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Analysis of Miocene Depositional Systems in Offshore Area of Strait of Hormuz Based on 3D-Seismic Data

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Abstract: The aim of this research are to delineate depositional systems of Strait of Hormuz area (Eastern part of Persian Gulf) included turbidity and Mass Transport Complexes (MTCs) which is characterized on seismic by chaotic reflections, scoured bases and mounded external geometry. And also to identify predominant channels types, using 3D-seismic interpretation techniques. The depositional systems are expected to be triggered by sea level variations and salt tectonic, whose volume is proportional to salt flow vigor. Two different sizes of turbidities have been detected in the study area. One is in large scale within the Mishan Formation. The other is somewhat small and only detected within the Aghajari Formation. The latter Formation represents reduction of salt movement intensity and relatively low sedimentation rate. Moreover, big channels are detected within Mishan Formation, whereas, the smaller channels are distinguished within Aghajari Formation. Presence of aforementioned depositional systems in Aghajari and Mishan Formations are clear evidences for salt deformational activities during deposition.

Key words: Seismic, turbidities, channels, mass transport complexes, salt tectonic, strait of Hormuz

INTRODUCTION

A depositional system as a three-dimensional assemblage of lithofacies (Ficher and McGowen, 1967) is a stratigraphic record which facilitates inferring ancient processes and environments. The fundamental unit of the depositional system is the lithofacies, whose genesis is inferred from the interpretation of sedimentary structures, textural variation, bedding characteristics, internal and external stratigraphic relations and association with adjacent facies. High quality 3D seismic which has been used in this study is a powerful tool which allows interpretation of sedimentary features and better understanding depositional environment. In this regards, different interpretation techniques such as conventional seismic interpretation to extraction of various types of attributes are required for detection of subtle features.

The main objective of this research is to infer depositional system, mass transport complexes and predominant channel types within the Miocene Sediments (Mishan and Aghajari Formations) in the offshore area of the Strait of Hormuz (Eastern part of the Persian Gulf) through delineation of subtle stratigraphic features. This would help to understand the Miocene tectonic evolution in relationship with Hormuz salt activity within this region which has high potential for hydrocarbon exploration. The study area is an ideal place to study depositional systems. Turbidities and Mass Transport Complexes (MTCs) including slumps, debris flows and slides are considered as distinctive features for revealing depositional systems of the study area which experienced different geological settings during Mesozoic and Tertiary. During Miocene compressional forces and subsidence led to establishment of slope depositional environment. Detailed 3D-seismic interpretation methods have been used for better understanding of the interplay of sea level changes and salt tectonics on the slope depositional system. The changes in sea level dictated the volume of supplied sediments and also accommodation for deposition. Salt movement affected the slope's depositional gradient and slope stability, as well as creation of localized accommodation in the form of intra-slope basins.

GEOLOGICAL SETTING OF THE STUDY AREA

The study area is located in the eastern part of Persian Gulf and is a part of the Zagros Fold Thrust Belt (ZFTB). The ZFTB as part of Himalayan-Alpine Orogeny system is bounded to the NE by the Main Zagros Thrust Fault (MZTF) and to the SW by the Persian Gulf, which represents its present-day active foreland basin (Fig. 1).

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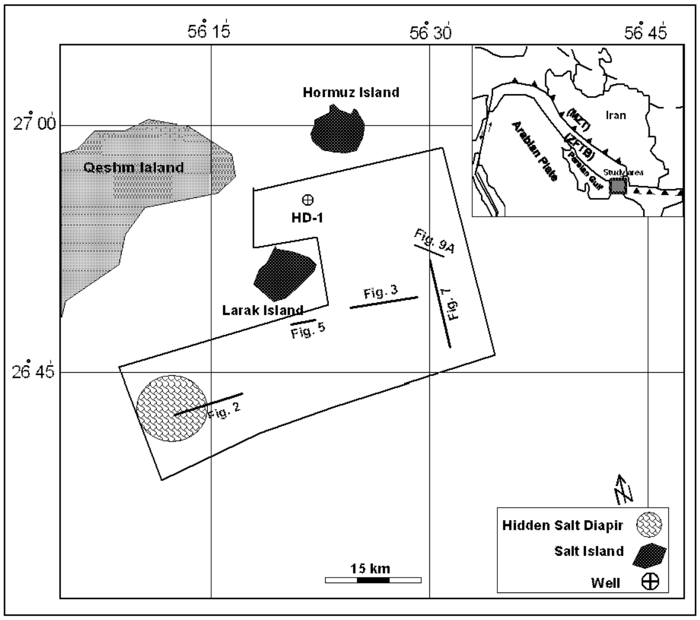

Fig. 1: Map of the study area showing Qeshm Island, with Hurmuz and Larak salt-related Islands and also showing locations of seismic profiles

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; Abdollahie Fard *et al.*, 2006).

