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Research paper

Characterizing halokinesis and timing of salt movement in the Abu Musa salt diapir, Persian Gulf, offshore Iran

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ABSTRACT

Geometric and stratigraphic characteristics of halokinetic sequences adjacent to the salt diapirs highlight the sedimentation response to variation in the rate of salt rise. The style of salt movement-sedimentation interaction and episodes of salt movement can be reconstructed by mapping these halokinetic sequences adjacent to the diapirs. Detailed interpretation of 2D seismic profiles adjacent to the Abu Musa salt diapir within the Persian Gulf Basin, offshore Iran, indicates that this diapir originated from the Miocene Fars salt, which created a central- and several ring-like peripheral-salt structures. Our results show that the evolution of the salt structures take place in three stages-mound, dome and post-dome- associated with sedimentation cycles periodically by passive and active rising to present. The pattern of these halokinetic sequences reveals that the Fars salt rose since Mid-Miocene coeval sedimentation of the Gachsaran Formation. The main mechanism of driving salt body has been the differential loading caused by down-building processes.

1. Introduction

“Historically, salt has played an important role in petroleum exploration since the Spindletop Dome discovery in Beaumont, Texas in 1906.” – Archer et al. (2012).

Extensive studies on salt domes in the salt bearing sedimentary basins, worldwide, based on integrated outcrop, analogue and numerical modeling, and seismic section interpretations (e.g., Ramberg, 1981, Trusheim, 1960, Vendeville and Jackson, 1992a; Talbot, 1995; Giles and Lawton, 2002, Hudec and Jackson, 2007, 2017; Mukherjee et al., 2010; Giles and Rowan, 2012; Misra and Mukherjee, 2018; Soto et al., 2017; Wu et al., 2018a,b; Vatandoust and Farzipour Saein, 2019; Motamedi and Gharabeigli, 2019) reveal that halokinetic sequences (HS), salt-driven depositions adjacent to a salt diapir, usually within 1 km of a steep salt body or diapir, contain valuable information about the kinematics and relative timing of salt movement during diapirism with respect to sedimentation. These sedimentary sequences bound by angular unconformities formed by salt extrusion-sedimentation interaction (Giles and Lawton, 2002). The creation of these sequences depends on the rate of salt extrusion, usually few mm or cm per year (e.g., Bruthans et al., 2006; Weinberger et al., 2006; Mukherjee, 2011), versus local sediment-accumulation rate around salt structures (Hearon et al., 2014). Based on the geometry of the HS, Giles and Rowan (2012) introduced a spectrum of halokinetic sequences characterized by two end members known as the hook- and the wedge halokinetic sequences. The former sequence develops when the net diapir growth is relatively higher than the net sedimentation rate. On the other hand, the wedge-type of halokinetic sequence deposits when the sedimentation rate exceeds the salt growth rate. Growth strata covers or onlaps the diapir. Cusps adjacent to the salt structures form where the angular unconformity-bounded halokinetic sequences intersect the diapir. The vertical stacking of hook and wedge halokinetic sequences under different ratios of rates of sediment-accumulation to diapir-rise can create the tabular and tapered composite halokinetic sequences (CHS), respectively. The presence of wedge-shaped growth strata on the flank of salt diapirs has been extensively studied using surface and subsurface data (e.g. Davison et al., 2000a). Note that the rim synclines are the basins produced by dragging effect surrounding the extruding diapir (Mukherjee, 2014), whereas the halokinetic sequences are the geometric features of the sedimentary strata adjacent to the salt bodies. These sedimentary sequences are indicators of salt-sediment interaction, can control reservoir geometry and trap configuration, and influence hydrocarbon development, migration and seal (McGee et al., 1994; Hearon et al., 2014). Therefore, understanding and recognition of different episodes of salt movement and influence of these sequences on the formation of petroleum-bearing traps in sediment adjacent to salt

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diapir are important in the petroleum exploration programs in the salt-bearing sedimentary basins (Poprawski et al., 2014, 2016). The Persian Gulf basin is recognized as one of the largest hydrocarbon-bearing sedimentary basins worldwide (Konyuhov and Maleki, 2006). The occurrence of several islands originating from salt depositions (e.g. Hormuz and Fars salt formations) highlight the importance of salt tectonic regimes on the evolution of this sedimentary basin, which has long been the subject of interest (Orang et al., 2018 and references cited therein). More than 160 salt diapirs have extruded in the Zagros Mountains and the corresponding foreland, and ~20 of the islands in the southern Persian Gulf owe their existence to the salt extrusion (Harrison, 1930; Kent, 1958; Gansser, 1960; Player, 1969; Edegell, 1996; Talbot and Alavi, 1996).

In such salt-bearing basins, salt tectonics can control the formation and distribution of hydrocarbon traps (Ghanadian et al., 2017a,b,c). The Abu Musa Island, originating from the salt diapir, is investigated for the relations between sedimentation and salt movement during diapirism. The geometry of salt-driven depositions, the halokinetic sequences, for the strata adjacent to the salt structure of the Abu Musa diapir was documented using high resolution 2D seismic sections in this study. These evidences can help to better understand the geometric feature of the sedimentary sequences resulted from salt-sediment interaction and also to characterize episodes of salt movement (similar approach in Masrouhi et al., 2014; Moraleda et al., 2015; Grimstad, 2016). These data provide new information on the evolution of this diapir that can be useful in exploration. For better understanding of the distributions of salt-related structural features and how salt mobilizes, the halokinetic sequences adjacent to the Abu Musa salt diapir was investigated, which provides information about the progressive evolution of the salt structures and the main time intervals of diapirism during the geological history of the Persian Gulf basin.

2. Geology & tectonics

The Persian Gulf is an asymmetric shallow tectonic trough and is recognized as the foredeep of a foreland basin originated from the Zagros collisional orogeny started since Miocene (Alavi, 1994, 2004; Sharland et al., 2001). This depression formed in the front/south of the Zagros Fold-Thrust Belt in the Late Tertiary. The Persian Gulf and the Zagros Fold-Thrust Belt together constitute presently the NE part of the African-Arabian Plate. The Fold-Thrust Belt formed due to the tectonics related with the opening and closing of the Neo-Tethys Ocean, which was located between the African-Arabian and Eurasian plates during the Cenozoic (Dercourt et al., 1986; Dewey et al., 1973; Alavi, 1994; Stampfli and Borel, 2002).

The study area, the Abu Musa Island, is an offshore area located in the eastern part of the Persian Gulf (Fig. 1). This area is bound by the NW-SE trending Zagros Fold-Thrust Belt in the north and the NW-SE trending Oman Fold-Thrust Belt in the southeast. This area was affected by several tectonic events viz., rifting (Permian and Triassic), convergence (Late Cretaceous) and crustal shortening and collision (Neogene), which produced important tectono-sedimentary megasequences (Alavi, 2004) (Megasequences I-VII, Fig. 2). Angular unconformities are the most important outcome of the tectonic events. Based on these unconformities, it seems that the study area was affected by at least six tectono-sedimentary events differentiated by horizons of strong angular unconformities (Ezati Asl, 2019a). In the Late Proterozoic (640–620 Ma) a series of island arcs and micro-continental fragments accreted to the northeastern margin of the African craton (Beydoun, 1991; Sharland et al., 2001) and constituted the Arabian shield. The distribution and sedimentation of the Hormuz salt in the northern part of the Arabian plate was controlled by the extensional collapses due to the Najid event, a rifting process producing sub-basins trending N–S, during the Late Proterozoic –Early Cambrian (570-530 Ma; Sharland et al., 2001; Stampfli and Borel, 2004). The Hormuz salt, known as the Hormuz Formation, is the oldest rock units overlay the basement of the Zagros Fold-Thrust Belt and crop out through several salt diapirs within the Zagros and Persian Gulf basins. The Hormuz Formation includes evaporites, carbonates and varicolored sandstones and shales (Alavi, 1994; Sharland et al., 2001). The compressional tectonics in the Oligocene uplifted the eastern part of study area, which is the northern continuation of the Oman mountains. The compression ceased marine connection between the Persian Gulf and open marine Indian Ocean. These led to gradual subsidence and development of a new closing foredeep basin where the depocenter migrated towards west (Letouzey et al., 2004; Orang et al., 2018). Newer sediments in these accommodation spaces, the equivalent Asmari Formation (Early Miocene), deposited with two different facies. These include limestone related to a shallow-low energy marine environment. The sediments laterally change to evaporites, particularly salt in the bottom with intercalation of claystone and anhydrite in top that known as the Fars Salt (Kashfi, 1983). This salt deposited during the Lower Miocene and is lateral equivalent of the upper Asmari limestone (Jahani et al., 2009).

