



Investigating the Geological Fault Framework Offshore Lebanon: Insight into the Earthquake Geology of the Eastern Mediterranean Region

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Abstract—The tectonic setting of Lebanon in the eastern Mediterranean region is a restraining bend along the Dead Sea Transform Fault, which is the plate boundary between Arabia and Africa. Within the Lebanese Restraining Bend, the plate boundary splays into several fault branches that are mapped onshore Lebanon and known to have contributed to the evolution of the Lebanese structural framework. Different models have been proposed about the geological structures offshore Lebanon, and how those structures could relate to the onshore tectonics. Based on 2D seismic reflection data, a previously interpreted thrust fault system offshore Lebanon referred to as “Mount Lebanon thrust” was suggested to be responsible for the 9 July 551 M 7.2 earthquake, which was one of the most destructive in the history of the Levant. This thrust system has been accepted as the main structure behind the offshore seismic activity. The objective of this paper is to use current 3D seismic reflection data in order to interpret the main tectonic structures offshore Lebanon, and to differentiate features formed by tectonic activity from others caused by different mechanisms such as subsurface salt movement. Such information is very useful in understanding the tectonic framework of the region from the earthquake geology perspective. A bathymetric map of the Lebanese offshore area was generated and used to delineate the seafloor features. Major and minor faults were interpreted and used to identify and understand the behavior of potential tsunami-generating structures. After careful investigation of the offshore area using the available 3D seismic data, the authors were not able to confirm the existence of Mount Lebanon thrust. Instead, they propose that the Latakia ridge that lies between Lebanon and Cyprus is a major and prominent structure that can trigger high-magnitude tsunamigenic earthquakes.

Keywords: Dead Sea transform fault, Lebanese restraining bend, Levant basin, Latakia ridge, Seismic interpretation, Lebanon.

1. Introduction

This paper aims to understand the geologic and tectonic framework offshore Lebanon in the northern Levant basin and along its continental margin next to an active transform plate boundary that is the Dead Sea Transform Fault (DSTF) (Fig. 1). In effect, it is very important to investigate the earthquake geology of this region that was hit by several large and destructive earthquakes throughout history, some of which are thought to have originated offshore along a thrust system that accommodates some of the plate motion away from the Lebanese Restraining Bend (LRB). This thrust system has been suggested to explain the tectonics of the Levant basin offshore of the LRB, the tectonic interactions between the offshore and onshore structures, and the role those structures have on the development of the overall Lebanese physiography (i.e. continental margin, coastal area, mountain ranges) (e.g. Ben-Avraham et al., 2006; Butler et al., 1998; Daeron et al., 2007; Elias et al., 2007; Schattner et al., 2006).

The investigation was done by performing 3D seismic interpretation of the major and minor faults offshore Lebanon, which helped to examine the cause of the seafloor morphology along the margin and in the basin, and to locate and investigate the potential tsunami-generating structures. In effect, major active faults may show offsets in the stratigraphic units and reach the seafloor, which can be reflected in the bathymetry. Examples of continental transform faults affecting nearby continental margins exist, though not very common (e.g. Adams, 1984; Holbrook et al., 1996; Norris & Toy, 2014), and understanding the transform fault/margin interrelation provides a lot of

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value to understanding the tectonics of such environments.

One of the largest earthquakes that happened in Lebanese history was the 9 July 551 earthquake that caused a tsunami along the Lebanese coast (e.g. Sbeinati et al., 2005). This earthquake of magnitude 7.2 destroyed Beirut and has been associated with offshore structures (e.g. Darawcheh et al., 2000; Elias et al., 2007). A reassessment of the previously proposed active structures in the offshore area was performed for a better understanding of the overall tectonic framework of the region. The findings put more weight on the Latakia ridge as a major seafloor structure located in the northwestern part of the Lebanese offshore area (Fig. 1). In fact, it is an intriguing fault-related feature that is examined in this paper and is prone to generate large tsunamigenic earthquakes.

2. Tectonic Setting

The Levant basin is bordered by the Latakia ridge to the north, the eastern Mediterranean coast to the east, the Nile Delta to the south, and Eratosthenes seamount to the west (Ghalayini et al., 2016; Fig. 1). It was developed by a series of rifting in the Permian, followed by compression in the Cenozoic and uplifting events until the Miocene. This resulted in extensional structures such as normal faults that in turn were affected by the compressive stresses leading to inversion and folding (Ghalayini & Eid, 2020).

The study area is located offshore of a complex, active tectonic region dominated by the transpressive regime of the LRB (Figs. 1 and 2). This bend is about 170 km long and constitutes the rightward bending of the DSTF that extends from the Red Sea to south-eastern Türkiye along a general N-S trend (e.g. Nemer, 2023; Nemer & Meghraoui, 2020). The DSTF has affected the Levant basin margin and onshore area, with potential effect in the offshore, but less effect in the deep basin (Carton et al., 2009; Nader et al., 2018).

The LRB has resulted in the formation of Mount Lebanon and Anti-Lebanon ranges, and it is thought to have initiated its transpressional regime about 10–15 million years ago (Carton et al., 2009; Fig. 2).

Figure 1

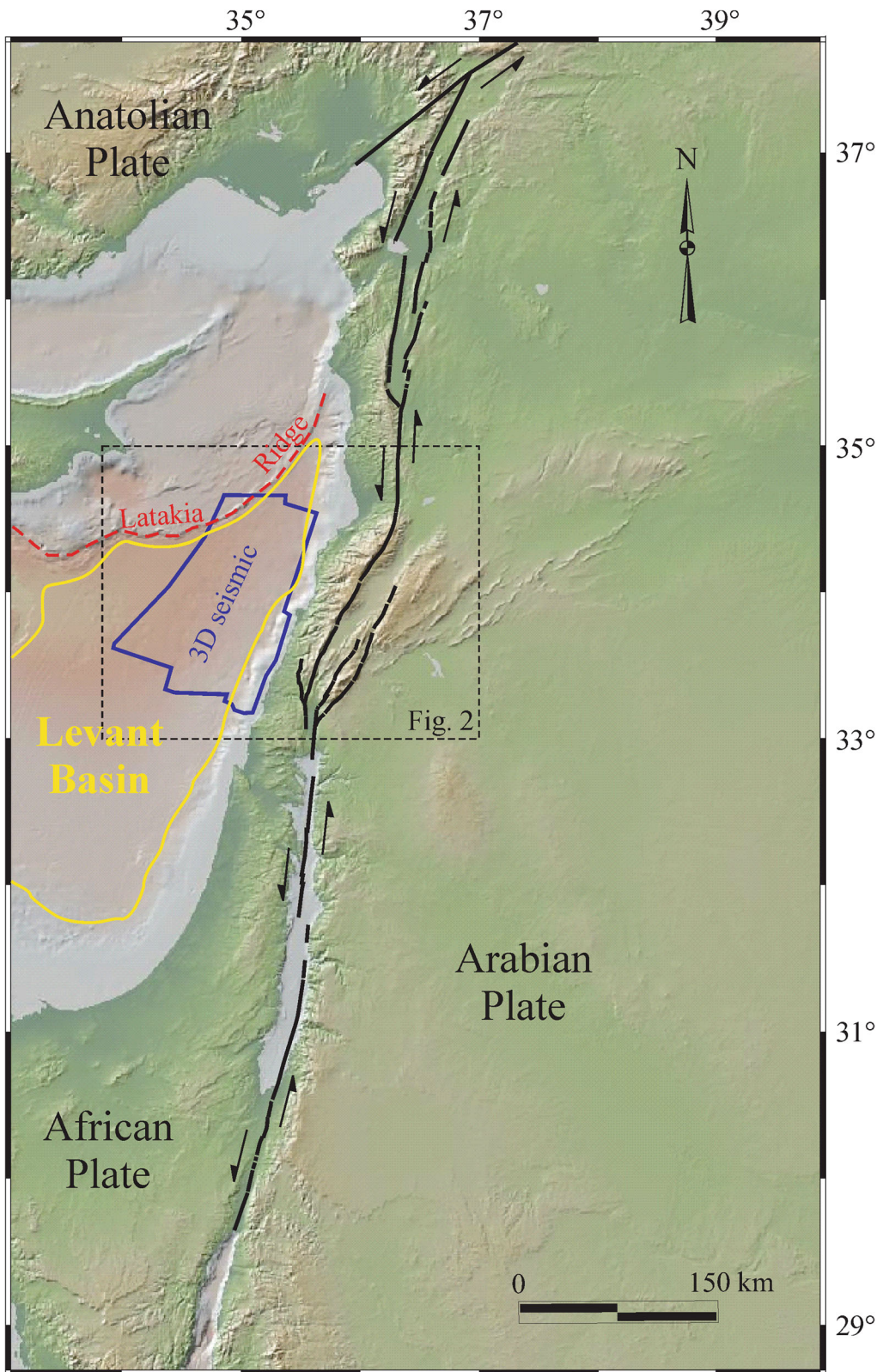
Regional map of the eastern Mediterranean area showing: Arabian, African, and Anatolian plates; Dead Sea Transform Fault (black fault lines); Lebanese Restraining Bend and study area (inside dashed black frame); Latakia ridge (dashed red); Levant basin (yellow); 3D seismic volume of this study (dark blue). Background topography is from <https://www.geomapapp.org>

A series of strike-slip faults branches from the DSTF within the LRB: the main Yammouneh fault, the Roum, the Rachaya, and the Serghaya faults (Nemer & Meghraoui, 2006; Nemer et al., 2008a and b; Nemer & Meghraoui, 2020; Nemer, 2023; Nemer et al., 2023; Fig. 2). The Yammouneh fault may have led to the initiation of smaller scale EW faulting near the Lebanese margin by breaking the onshore Lebanese crust into several small blocks. In addition, the sinistral movement along the Yammouneh fault has led to the rotation of those blocks that is accommodated by dextral strike-slip movements along the EW faults (Ben-Avraham et al., 2006; Ghalayini et al., 2014; Goren et al., 2015; Schattner et al., 2006).

