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The Structural Imaging in Offshore Area of Strait of Hormuz Based on 3D-Seismic Data

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Abstract: The aim of this study is to describe tectono-depositional structures resultant of Cretaceous, Tertiary and Miocene tectonic activities in offshore area of Strait of Hormuz (Eastern part of Persian Gulf) using various seismic interpretation and palinspastic restoration techniques. High quality 3D-seismic data from the offshore area of Strait of Hormuz display complex structural imaging of that found at the Northeastern margin of Arabian plate. Seismic profiles show presence of two main unconformity surfaces; the lowermost is at the base of upper Cretaceous that is called Turonian Unconformity or top Bangestan group and the upper one is at base of Miocene and is named Guri Unconformity. The overlying structures of these unconformities seem to have been exposed to compressional and extensional tectonic events; one during late Cretaceous is Oman Orogeny and the other during Oligocene-Miocene epoch is Zagros Orogeny. These events had a significant role in triggering Cambrian Hormuz Salt and formation salt diapirs. Furthermore, the tectonic activities and sea level variations have played an effective role in creation of the turbidities and mass transport complexes intra Mid Miocene Mishan Formation which are considered good places of gathering hydrocarbon due to having reservoir properties.

Key words: Restoration, salt weld, unconformity, compressional, extensional tectonic activities, Strait of Hormuz

INTRODUCTION

Due to the fact that the Strait of Hormuz area that separates the Persian Gulf from Oman Sea is surrounded by four major structural-stratigraphic provinces: (1) the Zagros fold belt to the North-West, (2) the Arabian platform to the Southwest, (3) the Makarn basin to the east and (4) the Oman Mountains and Musandam Peninsula to the South (Fig. 1), the Strait of Hormuz area is considered the most complicated region. Furthermore, Oman and Zagros Orogeny had a significant role in complexion of area structure and triggering Cambrian Hormuz Salt. This, in turn, led to deformation of Gurpi and Pabdeh Formations dated as upper Cretaceous and lower Paleocene.

Understanding how the complex deeper upper cretaceous formations structures created are still somewhat ambiguous. Therefore, the study try to describe tectono-depositional structures resultant of Cretaceous, Tertiary and Miocene tectonic activities for deciphering the geological history of the Strait of Hormuz area.

High quality 3D-seismic data covered the offshore area of Strait of Hormuz in a regular grid. Interpretation of

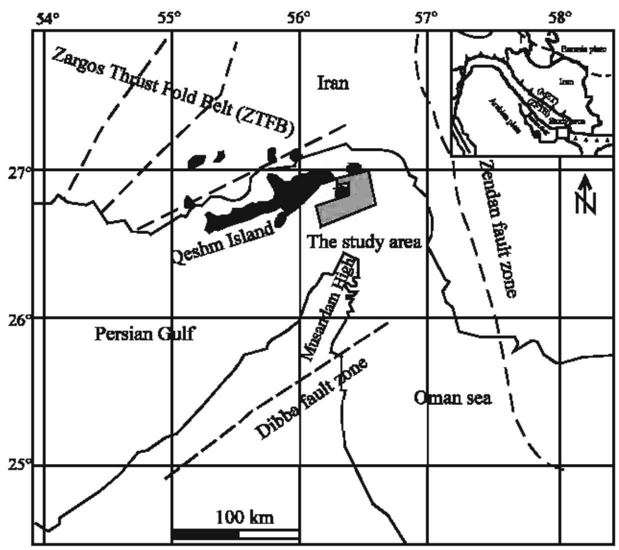

Fig. 1: Structural elements map of Eastern North part of Arabian plate included Strait of Hormuz area

3D-seismic data and restoration technique could clarify structural imaging and retort some structural ambiguities in the study area.

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Restoration is a suitable technique for validation seismic interpretation and better understanding of complex structures through analysis tectonic events that occurred in Cretaceous until recent time in the study area.