Continental collision between Arabian and Eurasia plates probably began in the 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 (Guri unconformity) which Mid-Miocene sediments overlain eroded Paleocene-early Miocene sediments.

In this process, the Cambrian Hormuz Salt came to play an important role, acting as decollement surfaces between the basement and the cover sequence and the old structural trends and elements were rejuvenated.

Marls, limestones and clastic sediments of the Mishan and Aghajari Formations had overlain base Mishan unconformity surface following the Arabian-Eurasia Continental collision as it attributed to the main phase of Zagros folding (Sherkati *et al.*, 2005; Abdollahie Fard *et al.*, 2006). Structuring is controlled by the southward transportation of the Zagros Fold/Thrust Belt and it led to lateral variations in thickness and depositional facieses.

CONTROLLING FACTORS OF TURBIDITY SYSTEMS

Turbidity systems are controlled by three major factors: tectonics, climate and sea level fluctuations. Tectonism influences the nature of the basin's drainage (i.e. its geometry and gradients) as well as the geometry of the receiving basin (Readings and Richards, 1994; Bouma, 2000; Weimer and Slatt, 2004).

Climate influences the rate and type of weathering, precipitation and runoff, thereby determining the sediment type as well as amount of sediment entering the basin. Major climatic changes (e.g., glacial and interglacial ages) result in sea-level fluctuations that affect the rate of sediment supply and type of sediment dispersal pattern. The interplay of these various factors determines accommodation space and sediment supply in the deepwater which influences the systems' facies association and depositional elements.

Regional basin accommodation can be created by tectonic. Accommodation space within the basin can change due to sea level fluctuations. A relative rise in sea level creates increased accommodation space within the shelf region, whereas a relative drop in sea level decreases accommodation space within the basin. Locally confined accommodation space can also be generated by syn-depositional tectonic activity. It is clear that tectonism and sea level variation have a major role in creation of accommodation of deposits in this area and subsequently formation of turbidities. By the way, the role of other aforementioned factors should be taken into account.

SEISMIC INTERPRETATION OF DEPOSITIONAL SYSTEMS

The seismic data indicate that the maximum depth of the Aghajari and Mishan Formations in the study area is about 2000 m (1.8 sec of 2 way time) below the sea level in minibasin between two salt welds (Fig. 1, 2). Deposition of sediments within this area is strongly controlled by salt tectonics and other related factors. Turbidity systems and mass transport complexes within the Mishan and Aghajari Formations are considered as evidences for salt flow in this area. Seismic facieses of present data can be used to define the different depositional systems based on reflection continuity, amplitude and external geometry as imaged by seismic attributes.

The overlying sediments composed mainly of MTCs interbedded with parallel to sub-parallel and chaotic and hummocky seismic facies. This pattern of deposition suggests periodic changes in sediment supply and accommodation within the basin. The MTCs correspond to periods of high sediment supply that may be related to early low-stands of sea level. Hummocky seismic facies denote to rapidly deposit MTC. Whereas, the parallel to sub–parallel seismic facies correspond to periods of low sediment supply in the basin associated with high-stands of sea level.

Evidence of deformational activities (slumping and salt movement) within the overall area includes faults, scarps and hummocky features which are characterized by reflection discontinuities.