The Lebanese offshore area across the Levant basin has other structures that have been interpreted on 2D and 3D seismic reflection data. These structures that formed in response to the overall tectonic stress regime include normal, strike-slip, reverse, and transpressive/transpressive faults (e.g. Ben-Avraham et al., 2006; Ghalayini et al., 2014; Hall et al., 2005; Schattner et al., 2006; Wdowinski et al., 2006; Fig. 2).

2.1. Faults of Saida-Tyre Plateau

The Saida-Tyre plateau (STP) is located in the south of the Lebanese offshore area. This plateau resembles a 200 km² mound of about 6 km-thick pre-Cenozoic sediments (Ghalayini et al., 2014) under which a relatively thick continental crust is present (Nader et al., 2018). A deep-rooted vertical fault (F1; Fig. 2) marks the northern part of this plateau and appears to offset the whole sedimentary section by about 2 km (Ghalayini et al., 2014; their Fig. 4). This fault and other faults to the west of the STP seem to have initiated due to extensional forces and then were reactivated into strike-slip movements after the Mesozoic period (Ghalayini et al., 2018). As to the mound shape, it is believed that reefs grew in the



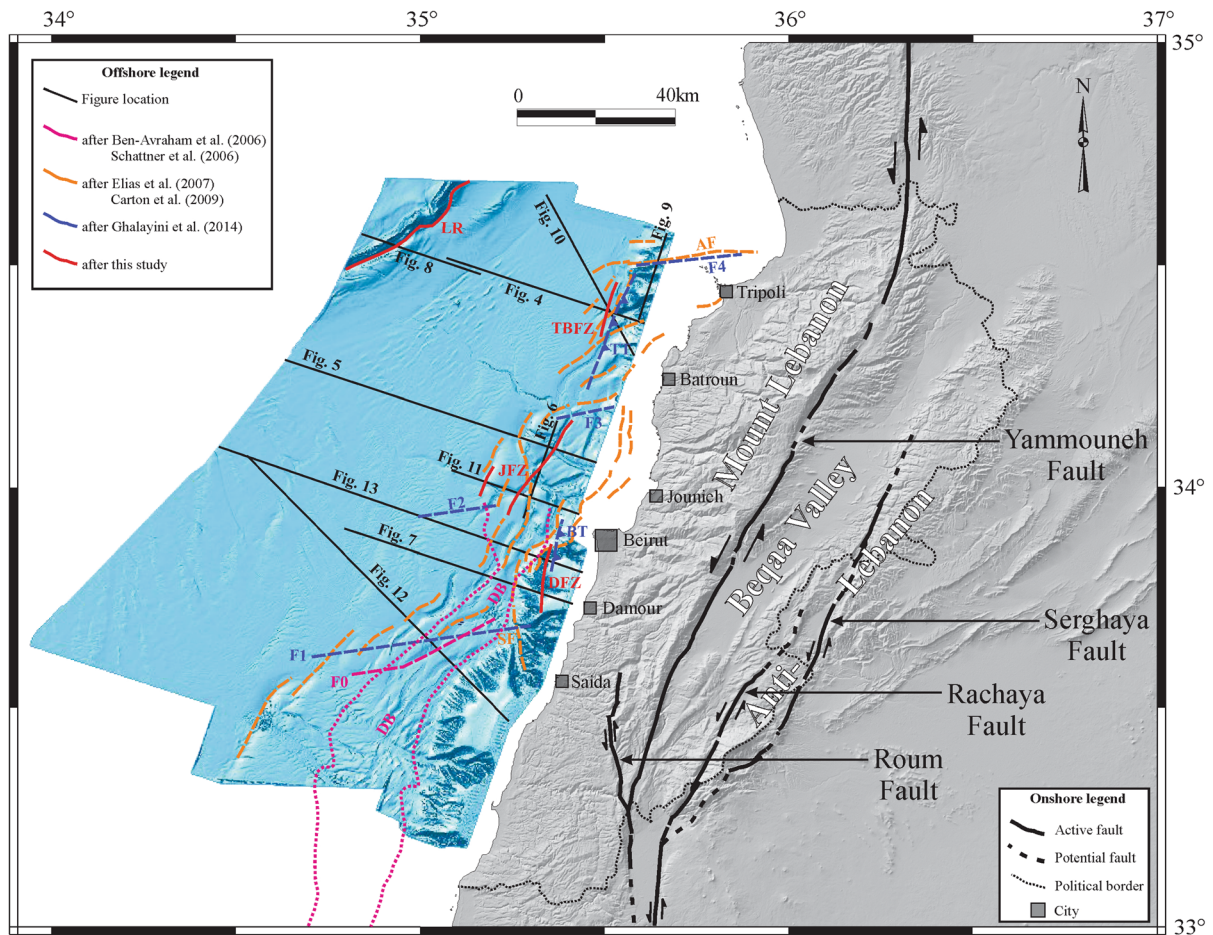


Figure 2

Right (onshore): DEM (SRTM 90 m) of the Lebanese Restraining Bend with the main physiographic units and faults. Left (offshore): monochromatic bathymetric map of the study area generated from the 3D seismic data, with figure locations and structures of this and previous studies (by color). *AF* Aabde fault, *BT* Beirut thrust, *DB* deformation belt, *DFZ* Damour fault zone, *F#* fault mentioned in text, *JFZ* Jounieh fault zone, *LR* Latakia ridge, *SF* Saïda fault, *TBFZ* Tripoli-Batroun fault zone, *TT* Tripoli thrust. Location in Fig. 1

Cretaceous period and developed massive platforms in shallow marine environments, which could explain the mound shape of the sedimentary package of the STP (Nader et al., 2018).

2.2. Normal Faults

The deep Levant basin is characterized by a range of NW–SE high-angle normal faults dipping NE or SW (Ghalayini et al., 2014). These evenly spread faults are also called “layer-bound faults” as they are bounded by the Eocene layers and the Messinian salt (Ghalayini et al., 2016). It is believed that these faults

have initiated at the beginning or during the deposition of the Miocene salt layer. In addition, these faults are dominant where a thick layer of salt is present, and they decrease in number in the southern Levant basin to become absent along the margin (Ghalayini et al., 2014). Kosi et al. (2012) suggested these faults to be “piano key faults” where they form a series of horsts and grabens that develop an enechelon array in map view. However, other studies suggest that “piano key faults” may not be the case for those faults as they have different dip directions (e.g. Ghalayini et al., 2018).

2.3. ENE-WSW Strike-Slip Faults

There exist five main strike-slip faults in the Levant basin offshore Lebanon that have been mapped (Fig. 2), all of which are considered to be steep to vertical (Ben-Avraham et al., 2006; Ghalayini et al., 2014). F0 is the Damour fault that was mapped by Ben-Avraham et al. (2006) offshore Damour as a dextral strike-slip fault at the base of the continental slope. F1, F2, F3, and F4 were mapped by Ghalayini et al. (2014). F1 is the fault mentioned in Sect. 2.1 that is approximately 50 km long. F2 is located in the deep basin facing Beirut and is about 25 km long (their Fig. 4). F3 is located closer to the margin near Batroun, it is about 15 km long, and it seems to offset several stratigraphic units (their Fig. 10). F4 faces Tripoli and cuts through the Cretaceous units up to reach the seafloor; it displays some dip-slip component as well (their Fig. 11). For this reason, F4 is assumed to be currently active, whereas F2 and F3 were described as active during the Miocene and the Oligocene, respectively, and F1 was active before the Messinian (Ghalayini et al., 2014). F0 displaces Plio-Pleistocene sedimentary layers, reaches the seafloor, and could be related to salt tectonics (Ben-Avraham et al., 2006). Other strike-slip faults also exist on the Levant margin and are thought to be linked to older offshore structures (Ghalayini et al., 2014).

2.4. Reverse Faults

Elias et al. (2007) presented geophysical data acquired in 2003 by the Shalimar survey offshore Lebanon. They proposed the presence of active thrust faults “with a complex geometry”. They also suggested that “range-front ramps reach the seafloor at the base of the continental slope between Saida and Tripoli” (Fig. 2), and that Plio-Quaternary deposits are folded above blind thrusts. They called the proposed thrust system “Mount Lebanon thrust” (MLT) (the same as the “Tripoli-Roum thrust” in Daeron et al. (2004)) and suggested that, together with other onshore structures, it has caused the Plio-Quaternary development of Mount Lebanon (Elias et al., 2007).

Carton et al. (2009) also used the Shalimar data and indicated the presence of a 90 km × 30 km fold-and-thrust belt offshore Lebanon that is bounded by “lateral ramps”: the Aabde fault in the north, and a left-stepping branch of the Roum fault in the south (Fig. 2; their Fig. 18). They mentioned that most of the thrusts are blind, with some faults reaching the seafloor. South of the aforementioned fold-and-thrust belt, they noted a domain that was not affected by much compression. However, they observed deep and shallow folding that they attributed to a fault zone, which they called the “South Lebanon thrust” (Carton et al., 2009).

Ghalayini et al. (2014) mapped two thrust faults offshore Lebanon: the “Beirut thrust” and the “Tripoli thrust” (Fig. 2; their Fig. 4). Both faults were suggested to be inactive based on their Fig. correlation with their surrounding stratigraphy.

