrocarbon, and economic potential (e.g. Talbot & Alavi,1996; Sattarzadeh et al., 1999; Hessami et al., 2001; Molinaro et al., 2005; Alavi, 2007; Sherkati et al., 2005; Jahani et al., 2009, 2017; Aftabi et al., 2010; Piryaei et al., 2011; Motamedi et al., 2011; Koyi et al., 2016; Atapour& Aftabi, 2017; Stewart, 2017; Motamedi & Gharabeigli, 2018; Hassanpour et al., 2018, 2020; Snidero et al., 2019, 2020), but more research is needed to fully characterize the salt-sediment interaction based on surface and subsurface sets.

The main purpose of this study is to describe and interpret halokinetic sequences in the Handun salt diapir for a better understanding of the salt-related sedimentary features. This surface example can be an accessible analogue model for further investigations around the salt diapirs in subsurface sections of the eastern Zagros and Persian Gulf areas.

Geological setting

The Bandar Abbas area which is known also in the literature as the hinterland, syntaxis, and embayment and is a transitional zone between the Zagros belt, the Makran convergence zone, and the Oman Mountains (e.g. Falcon, 1969; Iranpanah, 1988; Motiei, 1995; Talbot & Alavi, 1996; Sepehr, 2000; Molinaro et al., 2004, 2005; Piryaei et al., 2011; Orang et al., 2018). This area is bounded by the Main Zagros Thrust Fault (MZT) to the northeast, the Persian Gulf to the south, the Zendan or striking Minab Fault, and the Makran accretionary prism to the southeast (Fig. 1). Regional geology of the Bandar Abbas area has been studied to explore hydrocarbon and mining potentials by NIOC, and GSI (e.g. Shepherd & James, 1959; Wynd, 1965; James & Wynd, 1965; Player, 1969; Murris, 1980; Motiei, 1993). Based on the studies carried out in the Bandar Abbas area, the main characteristics of the area are as below:

1- The existence of isolated or still buried diapirs (or salt plugs) and associated variable sedimentary settings (e.g. Motiei, 1995; Molinaro et al., 2004, 2005). 2- Presence of structures with major E-W and NE-SSW trends among which Gahkum, Faraghan, and Kuh-e-Khush structures are exceptionally oriented in the NW-SE direction (Motiei, 1995). 3- Presence of the most significant large scale fault detachment folds or whale-back anticlines, associated with basement strike-slip faults which deform the sedimentary cover (e.g. Faraghan, Baz, Muran, and Shu), and rhombic sets of conjugate strike-slip faults are separated by a few areas showing only extensional zones (e.g. Sattarzadeh et al., 1999; Hessami et al., 2001; Yassaghi, 2006; Koyi et al., 2016). 4- Halokinesis of the Hormuz salt from early Paleozoic (Cambrian?) to recent (e.g. Jahani, et al., 2009; Hassanpour et al., 2018, 2020; Snidero et al., 2019, 2020) and halokinesis of the Late Oligocene-Early Miocene Fars Salt around the Lengeh Trough (e.g. Hassanpour et al., 2020; Snidero et al., 2020). The salt diapirs exposed in the core of the anticlines, fold flanks, periclinal terminations of anticlines, and rarely in synclines (e.g. Harrison, 1930; Kent, 1958; Player, 1969; Jahani et al., 2007, 2009). 5- Foreland basin evolution from the Upper Cretaceous to recent and its migration during the Cenozoic time (e.g. Ziegler, 2001; Piryaei et al., 2011; Saura et al., 2015; Orang et al., 2018).

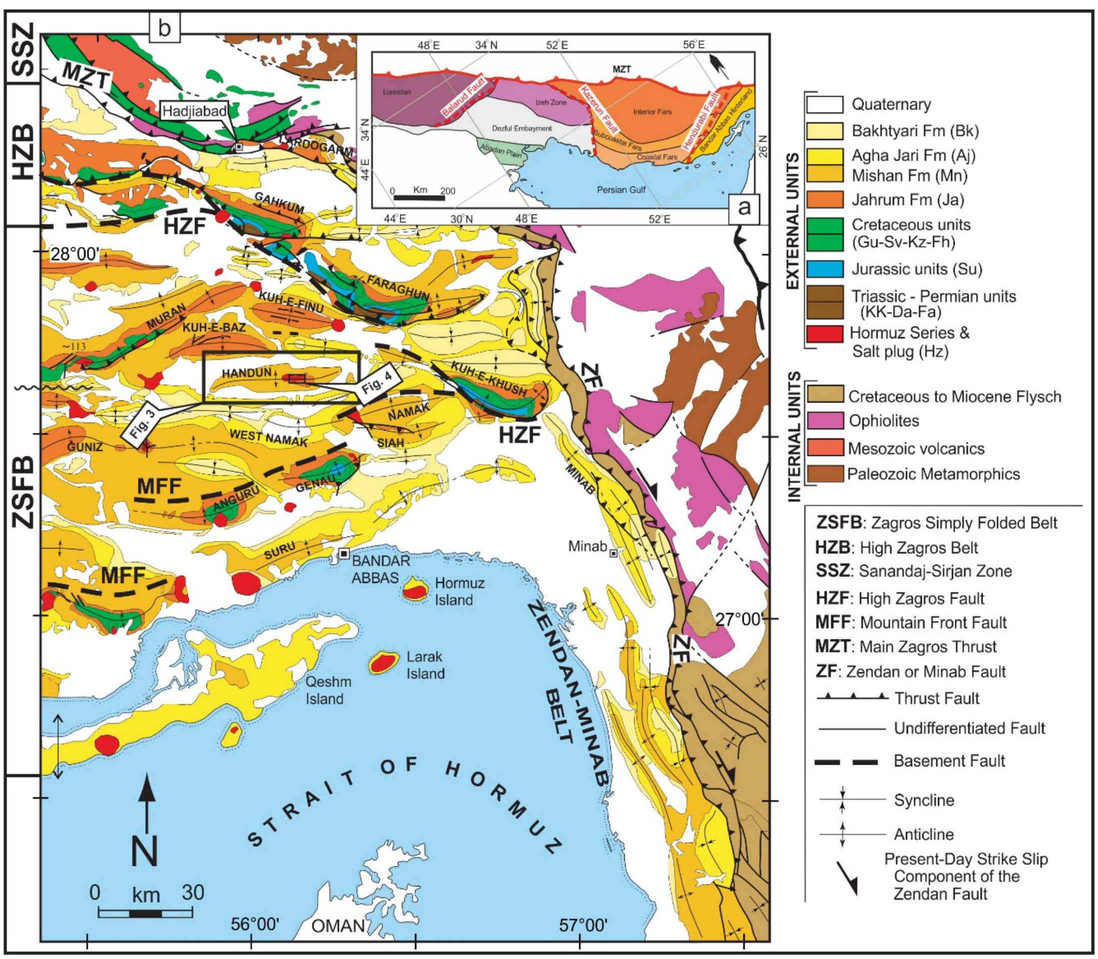

Figure 1. (a) Simplified local subdivisions of Zagros Fold–Thrust Belt (ZFTB) and the location of the most important basement faults (modified from Motiei, 1995; Berberian, 1995). (b) Structural and geological map of Bandar–Abbas area (modified from Molinaro et al., 2005)