3. Data and method

The data for this study is extracted from the 2D seismic sections with NE-SW and NW-SE trends and 12 km depth which cover all sedimentary blanket of the Zagros Fold-Thrust Belt (Fig. 3) around the Abu Musa island provided by the Iranian Offshore Oil Company (IOOC). Unfortunately, the seismic grid does not cover the Abu Musa Island and the shallow waters around the island. Seismic data and well information are subject to availability in the format of the Petrel software (2011.1 version) provided by the IOOC. All these published information were applied for analyzing the study area structurally and to assess the tectonic history of the salt structures. The drilled wells are not deeper than the Fahliyan Formation (Early Cretaceous) and the seismic horizons related to the tops of the formations to this depth are drawn using tie top of formation from the wells on the seismic sections prepared by the IOOC. The age of depositions of formation obtained from published data is based on fossil cutting from drilling wells and field studies (e.g. Nayebi et al., 2000, 2001; Ghavidel Syooki, 2000, 2004; Ghazban, 2007; Orang et al., 2018). Detailed analyses of three seismic transects, AA′, BB′ and CC’ (Fig. 3) along and across the study area allowed to interpret and track the key seismic reflections that come from the top of the formation in the exploration wells W1 and W2 (Fig. 3). This led to recognizing different seismic facies, strata terminations, as well as major unconformities. Several key horizons were picked and traced from Early Permian to present on seismic sections using well-to-seismic calibration using the Petrel software. The lack of deeper wells, precludes study of formations below the Permian (Figs. 4–6).

The stratigraphic analysis of halokinetic sequences in the salt minibasins provides valuable information about the style and the timing of salt movement relative to sediment deposition. The presence of growth strata in the flank of salt structures has been documented extensively by previous workers using surface and subsurface data (e.g. Bornhauser, 1969; Johnson and Bredeson, 1971; Lemon, 1985, Davison et al., 2000a). The folding of growth strata due to upward salt movement is called drape folding and, it produces high dips and even overturned layers adjacent to salt structures. Hence, the geometric features created in the halokinetic sequence will be an important key to timing and detecting the activity periods of salt structures. Growth strata and unconformities indicate halokinetic movements that are associated with periods of salt diapirism. Other features, e.g., truncation, onlap, offlap, pinch-out and the change in the dip and thickness of the strata near the salt structures are the ways to identify the halokinetic sequences and the main periods of diapirism (Giles and Lawton, 2002; Hudec and Jackson, 2007; Giles and Rowan, 2012, Moraleda et al., 2015). Following Giles and Rowan (2012), several halokinetic sequences adjacent to the salt structure were mapped along three seismic sections, AA′, BB′ and CC’ (Figs. 7–9) as follows.

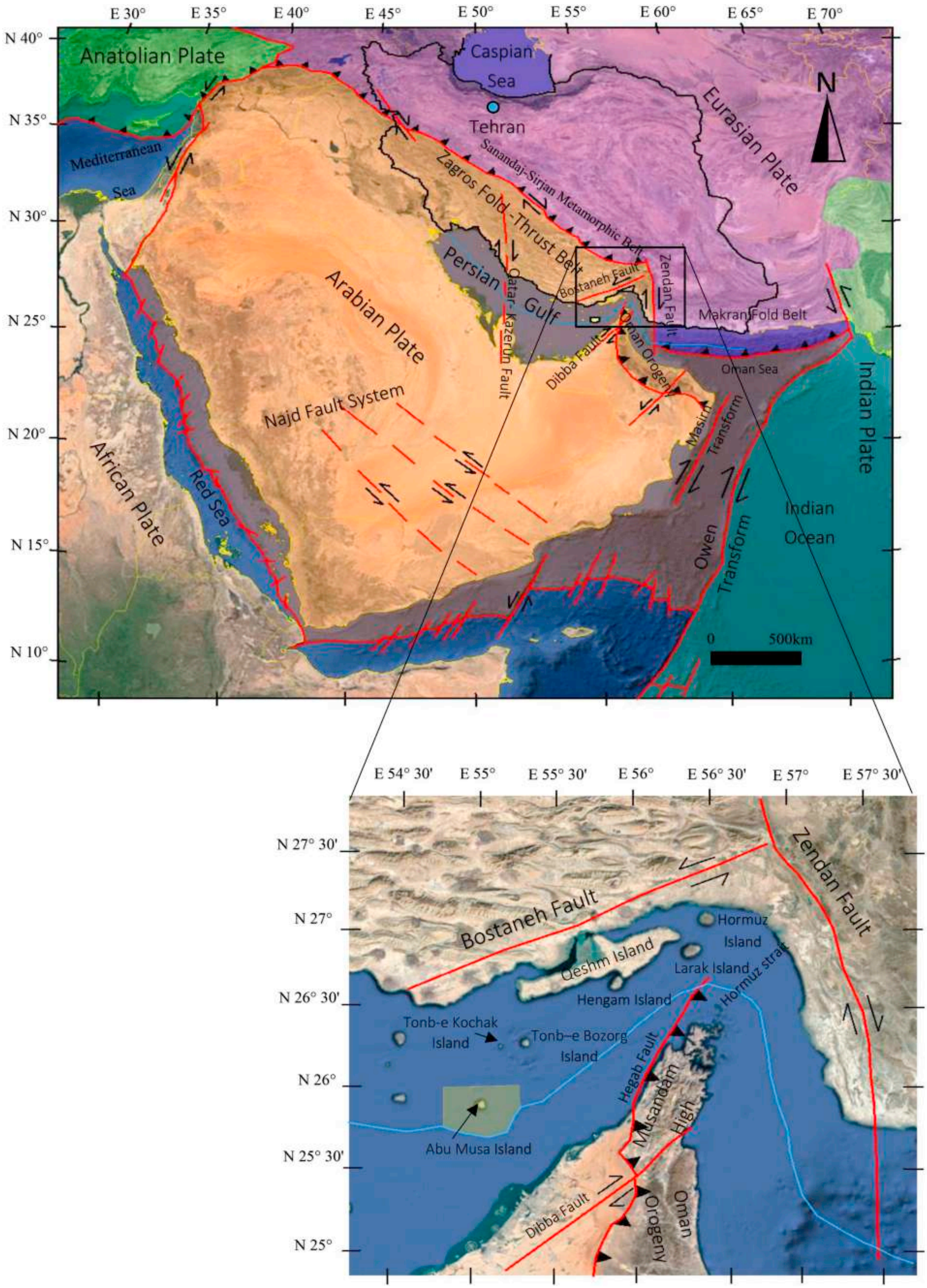
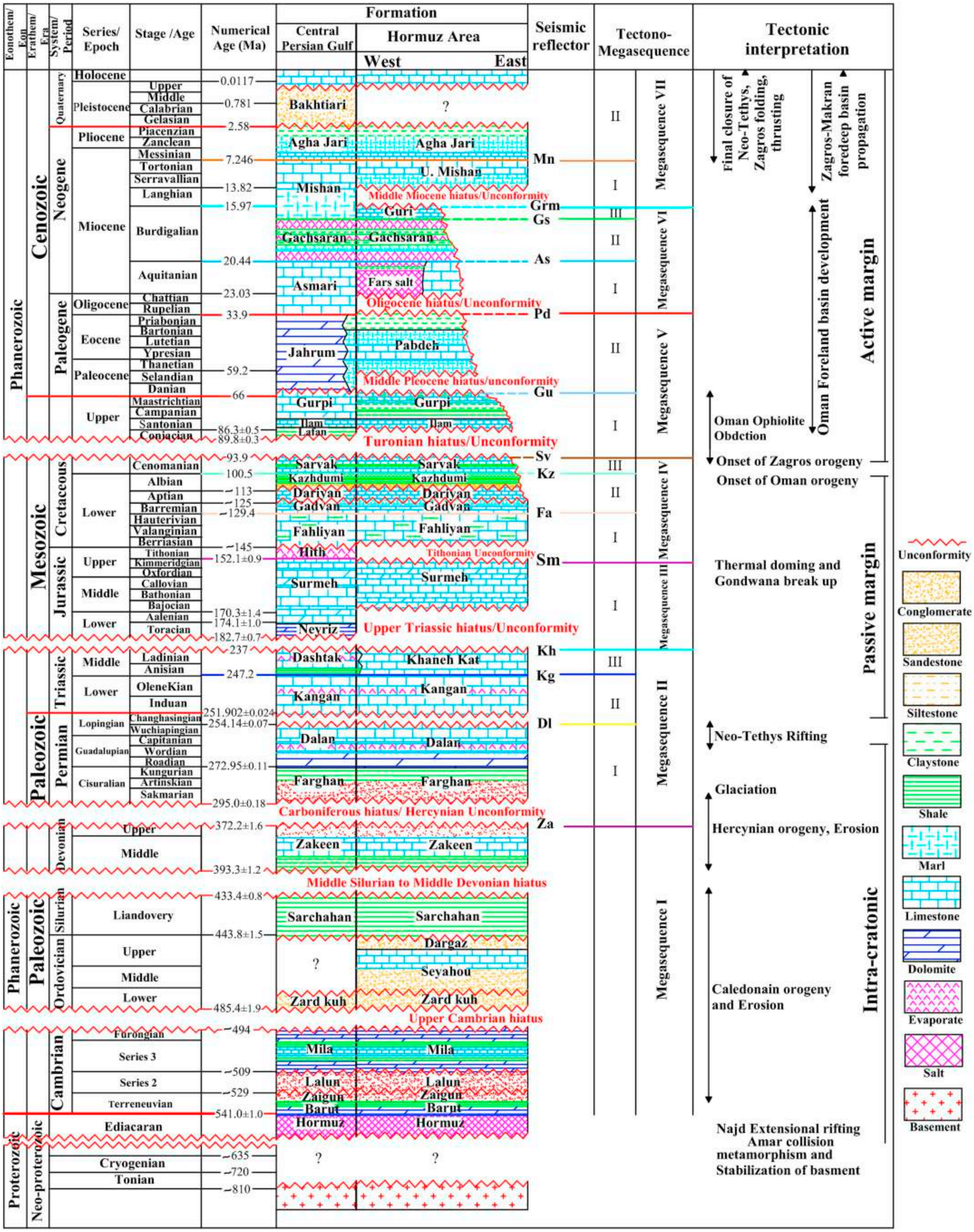