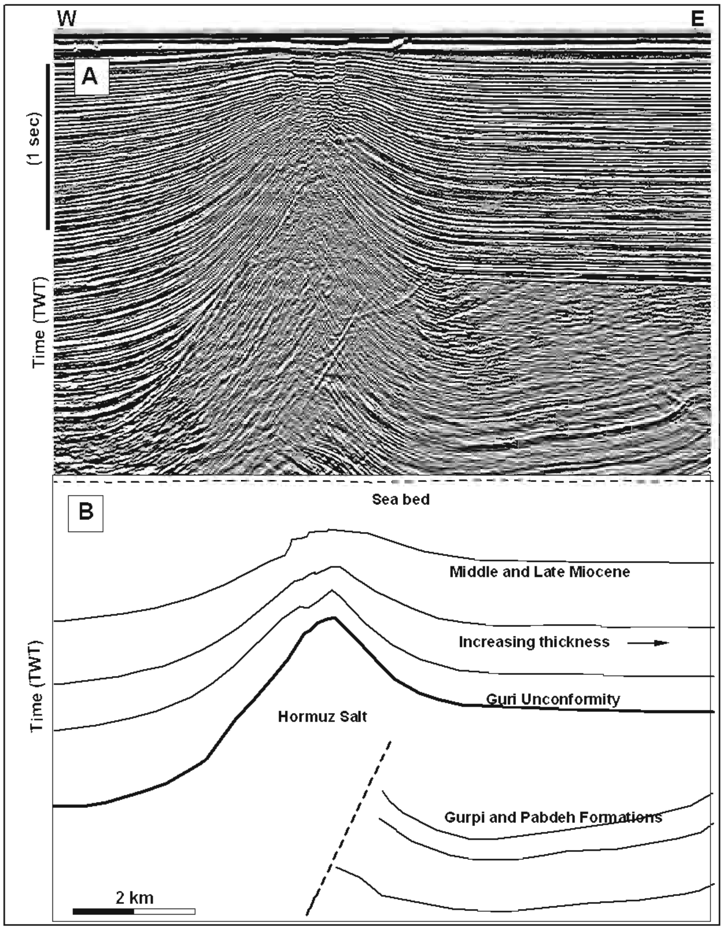

Fig. 2: (A) Uninterpreted and (B) interpreted seismic profile showing Late-Mid Miocene Aghajari and Mishan Formations affected by salt tectonic which contain channels, turbidities and Mass Transport complexes over Guri unconformity surface

TURBIDITIES IN THE STUDY AREA

Turbidity current is a sediment gravity flow which travels over large distances and carry with it very coarse sediment. Turbidity currents travel long distances because of auto- suspension, an effect by which the turbulence generated by the plume of sediment-water mixture creates an upward force and helps suspend the sediment. Aforementioned currents are triggered by a number of mechanisms, including sediment loading, river discharge, storm waves, tsunamis and of course, earthquakes (Goldfinger *et al*., 2003). The sedimentary deposits of turbidity currents are chiefly composed of sands, silty sands and gravelly sands and are called turbidities.

Marine turbidities in study area can be divided into two groups based on its volume and intensity.1- High-density, high-velocity turbidity currents. 2- low-density, low-velocity Turbidity currents.

Turbidity lobe (minibasin) resultant of the first currents has been seen and mapped on seismic sections within Mishan Formation at the depth 1300 m (1.16 sec TWT) below the sea level (Fig. 3A). This turbidity horizon was mapped across area using a 10 x 10 grid of inlines and crosslines. It has an approximate area of 41 km^2 and maximum thickness almost 225 m (0.2 sec TWT). Intensity and strength of the turbidity currents led to create large canyon as result of sediments movement that eroded and corroded the canyon walls as showed in (Fig. 3B). Seismic data show that turbidity current was flowing toward