6- Deformational effects of the Oman Mountains resulted in the truncation of early Miocene to late Cretaceous successions in the most SE Zagros and around Strait of Hormuz (i.e. angular unconformity at the base of the Guri Member) (e.g. Jahani, et al., 2009; Piryaei et al., 2011; Orang et al., 2018; Snidero et al., 2020, Hassanpour et al., 2020). 7- Existence of structural highs pierced by Hormuz salt such as Hormuz-Barez and Sepid (HBS), Hormuz-Dastan and Farshid (HD), and Hormuz-Aras (HA) (Snidero et al., 2020).

A simplified stratigraphic column of this area from the late Proterozoic-Early Cambrian Hormuz salt to recent sediments deposited on the crystalline basement of the Arabian plate, in the northeast of Gondwanaland (Molinaro et al., 2004), is shown in Figure 2. In general, pre-Upper Cretaceous rocks are not well exposed in the most of Bandar Abbas area (Fig. 1). In a few locations such as Gahkum and Faraghan High Zagros reverse fault exhumed rock units as old as Ordovician. In addition, salt diapirs led to exposing parts of the pre-Upper Cretaceous successions in some anticlinal cores (e.g. Handun, Genow, Anguru, Khamir anticlines) (Fig.1). The Cretaceous stratigraphic units were frequently influenced by Arabian Plate tilting and subsequent normal faulting and associated exotic blocks and turbidites deposited within the Gurpi pelagic marls in its northeastern margin. This event was followed by Upper Cretaceous obduction of the radiolarite and ophiolitic complex and inverted of the former broken Arabian Platform (Piryaei et al., 2011). The Paleocene-Eocene platform carbonates of the Jahrum Formation show a general NE-SW trending clinoform geometry. It thins towards the salt diapir and interior parts of Zagros where deeply truncates by the basal Razak unconformity. While towards the basin in the SW, it prograded out over the Pabdeh pelagic marls with minor truncation by overlying unconformity. The Asmari Formation is limited to the Rupelian time, bounded between two unconformities, and appeared in the distal platform. This unit shows the similar clinoform geometry as the underlying Jahrum Formation and grades to the uppermost parts of the Pabdeh Formation. Development of the overlying Lower Miocene Razak and its equivalent Gachsaran Formations occurred in a lowstand started by the deposition of the Fars Salt in the basinal setting (Ehrenberg et al., 2007). The sedimentation of Middle Miocene to recent sediments (Guri, Mishan, Agha Jari, and Bakhtiyari Formations) were controlled by the Arabian-Eurasian collision, SW foredeep migration, and shortening of the Zagros (Koop & Stoneley, 1982).

The Handun anticline

The Handun anticline (Kuh-e Handun or Ardan in Bosák et al., 1998; Kuh-I Hardun in Harrison, 1930) is located in the north of the Bandar Abbas area (SE Zagros). This anticline is a faulted detachment fold that developed on the Hormuz décollement level (e.g. Falcon, 1969, 1974; Molinaro et al., 2004, 2005; Sherkati et al., 2005; Jahani, 2008). This "whale-back" shaped anticline has a 40 km length and 10 km width and is located in the south of the Finu and Baz and north of the West Namak anticlines. Structurally, the anticline is doubly plunging with the flank dipping northward, which is characterized by E-W trending (Fig. 3a).

The exposed Handun salt diapir is located in the core and axis of the anticline (Bosák et al., 1998) (Fig. 3b). The present-day shape of the salt diapir (about 6 km in 2 km) is a result of being pinched-out or truncated by strain, which is stronger in the salt zone than the non-salt zone (Callot et al., 2007). The salt diapir is an isolated salt plug formed of a salt stock, which has been divided into two western and eastern segments by an eroded crater (Ramsey et al., 2008). The surrounding Jahrum and Razak Formations and Guri Member create an amphitheater view around the diapir in the core of the anticline.

Stratigraphic units of the Handun anticline

Three types of allochthonous, para-autochthonous, and autochthonous units or sediments could be distinguished in the Handun anticline. Allochthonous sediments were elevated by salt diapir from the Late Proterozoic (Ediacaran)-Early Cambrian Hormuz series or its overlying units. These sediments include altered salt, altered tuffit and ignimbrites, stromatolite, and reddish sandstone with ripple marks (Figs. 4a and 4b). Two iron ores exposed in the salt diapir show the maximum relationship of salt-overburden sediments interaction (Snidero et al., 2019).