Balanced cross-sections can be restored so that the beds are placed back into their depositional, pre-deformational position. Balanced cross-sections link the deformed and undeformed states; therefore, finite strain analysis can be performed, which can be used as a predictive tool for fracture distribution and orientation. Furthermore, a balanced structural model validates the seismic interpretation through restoration to a depositional, pre-deformational state achieved by applying certain geometric rules. And it promotes a better understanding of the geological history of the study area.

REGIONAL TECTONO-DEPOSITIONAL SETTING

The study area locates in the Eastern part of Persian Gulf and is a part of the Zagros Fold-Belt (ZFTB). The belt is bounded to the NE by the Main Zagros Thrust Fault (MZT) and to the SW by the Persian Gulf, which represents its present-day active foreland basin. Topography along the Northern shoreline of the Persian Gulf represents the present day Zagros deformation front (Fig. 1).

The complex geodynamic history of ZFTB is summarized in five stages: (i) platform phase during the Paleozoic, (ii) rifting during the Permian and Triassic, (iii) passive continental margin of the Neo-Tethys ocean in the Jurassic-early Cretaceous, (iv) ophiolite emplacement dated as late Cretaceous and (v) collision and crustal shortening since the Neogene (Sherkati *et al*., 2006; Abdollahiefard *et al*., 2006).

During Permian, a regional shallow marine transgression with basal coastal clastics covered the entire region (Jahani *et al*., 2007). Vertical movement of salt bodies affected this Permian basin. As, there are evidences for thinning of Permian Dalan Formation at crest of salt related structures in central part of the Persian Gulf based on seismic profiles). Movement of Hormuz Salt continued up to present time. The climax of salt movement in the Persian Gulf area is Turonian time as the thickness of the Upper Cretaceous Sarvak Formation varies tremendously based on seismic profiles and well data. In addition, compressional events of Oman Orogeny in Late Cretaceous-Early Tertiary time (ophiolites emplacement in Oman; Glennie, 2000) affected the study area (folding and thrusting of Upper Cretaceous Gurpi and Lower Tertiary Pabdeh Formations beneath the pre Mid-Miocene base Guri Unconformity surface). Continental collision probably began in late Paleocene-Oligocene at the Northern promontory of the Arabian plate (Yilmaz, 1993) and propagated Southeastwards into the Lower Miocene (Sherkati *et al*., 2006), creating a considerable unconformity surface which middle Miocene sediments overlain eroded Paleocene-early Miocene sediments. Growth strata of Mid Miocene Mishan and Upper Miocene-Pliocene Aghajari Formation are attributed to the main phase of Zagros folding (Sherkati *et al*., 2005; Abdollahiefard *et al*., 2006).

SEISMIC DATA ACQUISITION

The seismic survey in the study area consisted of 192 prime 3D lines shot with a full fold of 62. The acquisition bin geometry was 6.25×25 m. The sail lines were shot using a two gun and six streamer configurations. Streamer cable length was 4600 m and each streamer recorded 368 channels. Recorded lengths recorded during these surveys were generally 6 sec. Sample rate was 2 msec.

THE SEISMIC INTERPRETATION OF STUDY AREA FROM MIOCENE TO RECENT TIME

The seismic data of the study area shown on seismic profiles (Fig. 2, 3), illustrate presence of two main horizons represent two regional unconformities occurred in Miocene and Touronian epoch are respectively Guri Unconformity and Bangestan Unconformity (equivalent Wasia Group in Oman area). The latter event has

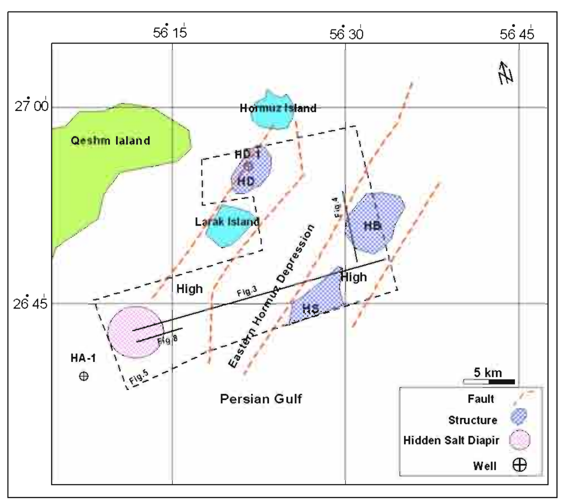

Fig. 2: Map of the study area showing Hormuz and Larak salt-related islands and a hidden salt diapir and also showing parallel NE-SW trending graben and horsts and fault zones discovered by seismic data