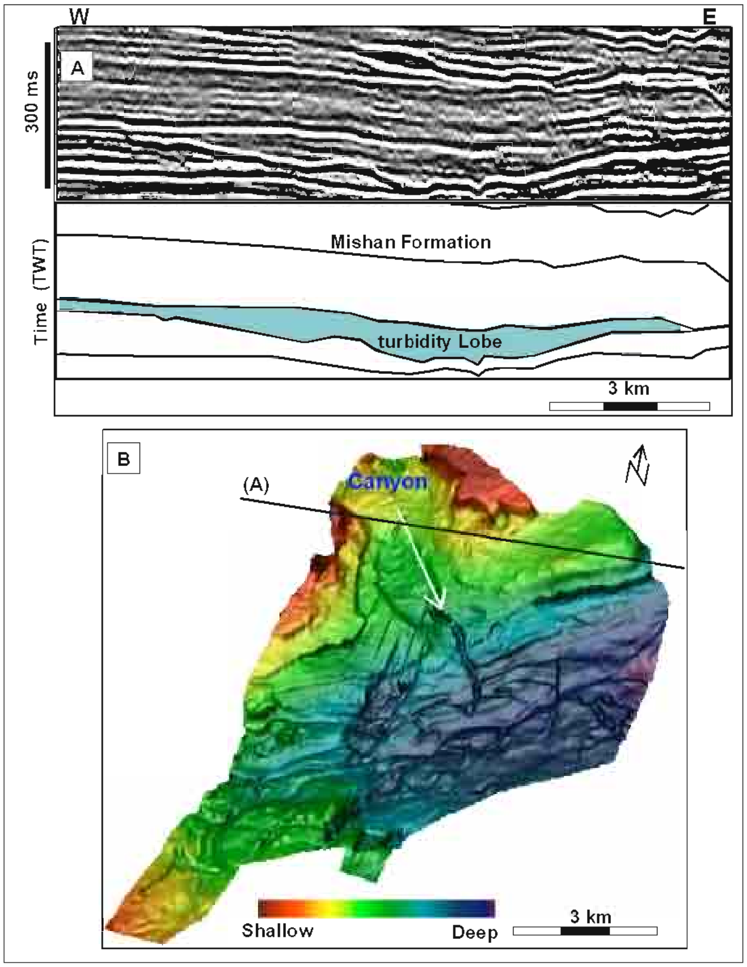

Fig. 3: (A) Uninterpreted and interpreted seismic profile displaying the ponded lobe resultant of turbidity currents within Mishan Formations at time 1.16 sec that is characterized by parallel or sub parallel reflections, (B) illumination map of turbidity lobe showing submarine turbidity currents movement direction (toward Southeast)

Southeast of the study area. It means that Submarine currents path was from salt diapir direction toward basinward (Fig. 3). This denotes that salt flow had a major role in creating these currents, because the aforementioned currents usually originate either as result of salinity and temperature degree variations (Harami, 1979) or tectonic events. In other words, increasing temperature and salinity of the sea water is often associated with tectonic activities such as salt flow. Consequently, turbidity currents are generated.

It is observed on seismic section in (Fig. 3A) that deposited sediments are characterized by parallel and sub parallel High Amplitude Reflections (HAR), or discontinuous to shingled and mounded external geometry. They correspond to sheet sand, whereas discontinuous HAR in downslope may be interpreted as channel-fills and mounded geometry is characteristics of slides, slumps and debris flows.

We propose that slides originated as the flow traveled down-slope due to salt movement. By decreasing flow traveled intensity that was corresponding to decreasing salt movement rate, they deposited coarse-grained sediments along its path in the up dip portion. Meanwhile, the fine-grained sediments travel further minibasin and later spread out downslope, forming the fine-grained geometry characteristic of deposits. The progression from coarse-grained to fine-grained geometry is attributed to depositional gradient changes.

It is seen on illumination map, presence of lateral channels in midslope of turbidity lobe. It is interpreted as result of drifted slides flow from upslope and deposited in form of channels. Then, the water laterally overflowed to the channels and deposited the sediment on the channels sides in form of levees (Fig. 3B). RMS amplitude map reveals lateral levees and canyon mouth edges by red color. Coarser sediments were deposited near the canyon mouth, while finer-grained sediments were spread into downslope behind aforementioned levees (light green and dark blue) on RMS amplitude map (Fig. 4A, B).

Other turbidity lobe is also detected in the study area in form of minibasin and is smaller than the aforementioned first turbidity lobe that was believed to be generated by low-density, low-velocity Turbidity currents (Fig. 5).

Turbidity lobe is distinguished on seismic section at depth 230 m (200 ms TWT) within Aghajari Formation (Fig. 5A). The turbidity horizon was mapped across area using a 10×10 grid of inlines and crosslines at the depths 230-450 m (200-397 ms TWT). It has an approximate area of 21.5 km^2.