2.5. Transpressional/Transtensional Faults

Schattner et al. (2006) proposed the presence of a fault zone that extends northward from offshore the Carmel structure up to Beirut (Fig. 2; their Fig. 5) along the Lebanese continental slope. This fault zone was suggested to cause the uplift of the Lebanese continental margin relative to the Levant basin along “deep-rooted faults” that result in the formation of elongated folds by transpressional movements (Schattner et al., 2006). Hall et al. (2005) used 2D seismic reflection sections to describe the structural architecture of the Cyprus arc. They determined that two phases of deformation characterize the structural history of the deformation front, with each phase representing a different deformation system: compression during the Miocene, and strike-slip in the Plio-Quaternary (Hall et al., 2005). Klimke and Ehrhardt (2014) used 2D seismic data to the south of Cyprus and inferred that a collision front is located north of the Hecataeus rise and continues along the Latakia ridge (their Fig. 14). Gunes et al. (2018) suggested the occurrence of “regionally extensive fold-thrust belts” along the Cyprus arc during the pre-Messinian, whereby compression gave way and got replaced by transtension and transpression from the Messinian onward (their Fig. 22).

3. Data and Methodology

To attain the objectives of this study, the authors used a large set of 3D seismic reflection data (in the time domain) owned by the Lebanese Ministry of Energy and Water. The data consists of a mega-merged seismic volume that combines multiple surveys from multiple service companies acquired and processed differently over several years. This, however, has resulted in the unavailability of the seismic data parameters that are otherwise found in a typical seismic report. The interpretation of the 3D seismic data was done using Petrel 2016.

A bathymetric map was generated from the seismic data with a grid increment of 50 m × 50 m. It shows all the seafloor features that are interesting to understand (Figs. 2 and 3). In addition, faults were interpreted and separated into minor and major faults. The fault interpretation helped to delineate the major structures that affect the tectonics of the region, and the minor faults were vital to understand the overall geological fault framework. A reassessment of the previous work was done by comparing the previously interpreted seismic data with seismic interpretation of the same structures using the current 3D data.

4. Seafloor Features

The bathymetric map reveals lots of features that disrupt the seafloor (Figs. 2 and 3). The analysis of these features is essential to check whether they have been caused by tectonic activities. Such distinct features have led to the division of the Lebanese offshore area into three different regions.

Region 1 includes the whole Lebanese margin (northern, central, and southern) where most of the features and rugged bathymetry exist (Fig. 3). In the northern margin, a topographic high exists (TH1), and it is crosscut by deep eroding channels. In the central margin, features with polygonal morphologies dominate the region. Numbered from 1 to 7, those polygons are shown as morphological highs in map view (Fig. 3). They are bounded by channels and canyons that seem to be related to the presence of the rivers along the Lebanese margin (Ghalayini & Eid, 2020). A clear example of this is where the

bathymetry shows two major canyon branches (Ch1 and Ch2) that form from small channels originating at the margin; these channels converge afterward and extend into the deep basin through canyons (Fig. 3). In the southern margin, another big topographic high exists (TH2). It is excessively worn away along its western flank which marks deep v-shaped channels in map view. To its northwest, elongated lens-shaped features are abundantly exposed (L1–L4 in Fig. 3). They form as depressions parallel to the margin along a NE-SW direction.

Region 2 includes the northwestern part of the study area where a part of the Latakia ridge exists as a major structure and a clear disruption in the seafloor (TH3 in Fig. 3). Region 3 covers the remaining part of the study area. It is characterized by a smooth topography with few disruptions but no distinct features (Fig. 3).

5. Seismic Data

5.1. Minor Faults

Minor faults are small, shallow faults that are affected by the tectonic stresses of the area in which they are present. They can be reverse, normal, or strike-slip. However, these faults do not interfere with or influence the activity of other deeper faults or structures. Also, these faults can trigger only small-magnitude earthquakes (USGS, 2015). In the study area, most of the minor normal faults are present in Regions 1 and 2. Their number is reduced in Region 3.

5.2. Major Faults

By major faults the authors refer to the deep faults that may extend up to the surface, reach the seafloor, or cause the formation of structures that affect the seafloor. They disrupt different stratigraphic layers and displace them. This type of faults can trigger relatively large earthquakes. For this reason, major faults are considered essential for studying and interpreting the structures that can potentially cause large earthquakes and generate tsunamis. In the study area, the major faults exist in Regions 1 and 2.

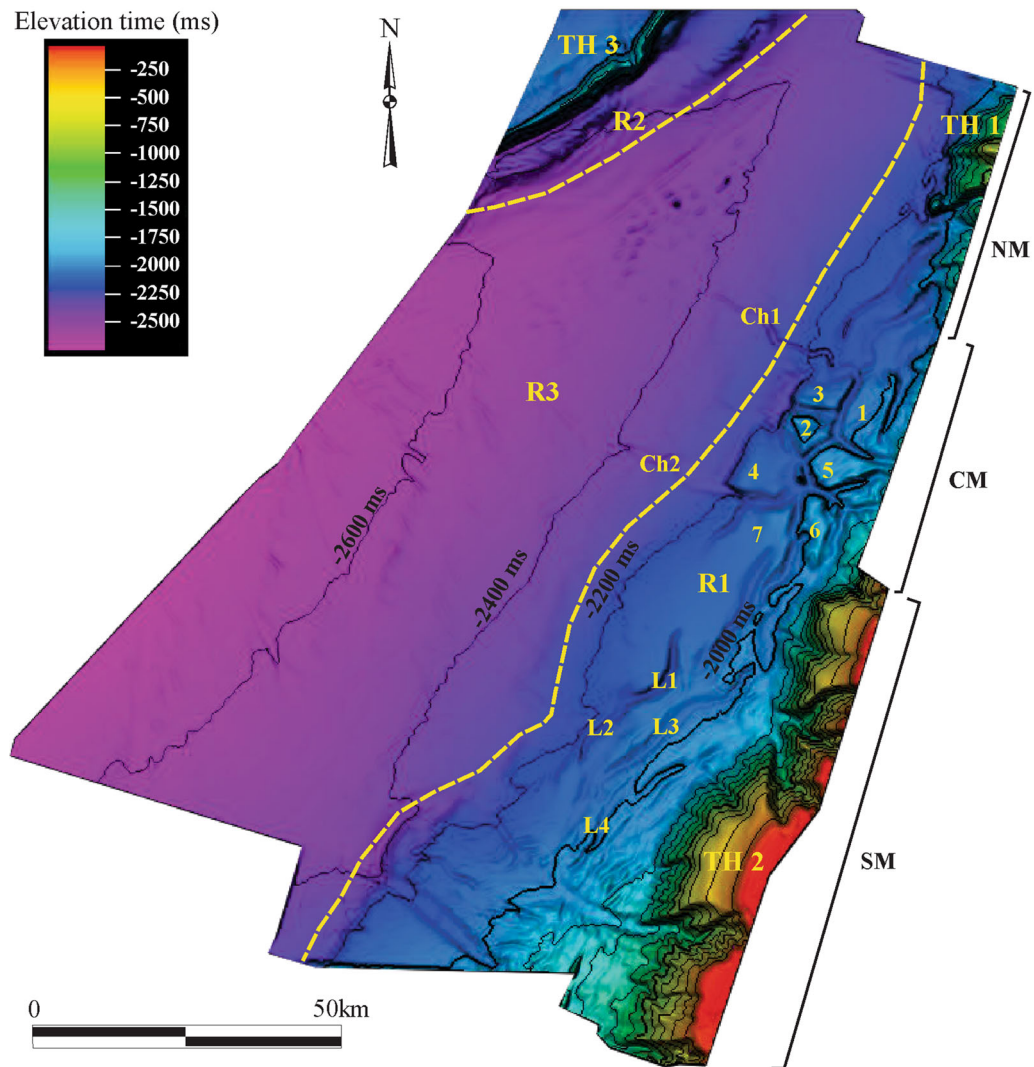


Figure 3

Color-scaled bathymetric map of the study area (Fig. 2-left) generated from the 3D seismic data showing the regions and features discussed in the text. *Ch#* channel, *CM* central margin, *L#* lens-shaped feature, *NM* northern margin, *R#* Region, *SM* southern margin, *TH #* topographic high, 1–7 morphological highs. Contour interval is 200 ms. Dashed yellow lines separate regions

5.3. Results and Discussion

5.3.1 Region 1

In the northern margin, the seismic data show an antiformal structure that reaches the seafloor in the east (Fig. 4). This structure seems to be caused by a transpressional structure that has uplifted the layers adjacent to the margin as a positive flower structure (Ben-Avraham et al., 2006). The authors call it the

Tripoli-Batroun fault zone and it may be considered a recent structure for the following reasons (Fig. 4):

1. The difference in the base-of-salt regional level of about 900 ms across the structure indicates that it is a post-salt structure.
2. The change in thickness of the topmost layers from ~ 500 ms in the west to ~ 800 ms at the western flank of the structure implies that the latter has formed during the deposition of these recent layers, hence, it is a recent structure.