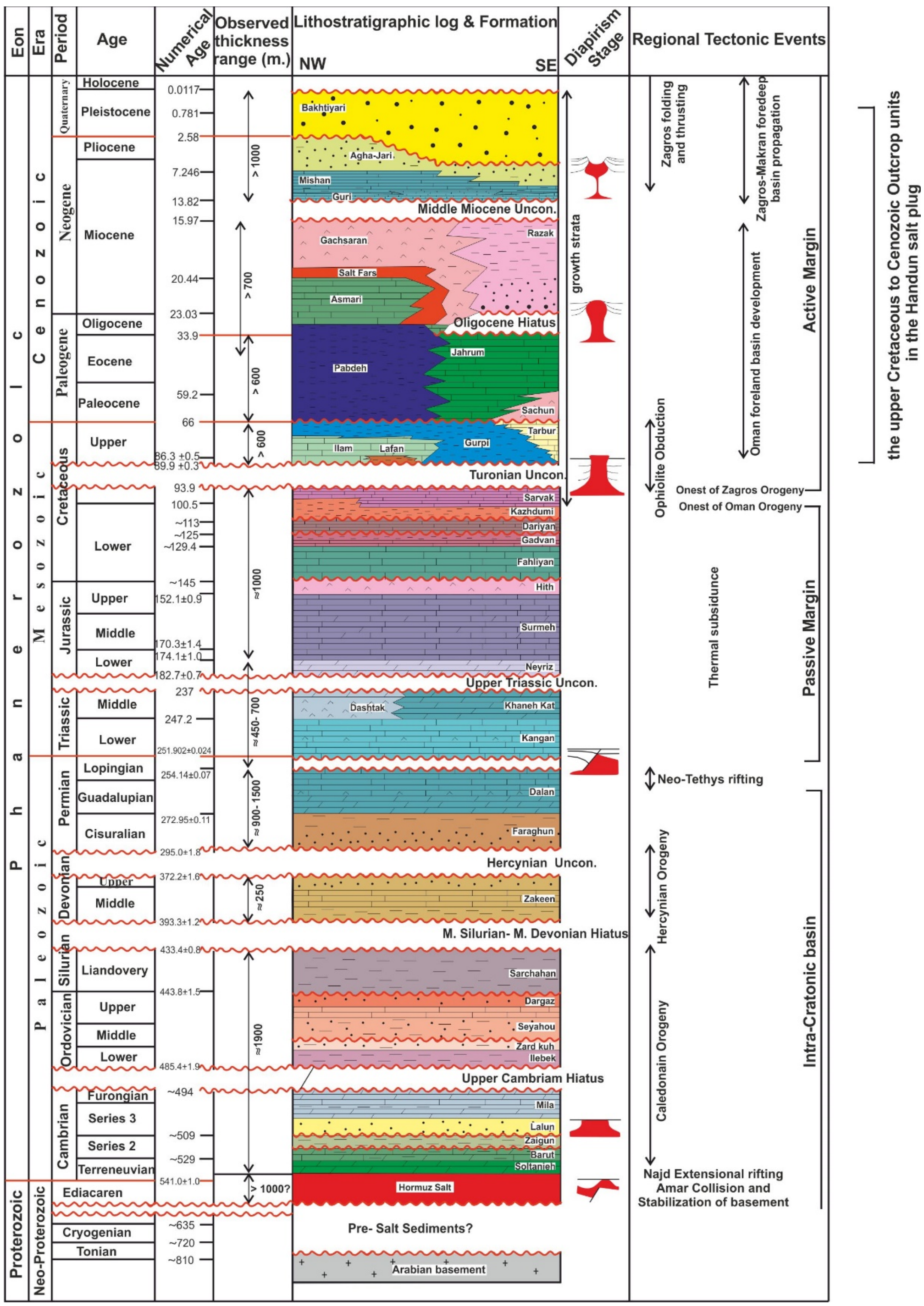

Figure 2. Tectonostratigraphic history in the Bandar–Abbas area. Note the main tectonic events in the area (compiled and modified after Motiei, 1995; Molinaro et al., 2004; Sherkati et al., 2005; Fakhari et al., 2008; Jahani et al., 2009; Piryaei et al., 2011; Tavakoli–Shirazi et al., 2013; Ezati–Asl et al., 2019; Snidero et al., 2019)

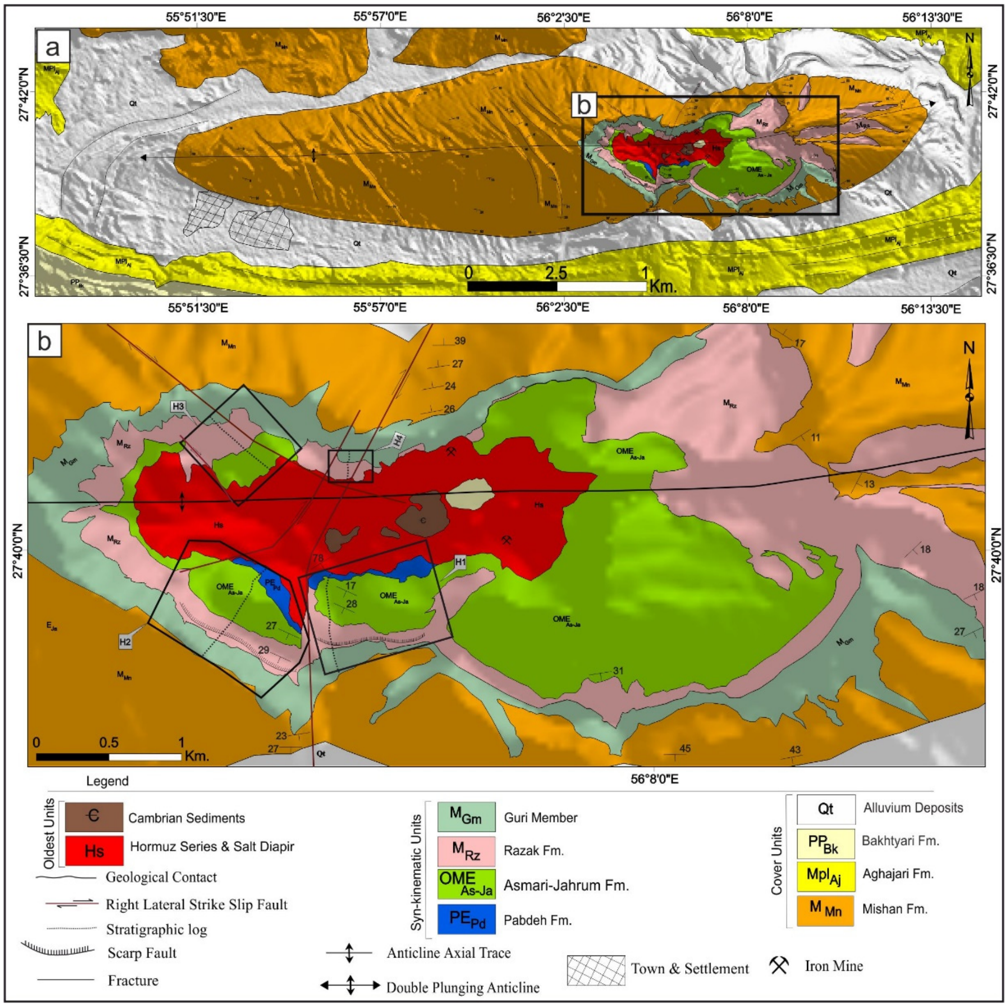

Figure 3. (a) Geological map of the Handun anticline and (b) the Handun salt diapir were modified and complemented by Shuttle Radar Topography Mission (SRTM) elevation data, satellite Landsat 7 Images and geological information based upon new fieldwork of the first author. Black line boxes in (b) display the location of four studied flanks and more detail explain the next pages in the paper

Among these sediments there exist an isolated brecciated/conglomeratic block in the eastern part of the anticline (Figs. 4a and 4c) which is attributed to the Bakhtiyari Formation (e.g. Bosák et al., 1998; Jahani, 2008 and Motamedi et al., 2011). The block consists totally of stacked cycles of agglomerates-conglomerates containing igneous (e.g. rhyolite, ignimbrite, hematite, magnetite), sedimentary (e.g. carbonate and sandstone), and metamorphic (e.g. mylonite schist) clasts in a rhyolite matrix ranges in size from 3 to 10 cm (Fig. 4d). No lithological, textural and genetic similarities could be found between these sediments and conglomerates of the Bakhtiyari Formation. Therefore the presence of this conglomeratic block within the salt diapir materials is interpreted to be deposited in a sagging crest mini-basin over the widening diapir.