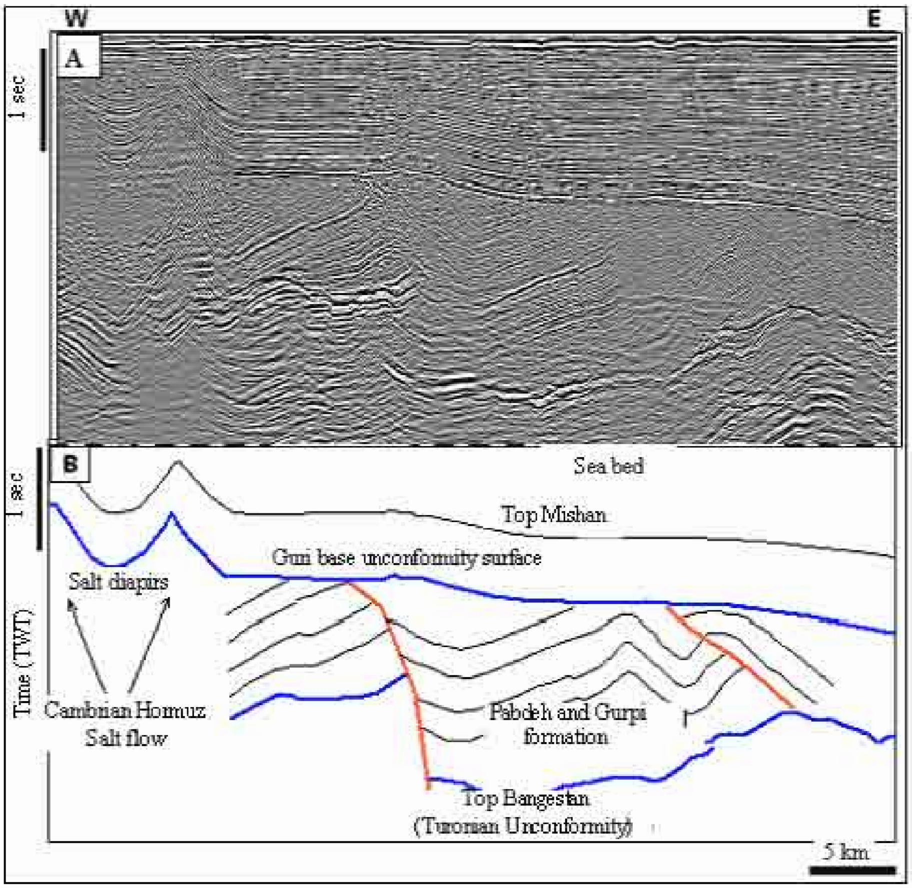

Fig. 3: (A) Uninterpreted and (B) interpreted seismic profile showing different formations of the study area. Location of the seismic profile is shown on Fig. 2

simultaneously formed with Oman Orogeny, whereas the first event happened at onset of Zagros Orogeny. Both of the unconformity surfaces have been tied to HD-1 well located approximately 21 km north of the seismic profile (Fig. 2, 3).

The shallowest Guri base Unconformity surface consists of limestone rock. Therefore, it is a strong and characteristic reflector. The event is created by a drop in impedance at base of Guri base Unconformity surface covering the Pabdeh Formation (marls and shales) underlying, creating a strong trough; this is made stronger by a thin high impedance interval just above the Padbeh. Guri base Unconformity surface constitutes base of Mid-Miocene Mishan Formation.

The Guri base Unconformity surface is the most conspicuous seismic reflector mapped in the study area. It clearly shows the deep truncation of older strata. Nearly all the deeper reflectors and associated sediments have been truncated, forming an evident angular unconformity. In general, the unconformity surface dips toward the East and the hiatus increases in the same direction. In the Eastern most part of the area, at the boundary to the Oman Sea, the unconformity has been tied to the Musendam Unconformity (Fig. 1, 5).