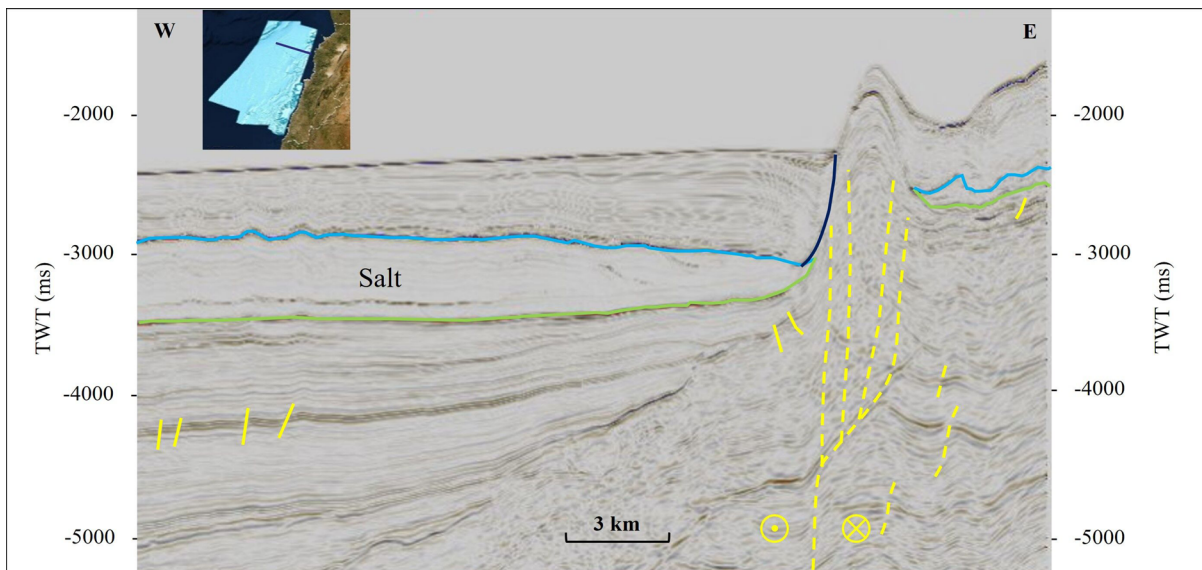


Figure 4

2D seismic section of the 3D data from the northern margin showing the salt layer being offset across the Tripoli-Batroun transpressive fault zone (dashed yellow) under a topographic high that reaches the seafloor. Yellow faults originate in the pre-salt layers. Sinistral strike-slip movement is in accordance with onshore tectonics. Dark blue fault affects the post-salt layers. Transpression is concentrated along the margin. Location in inset and in Fig. 2

3. A non-active structure should be less protruding and more covered by continuous sedimentation.

A growth fault (GF) seems to exist where the stratigraphy thickens near the antiform (Fig. 4). The presence of the growth fault close to a major transpressional fault should have been preceded by compression and the formation of the antiform, and then it got initiated by the presence of the salt layer that started to evacuate under the gravitational loading of sediments at the western flank of the antiform. As a result, the syn-deposition of sediments occurred at the hanging wall of the growth fault. The Tripoli-Batroun fault zone is a major structure, but it is limited in extent as it dies out southward to the west of Batroun (Fig. 2).

In the central margin, a major fault zone is observed west of Jounieh. The authors call it the Jounieh fault zone, it is limited in extent along its strike and displays a geometry that also matches a transpressional regime (Fig. 5). In the central margin, several events seemed to have occurred successively, which affected the tectonics of the area, and hence the formation of the offshore morphological highs.

Before the deposition of the salt layer, compressional forces were predominant. Afterward, the salt layer got deposited. Extension then took place leading to the thinning of the post-salt overburden in places, which in turn caused differential loading above the salt. This has led to the initiation of simultaneous normal faulting in the post-salt layer and reactive diapirism of the salt itself, which led to the forming of horsts and grabens that are revealed as highs and lows along the seafloor, respectively (Figs. 3 and 6). To be noted that the localization of the transpressional structures along the margin and the presence of the salt layer have played a major role in decoupling the faulting behavior in the pre- and post-salt layers, as well as along the margin.

In the southern margin, another major fault zone appears west of Damour (Fig. 7). The authors call it the Damour fault zone. It caused an uplift at the margin of about 1500 ms (Fig. 7), and its behavior seems to be in accordance with the transpressional fault zones that lie further north (i.e. the Tripoli-Batroun, and Jounieh fault zones), with a wider flower structure that seems to affect the onshore area to the east of the coverage of the seismic data. To be

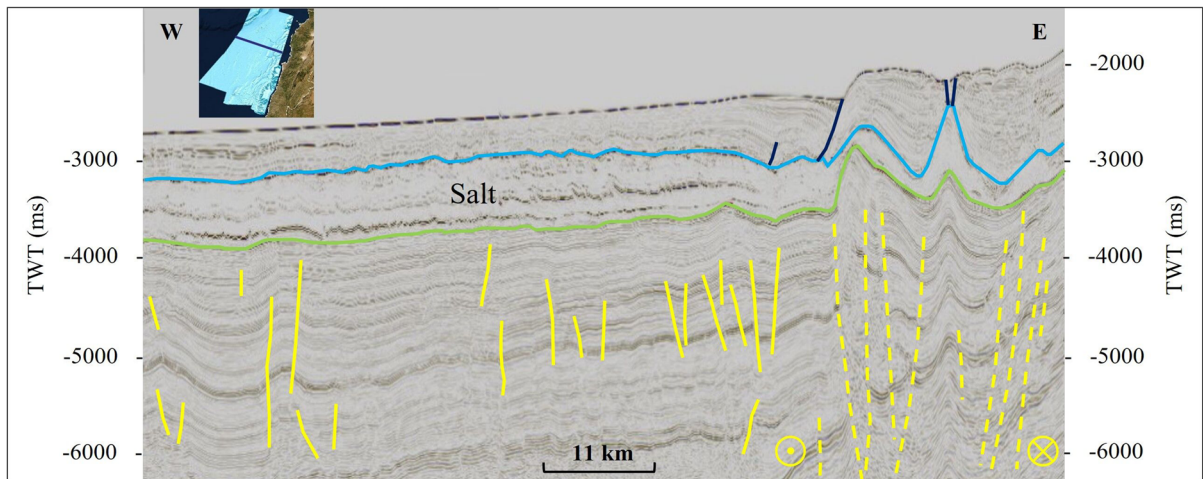


Figure 5

2D seismic section of the 3D data from the central margin showing the salt layer being affected by the Jounieh fault zone (dashed yellow). Yellow faults originate in the pre-salt layers. Sinistral strike-slip movement is in accordance with onshore tectonics. Dark blue faults affect the post-salt layers. Seafloor morphology is related to salt movement rather than to major tectonic faulting reaching the seafloor. The “antiforms” within the fault zone lie under salt highs and are due to velocity pull-up effects. Transpression is concentrated along the margin. Location in inset and in Fig. 2

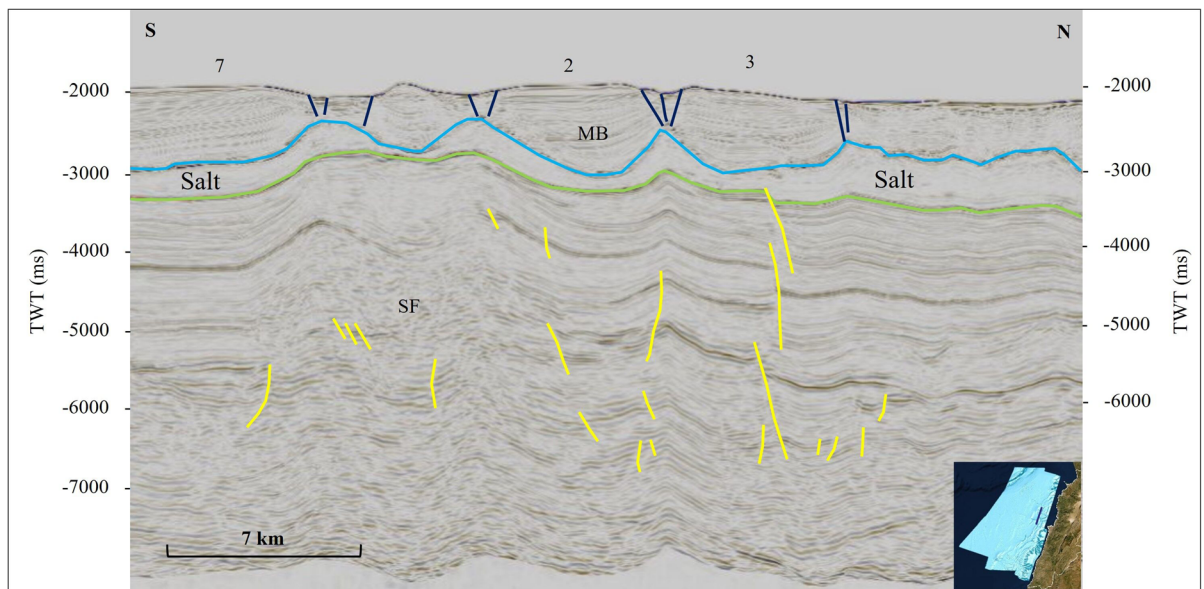


Figure 6

2D seismic section of the 3D data from the central margin showing the morphological highs along the seafloor (2, 3, and 7; cf. Figure 3), and salt changing thickness under differential overlying deposition. Yellow faults originate in the pre-salt layers. Dark blue faults affect the post-salt layers. Note the normal faults in the post-salt layer above the salt highs implying reactive diapirism, and the “antiforms” under the salt highs due to velocity pull-up effects. *MB* minibasin, *SF* seismic signal fading. Location in inset and in Fig. 2

noted that all the faults’ offsets are estimated by taking the regional level of the base of salt or the overall trend of salt across the faults. The v-shaped

valleys that are present on the southern and northern flanks of TH2 and exposed on the bathymetric map represent erosional features (Fig. 3). These are

