The seismic evidence of passively evolving Messinian Salt in the Offshore Syria

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Abstract: Accurate interpretation and analysis of good quality 2D-seismic data has contributed to understanding evolution of salt diapirism in the Syrian Offshore located in the easternmost Mediterranean. Salt diapirs in the study area are mainly characterized by sub-annular shape structures resultant of flow and withdrawal of the Messinian Salt as passive diapirs during the Plio-Pleistocene-Recent times. Analysis and interpretation of seismic data in the Syrian Offshore indicates that the Messinian Salt diapirs have evolved and rose up passively by downbuilding during and after deposition of Plio-Pleistocene Formation and persisted to rise until the present time. The deposition and the compressional tectonic forces had a significant role in triggering Messinian Salt and creating the sub-annular shape structures. The accelerated deposition of the lower Plio-Pleistocene Formation created utmost subsidence of the Latakia Basin and passive diapirism of the Messinian Salt. Additional proofs in the Plio-Pleistocene sediments, such as thickness variations constrain the passive diapirism of the Syrian Offshore. This article offers models for the subsurface evolution of Messinian Salt diapirs in the study area based on analysis and interpretation of 2D-seismic data sets. The relevance between the evolution of Messinian Salt and deposition processes is also explained and an ideal evolutionary model offered as to their passive origins.

1 Introduction

The study area (Syrian Offshore) is located in the easternmost Mediterranean Region which is considered one of the most complicated regions in the world, being affected by differential motion along the boundaries of three major tectonic plates. The study area contains Messinian Salt deposits which has undergone widespread halokinesis since Plio-Pleistocene to a recent folding stage. Detailed interpretation of 2D-seismic data used to find out hydrocarbons, has been exploited to get insight and better understanding the growth and evolution of Messinian Salt, distribution and their deformation by the sedimentary processes and tectonic events. The good-quality 2D seismic data has been used to explain the structural image of study area and obtain a better comprehension of the tectonic evolution. And to make a model of the subsurface that can help identify the geological and depositional features.

In the study area, the 2D-seismic profiles show existence of the sub-annular shape salt diapirs disappeared beneath seabed are related to the Messinian Salt. Many of the salt-related shapes have been delineated in the Syrian Offshore (Fig.1). The sub-annular shape salt diapirs are significant structures due to their close association with oil and gas traps. A study of the geometry and emergence of diverse styles of salt diapir in the study area is significant and indispensable to get a better conception the oil reservation systems and for further oil exploration operations orientation. Salt diapirs originate by three main methods: active, reactive and passive [32]. A passive diapir (downbuilding) [6] grows while maintaining its crest or at near depositional surface while its base sinks. This method permits salt diapirs to grow without displacing the surrounding sediments. it continues to grow as the surrounding sediments continue to go down until salt source is exhausted [32 24, 17]. Most diapirs are triggered by tectonic events [18, 19, 31, 4]. The structural shape and manner of growth of particular diapirs pertain to sediment supply and basin subsidence rates adjacent to the diapirs [5, Hudic et al. 2009], as well as the regional tectonic system [11, 20]
Figure 1: Structural elements map of the eastern Mediterranean Basin displaying plate movement directions, and location of the study area (modified from Breman, 2006; 26, 7).

2 Geological-tectonic history

The easternmost Mediterranean Basin is structurally one of the most complicated regions in the world, being affected by differential motion along the boundaries of three major tectonic plates (figure1) [27, 2]. Plate-tectonic convergence between the African and Eurasian plates is thought to have begun during the Cenomanian Period (Pralle 1994) and continued into the Pliocene and Quaternary.

The initial closure of the Neo-Tethys Ocean due to plate-tectonic convergence came to an end during the late Maastrichtian and was accompanied by the emplacement of ophiolites [13, 14]. The initial closure of the Neo-Tethys corresponding to the present-time Eastern Mediterranean is represented by the southernmost external subduction zone, which marks the plate-tectonic boundary between the African and Eurasian plates. An ophiolite belt is observed along this boundary including the ophiolites of Baër-Bassit, Hatay.