Wells data in Strait of Hormuz area denote to the amount of truncation increases eastward. For example, on the HA-1 well located approximately 14 km Southwest of the seismic profile (Fig. 2, 3); the upper part of the Eocene Pabdeh Formation is eroded. Eastward, on the HD-1 well to the Northeastern part of the study area, the erosion becomes more severe and nearly all of the Pabdeh Formation is eroded. Furthermore, overlying Gachsaran Formation disappears completely (Fig. 5).

In the South Eastern most part of the study area, the erosion is less severe. Oligocene-lower Miocene Fars Salt has been seen beneath Guri base Unconformity surface which seems completely displaced and depleted and led to creation of salt welds due to vertical movements of Zagros events (Fig. 4, 5). These welds appear that had an

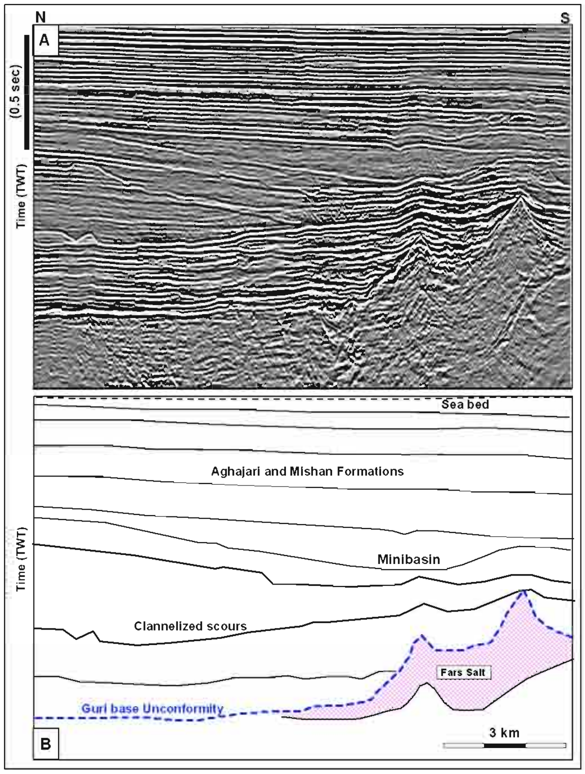

Fig. 4: (A) Uninterpreted and (B) interpreted seismic profile showing channels in Mishan Formation. And also displaying Fars salt diapir dated as Oligocene below Guri unconformity surface. Location of the seismic profile is shown on Fig. 2

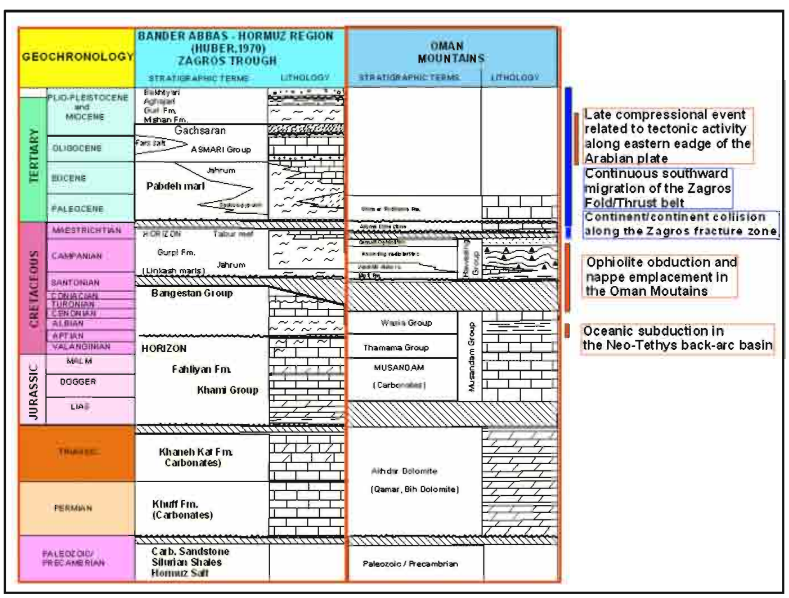

Fig. 5: Showing the important tectonic events affecting on Hormuz area that occurred in all Mesozoic and Cenozoic and also displaying stratigraphic correlation for the Iran- Oman (Michaelis and Pauken, 1990)

important role in forming minibasins within Mishan Formation the container Mass Transport Complexes (MTC) resultant of submarine turbidity currents.