The para-autochthonous units include a few isolated packages of the Lower Cambrian strata (e.g. Zaigun and Lalun Formations?), which are exposed in the central part of the Handun anticline. These well-bedded stratigraphic units show tens of meters thickness and hundreds of meters length composed of altered carbonate and shales with greenish-black colour and purple to red sandstone (Fig. 4e). No evidence of halokinesis has been observed within these Lower Paleozoic units which indicates that this area was paleohigh and site of siliciclastic deposition, while the surrounding basin was dominated by the lowstand basinal evaporites.

Autochthonous or syn-halokinesis sedimentary units are the exposed Upper Cretaceous to

Miocene strata, which is affected by salt diapir, and include:

- Maastrichtian Tarbur/Gurpi Formation: This highly fractured interval is only cropping out in the southern flank of the Handun structure and contained by salt clasts (Figs. 5a and 5b).

-The Paleocene-Eocene Pabdeh-Jahrum Formations: This succession is strongly influenced by the salt diapir in all studied sections. Depends on the negative and positive accommodation spaces created by the salt diapir, shallow-water carbonates of the Jahrum Formation and deep pelagic marls of the Pabdeh Formation are interplaying around the salt diapir. The Jahrum Formation is deeply truncated by the basal Razak unconformity either towards the uplifted salt diapir or towards the interior parts of the Zagros, while SW-wards to the basinal setting, the dolomitic limestones of the Jahrum Formation grades to the pelagic marls of Pabdeh Formation (Figs. 3 and 5c). Extensive syn-sedimentary halokinesis which has been occurred during the Eocene time could well be documented by the presence of diapiric or salt breccia (Fig. 5d), hook-shaped growth strata (Fig. 5e), and salt slice (Fig. 5f) in the carbonate of the Jahrum Formation. Presence of abundant large benthic foraminifera (LBF) such as *Dictyoconus* sp., *Nummulites* sp., *Pseudoaccordiella* sp., *Coskinolina* sp., *Orbitolites* sp., *Penarchaias* sp., *Neotaberina neaniconina* sp., *Austrotrillina eocenica, Medocia blayensis, Rhabdorites* sp., *Pseudolituonella robineti* sp., *Neorhipidionina cf. williamsoni* shows the Eocene age for the Jahrum Formation around the salt diapir. The thickness of the Jahrum Formation reaches up to 600 m in the Handun anticline.

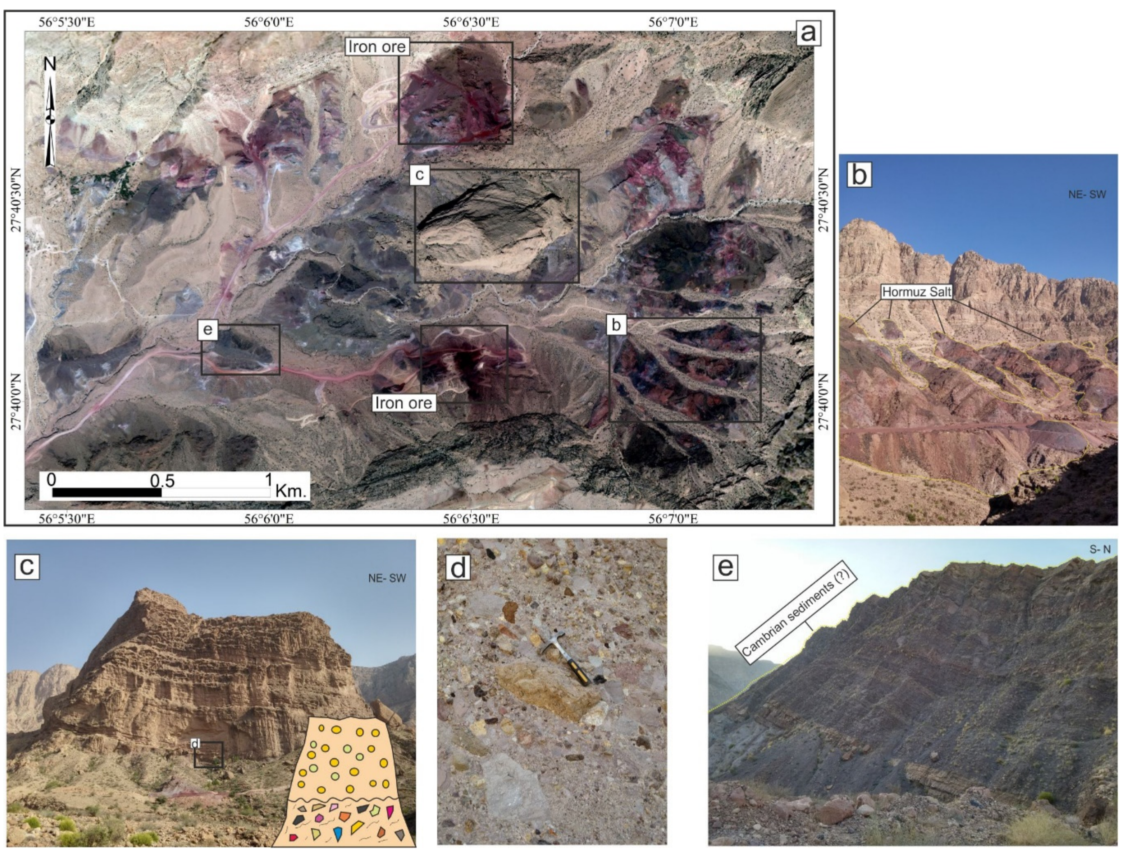

Figure 4. (a) SAS. Planet image of the Handun salt diapir in the core of the anticline and field photographs showing: (b) The Hormuz salt and the relationships between salt–overburden sediments, the variegated colour derived from different chemical elements in the Hormuz deposits. (c) An isolated block in the eastern part of the diapir, schematic drawing of the block shown lower brecciated and upper conglomerate parts that an unconformity separated two parts. (d) Close up view of the lower brecciated part in (c). (e) Cambrian sediments (?) exposed in the Hormuz salt

-The Oligocene-Middle Miocene Razak Formation and Guri Member: The Razak Formation forms a prograding sequence of falling stage siliciclastic cycles (Alavi, 2004). In the Handun salt diapir, the base of Razak Formation starts with conglomeratic beds (Fig. 5g) and grade onwards to varicolored calcareous sandstone, shale, and siltstone (Figs. 5h and 5i). The Razak Formation unconformably overlies on the Jahrum Formation and conformably onlapped by carbonates of the Burdigalian–Langhian Guri Member (Fig. 5i). The Guri Member is transitionally overlain by the Langhian Mishan Formation (Daneshian et al., 2016) as a covering unit of the Handun anticline (Fig. 3).

The anticline is numerable in the Bandar-Abbas area that is completely covered by the Mishan Formation and lateral fold propagation documented in the drainage patterns (Ramsey et al., 2008; Ginés et al., 2019). From the Middle Miocene to Pleistocene, syn-orogenic coarsening upward sediments of the Agha Jari and Bakhtiyari Formations develop in exterior parts of the Handun structure. These Formations have strongly been affected by the Zagros Neogene orogeny rather than halokinetic events.