A northward subduction of the African plate is considered to have begun south of Cyprus in the early Miocene [10, 27] followed by a very active period in the late Miocene with the collision of the northern portion of the Arabian plate with Eurasia, the closure of the Neotethyan Biltis Ocean and the westwards extrusion of Turkey to form the Anatolian plate. The boundaries between the various plates constitute the principal tectonic elements of the eastern Mediterranean region. These plate boundaries are the Anatolian Fault Zone, the Cyprean Arc, the Latakia Ridge and the Dead Sea Fault Zone (figure1). The African Plate subducts beneath the southern margin of the Anatolian Block. This collision occurs along a large approximately west-east trending arc complex consisting of, Cyprean Arc (subduction arcs), the west Latakia ridge (figure1).

The Levantine Basin occupies the northern part of the African Plate and is a remnant of the southern branch of the Neo-Tethys [30, 13].

Rifting and widespread volcanism Within the Levantine Basin continued into the early Cretaceous [8]. The associated marine regression led to widespread subaerial exposure of the shallow-water carbonate platform resulting in intense erosion.

The Late Miocene records a shift in the maximum stress direction from NW-SE to N-S corresponding to the initiation of the Dead Sea Transform fault system (Fig.1), which separates the Arabian Plate from the African Plate [1]. The aforementioned shift caused a change from a compressional regime to a sinistral strike-slip regime during the Pliocene to present along the African–Eurasian plate boundary [12, 16].

The Syrian Coastal chain, more than 1,500 m high, occupy most of the Syrian Onshore area west of the Dead Sea Transform fault system and Ghab Plain (Figs 1 & 2). An extensive karst terrain, a gently dipping western limb, and a chaotic, uplifted eastern limb where the oldest strata are exposed [8].
Figure 2: schematic geological section displaying the exposed geological formations (from Ghab Plain eastward to Mediterranean Sea to west) which were exposed to regional compressional tectonic events, led to uplift the region during the Late Paleogene time.

During the Messinian in the latest Miocene the whole of the Mediterranean was affected by a substantial fall in sea level [22, 23], and led to the sedimentation of salt layers.

3 Methodology

3.1 The Study area and database
The study area consists of three offshore basins. It is constrained to the east by the Syria coastlines and to the south by the Levantine Basin (figure 3). Its western and northern boundaries consist of the Eratosthenes Seamount and Cyprus and the Cyprus Arc, respectively. Its bathymetry reaches more than 2000 m in the central parts and shallows towards the margin (figure 3).

The 2D seismic dataset used in this study (figure 1) consists of 72 2D multichannel seismic profiles, acquired by CGG Veritas in 2005. The seismic data were recorded using a streamer with a total length of 7000 m and with 25 m group interval. They were carried out on a relatively dense grid of 4 x 4 km and on a denser grid 2 x 4 km in two certain areas, in the north and the middle. They cover a total area of approximately 9500 km², extending from the north, Turkey’s border, to the south, Lebanon’s border. The seismic profiles were carried out in NW-SE and NE-SW directions such that they are parallel and perpendicular to the main structural trends.

The 2D seismic data have been mainly used to obtain the sub-seabed geological structures, particularly below the Messinian Salt deposits. The quality and resolution of individual 2D seismic profiles varies considerably across the area analysed. Generally, those in the northern parts of the study area are of poorer quality than those in the central and southern parts, because of dense Messinian Salt diapirs beneath seabed. There are no drilled wells in the study area.

Figure 3: Time grid of the seabed in the study area showing the Syrian local offshore Basins and relief variation.

3.2 Identifying Messinian Salt deposits on seismic data of the study area
The occurrence of salt layers in the study area is established by the nature of the seismic reflection, interval velocity analysis, and drilled well data in Levantine Basin. Bear in mind that the determination of salt layers by seismic exploration is possible only when the thickness is more than tuning thickness. Thin layers are generally impossible to detect.

The seismic interpretation of the Messinian Salt deposits is primarily based on the definition of its top and base boundaries in the study area. The Messinian Salt form a distinctly-defined seismic stratigraphic unit confined by the Oligo-Miocene and Plio-Pleistocene siliclastic formations, based on well data in adjacent Levantine Basin [28]. It has been termed; the upper and lower boundaries of the Messinian Salt respectively, or Reflector (A) and Reflector (B) (figure 4).
Figure 4: identifying the boundaries of the Messinian Salt deposits in the study area (Reflectors A & B).