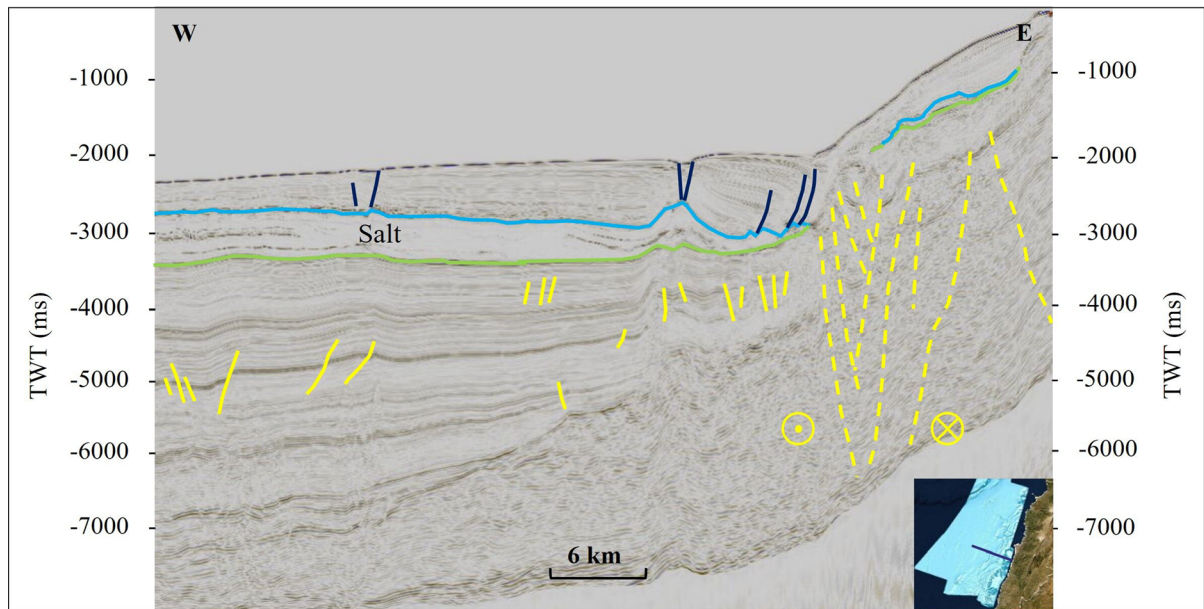


Figure 7

2D seismic section of the 3D data from the southern margin showing the salt layer changing thickness and uplifted across the Damour fault zone (dashed yellow). Yellow faults originate in the pre-salt layers. Sinistral strike-slip movement is in accordance with onshore tectonics. Dark blue faults affect the post-salt layers. Note the normal faults in the post-salt layers due to salt movement. The “antiform” under the salt high in the middle is due to velocity pull-up effect. Seafloor morphology is caused by tectonic uplift and salt evacuation under its overburden as shown at the slope break. Transpression is concentrated along the margin. Location in inset and in Fig. 2

probably caused by the underwater flow of margin rivers across the coast, which has formed this “marginal fan” feature. The seismic data reveal that the lens-shaped features to the west of TH2 are formed due to extensional forces affecting the post-salt layers. In addition, reactive diapirism exists in this region, and normal faults have formed grabens that mark the lows of the lens-shaped features on the seafloor (Sarieddine, 2022).

Although the central and southern margins are both affected by reactive diapirism, different features are observed (i.e. morphological highs in the former and lens-shaped features in the latter). This may be due to the stage of development of the salt evacuation in each. Salt diapirs are more developed in the central margin (Fig. 6), and that’s why the morphological highs are more prominent in there (Fig. 3).

5.3.2 Region 2

The seismic data of Region 2 display a prominent uplift with a vertical offset of about 1000 ms that is

caused by deep faulting (Fig. 8). Compressional faulting dominated the region in the Miocene (e.g. Gunes et al., 2018; Sect. 2.5), and the high topographic feature of this region (TH3 or Latakia ridge, Fig. 3) seems to have been highly affected by that faulting. Moreover, the Latakia ridge appears to be active as current transtensional faults (e.g. Gunes et al., 2018; Hall et al., 2005; Schattner et al., 2006; Wdowski et al., 2006) reach the topmost layer that is being deposited, and they disrupt the seafloor (Fig. 8). The authors underline that along the strike of the ridge, transtension alternates with transpression depending on the geometrical variation of the strike-slip movement along the trend of the structure.

The faulting that has controlled the Latakia ridge can be considered major in both the compressional phase and the current strike-slip phase. And given that this ridge is active and constitutes a very prominent feature of the seafloor that extends for a couple of hundred of kilometers, it is the most intriguing structure in the Lebanese offshore area (Fig. 1). In addition, the presence of transtensional

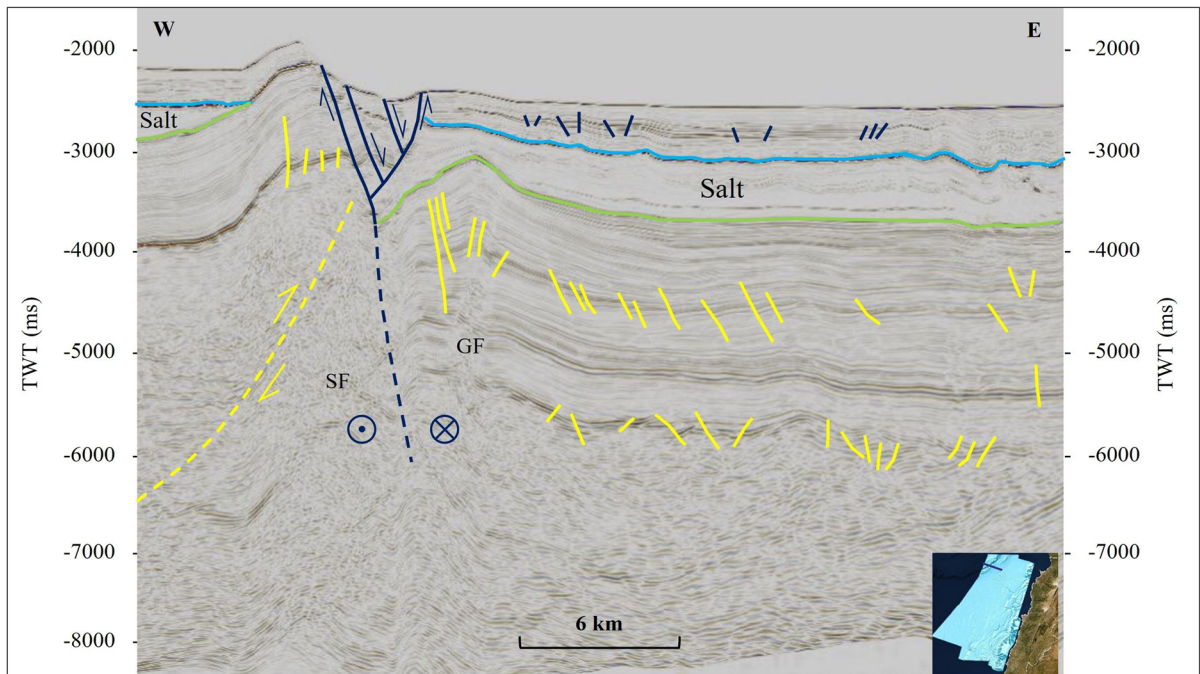


Figure 8

2D seismic section of the 3D data across the Latakia ridge showing a composite structure of old reverse faulting (dashed yellow) and newer transtensional faulting. Yellow faults originate in the pre-salt layers. Dark blue faults affect the post-salt layers and the negative flower structure. Sinistral strike-slip movement is in accordance with regional tectonics. Note the difference in elevation of the base of salt (green horizon) across the structure. Break in the seafloor is evidently related to recent faulting. *GF* possible gas flow effect (chimney); *SF* seismic signal fading. Location in inset and in Fig. 2

and transpressional faults that reach the seafloor along it (e.g. Figure 8) implies that it can be associated with tsunamigenic earthquake activity in the region (Darawchek et al., 2022).

5.3.3 Region 3

The seismic data of Region 3 do not show features associated with deep major faults. However, minor and shallow normal faults are present in the shallow stratigraphic layers.

6. Synthesis

6.1. Reassessing the Previously Studied Offshore Structures

Previous studies conducted offshore Lebanon uncovered some aspects related to the offshore features and structures using geophysical and seismic

data. However, most of those studies used 2D, low-resolution, seismic reflection data that were available at the time. In this section, the authors use their bathymetric map and higher quality 3D seismic data to reassess the previously studied offshore structures, and to differentiate between faults formed by tectonic activity from others caused by different mechanisms such as subsurface salt movement.

Elias et al. (2007) related the rugged bathymetry offshore Lebanon (Fig. 3) to submarine seismic breaks that “unambiguously define the source of the A.D. 551 earthquake”. They suggested that Plio-Quaternary turbidites above the salt layer display a warped seafloor with anticlines developing above blind thrusts. In addition, they used submarine acoustic images to suggest that the bathymetry shows “ruptures and scarps” that resemble subaerial seismic dip-slip ruptures (Elias et al., 2007). By displaying Elias et al.’s (2007) “fresh seafloor seismic breaks” on the bathymetric map (Fig. 2), the authors were able to relate those features to the bathymetric highs