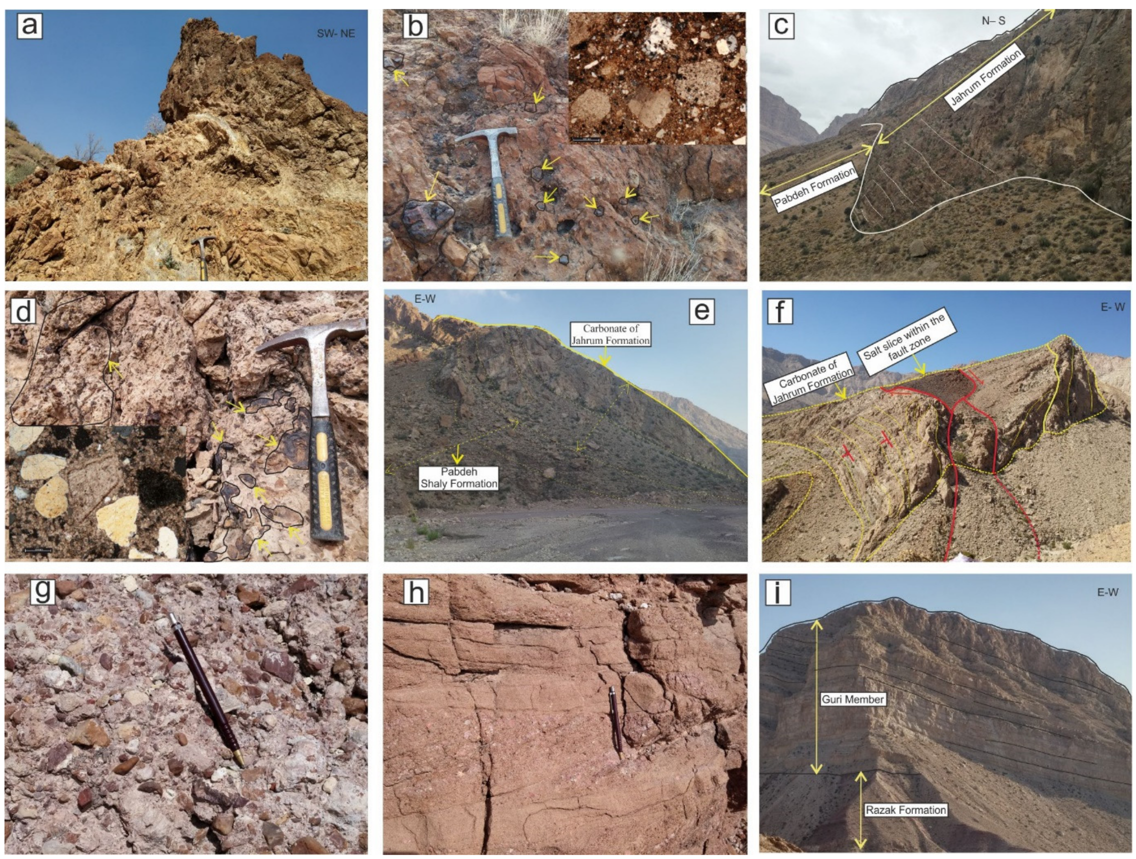

Figure 5. Field photographs of stratigraphic units most affected by salt are seen in the study area. (a) Dominant lithologies of shale and carbonate of the Gurpi Formation (b). Close–up of diapiric breccia in the Gurpi Formation that some of them showing by yellow arrows. A microscopic image of the breccia shows in the upper right corner. Scale bar 500µm (×25) (XPL). (c) The Jahrum Formation interfingers with Pabdeh shaly Formation (d) Close–up view of diapiric breccia in the Jahrum Formation (arrows) and the microscopic image of it shows in the down left corner. Scale bar 500µm (×25) (XPL). (e) Overturned carbonates of Jahrum Formation in the south flank. (f) A salt slice within the fault zone in the carbonate of Jahrum Formation (g) Close–up view of the conglomeratic bed in the base of Razak Formation which often contains rounded clastic pebbles chert and clasts derived from salt. (h) Red sandstone, showing the diversity of clast size in the Razak Formation (i) Cliff–forming limestone of the Guri Member underlying coloured siltstone of the Razak Formation by sharp concordance contact

Halokinetic sequences

Halokinetic sequences are charaterised by growth strata resulted from varying rates in salt and sediment accumulation (Jahani et al., 2009). Excellent exposures and three-dimensional geometry can provide enough data, revealing halokinetic growth strata, buried and rise salt along with four domains in the Handun salt diapir (Fig. 3b). The halokinetic sequences have been studied in four sections around the Handun salt diapir (Fig. 3b).

Southern Flank (Section H1)

In the southern flank (Figs. 3b and 6a), the halokinetic sequence can be grouped into three phases.

Phase 1 (sequences I-IV), includes hooky shaped growth strata deposited in the Paleocene to Lower-Middle Eocene time interval. This type of growth strata forms when salt bodies are withdrawing and the rate of subsidence is much higher than the rate of sedimentation. These sequences are composed of shallow-water carbonates (Jahrum Formation) close to the diapir any marly facies (Pabdeh Formation) in the downbuilding deeper setting. The sequences contain many debris salt and massive, brown, and brick red rudstone facies (Fig. 6b).

Phase 2 (sequences V-VII), includes wedge-shaped growth strata deposited from Middle-Late Eocene to probably Rupelian times (Fig. 6b). This phase shows a slow rate of salt rising and a high sedimentation rate. The amount of salt debris and slumped sediments decrease during this phase. Sequence VII, which is attributed to the Rupelian time, depends on the siliciclastic and carbonate ratio can be referred to as either Asmari or Razak Formation. Towards the distal platform, the shallow-water carbonates of the sequences grade to the marls of the uppermost Pabdeh Formation (Fig. 6b). The shallow-water facies is characterized by grey (to brown when weathered), medium to very thick-bedded crystalline dolostone, and dolomitic limestone, close to diapir. Far from the salt diapir, the Jahrum Formation consists mainly of large benthic foraminifera, algae, and bivalve debris. Phase 2 is truncated by a regional unconformity at the basal part of Razak Formation (Fig. 6b).

Phase 3 (sequences VIII and IX) include low angle and smooth growth strata (Fig. 6b). In this stage, the salt diapir rising becomes very slow or stop which resulting in a low angle to nearly tabular bedding pattern with less lateral facies and thickness variations. Sequence VIII is dominated mainly by coarse to fine-grained siliciclastics and coloured marls interbedded with argillaceous limestone. (Razak Formation). This siliciclastic sequence is 320 m thick in this section (southern flank) while it thins to less than 150 m in the northern flank of the diapir. Sequence IX is composed mainly of the bioclastic carbonates of the Guri Member and forms the highest topography around the anticline (Figs. 6a and 6b).