Reflector (A) is a strong positive reflector resulted due to the high acoustic impedance contrast at the contact between the Pliocene marine siliciclastic sediments and the top of the Messinian Salt deposits (figure 4). This Reflector is regionally persistent and almost most of the study area, although it appears to be distorted by a series of depressions and highs. The Messinian Salt varies in appearance on the seismic data, from seismically opaque to a layer with several strong internal reflectors, which would be normal for evaporites. The high velocities for this layer, calculated from the stacking velocities, also indicate that this layer is composed mainly of salt. Reflector (A) is overlain by seismic reflections of the Plio-Pleistocene sediments, displaying progradational patterns sediments (figure 5). These reflections that onlap Reflector (A) in the marginal area, and downlap it in the coastal area (figures 5 & 9). The basal part of the Plio-Pleistocene Formation appears to be deformed concordantly on Reflector (A).

Reflector (B) is a strong reflector generated by the relatively large negative acoustic impedance contrast at the contact between the Messinian Salt deposits and the underlying Oligo-Miocene marine siliciclastic sediments (figure 4). Therefore, Reflector (B) is defined only on the basis of the change in seismic attributes between the Messinian Salt and the underlying marine deep-water sediments. In southern part of study area, this Reflector generally dips southwestward, with a variable angle of 5-15°, as calculated on seismic sections perpendicular to its strike (figure 5).

The two reflectors (B) and (A) converge with each other towards the continental margins such that the Messinian Salt deposits thickness tapers in a wedge-like pattern (figures 5 & 9).
The Messinian Salt deposits sit down in north and south of the study area as indicated in figure 6. The isopach map of this salt has been generated by computing the time thickness of the seismic unit comprised between Reflectors (B and A) multiplied by Stacking velocity of Messinian Salt estimated 4000 m/sec. On this map, the isopach contours show a general thickening of the Messinian deposits towards the north and the northwest, to reach more 900 m. In the southern part of the study area, the Messinian Salt thickness regularly increases the southward (figure 6). This is taken to indicate a south and northward depositional thickening of the salt. The geometric relationship is suggestive of a pinch-out of the thick wedge of the Messinian Salt close to the position of the boundary. The regular variation in thickness and in seismic character observed east of this boundary suggests differences in the depositional and/or erosional processes in the two areas.
Figure 6: isopach Map of Messinian Salt displaying northward and northwestern thickening which reach more than 900 m, also displaying location of the sub-annular shape salt structures which appear as closed annular contours.

The distribution of Messinian Salt within the Levantine Basin of the study area is bordered to the west by the Latakia Ridge and to the east by an uneven edge, often fault related, marking an irregular limit on the eastern side of the basin. The thickness of the salt calculated near the centre of the basin is between 500 and 550 m, possibly reaching more than 600 m in some areas (figure 6).

In the central part of the study area, the entire Messinian Salt is absent (figure 6), probably due to later erosion in early Pliocene time, or salt withdrawal towards the Latakia and Levantine Basins result of the differential loading of the overburden.

Within the salt interval there are often sediment packages forming distinctive features within the otherwise opaque salt package. A similar feature is found at the base of the salt, bordering a fault zone (figure 7). These may be reefs or reefal sediments, formed during two or more stages. The most significant reefs are present on top of deeper fault zones, but on many successive lines a zone of reef-like features can be followed over many parallel lines, indicating that this is a coherent sedimentary feature, extending for several tens of kilometers.

Figure 7: seismic section showing reefs within the Messinian Salt.

The Messinian Salt in the Cyprean Basin is restricted to the southwestern part (figures 2& 6). The thickness of the salt is relatively thin, only a few hundred ms TWT or less than 300 m, thinning towards north, east and south, but thickening westwards.

Salt deposits in the Latakia Basin are extensive and cover most of the basin. The thickness increases towards the west to around 900 m due to a very high degree of diapirism. A fault-related depression in the northeastern part of the Latakia
The Latakia Basin has a thick of salt, more than 900 m. In the northeastern part of the Latakia Basin. The salt is strongly deformed and diapiric, forming dense finger-like diapiric structures which appear on the isopach map as closed circular contours (figure 6).

The diapirs are currently moving upwards, reflected in the undulations on the sea bed (figure 11(H)). Locally the top of the salt diapirs may be located only 200-300 m/sec below the sea bed.