The sediments thickness the covering the Guri base Unconformity surface composite of limestone, marls and minor shales of the Mishan Formation and shales with minor limestones and sandstones of the overlying Aghajari Formation varies from less than 350 m (300 msec of two way time) in the Western part to more than 2000 m (1.8 sec of TWT) in the East. These formations contain plenty of channels with turbidites which is believed that were created by different factors such as salt tectonic and sea level variations.

The sea level variations have major effects on rate of sediment supply and type of sediment and subsequently affect on creation turbidity currents and sedimentation rates. A relative rise in sea level creates increased accommodation space within the shelf and slope region, whereas a relative drop in sea level decreases accommodation space within the basin. Locally confined accommodation can also be generated by syn-depositional tectonic activity. The salt tectonic also plays a major role in creation of accommodation of deposits in this area and subsequently, formation of turbidites.

Channels with evident erosional bases occasionally occur internally within the interval. Some of the scoured features display internal large scale sigmoidal cross bedding. These beds, which form in the direction from western north to eastern south, may have originated from submarine progradation or, more likely, as channel fill by lateral accretion.

In most the study area, the internal reflections of Mishan and Aghajari Formations the deposited simultaneously with Zagros events are parallel or semi parallel, (Fig. 3). Besides, the faults intra the aforementioned formations range from normal faults with small throws originated by salt solution in crests of salt diapirs to very small faults and fractures originated by turbidity currents intensity. This indicates to the sediments are gently folded by Zagros Orogeny. In other words, Zagros events have had very little effect on these formations.

THE SEISMIC INTERPRETATION OF STUDY AREA FROM LOWER CRETACEOUS TO LOWER MIOCENE TIME

Turonian Unconformity interpreted as top Bangestan group shown on seismic profile (Fig. 3) is picked on a black peak it represents the transition between marl and shale in the Gurpi Formation to the limestones of Sarvak Formation (Bangestan group). This transition is characterized by a large increase in acoustic impedance. The horizon is also a characteristic and strong seismic reflector in most of the study area, but presence of a lot of multiples, makes the interpretation difficult, especially below structural highs.

The nature of the sediments between the two regional unconformities (Guri and Turonian Unconformity surfaces) is speculative and is probable to be Eocene Pabdeh, Upper Cretaceous Gurpi marls and shales or a combination of both.

Ophiolite obduction (Oman Orogeny) that took place during much of late Cretaceous time affected the on sedimentological pattern of Gurpi Formation. In addition, another related factor that caused local variations in depositional environment and thickness were halokinesis related to Cambrian Hormuz Salt (Fig. 3, 5). Hence, The significant compressional and extensional tectonic movements of Oman Orogeny played an effective role in creation of complex structure of the Hormuz area particularly, the interval intercepted between two unconformity surfaces through making of reverse, thrust and normal faults and these features had a vital role in salt flow activations from Cambrian Hormuz Salt Formation and also acted as conduits for active diapirism.

The faulting seen in some zones over top of Bangestan of the study area shows clear indications of intense compression and lateral movements related to the Late Cretaceous-Early Tertiary event of the Oman Orogeny (Fig. 3).

In the study area, where this thrusting appears, there is a chaotic zone in the Pabdeh/Gurpi interval, where some characteristic and strong intra Gurpi reflections seen elsewhere suddenly disappear. It seems that the iterated lateral compressional movements of Oman Orogeny occurred along some of the faults in soft Pabdeh/Gurpi Formations the eastern part of the area, led to squashing rocks and creation chaotic zones (Fig. 3). Besides, the late compressional events with rejuvenation of thrusting related to the Oman Orogeny had a major influence on the structuring of the study area. Moreover, presence harpoon type structures across the faults reveal inversion tectonics in this area. The original movement in these faults is normal, but compressional movements forced them to act as reverse faults at later stages.