Turbidity current path was eastward as shown on illumination map (Fig. 5B), i.e., Submarine currents were overflowing from salt diaper (Larak Island) direction toward basinward. Turbidity lob has also been revealed on RMS amplitude map clearly (Fig. 6). The deposited

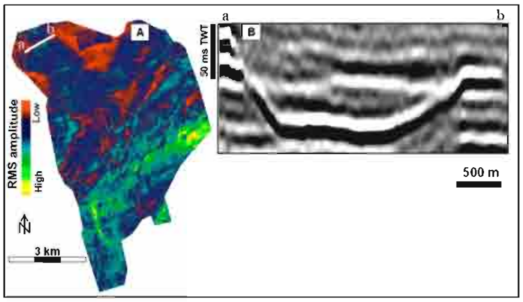

Fig. 4: (A) RMS amplitude map of turbidity lobe showing lateral channels directions, (B) Seismic profile of canyon mouth of turbidity lobe

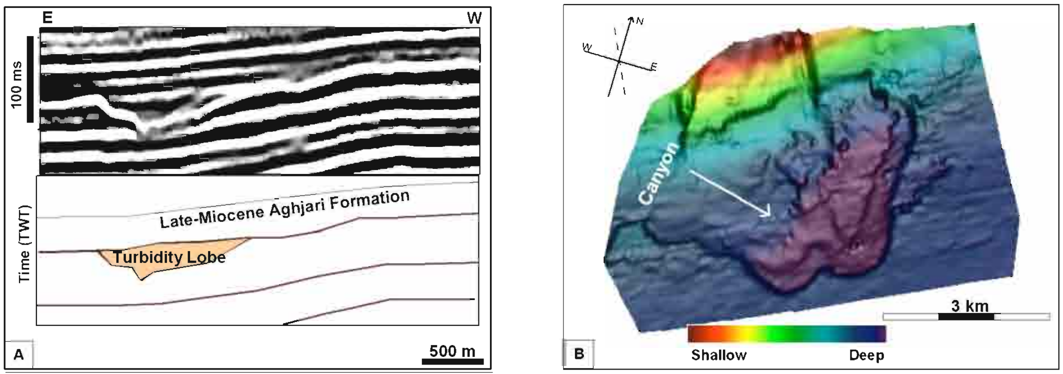

Fig. 5: (A) Uninterpreted and interpreted seismic profile showing turbidity lobe resultant of turbidity currents within Aghajari Formation and (B) illumination map of above turbidity lobe

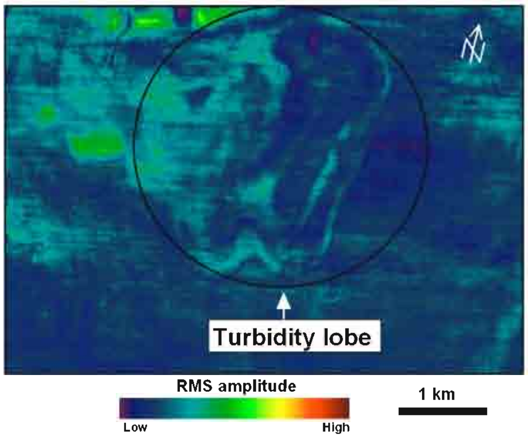

Fig. 6: RMS amplitude map showing turbidity minibasin limits within Aghajari Formation inside black circle

sediments of the turbidity lobe are characterized by parallel and sub parallel HAR, to shingled that formed in response to large impedance contrasts between lithology interfaces and they may exhibit terminations such as truncations, onlaps and downlaps against the bounding surface.

In summary, the submarine currents have deposited coarse grained sediments along its path in the up dip minibasin as probably evidenced by increased scouring.

MASS TRANSPORT COMPLEXES (MTCS)

Numerous mass transport complexes are seen on seismic sections within Mishan Formation in the eastern part of the study area; however, three packages of MTC (A), MTC (B) and MTC (C) have been classified based upon their deposit time (Fig. 7). These deposits are characterized on seismic by chaotic reflections, scoured bases (basal shear surfaces) and mounded external geometry. Associated depositional features were also identified such as minibasin edges the container aforementioned sediments.

MTC (A): MTC (A) is the oldest of the mass transport packages that was studied. It has approximately 7 km length, with a maximum thickness of 120 m (100 ms TWT). The unit is characterized by low amplitude chaotic reflections and is expected to be characterized by high pelagic sedimentation within the minibasin (Fig. 7).