The isochron map of top of the Messinian Salt, i.e. Reflector (A), generated on 2D seismic data is displayed in figure 7. This reflector exhibits an irregular geometry. A series of sub-annular shape structures and composite structural depressions are observed at this surface in the northern part of study area (figure 6).

![Isochron map of Plio-Pleistocene base showing variation of depth of Reflector (A) beneath seabed salt towards the north and the northwest, to reach more 900 m, also showing the sub-annular salt structures (the closed annular contours).](image)

The depressions observed in figure 8 are attributed to post-depositional deformation of Messinian Salt. In the eastern part of the study area, Messinian Salt pinches out at depth of 2200 to 2500 m/sec, where Reflectors (A) and (B) merge into a single positive high amplitude reflection (figures 5 & 9).
Figure 9: (A) uninterpreted and (B) interpreted seismic profile displaying thinning Messinian Salt (as indicated by arrows) with increasing Plio-Pleistocene sediments towards the continental or coastal margin.

At the bottom of the Messinian Salt, strong continuous reflectors may indicate siliciclastic sediments or limestones. Often a negative acoustic-impedance contrast appears at the contact between the salt and underlying sediments. The Salt deposits onlap pre-salt sediments. In some cases they overlie an erosional surface and are conformably overlain with marine transgressive series. The salty layers are the thickest in the northern part of the study area. The comparison between the different sections clearly shows that the vertical successions vary greatly.
3.4 Seismic stratigraphy of the Plio-Pleistocene Formation

Plio-Pleistocene Formation is bounded at the base by Reflector (A) and it is composed of a wedge of prograding and aggrading shelf to base-of-slope deposits, of Pliocene to recent age. This formation is composed mainly of sand in its basal part, and of hemipelagic turbiditic claystones, alternating with sandstones, siltstones and marls in its upper part (FreyMartinez et al., 2005). The reflections at the base of this Formation onlap and downlap against Reflector (A) in some parts of the study area. Whilst they are concordant to it in other parts.

The sediments thickness of the Plio-Pleistocene successions varies from less than 350 m along the continental margin and along the northwestern edge of Latakia Ridge to more than 2000 m in Latakia and Levantine Basins of the study area (figure 1). This formation contains plenty of channels (figure 10) with turbidities which is believed that were created by different factors such as salt tectonic and sea level variations.

![Figure 10: Seismic profile showing a marine channel within the Plio-Pleistocene Formation.](image)

The sea level variations have major effects on rate of sediment supply and type of sediment and subsequently affect on creation of 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.

Plio-Pleistocene Formation is extensively affected by deformation mainly observed at the continental margin and close to the pinch-out of Messinian Salt (figure 5).

3.5 Proof for passively salt evolution in the Syrian offshore

Structures of certain attention in the Syrian offshore are the asymmetrical to annular and sub-annular shape salt diapirs. These diapirs formed and flowed passively from, the Messinian Salt. Some the salt diapirs are not deep and lie about 250 m below the seabed, whilst others exist more deep about 400-500 m below seabed (figure 11 (H). These salt domes are isolated by set of minibasins.

3.6 Evolutionary model of the Messinian Salt diapirs

We have derived an ideal evolutionary model of passive salt growth in the study area having sub-annular shape structures, based on the evolution models, comprehensive analysis of structural features, and the relationship between salt diapirism and the deposition. We recognized six stages of salt tectonic evolution shown in figure 11.

(A) During the Late Paleogene and the early Neogene, the Syrian offshore and adjacent Coastal chain located west of the Dead Sea fault system were exposed to regional compressional tectonic events, caused to uplift the region (figure 11(A), and deformation, and folding sedimentary formations.

(B) After that, salt deposition took place during the Messinian in the latest Miocene time, the entire the eastern Mediterranean was affected by a fundamental subsidence in sea level [29, 23]. This was generated by an incorporation of tectonic uplift, combined with other factors, that caused a narrowing and closing of the connection between the
Mediterranean Sea and Atlantic Ocean. The lack of water combined with the high evaporation rates in the eastern Mediterranean basin resulted in a drop in sea level, and an increase in salinity, which led to the deposition of the Messinian Salt [9].