Fig. 1. Location and tectonic setting of the study area between the Arabian and the Iranian plates.



(caption on next page)

Fig. 2. Simplified lithostratigraphic column of the Hormuz strait in the east of Persian Gulf. Chronostratigraphic lithostratigraphic chart based on the International Commission on Stratigraphy v 2017/02. Lithostratigraphic column of central Persian Gulf from: Sharland et al. (2001), Ziegler (2001), Alavi (2004) and Ghazban (2007). Lithostratigraphic column of Hormuz strait based on cutting collected from the exploration wells of the Hormuz area (Nayebi et al., 2000, 2001) works in field, Zagros area (e.g., Ghavidel Syooki, 2004) and extract text (e.g., Orang et al., 2018). The stratigraphic positions of the interpreted seismic horizons in this study are shown. Abbreviations: (Mn) top Mishan (Middle-Late Miocene), (Grm) top Guri member (Early-Middle Miocene), (Mm) Middle Miocene unconformity Horizon, (Gs) top Gachsaran (Early Miocene), (As) top Asmari (Early Miocene), (Pd) top Pabdeh (Late Paleocene-Eocene), (Ol) Oligocene unconformity Horizon, (Gu) top Gurpi (Maastrichtian-Early Paleocene), (Sv) top Sarvak (Cenomanian), (Tu) Turonian unconformity Horizon, (Kz), top Kazhdumi (Albian), (Fa) top Fahliyan (Early Cretaceous), (Sm) top Surmeh (Middle-Upper Jurassic), (Ti) Tithoniain unconformity Horizon, (Kh) top Khanehkat (Middle Triassic), (UT) Upper Triassic unconformity, (Kg) top Kangan (Early Triassic), (Dl) top Dalan (Late Permian), (Za) top Zakeen (Middle-Late Devonian).

4. Results

4.1. Salt-related structures

Interpretation of 2D seismic sections revealed the present configuration of the salt structures within the Abu Musa salt diapir. The geometric distribution of these structures is a central salt structure, the Abu Musa salt diapir (island) and associated several structures around it with ring-like arrangement (SD1, SD2 and SD3). The central and the surrounding salt structures can be considered as a salt diapir and associated ring-like salt walls, respectively (Figs. 4–6).

Two genetic models of the Abu Musa diapir has been available (e.g. Lawson, 1998). One of these considers that the source salt layers is the Infra-Cambrian Hormuz salt, which supply most of the salt diapirs located in the Zagros, Persian Gulf, Oman and United Arab Emirates, and has affected the entire sedimentary sequence of study area since Paleozoic. Due to the limited resolution and coverage of seismic sections of the present study, it is not possible to interpret the presence of Hormuz salt body in the diapir. The presence of welding points and rim syncline structures above the Pabdeh horizon (Paleocene-Oligocene) (Figs. 4–6) created by the withdrawal of the other source salt layer, the Fars salt, indicates that this salt body was fed at shallow-depth. There are no halokinetic sequences below the Oligocene surface because there was no diapir at that level. The upturned seismic expression below the salt and Oligocene horizon is simply a velocity pull-up beneath the shallow salt body. Several halokinetic sequences were identified adjacent to the central and the ring-like salt structures along the studied transects as described in the following sections.

4.2. Halokinetic sequences

Tracking the seismic reflectors and geometric relationship of sedimentary sequences adjacent to the salt structures on the 2D seismic profiles enables to identify the main strata terminations, unconformities and halokinetic sequences in the mini-basins surrounding the salt structures. Figs. 7–9 present the distribution of the halokinetic sequences adjacent to the different salt structures related to the Abu Musa salt diapir along three seismic sections (AA′, BB′ and CC′), and are

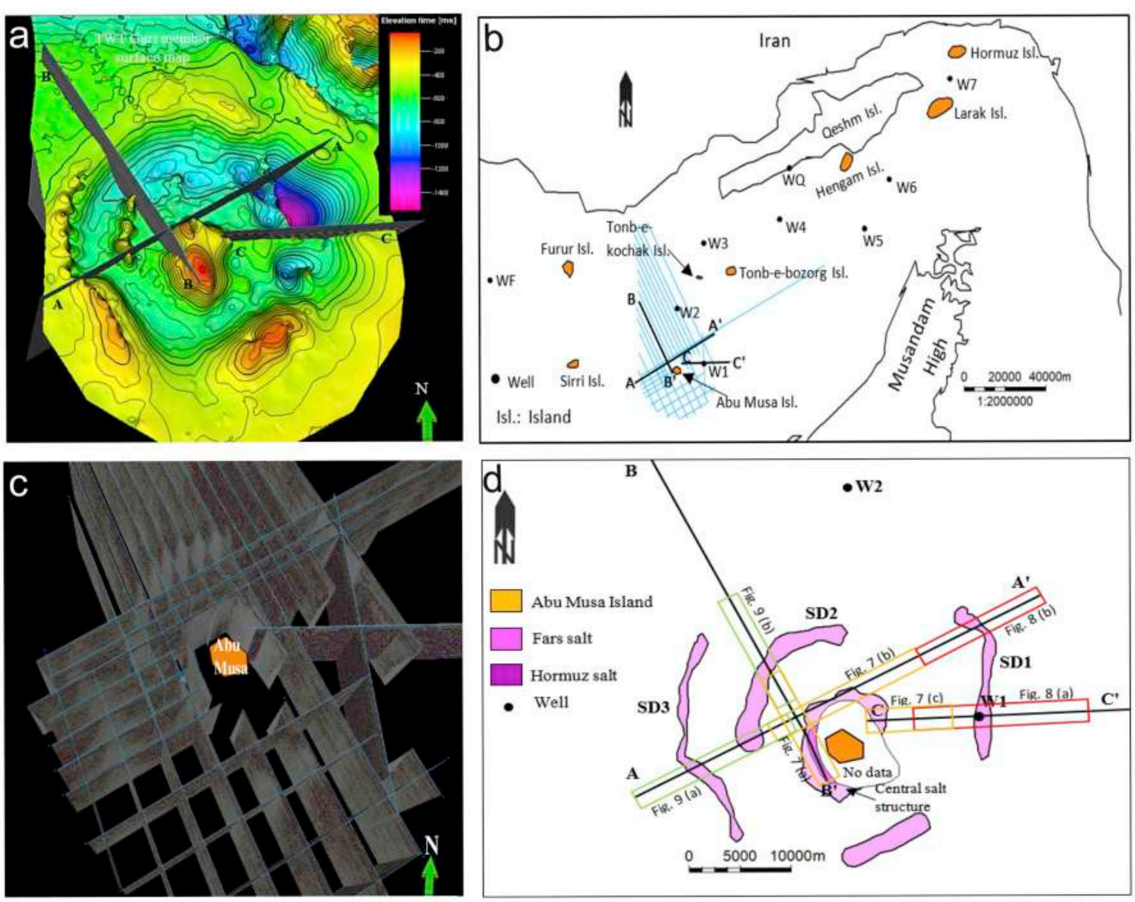


Fig. 3. (a) Guri member structure map of the Abu Musa diapir (**b**)the location of AA′, BB′ and CC′ seismic sections along the NE-SW, NW-SE and E-W trends, respectively. **(c)** Sketch map of the Abu Musa Island on the seismic sections (**d**) Sketch showing the location of Abu Musa Island and identified buried salt structures within the Abu Musa diapir as the Fars salt structures.