PALINSPASTIC ANALYSIS OF SEISMIC PROFILE

The seismic data and the depth-converted geoseismic section used as input for the restoration are presented in (Fig. 3). Due to intense deformation of the overburden overlying Turonian unconformity, the geoseismic section was restored to its paleostructure in four stages, from upper Cretaceous (Turonian Unconformity) to lower Miocene (Guri base Unconformity), using 2D move software (Fig. 6). The geoseismic section was balanced by fault parallel flow and flexural slip unfolding methods. The

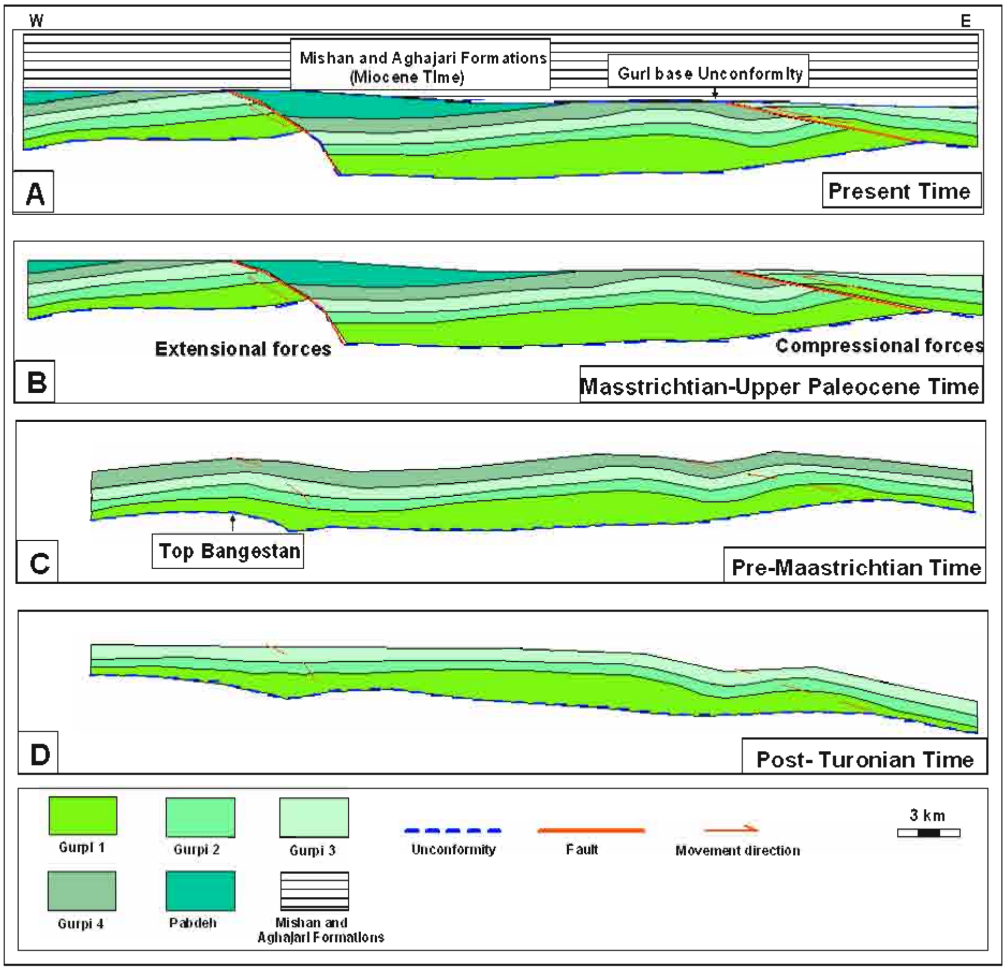

Fig. 6: Restoration of seismic profile in the Fig. 3 (using 2D move) carried out in four stages from Turonian to present Time. The restoration panel is a schematic representation of deformation in the Pabdeh and Gurpi Formations above Turonian Unconformity

restored section was decompacted at each stage to investigate scenario for the structural evolution of the eastern part of Persian Gulf. The model describes tectonic activities which occurred after Turonian time and also extrapolates scenario of Cambrian Hormuz Salt movement and creation of salt diapirs in this area