The huge thickness of the Messinian Salt in study area, proposes that the precipitation was in shallow water and the evaporation rate was greater than the rate of sea water recharge because of restricted connectivity between the Mediterranean basin and Atlantic Ocean and a widespread thick deposit of salt, the Messinian Salt deposits was deposited in separated minibasins (figure 11(B)).

(C) During early Pliocene time, the study area experienced a strong compressional tectonic event due to continental collision of Eurasia, Africa, and Arabian plates. This event led to the area uplift, causing the erosion of the higher parts, and formed a regional unconformity at top of the Messinian Salt deposits [25] (figure 11(C)).

(D) During Pliocene time, a regional shallow marine transgression covered the entire region with siliciclastic and mud forming the Pliocene sedimentary unit. Large quantities of these sediments were deposited on the Messinian Salt and accumulated in a series of wedges (figure 11(D)).

(E) During the early-to-mid Pleistocene, the entire easternmost Mediterranean including study area was severely deformed and accompanied by greatly rheomorphism in the Messinian Salt.

The Messinian Salt has flowed quickly after the deposition process under substantially thin overloads with subsequent downbuilding by clastic deposits, creating passive diapirs. The tops of these passive salt domes have continued close to the sedimentation level for the majority of their growth as the embracing salt was buried by gradual downbuilding of the overloads [4], (figure 11(E)). The high deposition rate, weight and compaction of the Pliocene sediments, played an important role in flow and forming the salt diapirs.

These salt domes that have created as sub-annular shapes (figure 9& 6) propose that the rate of vertical salt movement was fully as high as the rate of deposition in the rapidly falling neighboring minibasins [4, 17].

(F) The tectonic setting has been stable from late Pleistocene to Recent. The rate of vertical salt movement became much smaller than the deposition rate and for this reason, the salt diapir did not pierce the seabed. figure11 (F& H) indicates that the Messinian Salt diapirs grow and rise up near and beneath surface of the unconformity contemporaneously with deposition of the Plio-Pleistocene Formation in present time.
4 Discussion

We believe that the Messinian Salt diapirs in the study area rose up passively during and after deposition of the Pliocene-Pleistocene sediments. The accelerated continental collision of Eurasia, Africa, and Arabian plates[15] during the early Pleistocene, resulted in contemporary structural modulations along the Dead Sea fault axis. Along the northern Dead Sea fault, the Ghab Plain subsided continuously during the Plio-Pleistocene [8].

The Messinian Salt movement started in Pliocene-early Pleistocene time and has continued to the present time. This study, accomplished by accurate interpretation and analysis of the 2D seismic data, indicates that the Messinian Salt has persisted.
in growth by downbuilding of deposits into neighboring salt evacuation minibasins. Interpretation of seismic profiles in the study area shows large lateral thickness variations in the Plio-Pleistocene Formation covering the Messinian Salt. These layers are remarkably thickened westward and northwestward across the Syrian offshore area (Fig.6), as showed by a relatively large thicknesses of sediments of the Plio-Pleistocene Formation that covers the Messinian salt diapirs. These domes which have formed as sub-annular shape bodies propose that the rate of vertical salt growth was fully as high as the rate of deposition in the rapidly falling neighboring minibasins [4].

5 Conclusions
The interpretation of 2D- seismic data in the study area in the easternmost Mediterranean suggests that the Messinian Salt diapirs have evolved and rose up passively during and after deposition of Plio-Pleistocene Formation. The Messinian Salt rose up mainly during early-mid Pleistocene and continued to flow to present time. Interpretation of seismic profiles also indicates that downslope flow of salt occurred before significant deposition of Plio-Pleistocene sediments, thereby resulting in the redistribution of salt load and probable reactivation of faults.

The seismic reflection data has also contributed to the understanding of the deposition processes in the study area which is summarized as follows:

1. The active subsidence of the study area basins occurred during the Pliocene-Pleistocene, and continued slowly to the present time.
2) The aforementioned continental collision from the early Pliocene to mid Pleistocene is considered to have been an important event that influenced movement of the Messinian Salt. This event generated diapiric movement of the Messinian Salt leading to local uplift and the subsequent deposition of the Messinian Salt.
3) The base of the Plio-Pleistocene Formation is an unconformity surface that overlies the Messinian Salt representing the final closure of the Neo-Tethys Ocean.

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