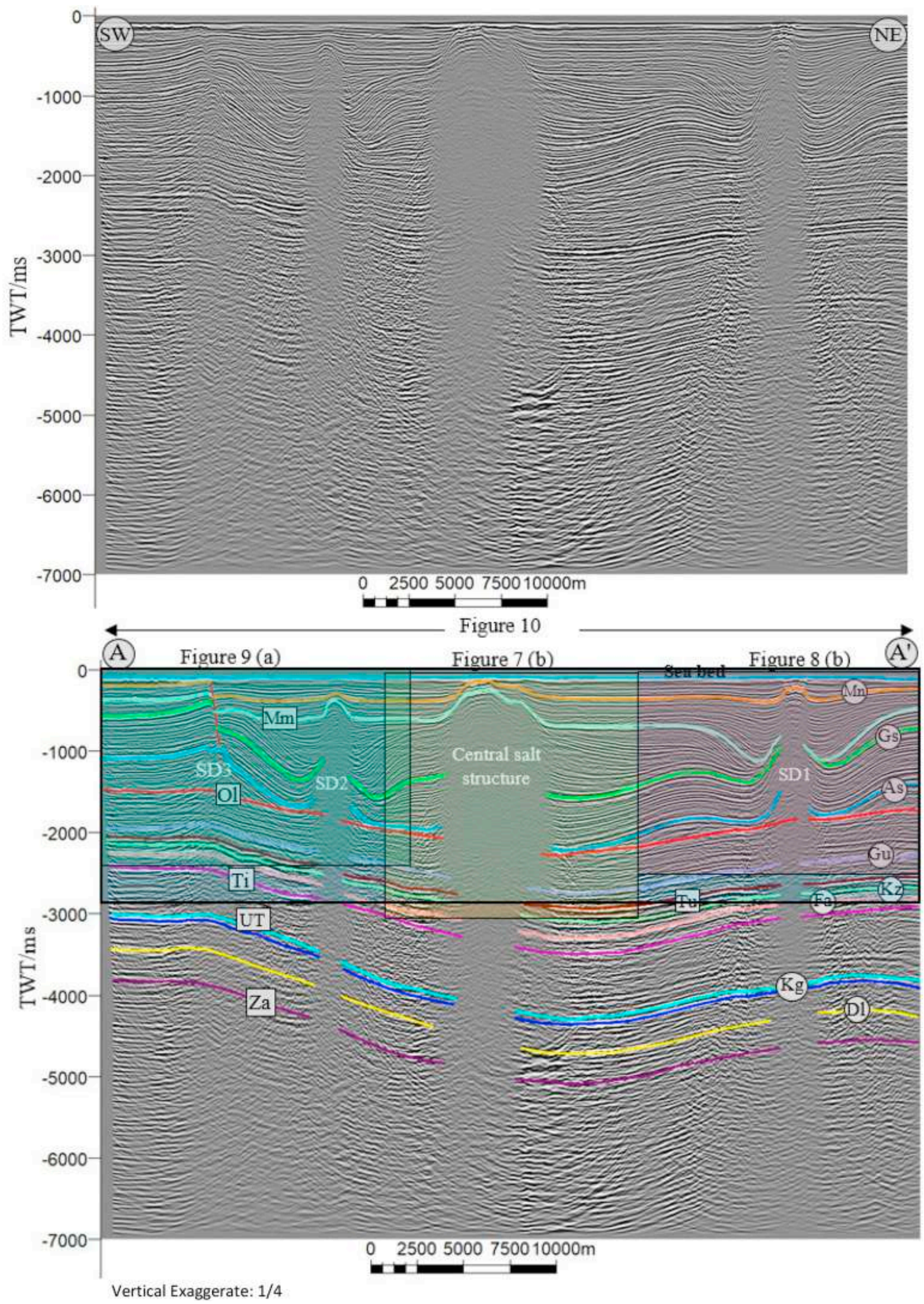


Fig. 4. Un-interpreted and interpreted AA′ seismic sections NE-SW through the Abu Musa salt diapir. The interpreted SD1, SD2, SD3, the upper part of central salt structures, the location of seismic horizons (letters in circles) and major unconformities (letters in rectangles) are presented. Abbreviations as per Fig. 2 caption. Location of Figs. 7–10 shown by rectangles.

described as follows.

4.2.1. Halokinetic sequences adjacent to the central salt structure along AA′, BB′ and CC′

These sequences are of tabular and tapered geometries consisting of several hooks and wedges, respectively. The number and geometric characteristics of the halokinetic sequences vary in the flanks and in different parts of the central salt structure. This suggests a temporal change in the salt rising rate.

The western flank of the central salt structure is characterized by the presence of tabular (in the lower parts) and tapered halokinetic sequences extended up to the top of the Gachsaran horizon (Gs) (Fig. 7a). Tapered sequences reveal rise of the Fars salt body, up to the top of the Gachsaran horizon. The sedimentary sequences between the Gs and the Grm horizons are characterized by three thick tabular halokinetic sequences that indicate rising rate of salt body was equal or more than the sedimentation rate and was accompanied by a thin roofing. Thickening of the sequences indicates that withdrawal has been more than sedimentation. The deposits of the above-mentioned halokinetic sequences are limited by Oligocene unconformity at the bottom and Middle Miocene unconformity at the top (**Ol** and **Mm** in Fig. 5). The presence of three tapered halokinetic sequences above the

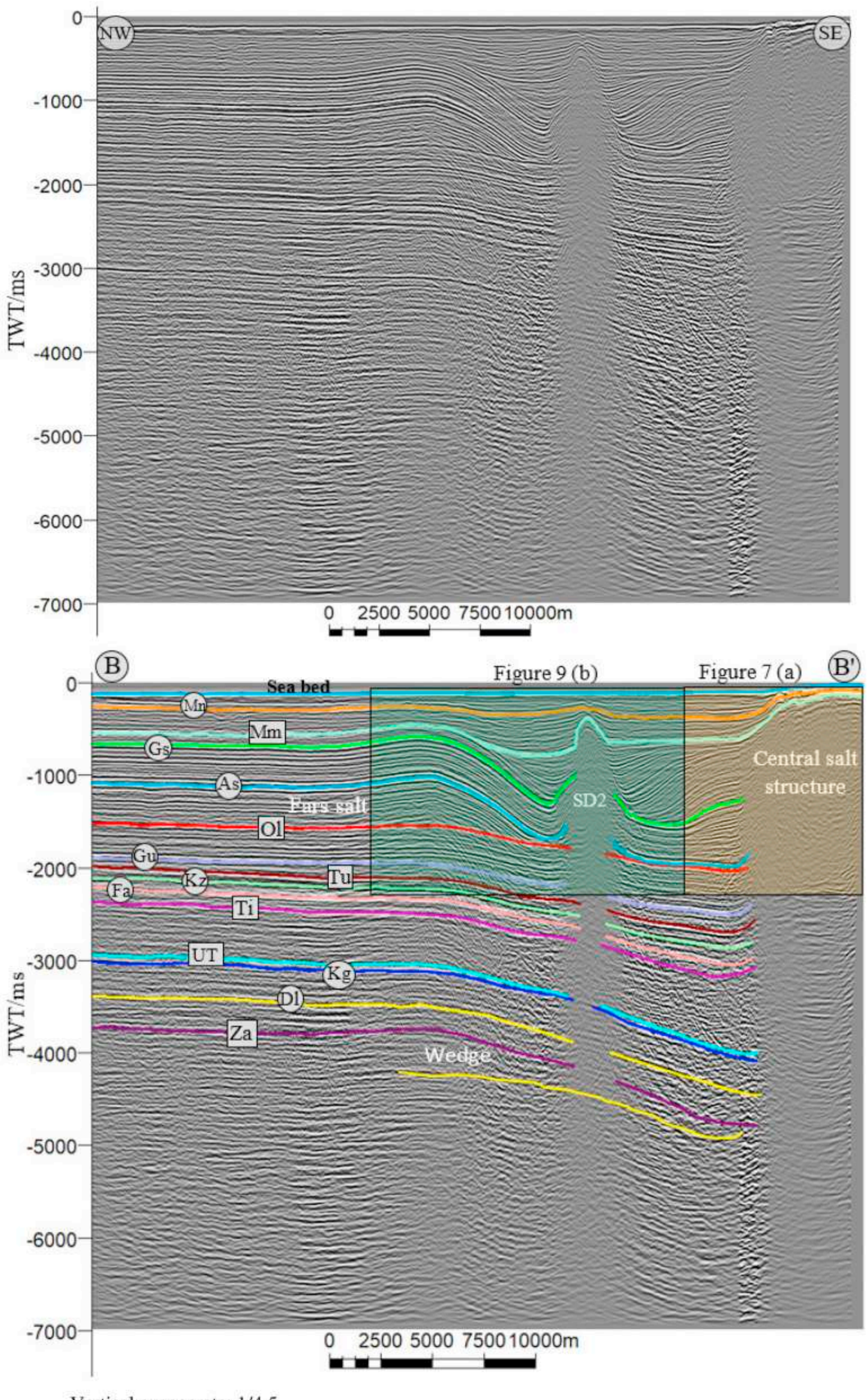


Fig. 5. Un-interpreted and interpreted BB′ seismic sections NW-SE through the Abu Musa diapir. The interpreted SD2 and the central salt structures, the location of seismic horizons (letters in circles) and major unconformities (letters in rectangles) are shown. Abbreviations as per Fig. 2 caption. Locations of Figs. 7 and 8 shown by rectangles.