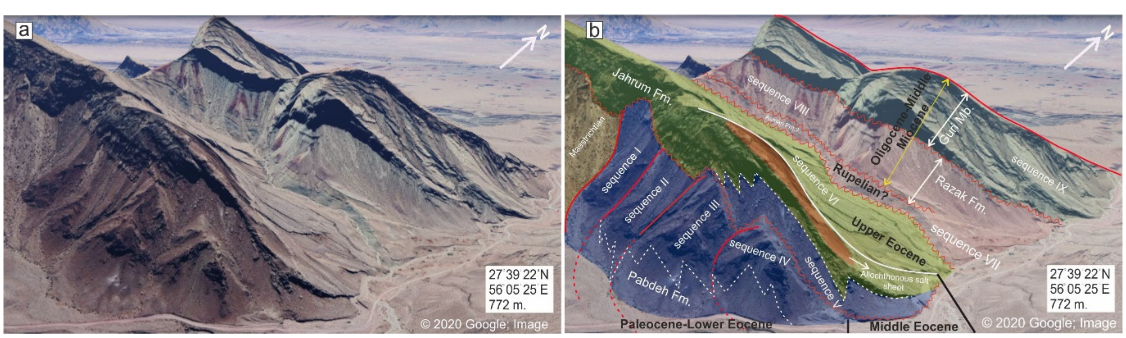

Figure 6. (a) © 2020 Google; Image; © 2020 CNES/ Airbus Landsat/Copernicus S flank (see Fig. 3) and (b) interpreted (a) showing the Formations, halokinetic growth strata, and sequences in the Formations (more detail in the main text)

Southwestern Flank (Section H2)

The southwestern flank starts with the Hormuz salt at the base, Pabdeh/Jahrum (525m) in the middle part, and Razak Formations and the Guri Member at the upper part. The halokinetic sequences during Phase 1 (I-IV; Jahrum/Pabdeh Formation) are hardly defined in this section. The sequences show medium to thick-bedded hook-shaped growth strata composed of dolostone and dolomitic limestones. During sea-level fall in the Middle-Upper Eocene, the Jahrum platform carbonates were prograded into the basinal marls of the Pabdeh Formation to the south. Towards the platform margin, these sequences contain abundant shallow-water benthic foraminifera and other skeletal and non-skeletal grains. The overlying halokinetic sequences during phases 2 and 3 (V-IX; Razak Formation and Guri Member) in section H2 are well comparable with section H1, composed mainly of varicolored shale, sandstone, and interbedded argillaceous limestone (Figs. 7a and 7b). A lensoid-shaped salt sheet with a few meters in width and tens of meters in length advanced within the Jahrum Formation during the extrusion of the diapir in Middle Eocene time which is comparable with the same event in section H1 (Fig. 6b).

Northwestern Flank (Section H3)

During Phase 1 (sequence I-V) the succession is composed of Jahrum Formation in which the Lower-Middle Eocene growth strata shows hook geometries (Figs. 8a and 8b). This phase is well correlated with its equivalent in sections H1 and H2 during which the sedimentary succession of the Handun structure shows the maximum halokinesis through time. The dolomitic limestones Jahrum Formation are majored by the presence of exotic salt slices and debris and diagenetic features in the three sections.

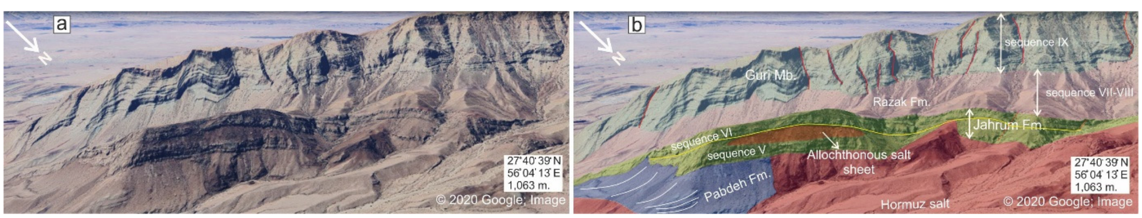

Figure 7. (a) © 2020 Google; Image; © 2020 CNES/ Airbus Landsat/Copernicus SW flank (see Fig.3) and (b) interpreted (a) showing the Formations, allochthonous salt sheet, and sequences in the Formations (more detail in the main text)

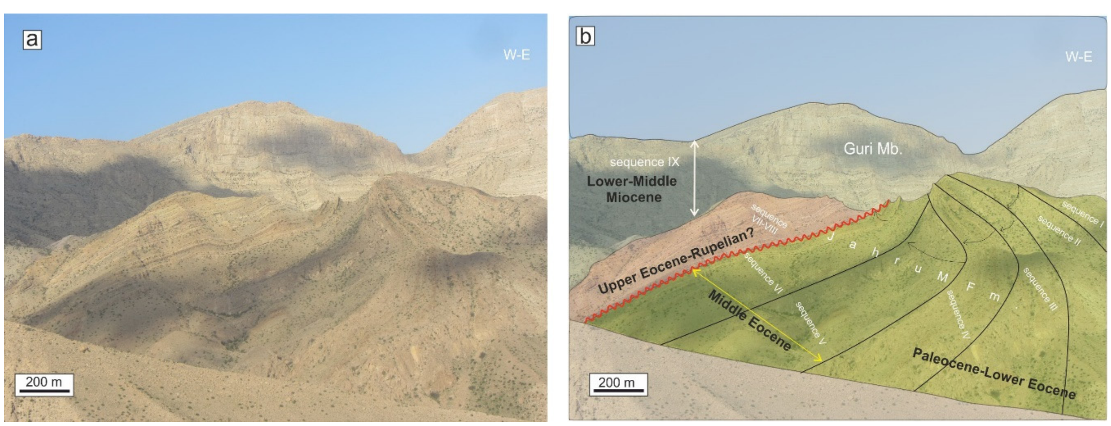

Figure 8. Field photograph and interpretation of the NW flank (a and b) showing the overturned succession of the Jahrum carbonate Formation attached to the diapir and followed by halokinetic growth strata

In this part of the anticline, not only marls of the Pabdeh Formation are not present but also the Upper Eocene and early Oligocene (sequences V-VII; Phase 2) not deposited due to major uplift. The geometries of the strata during Phase 3 (sequence VIII and IX) are not the easily definable due style of exposure but it is interpreted to be gentle or nearly tabular (Figs. 8a and 8b).