MTC (B): MTC (B) deposited on MTC (A) package in Mishan Formation. It has approximately 10 km long, with a maximum thickness of 90 m (80 ms TWT). The package is characterized undeformed blocks within the low amplitude chaotic mass (Fig. 7). It is presumed that MTC (B) was triggered by some sort of structural activity such as salt movement. The blocky features is interpreted in MTC (B), are gravity slides. They were transported with undeformed huge masses of sediments into deeper parts of basin.

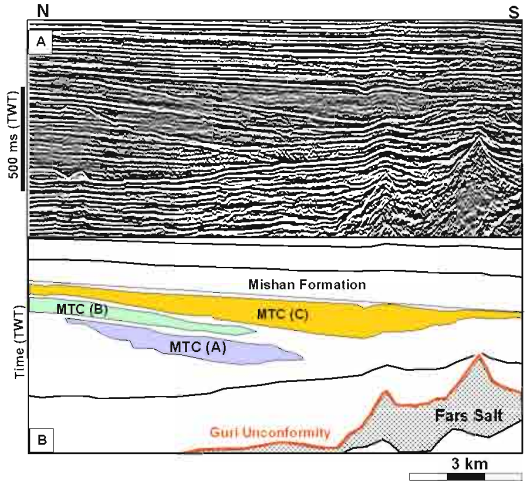

Fig. 7: (A) Uninterpreted and (B) interpreted seismic profile showing mapped seismic facieses (MTC A, B and C). Description is based on seismic reflectivity, event continuity and external geometry

MTC (C): MTC (C) is the latest of the mass transport packages. Its length is approximately 14 km, with a maximum thickness of 200 m (180 ms TWT). The deposit is characterized by variable amplitude chaotic reflections, a mounded external geometry and scoured base. The high amplitude of the basal shear surface corresponds to changes in acoustic impedance, which most likely corresponds to changes in lithology (Fig. 7).

A close examination of the unit suggests the deposit was formed by 2 different events. The first event is represented by undeformed, parallel and sub-parallel reflections and located on upper part of MTC (C), whereas the second event is characterized by chaotic, low amplitude reflection (Fig. 7A). The first event suggests it resulted from a low-sedimentation activity, which allowed only a short travel distance. And correspond to a simple salt movement or may be correspond to highstands of sea level that cause low sedimentation rates. The apparent nature the second event is presumed to have resulted from a longer travel distance that promoted a more intense reworking of the sediments.

We propose that as the high sediment supply resulted from increasing salt flow, or may as result of lowstands of sea level that cause high sedimentation

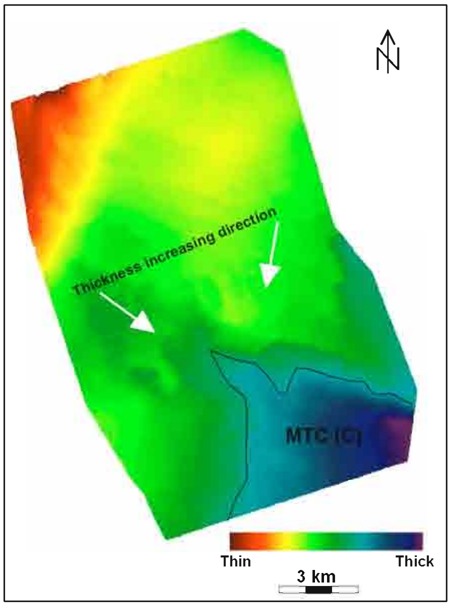

Fig. 8: Isochron map of MTC (C) package showing an overall lobate geometry that reflects the influence of topography on deposition.