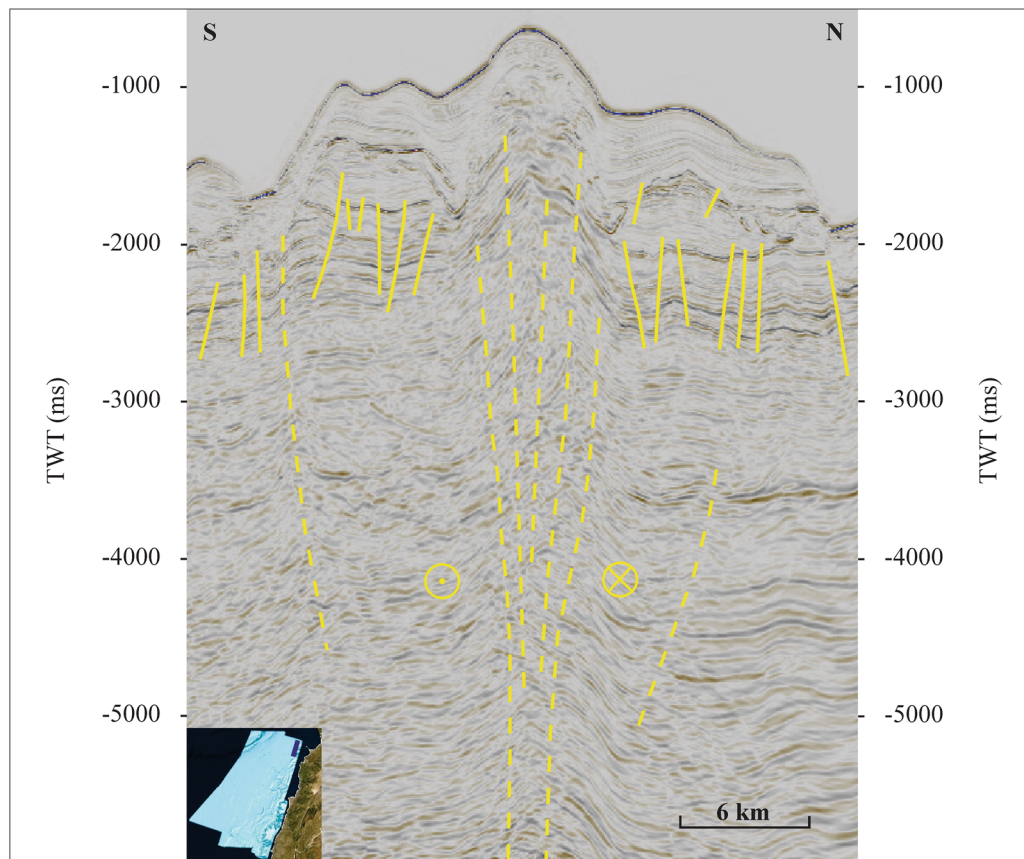


Figure 9

2D seismic section of the 3D data from the northern margin showing a transpressional fault zone that corresponds to Aabde fault of Carton et al. (2009) or Tripoli fault (F4) of Ghalayini et al. (2014). Salt layer is not shown because section is taken to the east of salt layer pinch-out. Dashed yellow faults originate deep in the section, some might extend upward to reach the seafloor. Sinistral strike-slip movement is in accordance with regional tectonics. Transpression is concentrated in the middle of the section. Location in inset and in Fig. 2

and lows that have formed in the post-salt layers due to salt tectonics rather than to major thrust faulting (e.g. Figure 6). These features and underlying faults are typically not tsunamigenic.

A NNE-SSW 2D seismic section located in the northern margin was interpreted by Carton et al. (2009) to show an offshore extension of the “Aabde fault” with a vertical offset of layers (their Fig. 12). A 3D seismic line at nearly the same location shows no clear faulting, but one could approximate a transpressional fault zone that might reach the seafloor and affect the bathymetry (Fig. 9). To be noted that this fault zone is the Tripoli fault of Ghalayini et al. (2014) (F4 in Sect. 2.3; Fig. 2).

On another NW–SE 2D seismic section also from the northern margin, Carton et al. (2009) observed an interruption of the salt layer close to the margin, and noted that instead of pinching out toward the margin, the salt layer was uplifted from the rest of undisturbed thicker salt layer in the basin (their Fig. 13). They suggested that this was caused by an east-dipping thrust fault that formed at the western edge of an anticline (Carton et al., 2009). A 3D seismic section of the same location reveals the Tripoli-Batroun fault zone (Sect. 5.3.1; Fig. 10). This fault zone shows a relatively large offset of the salt and pre-salt layers across a positive flower structure, but the seafloor mound located above does not seem to be directly related to it.

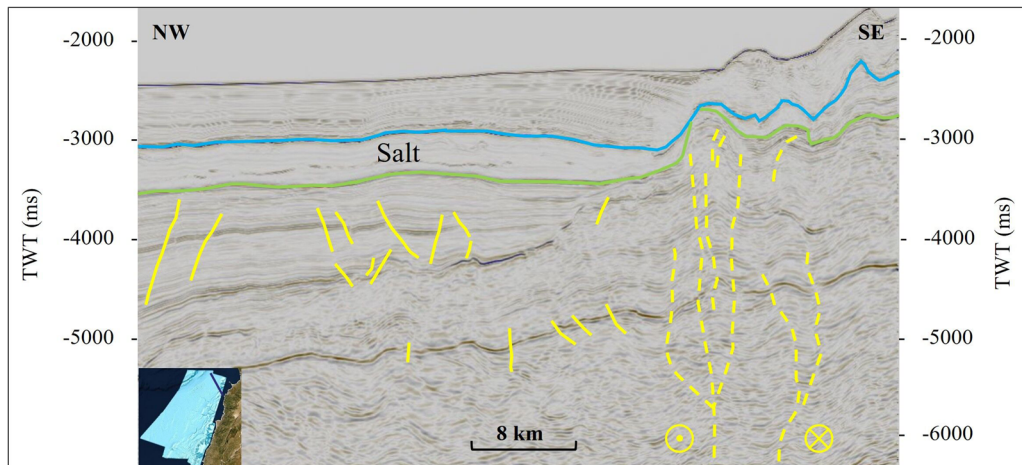


Figure 10

2D seismic section of the 3D data from the northern margin showing the Tripoli-Batroun fault zone effect (dashed yellow) being less pronounced than in Fig. 4, uplifting the salt layer without reaching the seafloor. Yellow faults originate in the pre-salt layers. Sinistral strike-slip movement is in accordance with onshore tectonics. Transpression is concentrated along the margin. Location in inset and in Fig. 2

West of Jounieh, Carton et al. (2009) interpreted steep reverse faults and suggested that they were interconnected at depth to form a lateral thrust ramp that extended from the onshore (their Fig. 10). In addition, scarp-like features along the seafloor were suggested to be the expressions of those deep faults that might reach the surface. They were interpreted to be related to the overall compression in the region (Carton et al., 2009). A 3D seismic section of the same location does not cover the whole margin area (Fig. 5). However, the authors interpret interconnected reverse faults of a positive flower structure as the Jounieh fault zone, without being able to confirm the presence of a system that connects with the onshore subsurface.

Northwest of Beirut, another NW–SE 2D seismic section was interpreted by Carton et al. (2009) and it showed deep sub-salt reverse faults and shallow post-salt normal faults (their Fig. 11). In addition, two reverse faults were interpreted to the east of the section affecting the margin. The shallow normal faults reach the seafloor, displace the post-salt layers, and root into the salt layer (Carton et al., 2009). A 3D seismic section for the same location, although it does not cover the whole margin area, marks the presence of deep reverse faults (the southern continuation of the Jounieh fault zone), as well as shallow normal and

listric faults (Fig. 11). The reverse faults seem to converge at depth, but they do not reach the seafloor. The seafloor scarp-like features are related to normal faulting above salt movement (Fig. 11).

Offshore Damour, another NW–SE 2D seismic section was interpreted by Carton et al. (2009) (their Fig. 15). Deep reverse faults were interpreted, some of them with peculiar geometries, and one of them being along the steep edge of the margin and reaching the seafloor. Carton et al. (2009) suggested transpressional faulting and folding at the base of the slope to the west of the margin (Ben-Avraham et al., 2006), and they interpreted a set of normal faults with salt rollers above the salt layer (their Fig. 15). A 3D seismic section for the same location reveals the Damour fault zone (a set of reverse faults along the margin that converge at depth as a transpressional structure) (Sect. 5.3.1; Fig. 7). Although it is hard to confirm from the seismic resolution that any particular fault reaches the seafloor, the slope break in there is very intriguing and necessitates further investigation on higher-resolution seismic data (Fig. 7).

Further south, Carton et al. (2009) interpreted a transpressional fault close to the slope break (their Fig. 16), referred to it as the “Saida fault” (Fig. 2), and suggested that it may be the “offshore extension of the Roum fault”. Based on the 3D seismic

interpretation presented here, the authors believe that this fault is a localized fault that is related to the Damour fault zone, and it does not connect with the Roum fault, the latter being one of the onshore branches of the DSTF within the LRB (Nemer, 2019; Nemer & Meghraoui, 2006; Fig. 2).

For the southern margin, a NW–SE 2D seismic section was also interpreted by Carton et al. (2009). In this seismic section, they interpreted a deep reverse fault that dies out in the salt layer (their Fig. 5). They suggested it to be a blind thrust ramp of the “South Lebanon thrust” (SLT) zone. They also noted that the post-salt layer is highly affected by normal faulting due to salt evacuation (Carton et al., 2009). A 3D seismic section of the same location did not reveal thrust faulting (Fig. 12). Instead, localized and minor faults seem to be present, and accordingly, the suggested SLT could not be confirmed. Still along the southern margin but on a different note, the fault zone and deformation belt of Schattner et al., (2006; their Fig. 4c) and Ben-Avraham et al., (2006; their Fig. 6, 7, 8, 10, 16) (Sect. 2.5, Fig. 2) don't seem to be related to a major tectonic structure that controls

their presence. The 3D seismic data show that they coincide with minor faulting in the post-salt layer that is probably related to salt movement (Figs. 2, 7, 12, 13).

The NNE–SSW-striking “Beirut thrust” of Ghalayini et al., (2014; Sect. 2.4) is located at a distance of about 12 km from Beirut. They suggested that it occurred before the deposition of the Messinian salt layer as it dies out at the base of this unit. In addition, they detected no evidence of deformation in the Messinian and Pliocene layers along the hanging wall of the thrust fault, and they proposed the Beirut thrust to be inactive and that those layers are post-kinematic (Ghalayini et al., 2014; their Fig. 12). The 3D seismic interpretation of a section that intersects the southern part of this fault shows a salt-layer pinch-out and offset along a sharp break in the seafloor, suggesting the presence of a recent bathymetric feature above a rather active transpressional structure that is the Damour fault zone (Fig. 13).