Northern Flank (Section H4)

This section displays the maximum effects of the halokinesis as a result of which phases 1 and 2 (sequence I to VII) are either not deposited due to intense uplift or deeply subsided into the downbuilding setting. In this section Phase 3 (Sequence VIII and IX; Razak Formation and Guri Member) represents hooky- shaped geometries (Figs. 9a and 9b) indicating that the maximum influences of the halokinetic events on the sedimentation systems are depended on the time of salt extrusion or spatial style of salt movements. The Razak Formation and the Guri Member have their minimum thicknesses in section 4, which can be because of the major activities of the salt diapir in the northern part of the Handun structure. The Guri Member limestones of the northern flank show flatiron morphology or triangular facets due to active tectonic and differential erosion of the steeply dipping strata (Bucci et al., 2007).
Figure 9.

Tectono-stratigraphic evolution of the Handun salt diaper

Tectono-stratigraphic evolution of the Handun salt diapir suggests how halokinesis affected accommodation spaces, sedimentation rates, and stratal geometries of the surrounding sedimentary successions (Figs. 10 and 11). Figure 10 includes schematic models from the generation of the salt diapir in the Lower Paleozoic to Lower Cenozoic times. There are no subsurface data and surface evidence for the pre-Upper Cretaceous units to show the halokinetic events in the Handun structure, on the contrary, the Lower Cenozoic interval can be well documented based on field data. Based on the observation the maximum deformation is traceable in the Eocene Jahrum Formation by the presence of salt sheet and other salt exotic materials. Figure 11 illustrates a correlation chart between the four measured sections around the Handun salt diapir through the uppermost part of the Cretaceous Tarbur/Gurpi Formations to Burdialian-Laghian Guri Member of the Mishan Formation Halokinetic sequences. In general Paleocene to Eocene interval shows a hook-shaped geometry in which the succession dies out towards section H4 indicating the maximum influence of the salt diapir.

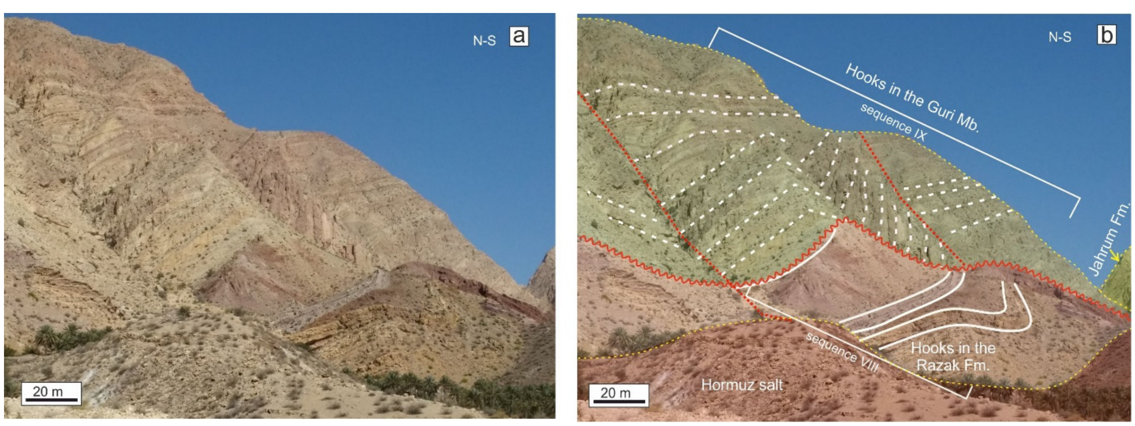

Figure 9. Field view and interpretation of the N flank (a and b) showing the overturned succession of the Razak Formation attached to the diapir and followed by hook halokinetic sequences in the Guri Member (more detail in the main text)

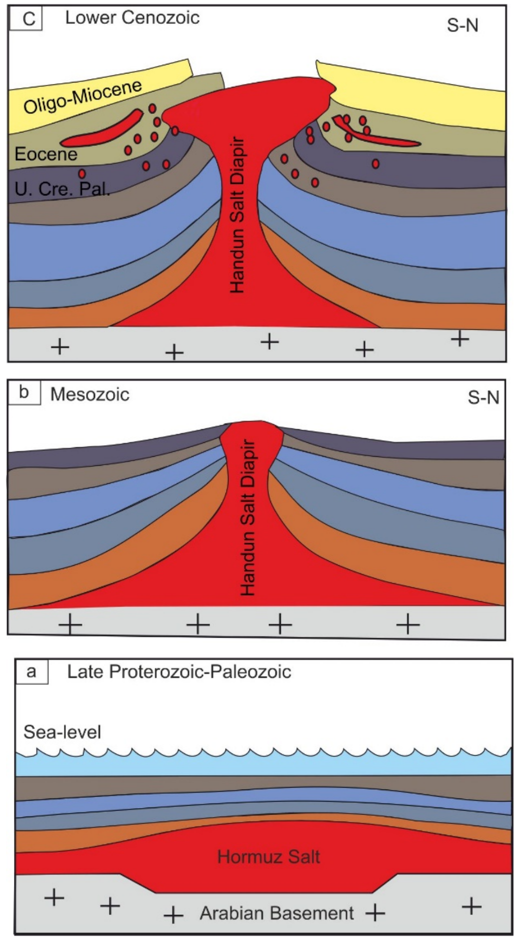

Figure 10. Schematic sketch of the structural evolution of the Handun salt diapir (not to scale). (a). Depositional of the Hormuz salt during the Late Proterozoic (Ediacaran)–Paleozoic times and passive diapirism in the Paleozoic, (b). Permo–Triassic extension and passive diapirism in the Mesozoic, (c). Downbuilding during the Upper Cretaceous–Paleogene and the Zagros Neogene orogeny caused the final piercement of the pre–existing salt dome through the surface

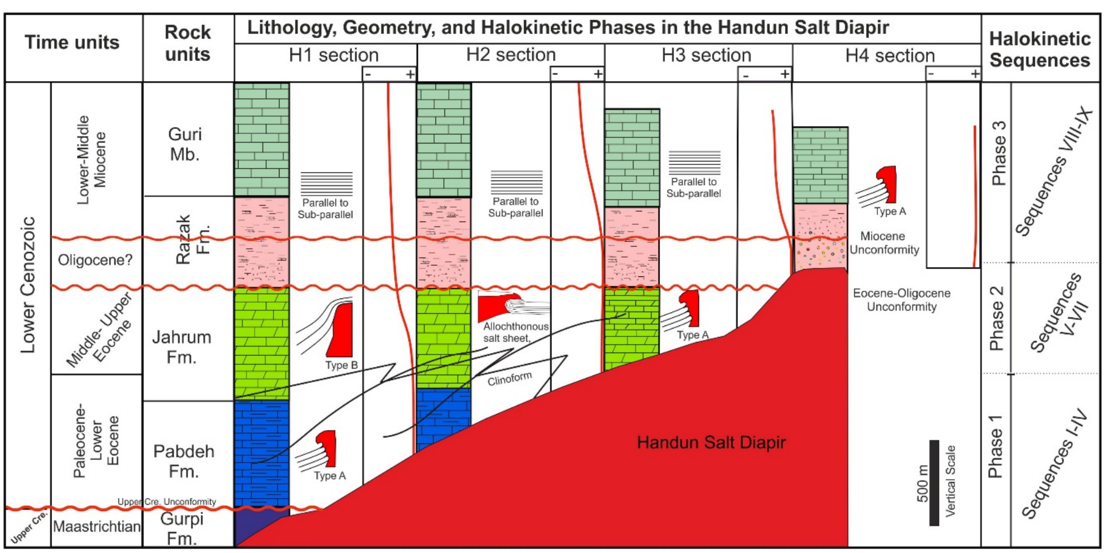

Figure 11. Schematic cross–section showing salt activity in the Handun salt diapir and related lithology and geometry changes. The intensity of the salt activity is showing in the last column of all sections (+ and – signs are the high and low intensity of salt activity, respectively) (more detail in the text)