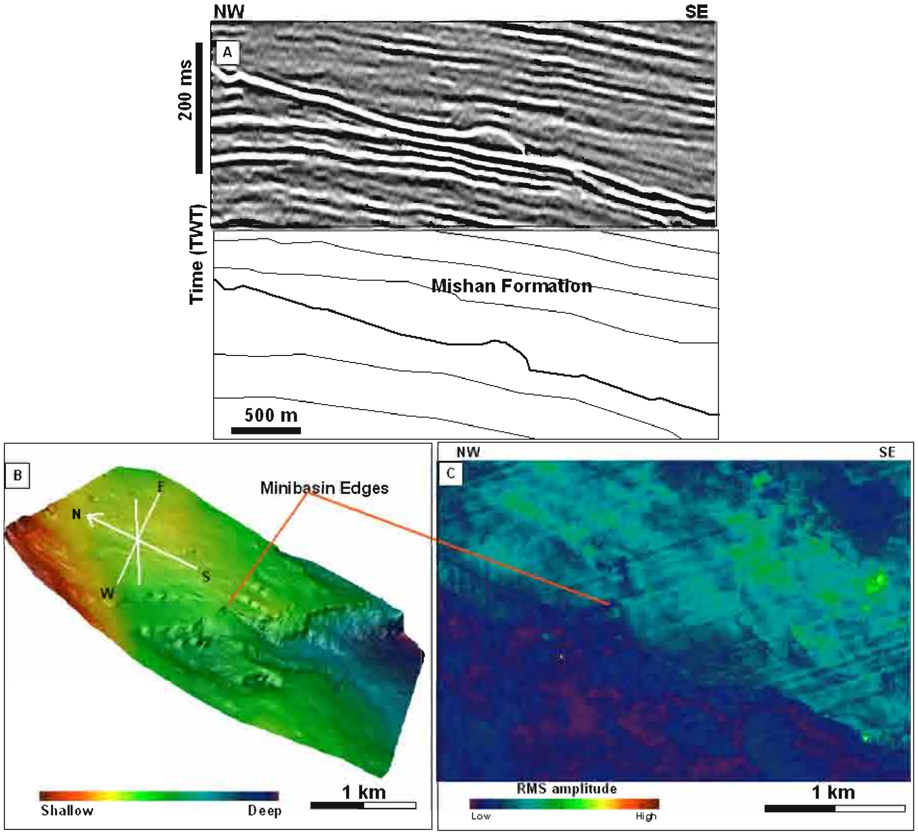

Fig. 9: (A) Uninterpreted and interpreted seismic profile displaying longitudinal section along minibasin edges to MTC (C), (B) Illumination map of local minibasin edges, (C) RMS amplitude map of local minibasin edges

rates. The isochron horizon map shows increasing thickness toward the southeast (Fig. 8).

In addition, we interpreted the line presented along RMS map in the (Fig. 9A) is minibasin edges in which sediments MTC (C) were gathered. It seems that this minibasin likely formed as result flow early Miocene Fars Salt and creating salt welds which led to make small local basins.

TYPES OF THE PREDOMINANT CHANNELS

Detecting channels is imperative in the petroleum industry due to the fact that the channels are major places of gathering the hydrocarbon due to high permeability. Moreover, the subtle study of submarine channels would provide important information of intensity and directions of turbidity currents, subsequently, the knowledge of geology history of region. Hence, the channels detection is a major aim for all of the explorers and searchers.

In the study area, three distinct channel types are distinguished on seismic sections at different depths. These types are grouped based upon their volume (channels (S), (M) and (L)) that were defined by v-shaped, linear depressions, suggesting either turbidity or debris flow/glide block origin (Fig. 10). The channels' linear to curvilinear geometry as shown by seismic attributes (RMS amplitude); however, the channels' fill channel (L) and associated overbank facies channel (M) are more typical of a turbidity origin. The linear geometry could be a reflection of the effect of prevailing depositional gradient on turbidity current. Alternatively, the channels may have been formed by glide block or debris flow action, later modified by turbidity low.

Channel type (S): Channel (S) is characterized by a small depression cutting into underlying strata. Channel (S) shows a curvilinear geometry in map view and is flanked by high amplitude deposits interpreted as sand-prone sediments (levees). This Channel can be interpreted as a channel-levee system based on the consistency of the sand-prone unit flanking the channel margin (Fig. 11), however, the channel on map-view suggests turbidity channel.

Channel type (M) and (L): On seismic sections, the types M and L are characterized by unusual V-shaped depressions (Fig. 10). Height of some these channels can be reach more than 85 m. They are characterized by straight to curvilinear geometry on map view (Fig. 12B). On seismic profile and map views, the channel (M) is characterized by High Amplitude Reflection (HAR) on the left flank of the channel margin (Fig. 12A).