Ghalayini et al. (2014) mapped the Tripoli thrust (Sect. 2.4; Fig. 2) and found that it affects the Cretaceous, upper Miocene, and Messinian units,

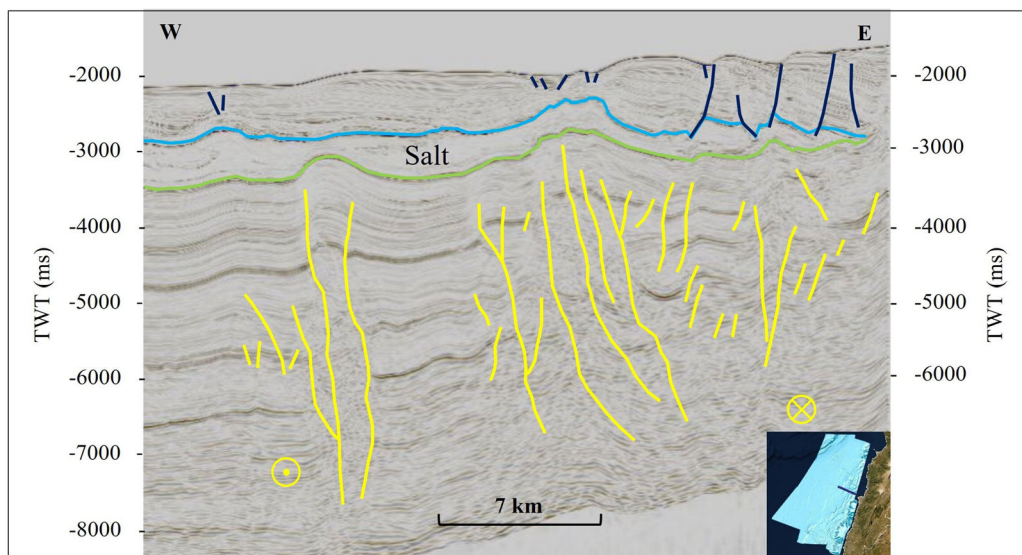


Figure 11

2D seismic section of the 3D data from the central margin showing mostly reverse faults (yellow) in the pre-salt layers, and normal and listric faults (dark blue) in the post-salt layers. Yellow faults correspond to the southern extent of the Jounieh fault zone. Sinistral strike-slip movement is in accordance with onshore tectonics. Seafloor morphology is related to shallow normal and listric faulting in the post-salt layers rather than to major tectonic faulting. Transpression is diffuse across the section, marking the attenuation of the Jounieh fault zone. Location in inset and in Fig. 2

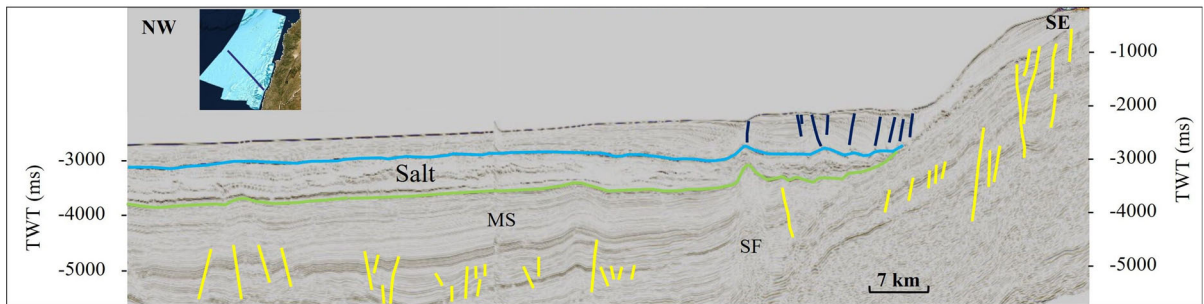


Figure 12

2D seismic section of the 3D data from the southern margin showing minor faulting in the pre-salt layers (yellow) and post-salt layers (dark blue), with no major thrusting. Seafloor morphology is related to shallow normal and listric faulting in the post-salt layers beyond the slope break. *MS* merging seam of 3D seismic volumes. *SF* seismic signal fading that might be due to possible gas chimney. Location in inset and in

Fig. 2

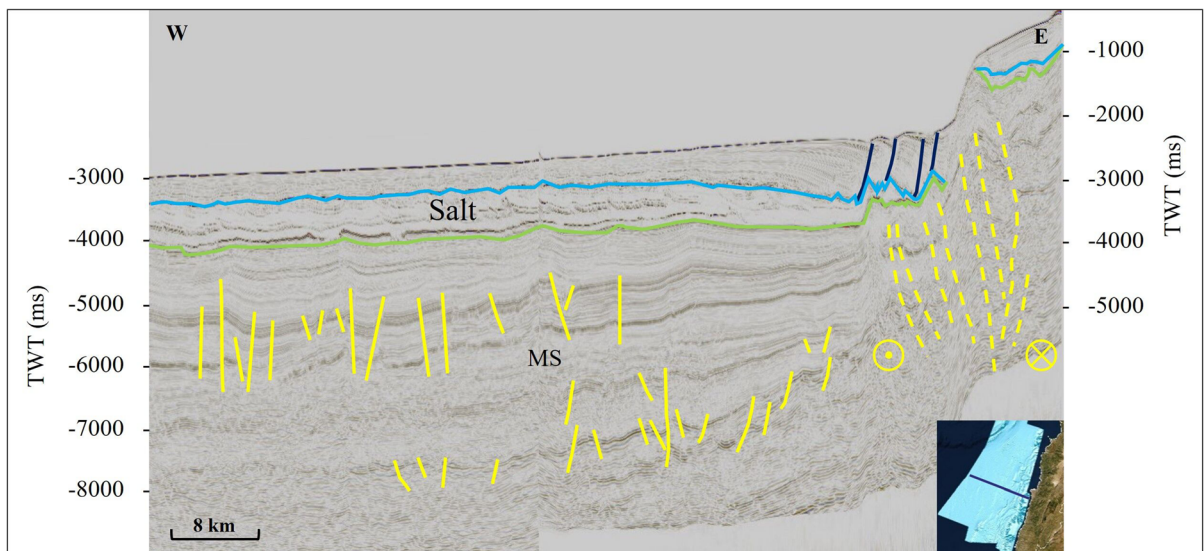


Figure 13

2D seismic section of the 3D data from the southern margin showing the salt layer pinching out and being offset across the Damour fault zone (dashed yellow). Yellow faults originate in the pre-salt layers. Sinistral strike-slip movement is in accordance with onshore tectonics. Dark blue faults affect the post-salt layers. Sharp break in the seafloor above the fault zone suggests active tectonic faulting, while seafloor morphology beyond the slope break is related to shallow normal and listric faulting in the post-salt layers. Transpression is concentrated along the margin. *MS* merging seam of 3D seismic volumes. Location in inset and in Fig. 2

with the Oligocene and Eocene layers onlapping the Senonian unconformity horizon (their Fig. 13a, b). They added that this thrust fault seems to have displaced the Cretaceous units by about 3 km, but it offsets the upper-Miocene and the base-Messinian units by only 0.2 and 0.1 km, respectively. With this, they suggested that the Tripoli thrust was active in the

pre-Miocene period and that it ceased its activity in the Messinian and Pliocene periods (Ghalayini et al., 2014). The 3D seismic interpretation of a section that lies a couple of kilometers further south of theirs shows the Tripoli-Batroun fault zone (Sect. 5.3.1; Fig. 4).

6.2. Implications for Earthquake Geology in the Eastern Mediterranean Region

The 3D seismic data of this study provided good subsurface imaging to investigate the active fault framework in the study area, and to highlight the corresponding seismogenic structures. The topographic high in the northern margin was affected by a faulting event that uplifted the layers close to the margin. The topographic high in the southern margin is an underwater fan that is created by the underwater flow of onshore rivers across the shoreline.

The morphological highs and lens-shaped features of the central and southern margins that were referred to as seafloor ruptures in previous studies, are caused by salt tectonics. The interrelation between faults and salt movement is expressed on the seafloor as highs and lows that are reflected in the bathymetry. The seafloor “ruptures and scarps” of Elias et al. (2007) are bathymetric features that have formed in the post-salt layers due to salt tectonics. Their underlying faults are not tsunamigenic.

The Tripoli-Batroun fault zone displays a sharp break in the seafloor in its northern part, suggesting it is an active transpressional fault zone, but it does not reach the seafloor further south. The Jounieh fault zone in its northern part does not reach the seafloor directly, although it affects the upper layers. However, offshore Beirut it shows a sharp break in the seafloor, which suggests it is an active transpressional fault zone. Further south, the Damour fault zone takes over as an active transpressional structure that affects the seafloor.

The above-mentioned transpressional structures are not continuous along their strikes (Fig. 2) in the sense that they do not interconnect to form a regional structure like the proposed 100–150 km-long MLT between Saida and Tripoli (Carton et al., 2009; Elias et al., 2007). Accordingly, their tsunamigenic potential is not evident and requires additional investigations on higher-resolution seismic data to better delineate the fault zone dimensions, followed by tsunami generation modeling along this margin of the Levant basin.

The 9 July 551 M 7.2 earthquake in the eastern Mediterranean region has drawn a lot of attention as it is considered one of the largest magnitude

earthquakes that struck the Levant margin. Several hypotheses about the source of this tsunamigenic earthquake have been put forward (e.g. Carton et al., 2009; Darawcheh et al., 2000; Elias et al., 2007), all of them suggesting the existence of a large offshore structure with a significant dip-slip component.