This is associated with shedding and drowning the major parts of the Paleocene-Eocene interval into the mini basin following by intense overturning in the Razak Formation and Guri Member strata (Fig. 11). Temporally the major halokinetic events occurred in the Middle Eocene time interval and the Jahrum Formation and spatially in the northern flank of the Handun anticline. From Section H4, which is located in the most uplifted area towards the sections H1, and H2 the Jahrum Formation is prograding and replacing with the Pabdeh Formation in the basin setting (Fig. 11). In the Lower Eocene the halokinetic sequences represent hooky-shaped geometries (Phase1; sequences I-IV) while the overlying sequences become wedge-shaped (Phase 2; sequences V-VII) and then low angle or nearly tabular (Phase 3; sequences VIII-IX). The sequences record a pulse of salt rise coeval to sedimentation due to the compression phase from northern Oman (Snidero et al., 2020; Hassanpour et al., 2020) and cause the establishment of tabular halokinetic sequences in succession. The halokinetic events of the Eocene time were generally coeval with the development of the Jahrum platform in the Zagros region at this time (Golonka, 2004; Haq & Al-Qahtani, 2005; Seton et al., 2012; Serra-Kiel et al., 2016; Sallam et al., 2108). The salt extrusion is characterized by an allochthonous salt sheet in the Jahrum carbonate due to the decrease of sedimentation rate (Poprawski et al., 2016).

Discussions

Configuration of the halokinetic sequences

The sedimentary successions around the Handun salt diapir are composed of both carbonate and mixed carbonate and siliciclastic sediments, which may produce different composite halokinetic sequences (CHS) styles. Configuration of the halokinetic sequences depends on at least three main factors including tectono-sedimentary settings and associated sediments, distance to the salt diapir, and related mini basins and temporal activities of the salt diapir. Among these factors, the depressed areas play a significant role in the configuration of the stratal geometries and the advance of the allochthonous salt sheet. These depocenters formed above areas where salt is withdrawn and typically stop growing when the floor of the mini basin touches down on subsalt strata (salt weld). These mini-basins are developed around the salt diapir, which led to various rates of downbuilding. In the northern flank either the Paleocene-Eocene is mostly subsided and disappeared or the sediments show strong conglomeratic and brecciated nature which was interpreted to be as a result of a high rate of downbuilding and shedding of the sediments into the mini basin. Due to the lack of index fossils within the sediments, the precise timing of the events around the salt diapir is one of the main concerns in the study of the halokinetic sequences.

The studies carried out based on seismic data indicate that Hormuz halokinesis in the SE Zagros and the Persian Gulf began in the Early Paleozoic (Cambrian?), shortly after the deposition of the Hormuz salt and continued up to the present (e.g., Jahani et al., 2009, 2017; Perotti et al., 2016; Snidero et al., 2019, 2020; Hassanpour et al., 2020). Based on field observations the Maastrichtian Gurpi/Tarbur Formation are the oldest exposed autochthonous unit affected by the halokinetic events. In the Upper Cretaceous, a contraction as a result of the continent–continent collision may have triggered such a salt movement (Falcon, 1974; Karim et al., 2011; Farahpour& Hessami, 2012; Mouthereau et al., 2012). Halokinetic evidence recorded in the Handun outcrop infers the diapir growth at least from Upper Cretaceous, while no subsurface data is available from the underlying units.

Intra-formational halokinetic growth strata within the Paleocene to Middle Eocene Pabdeh and Jahrum Formations shows the rate of salt withdrawal and rise. Further from the salt diapir, the bedding patterns become more tabular and gentle in the Oligocene to Lower-Middle

Miocene (Razak Formation and Guri Member) halokinesis. Angular to sub-angular pebbles from Hormuz debris or salt breccias observed in the Upper Cretaceous, Paleocene to Eocene, and the Lower-Middle Miocene strata, shows increasing salt breccia and thinning of the growth strata during the Middle Eocene (Jahrum Formation). Salt breccia suggests a nearly flat dome near the surface in a low energy environment and rapid transport from the diapir. The presence of soft-sediment deformation (overturned flap and minor fold) in the Jahrum carbonate strata indicates that its surface must be parallel to the bedding of its exposed length. In the NW flank, carbonates and fine-grained siliciclastic deposits with low-angle halokinetic growth strata are associated with salt extrusion during Oligocene to Lower Miocene.

Conclusions

This study provides a detailed perspective on the Handun salt diapir, based on the outcrop sections. Three stages or phases have been distinguished in Paleocene to Langhian succession in the Handun anticline. Phase 1 comprises halokinetic sequences I to IV in which the growth strata are hooky shaped and all truncated by an unconformity at the base of overlying units. Phase 1 is comparable between the section H1, H2, and H3, while in section H4 in the northern flank, this phase is deeply buried in the adjacent mini basin and therefore not exposed. The later section is characterised by conglomeratic and brecciated features because of strong uplift, fast and steep downbuilding. Phase 2 which introduces by sequence V to VII is unconformably lying on the underlying composite halokinetic sequence (CHS, Phase1) and characterised by high angle wedge-shaped growth strata. It occurred most probably in the Upper Eocene to Rupelian time interval composed of dolomitic limestones of the Jahrum Formation and its equivalent marls of the Pabdeh Formation. In general, this phase is an onlapping wedge covering the salt diapir and contains less amount of salt debris and as the underlying units are not exposed in the Sections H4. Phase 3 includes sequence VIII and IX and characterised in section H1 to H3 by low angle wedge-shaped to nearly tabular strata, but in Section H4 it becomes hooky shaped in the Razak and lower parts of the Guri Member and grading to tabular nature onwards. In total, the most halokinetic effects happened in the Middle Eocene time in all studied sections, whereas the distortions continued to lower Miocene Razak Formation and Guri Member in the northern flank. The conclusion shows this point that the deformations mainly depends on the location of the salt diapir and its spatial movements rather than other associated parameters.

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