The interpretation shows that through time, Pabdeh-Gurpi horizons lengths increasing rate relative to the original section lengths gradually decreases upward. Where amount of extension of Pabdeh-Gurpi Formations did not exceed 1% of the original length, this generally indicates to tectonic events during the initial stages of deposition of Gurpi Formation was active, lower layers thickness variation of Gurpi Formation along the seismic section is clear evidence (Fig. 6).

Presence of the normal and thrust faults intra Pabdeh-Gurpi Formations refers to the area intensely exposed to extensional and compressional tectonic movements. The area, in the initial stages, was stroked by intense extensional events in Maastrichtian- Paleocene time led to rotational movement of the overburden upward about 3° (Fig. 6C) and this corresponds to Oman Orogeny. Besides, the interpretation indicates to that Pabdeh-Gurpi Formations also exposed to compressional activities in Paleocene time led to form thrust faults (the left side of Fig. 3, 6), it is likely that the latter activities may be represent the latest phase of Oman Orogeny or onset of Zagros events (onset of Arabian and Eurasia continents collision). These events caused to trigger Cambrian Hormuz Salt and creation of normal fault with big throw due to salt flow Strength upward (the right side of Fig. 3, 6). The uniform thicknesses of Pabdeh-Gurpi Formations on two sides of normal and thrust faults denote to that formation of the normal fault and salt flow occurred post-deposition of Gurpi Formation (Fig. 3, 6C, B). Seismic interpretation reveals that the normal fault is not regional; it does not extend to the basement. It is likely that in upper Cretaceous-Lower Miocene time, the majority of Hormuz Salt moved up and settled beneath Guri base unconformity. After that, during deposition of Mishan and Aghajari Formations dated as mid Miocene-present time diapirs have mainly grown passively by downbuilding. They originated by maintaining their crest at or close to the sea floor while sediments accumulated in depotroughs between salt bodies. In other words, the diapirs crest remained at or near the surface of the sedimentation while its base sank together with the surrounding, subsiding Aghajari strata. The weight of the Aghajari sediments at synclines accelerates displacement of salt bodies and somehow uplifting of diapirs. By downbuilding, a diapir could pierce many kilometers of strong overburden, because the latter was being deposited only along the flanks of the diapir (Fig. 3). The interpretations show that in Mid-Miocene time, a significant part of Hormuz salt was evacuated upward and creation salt welds.

CONCLUSIONS

- Based on a kinematic model from restoration, which describes evolution of the study area history, Hormuz Salt has intensely flowed post-deposition Pabdeh-Gurpi Formations in Paleocene-Oligocene time that caused to create normal fault. The extensional and compressional movements (Oman Orogeny) were the main factor in triggering Cambrian Hormuz Salt.
- The Fault Parallel Flow algorithm and flexural-slip unfolding technique are determined suitable approaches in balancing faulted anticlines of the area.
- The seismic imaging indicates that the compressional events with rejuvenation of thrusting related to the Oman Orogeny had a major influence on the structuring of the study area.
- The Zagros Orogeny has had very little effect in the area as Guri base Unconformity surface is gently folded by this Orogeny. Furthermore, the Zagros Orogeny triggered a new salt tectonic event in the study area as both the Hormuz Salt and Fars Salt are affected.
- Evolution of salt diapirs in the study area has passed two active and passive diapirism stages. Cambrian Hormuz Salt rose up mainly in active form by tectonic events until Lower Miocene time. After that, it continued to flow mostly in passive form by downbuilding.
- Hormuz Salt tectonic, Zagros events and sea level variations had an effective role in creation of turbidites and mass transport complexes (MTC) within Mishan Formation.

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