Oligocene unconformity indicates that the salt body extruded coeval to sedimentation.

The northern flank of the central salt structure is characterized by the presence of tabular halokinetic sequences with different thickness in the lower parts and tapered halokinetic sequences indicating coeval rising of Fars salt body until top of the Gachsaran horizon (Fig. 7b). In

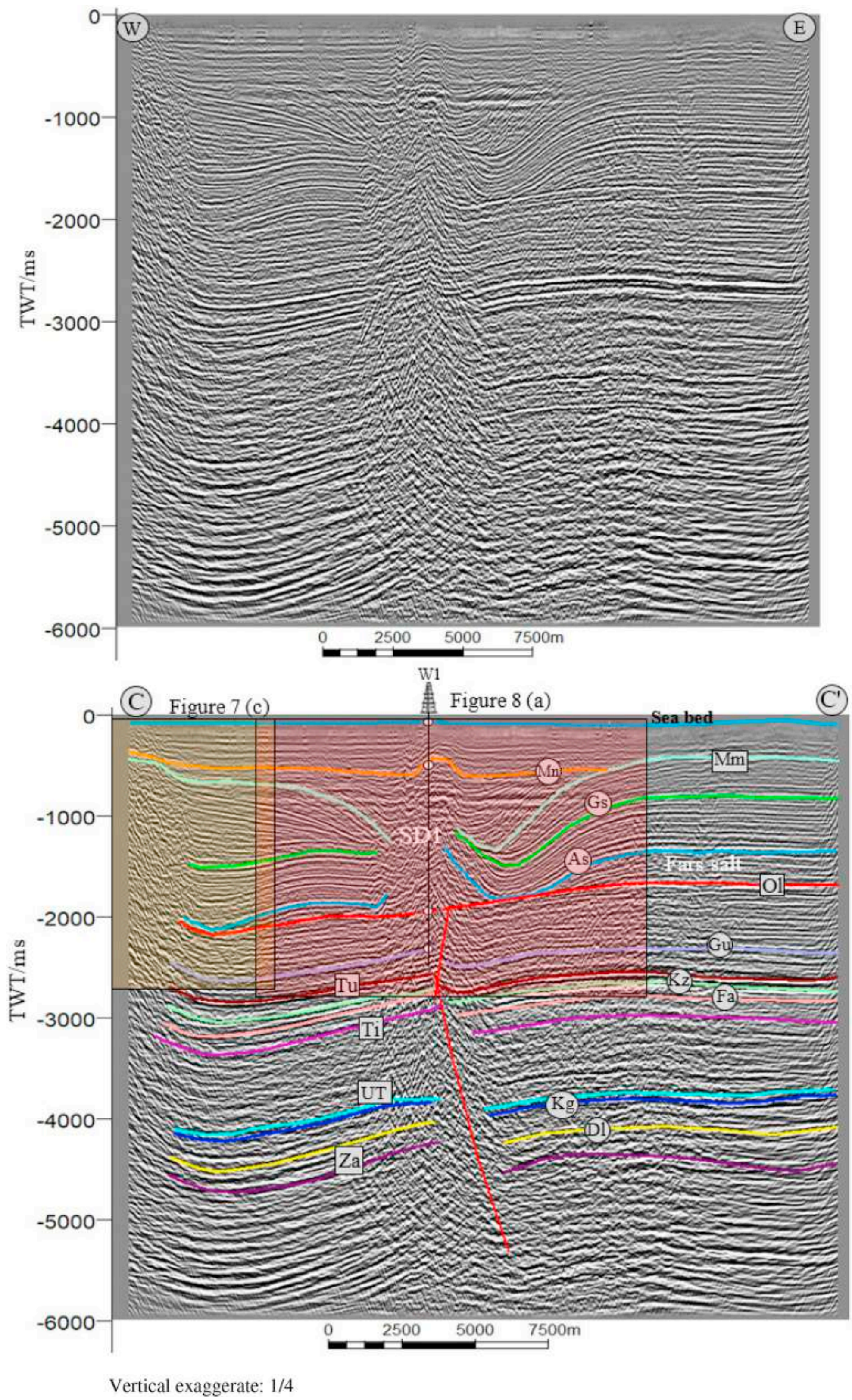


Fig. 6. Un-interpreted and interpreted CC′ seismic sections E-W around the Abu Musa diapir. The interpreted SD1 and central salt structures and the location of seismic horizons (letters in circles) and major unconformities (letters in rectangles) are shown. Abbreviations as per Fig. 2 caption. Locations of Figs. 7 and 8 shown by rectangles.

the northeastern flank, tapered sequences created earlier and show that the salt rising was earlier in this flank and extended to the top of the Gachsaran horizon. In the southwest flank, the reflectors of the end of the Gachsaran Formation is characterized by tapered halokinetic sequences. The lower parts of the Guri member deposits is characterized by the presence of tabular halokinetic sequences on the both flanks. The

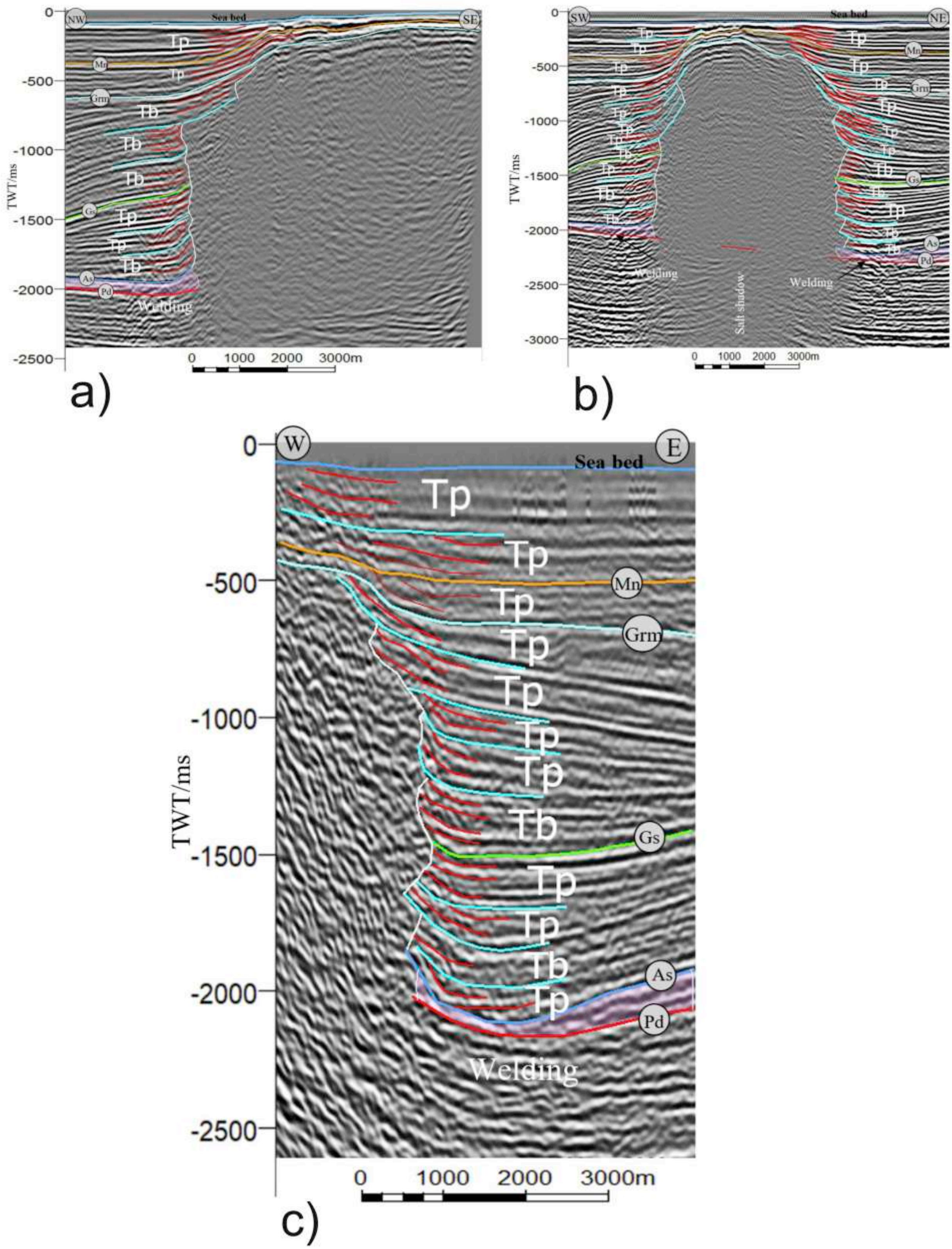


Fig. 7. (a–c) Interpreted seismic sections showing halokinetic sequences in the central salt structure, Abu Musa Diapir. Locations as per Figs. 4–6. "Tb" and "Tp" mark the tabular and tapered halokinetic sequences, respectively. Abbreviations in Fig. 2 caption.a) western flank of the central salt structure, b) northern flank of the central salt structure and c) eastern flank of the central salt structure.