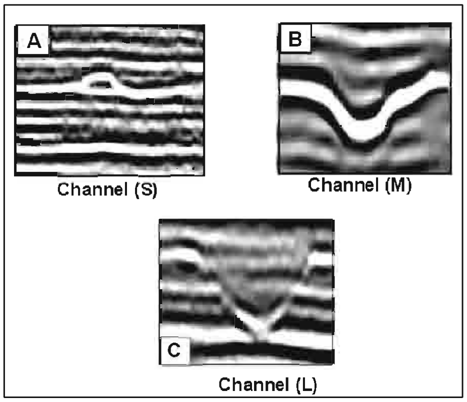

Fig. 10: Types of the predominant channels intra the Aghajari and Mishan Formations in the study area. Seismic section showing channel (L) filled with layered HAR seismic facieses

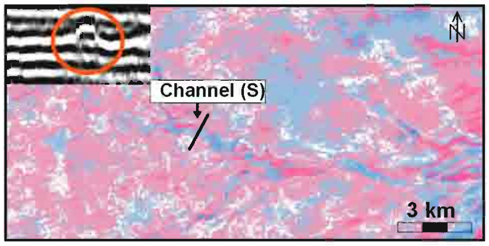

Fig. 11: Apparent polarity map showing the channel (S) within Aghajari Formation

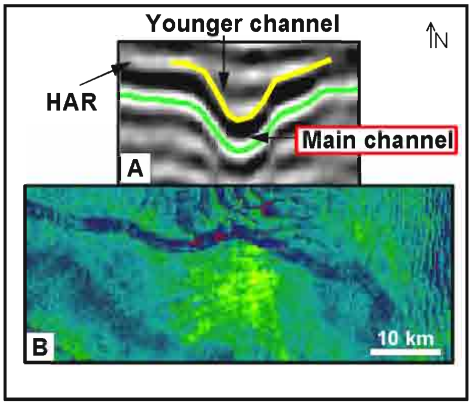

Fig. 12: (A) Seismic profile showing channel (M) type. (B) RMS amplitude map showing channel (M) within Mishan Formation

The restriction of the HAR to the left side of the channel margin could be due to earlier structural deformational events (salt flow) that changed the depositional gradient prior to erosion of the marginal sediments. It is seen the presence of a younger channel within the channel axis (Fig. 12A).

The channel (L) on seismic is characterized by a high amplitude channel fill (Fig. 10). A close observation of the seismic profile shows that the channel formed by other channels that merged in their paths. However, the presence of channels (M) and (L) in depositional system signify that the turbidity currents were vigorous and intense.

On the other hand, the whole channels (M) and (L) are seen within Mishan Formation which corresponded to climax of Cambrian Hormuz salt movement. Whereas, the majority of the channels (S) are seen within the Aghajari Formation sediments formed somewhat in quiet sedimentation circumstances.

CONCLUSIONS

The depositional systems mapped in the study area (Strait of Hormuz) reflect the influence of salt tectonism and sea-level changes on the transport and deposition of sediments. Our conclusions based on this study include the following:

- The sediments systems deposited during the different periods of sea-level change. Sea level changes may be linked to salt tectonic activities. For example, salt flow rate that was vigorous duration Mishan Formation sedimentation time. This led to deposition of turbidities and MTC in it. Indeed, MTC deposits (debris) have been seen in the Persian Gulf areas close to the study area associated with salt diapir (Zangard salt diapir in onshore area in northern west of the study area, for instance, raised increasing recycled Hormuz debris during the Mid-Miocene, suggesting higher rate salt growing during the Mid-Miocene (Jahani *et al*., 2007). It is generally noted that all MTC presented in Mishan Formation signify sediment high supply periods which correspond to low sea level. Whereas, scarcity of aforementioned deposits in Aghajari Formation signify sediment low supply periods corresponded to high sea level. Subsequently, it is inferred that the Mid-Late Miocene time was coeval with a change from semi-shallow marine sediments of the Mishan Formation to estuarine sediments of the Aghajari Formation.
- The isochron map of Mishan Formation in the study area shows increasing sediments thickness toward southeast and east. Consequently, transport directions were from diapirs sites basinward. This denotes tectonic activities in Mid-Miocene.
- The intrinsic properties of salt and overburden rocks (Mishan Formation), such as density contrast and initial thicknesses had an important role in the growth of salt bodies and creation of turbidity currents.
- Turbidity study in the Hormuz area presented a valuable way to determine past tectonic activities and climax periods of Hormuz salt movement that was in mid Miocene epoch.

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