Darawcheh et al. (2000) suggested the epicenter of the A.D. 551 earthquake to be on the offshore extension of the Roum fault. Other studies that built on the results of the Shalimar geophysical survey offshore Lebanon suggested the presence of seafloor breaks (Carton et al., 2009; Elias et al., 2007). Elias et al. (2007) interpreted those seafloor features to be the result of the MLT that was proposed to be bounded by two oblique lateral ramps from the north and south that correspond to the “Aabde” and “Saida” faults (Fig. 2), respectively. In addition, the MLT was interpreted to be responsible for the Plio-Quaternary growth of Mount Lebanon, and was proposed to be the source of the A.D. 551 earthquake (Carton et al., 2009; Elias et al., 2007).

After analyzing all the features observed on the bathymetric map by checking the 3D seismic data, salt tectonics appears to be causing many of those features. For instance, the morphological highs and the lens-shaped features along the margin (Sect. 4) are both caused by salt movement rather than by thrust faulting. Reactive diapirism forms salt diapirs due to the effect of extensional forces and normal faulting in the post-salt layer. Accordingly, in the Levant basin, salt tectonics is a major process that cannot be overlooked in favor of regional tectonics, despite the presence of important but localized transpressional fault zones along the margin (Sect. 5.3.1). Based on the above and after comparing the results of the previously interpreted seismic reflection data with the 3D seismic data presented here, the authors believe that no offshore structures form a regional system of faults that connect with the LRB from the onshore. Therefore, the authors believe that the presence of the MLT for instance is not evident and requires further investigation on high-resolution, deep seismic reflection data that cover both the offshore and onshore areas.

The major and active fault system that the authors interpreted underneath the Latakia ridge in Region 2 remains the most intriguing structure in the Lebanese

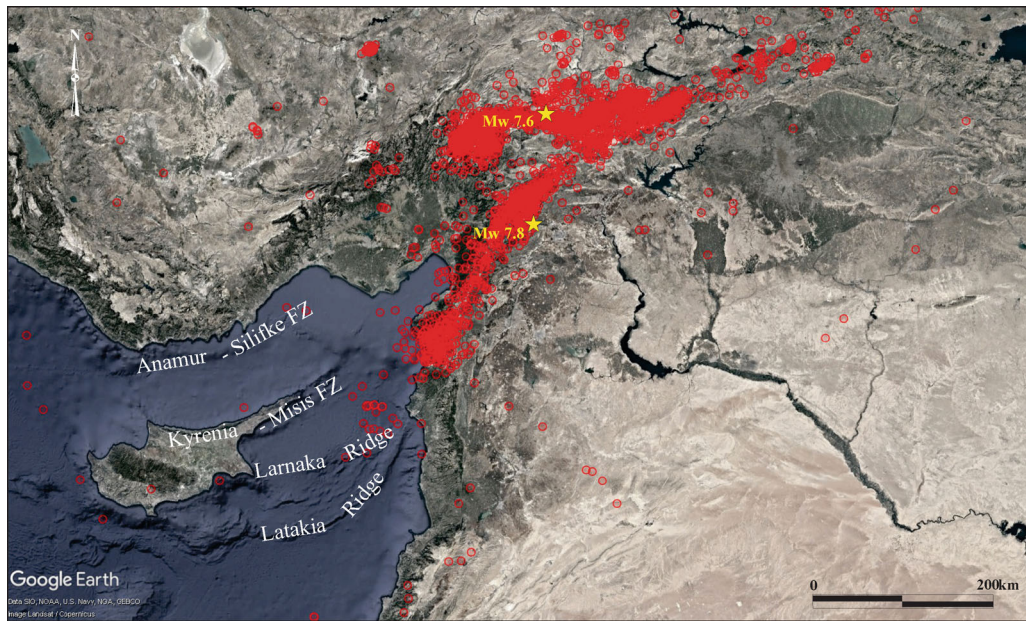


Figure 14

Cluster of epicenters of the 6 February 2023 Mw 7.8 and 7.6 earthquakes and associated seismic activity in Türkiye for the period of 6 February to 25 May 2023. The four main structures of the eastern Mediterranean area are annotated in white. Seismic data are from <https://www.emsc-csem.org/> plotted on Google Earth background

offshore area. This fault system led to about 1000 ms of vertical offset, which is a major uplift that affects the seafloor above it (Fig. 8). This prominent seafloor rupture has formed along the Cyprus arc where transcurrent movement is dominant (Wdowinski et al., 2006) with a variation of transpressional and transtensional behaviors, depending on the behavioral change of the strike-slip movement along the trend of the structure. Such rupture can generate high-magnitude earthquakes and can be considered a very plausible source of the A.D. 551 earthquake and its associated tsunami. Similar seafloor features lie along the Hellenic arc further west (Wdowinski et al., 2006), which was the cause of the 21 July 365 tsunamigenic earthquake (Pararas-Carayannis, 2011). That M 8.3 earthquake is considered one of the most destructive seismic events in the Mediterranean, and the tsunami wave that followed it affected the eastern Mediterranean coastal countries Greece, Libya, Egypt, and Cyprus (Pararas-Carayannis, 2011). With that in mind, and in the wake of the 6 February 2023 Mw 7.8 and 7.6 earthquakes in Türkiye, this earthquake doublet and its associated seismic activity

show a cluster of epicenters that extend from southern Türkiye to the eastern Mediterranean area, along a trend that matches the onshore continuation of the Latakia ridge (Fig. 14). The magnitude of the two main shocks and the density and trend of their associated seismic activity highlight the importance of properly defining the seismogenic structures in the region, both onshore and offshore.

Morhange et al. (2006) presented evidence for two major regional uplift occurrences along the Lebanese coast during the last 6000 years. They used ^{14}C dating of uplifted subtidal bioconstructions to understand sea-level variations due to crustal deformation. They measured an upper shoreline at about 1.2 to 1.4 m, and a lower one at about 0.8 ± 0.4 m. They dated the former to have lasted from about 6000 to 3000 years BP, and the latter from about 2700 to 1500 years BP. They proposed that these shorelines were uplifted due to the tectonic activity along the Yammouneh fault, the Tripoli-Roum thrust (i.e. MLT), and other transverse faults (Morhange et al., 2006). Elias et al. (2007) built on Morhange et al.'s (2006) results and suggested a tectonic activity along

MLT as the cause of the second uplift. They also related it to the A.D. 551 earthquake, and proposed an earthquake return period on MLT of about 1500 to 1750 years (Elias et al., 2007). Based on the results about the major tectonic role that the Latakia ridge has in the eastern Mediterranean area, the authors propose that the uplifts documented in Morhange et al. (2006) may be due to the transpressional structures that the authors mapped along the Lebanese margin, and that the last uplift that was contemporaneous with the A.D. 551 earthquake could have resulted from an earthquake that might have been triggered along the Lebanese margin by a major event that took place along the Latakia ridge that is about 70 km away in average. This sequence of events is in agreement with the historical record of John of Ephesus who associated the A.D. 551 earthquake with a tsunami and two events about one hour from each other, as reported in Zohar (2019). However, the authors underline that the triggering of an earthquake by another one is a major subject of ongoing research in seismology, which in the presented case requires additional investigation about the possibility of stress transfer from the Latakia ridge to the Lebanese margin.

Based on what has preceded, there is no major thrust system offshore Lebanon that connects to the LRB and accommodates some of the plate motion away from the bending of the DSTF. Instead, the authors believe that the uplift caused by the transpressional behavior along the restraining bend is paralleled along the margin by intermittent transpressive fault zones that are causing the uplift of the coastal regions.

7. Conclusion

This paper aimed to investigate the fault framework of the Lebanese offshore area, study the seafloor features, and examine the potential tsunami-generating structures. After generating a bathymetric map, the offshore morphological features were found distributed along the margin and along the Latakia ridge. The authors interpreted hundreds of faults on the 3D seismic data, both major and minor, and they

compared the results with previously published studies.

Faults along the margin are localized transpressive faults that include the Tripoli-Batroun, Jounieh, and Damour fault zones. These fault zones are limited in extent, and they do not interconnect laterally to form a continuous structure with a potentially tsunamigenic rupture along the seafloor. However, they are active and behind the uplifts of the Lebanese coastal areas. On the other hand, the faults of the noticeable Latakia ridge are much clearer in the seismic data, they reach the seafloor, and they interconnect laterally to form a very prominent structure along the seafloor that extends for a couple of hundreds of kilometers.

The 3D seismic data presented here could not confirm the presence of MLT that was proposed by Elias et al. (2007) and Carton et al. (2009) as a major system of thrust faults offshore Lebanon. Instead, the authors suggest that the Latakia ridge, with its prominent seafloor feature, may well be the most active structure offshore Lebanon that was likely the source of the 9 July 551 M 7.2 tsunamigenic earthquake. The authors underline that 3D seismic reflection data of relatively good quality can confirm or rule out the presence of major offshore structures like the MLT. In addition, the authors emphasize that tsunamis could be generated by slope instabilities triggered by earthquakes along the Dead Sea Transform Fault within or outside the Lebanese Restraining Bend, and that the hypocenters of the related events do not have to be located necessarily along the margin (Darawchek et al., 2022).

The 6 February 2023 Mw 7.8 and 7.6 earthquakes and their associated seismic sequence in Türkiye extend along a trend that matches the onshore continuation of the Latakia ridge. This mighty seismic activity underlines the importance of defining the onshore and offshore seismogenic structures in the region, with special attention to those that are potentially tsunamigenic.

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Author contributions RF: seismic interpretation, analysis, writing original draft, figures, review and editing. TN: conceptualization, funding acquisition, resources, mentoring, supervision, seismic interpretation, analysis, writing original draft, figures, review and editing. KS: seismic interpretation, analysis, figures. All authors reviewed the manuscript.

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Data Availability

The 3D seismic data of this study are owned by the Lebanese Ministry of Energy and Water and they are not available for public access.

Declarations

Conflict of Interest The authors declare that they have no known financial or personal interests that could influence the results reported in this paper.

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