upper parts of these deposits contains four tapered halokinetic sequences indicating the salt body has continuously risen with the sedimentation to the top of the Guri member horizon (Grm). The retreat and change in the dip of the halokinetic sequence highlight the variations in the rate of rise of salt body. The thickening of the Guri member deposits indicate that withdrawal has taken place more at this time interval. The upper and the lower boundaries of the above-mentioned deposits are bounded by Oligocene and Middle Miocene

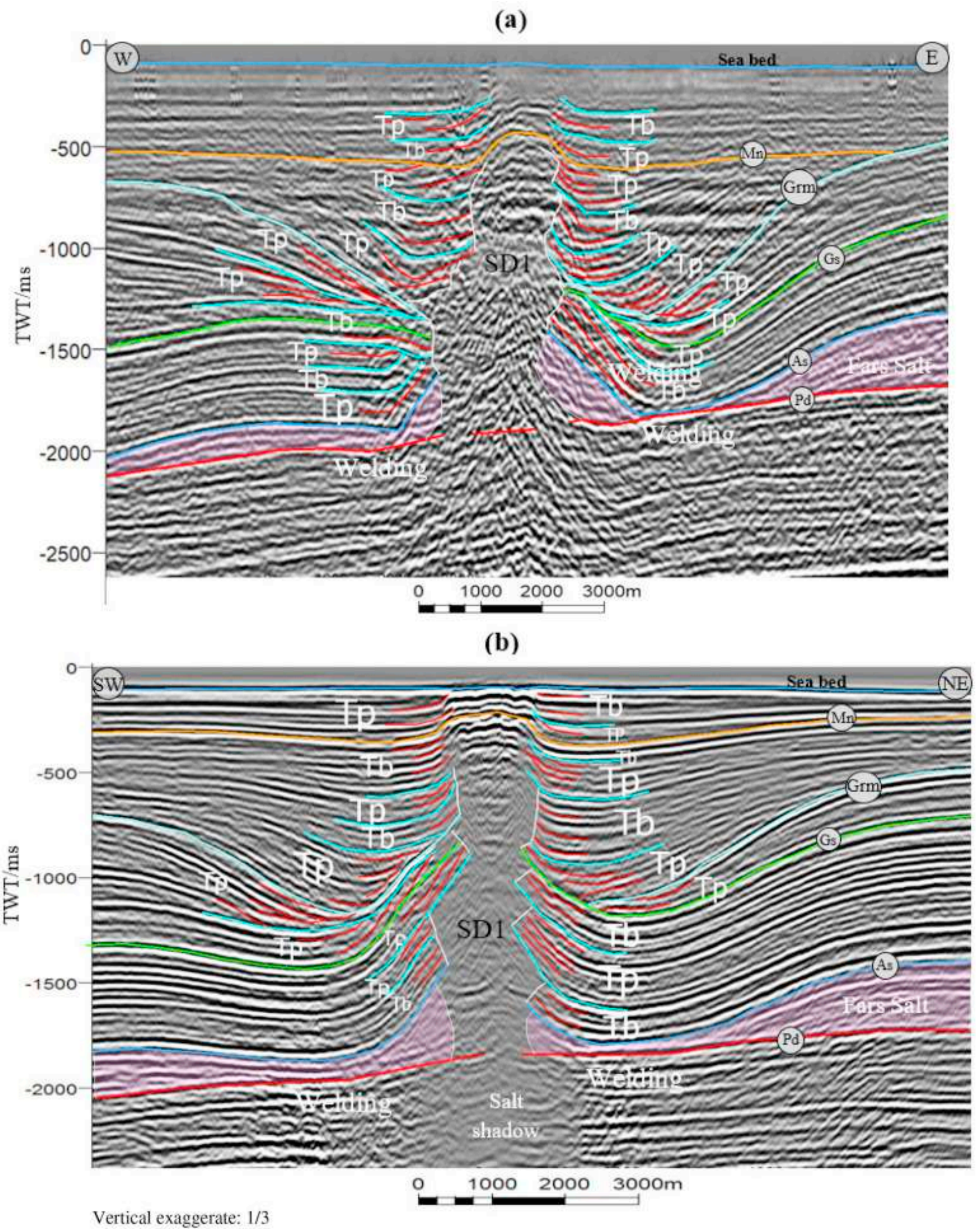


Fig. 8. (a, b) Un-interpreted and interpreted seismic sections showing halokinetic sequences on the SD1 salt structure along AA′ and CC' (locations as per Figs. 4 and 6). "Tb" and "Tp" mark the tabular and tapered halokinetic sequences, respectively. Details of the used letters in Fig. 2.

unconformities (**Ol**and **Mm** in Fig. 5), respectively. The presence of three recognizable tapered halokinetic sequences above the Mid-Miocene unconformity (Mm) (Fig. 2) indicates that the salt body moved up coeval to sedimentation up to the present day.

The eastern flank of the central salt structure is characterized by multiple tapered and tabular halokinetic sequences. The lower and upper parts of the Gachsaran Formation is characterized by tapered halokinetic sequences, while the middle parts of these deposits are characterized by a single tabular halokinetic sequences (Fig. 7c). The first tapered sequence shows that the Fars salt body rose up as the same time as the initial burial, which is different to other flank. The presence of one tabular halokinetic sequences at the lower parts of Guri member deposits and eight tapered halokinetic sequences up to the sea bed indicates the salt body continuously moved upward coeval to sedimentation.

Comparison of halokinetic sequences in different flanks shows that the rise of salt body in the eastern flank (Fig. 7c) was earlier. The tapered sequences in the eastern flank is more numerous but are thinner than those in the other flanks. These indicate continuously rising salt with varied rates spatially in short time intervals. The progress of flank on the salt rock toward the west in the eastern flank and the salt body piercing to the west on the northern flank (Fig. 7b) show that the salt has flown along northwest which is the same as orientation of Oman compressional stress.

4.2.2. Halokinetic sequences adjacent to SD1 salt structure along AA′ and CC′ sections

The Fars salt acted as the source layer of this salt structure. A significant thickness (~650 m) of the Gachsaran sediments deposited on the Fars salt, which triggered the salt movement. Based on the pattern of the halokinetic sequences, the geometric features and the timing of the salt movement differ around the SD1 structure (Fig. 8).

The eastern flank of the SD1 salt structure is characterized by the presence of tabular and tapered halokinetic sequences at the lower and

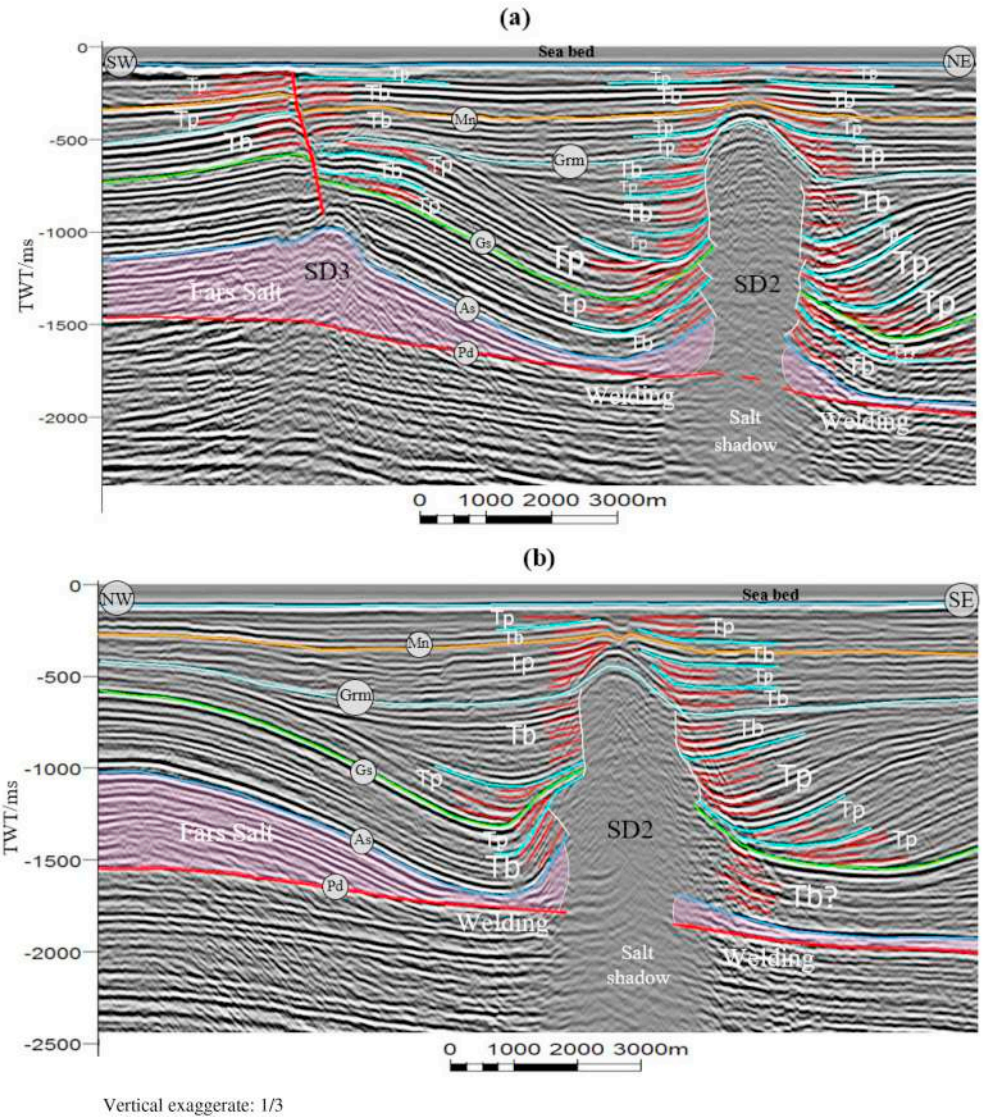


Fig. 9. (a, b) Un-interpreted and interpreted seismic sections showing halokinetic sequences on the SD2 and the SD3 salt structures along AA′ and BB’ (locations as per Figs. 4 and 5). “Tb” and “Tp” connote the tabular and tapered halokinetic sequences, respectively. Details of the used letters in Fig. 2.

the upper parts of the Gachsaran Formation deposits, respectively (Fig. 8a). The western flank of this salt structure is characterized by multiple tapered and tabular halokinetic sequences in the Gachsaran Formation deposits. The pattern of halokinetic sequences indicates that the onset of rising take placed earlier in the western flank. The presence of tapered halokinetic sequences on both the flanks of the salt structure in the Guri member deposits indicates that salt body has continuously risen with the sedimentation during the Guri member deposition. The number and the type of halokinetic sequences is almost the same in both the flanks above the Middle Miocene unconformity and show the continuous rise with sedimentation up to the present day. The feature, geometry and dip of the reflectors of halokinetic sequences differ in the both the flanks and suggest different rate of rising and withdrawal of salt body. The halokinetic sequences in the Guri member is reversed in the western flank due to the withdrawal and accumulation of deposits in the rim syncline. The salt body in the western flank interrupted by the halokinetic surface in the Guri member and cups features formed. Presence of salt debris on the Guri member horizon may indicate a salt emergent period.

The AA′ transect in the eastern flank of the SD1 salt structure is characterized by the presence of tabular and tapered halokinetic sequences (Fig. 8b). The pattern of halokinetic sequences in both the flanks is a little different and indicates that the salt rising in both the flanks was almost simultaneous. During deposition of Guri member, tapered halokinetic sequences on both the flanks indicates that the salt body has continuously risen with the sedimentation during the Guri member deposition. The number and characteristics of halokinetic sequences differ in both the flanks above the Middle Miocene unconformity.

4.2.3. Halokinetic sequences adjacent to the SD2 salt structure along the AA′ and the BB′ sections

The salt body of this structure came from the Fars salt source layer. A significant thickness (~650 m) of the Gachsaran sediments deposited on the Fars salt, which triggered salt movement. The geometric feature of halokinetic sequences and time of the salt movement differ around the SD2 salt structure (Fig. 9).

The AA′ transect in the both the flanks of the SD2 structure is characterized by tabular and tapered halokinetic sequences in the lower and the upper parts of the Gachsaran deposits, respectively (Fig. 9a). This pattern of halokinetic sequences indicates that the salt body was continuously rising coeval sedimentation and buried when the Guri member stopped depositing with a thin. The number and the type of halokinetic sequences is almost the same in both the flanks above the

Middle Miocene unconformity. The pattern of sequences in this time interval indicates continuous rise of salt coeval with sedimentation and then buried and again rising until the present-day.

The BB′ transect (Fig. 9b) in the northwestern flank of the SD2 structure is characterized by the presence of the tabular and tapered halokinetic sequences, respectively. In the southeastern flank during the Gachsaran deposition, due to noise in the reflectors or probably because of evaporative deposits, detection of halokinetic sequences is impossible and, looks tabular with uncertainty. The number and characteristics of halokinetic sequences differ on both the flanks during the Guri deposits sedimentation. In the northwestern flank, there are one tapered and one tabular, and in the southeastern flank, three tapered and one tabular halokinetic sequences, respectively. This pattern of sequences indicates continuously salt rising coeval with sedimentation, subsequent burial and finally rise to the present-day.

4.2.4. Halokinetic sequences adjacent to SD3 salt structure along the AA′ section

This salt structure, SD3, also derived from the Fars salt source layer. This salt structure emplaced under an antiformal structure resulted from generating rim syncline skirting the SD2 structure (Fig. 9a). Subsidence of the southwestern flank of the SD2 structure due to withdrawal and associated normal faulting created space for salt accumulation and the creation of SD3 structure. In this structure, the Gachsaran Formation works as an overburden and do not show any decipherable movement. In northeastern flank, the presence of tapered halokinetic sequences indicate the rising of salt body started with the beginning of the Guri member sedimentation. The Guri member in the northeastern flank contains a tabular halokinetic sequence in the middle parts that shows tranquility. The presence of tapered halokinetic sequences in the western flank indicates again salt rising during sedimentation of the upper Mishan to the present deposits.

5. Discussion

5.1. Timing of salt movement and evolution of salt structures in the Abu Musa diapir

When exactly the salts started flowing in the diapirs of the Zagros Mountains and the Persian Gulf basin is not accurately known. The episodes of salt movement can be dated using halokinetic sequences, which is located adjacent to the diapir.

Due to the lack of high resolution seismic data it is not possible to track the presence of the Hormuz salt source layer in the study area. But, based on the previous studies (e.g., Letouzey et al., 2004; Jahani et al., 2009; Motamedi et al., 2011; Callot et al., 2012), it seems that the first pulse of Hurmuz salt movement in the diapirs of the Zagros and Persian Gulf Basin occurred in the Early Paleozoic.

The presence of Fars salt in this area formed salt structures with a characteristic geometry in the Abu Musa region. The variation in the thickness and geometric pattern of the strata adjacent to the Abu Musa diapir, defined the halokinetic sequences and can express timing and evolutional stage of the salt structures in three stages (mound, dome and post dome stages: Trusheim, 1960) as follows (Fig. 10).

The first stage is mound stage. The presence of tapered halokinetic sequences in the Gachsaran deposits recorded the first movement of salt body. The withdrawal of evaporative body towards accumulation of salt body locations caused to gradual depression of overburden adjacent to the salt structure as synform feature. Increase in sediment loads due to accumulation in the depo-center withdrew the salt body towards the structure (the downbuilding process), which increased the accumulation of salt body and grew the structure. Sediment deposition during the early stages of salt movement tend to have more thickness towards the withdrawal place/depocenters flanks than towards the salt structure. Such a geometry is called either the “primary peripheral sink” (Trusheim, 1960) or the “primary rim syncline” (e.g., Vendeville et al., 2002). The sink has the geometry of a bowl-shaped depocenter.

The growth of the initial salt body is characterized by the presence of a tapered halokinetic sequence in most cases. Such sequences are well observed in the Gachsaran and the Guri member deposits.

The second evolutionary stage is known as dome stage. Continuation of deposition of sedimentary cycles resulted to more withdrawal of salt body and growth of structure. Withdrawal take placed near the surrounding root of the structure and therefore, the sedimentary sequences deposited in adjacent structure were thicker in the vicinity of the structure. Such a geometry is named the “secondary peripheral sink” or the “secondary rim syncline” (Vendeville et al., 2002). This kind of thickening is observed adjacent to structures in the Guri member, in the central salt structure and the SD2, and in the upper Mishan deposits of the SD1. The deposits of this stage include tapered and tabular halokinetic sequences, which represent continuous growth of the structure with roofing. Subsidence of the depocenters flanks caused its convex-downward base to progressively deform into horizontality, thereby bending the overlying strata into a convex-upward geometry. This is a typical of turtle-structure anticline (Vendeville et al., 2002).

The last stage, the post dome stage, started with the deposition of the Upper Mishan and the Agha Jari formations to the present, in the central salt structure and the SD2, and the Agha Jari formation to the present, in the SD1. At this stage, connection of salt body interrupted from source layer and the salt body grows due to passive diprism (Jackson, 1995). This geometry defined as a “tertiary peripheral sink” or a “tertiary rim syncline” (Vendeville et al., 2002). Near-uniform thickness within depocenter and flanks indicates that neither the depocenter nor its flank were subsiding during formation of the tertiary sink, whereas only the crest of the salt diapir rose.

5.2. Mechanism of diapirism in the Abu Musa salt diapir

Deposits surrounding salt structures can record the nature, timing, and mechanism of salt movement (e.g., Barton, 1933; Trusheim, 1960; Vendeville and Jackson, 1992a; Vendeville et al., 2002; Giles and Lawton, 2002; Hudec and Jackson, 2007; Giles and Rowan, 2012). Since the distribution of stress in salt bodies is considered to be homogenous and hydrostatic, the difference in stress between two points can be the most important factor of flow. Differential loading triggers salt flow and can be initiated by gravitational, tectonic, thermal and other events. The differential loading related to any of these factors is reflected in the feature and geometry of sequences surrounding salt structures. Therefore, attention to these components is an important key in understanding salt diapirism. The geometric feature of the deep salt-related depo-centers, rim-synclines and wedge-shaped sedimentary sequences surrounding the salt structures of the Abu Musa diapir resulting from the movement of Fars salt bodies indicates the performance of the down-building process (Barton, 1933; Hudec and Jackson, 2007; Giles and Rowan, 2012; Ezati Asl et al., 2019b). The accumulation of siliciclastics-evaporative sediments of the Gachsaran Formation with Miocene age as overburden on the evaporative layers of Fars salt resulted to increasing sediment loading and stresses. The Fars salt body started flowing by reaching a threshold of plastic deformation. Presence of tapered features support this evidence in the Gachsaran deposits, when the Fars salt body is raised shortly afterwards. The early salt movement, even before the successor-sediments being deposited, has recently received much attention. Several studies reported from the Atlantic margin in Brazil and Angola connote early salt flow and diapir formation during salt deposition (Quirk et al., 2012; Davison et al., 2000a), supported by observations of ongoing salt flow in the Red Sea (Mitchell et al., 2010). Also absence of faults in overburden sequences indicates that tectonic loading in the early growth has not been a significant impact on diapirs.

Gradual deposition of sediments in the depo-centers resulted to sink overburden in the Fars salt layer and hence, the withdrawal of the salt

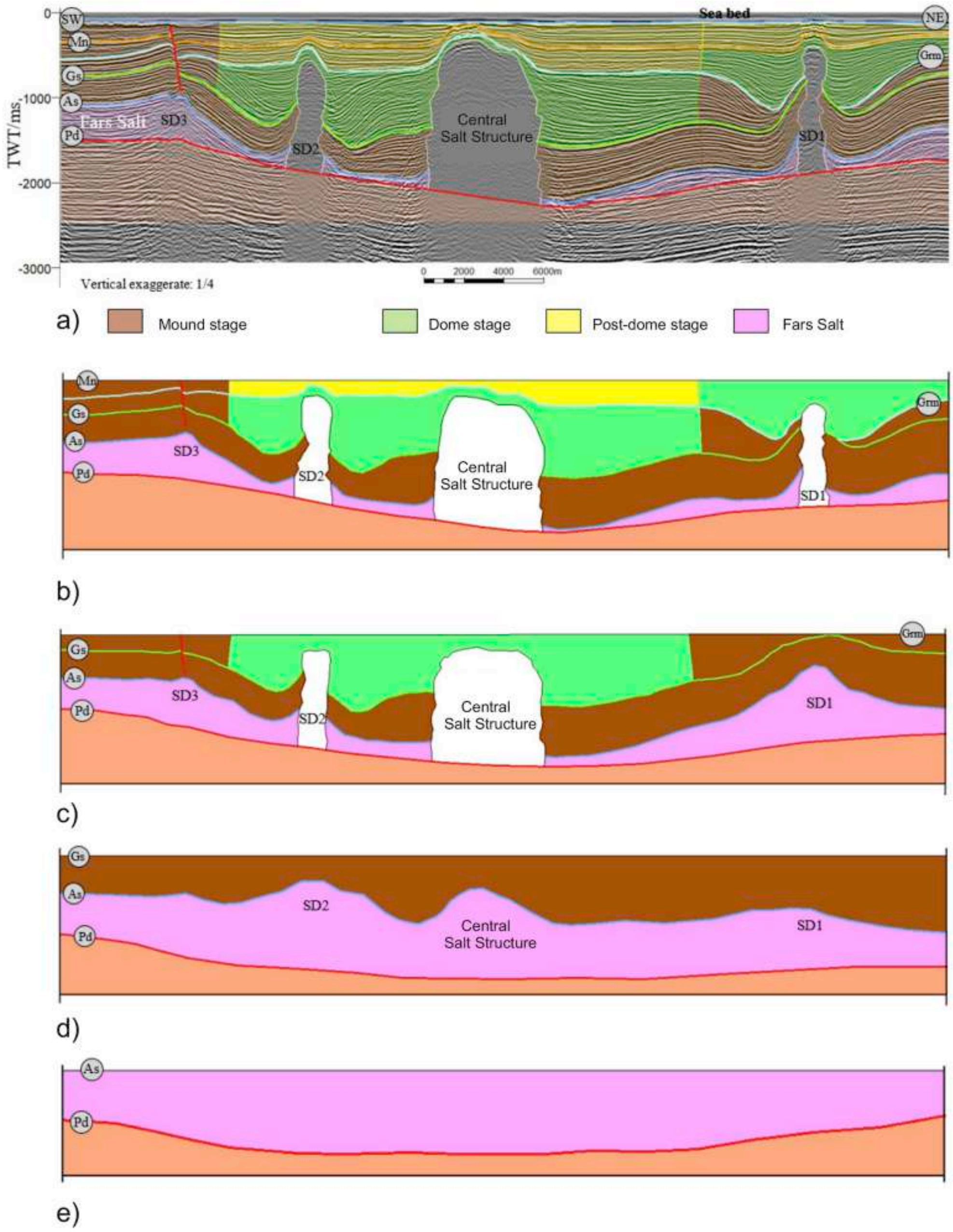


Fig. 10. Schematic evolutionary stages of the Central, SD1, SD2 and SD3 salt structures in the Abu Musa salt diapir. The sections obtained based on the method introduced by Gilardet et al., 2013). **a**) present-day configuration of the salt structures. **b**) Flattened section on the Mishan horizon. **c**) Flattened section on the Guri member horizon. **d**) Flattened section on the Gachsaran horizon. e) Flattened section on the Asmari horizon.

body towards the salt structure suggest the growth of diapirs is more related to sedimentation and down-building processes (Barton, 1933. All these evidences suggest differential loading resulting from gravitational loading was the most important factor in the movement that occurred as a halokinesis mechanism. Such a mechanism has been proposed as important driven-mechanisms of salt body in the evaporative basins of the world, especially in places where sedimentation leads to differential loading (e.g. Barton, 1933; Nettleton, 1934; Trusheim, 1960; Hudec and Jackson, 2007; Giles and Rowan, 2012).

6. Conclusions

The central and peripheral salt structures (e.g., SD1, SD2 and SD3) in the Abu Musa salt diapir (Persian Gulf) are analyzed for the growth and development of the halokinetic sequences adjacent to the diapir. Analyses and interpretation of geometric feature of the strata surrounding the salt structures on the seismic sections show that these sequences resulted from salt extrusion-sedimentation rates interaction. Hence, the main mechanism of driving salt body is the differential stress caused by down-building processes resulting from deposition of sediments around the structures. The geometric features of the sequences surrounding structures and welding points shows the central structure and the ring-like salt structures of the Abu Musa Island is fed from the Fars salt. The halokinetic sequences including the tabular and tapered features are derived from the periods of activity and growth of salt structures. These connote the timing of movement and evolutionary stages of the structures. The presence of wedge-shaped halokinetic sequences at different times reveals several rising phases occurring in the central structure and the surrounding ring-like structures. The Fars salt source layers began rising episodically in the Mid-Miocene coeval to the sedimentation of the Gachsaran Formation that created the central and peripheral salt structures of the Abu Musa diapir. This diapir developed in three stages-mound, dome and post dome-associated with sedimentation cycles periodically by passive and active rising.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2019.04.002.

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