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Tectonic isolation of the Levant basin offshore Galilee-Lebanon – effects of the Dead Sea fault plate boundary on the Levant continental margin, eastern Mediterranean

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Abstract

The continental margin of the central Levant, offshore northern Israel and southern Lebanon is characterized by a sharp continental-oceanic crustal transition, exhibited on the bathymetry as a steep continental slope. At the base of the slope a narrow zone of faulting deforms the upper Messinian-recent sedimentary sequence. Further into the basin no major deformations are observed. However, onland a restraining bend along the Dead Sea fault plate boundary results in the formation of the Lebanon and anti-Lebanon mountain ranges, which exhibit a large positive isostatic anomaly not compensated at depth. All these geologic features follow a NNE-SSW trend.

A dense network of multi-channel and single-channel seismic profiles, covering 5000 km of ship-track offshore northern Israel and southern Lebanon, was analyzed for the purpose of characterizing the continental margin. Additional seismic surveys covering the area between the Levant margin and the Cyprean arc were examined. Data were then incorporated with magnetic, gravity and earthquake measurements to reveal the deep crustal structure of the area and integrated with bathymetry data to describe the behavior of the young sedimentary basin fill.

Results indicate that the Levant basin, offshore northern Israel and southern Lebanon (up to Beirut) is more-or-less unaffected by the intense tectonic deformation occurring onland. The transition between the deformed area onland and the undeformed Levant basin occurs along the base of the continental slope. Along the base, the upper Messinian-recent sedimentary sequence is cut by two sets of faults: shallow growth faults resulting from salt tectonics and high angle faults, marking the surface expression of a deeper crustal discontinuity – the marine extension of the Carmel fault zone.

The central Levant continental margin is being reactivated by transpressional faulting of the marine continuation of the Carmel fault, at the base of the continental slope. This fault system coincides with the sharp continental-oceanic crustal transition, and acts as an isolator between the Levant basin and its land counterpart. To the north, this feature may initiate the formation of a new triple junction, with the Latakia ridge (part of the eastern Cyprean arc) and the East Anatolian fault.

Keywords: Tectonic isolation; Levant basin; Carmel fault zone; Dead Sea fault; Eastern Mediterranean

1. Introduction

The Levant continental margin, offshore northern Israel and southern Lebanon (up to Beirut), and the adjacent Levant basin (Fig. 1) evolved through several phases of continental breakup, from the late Paleozoic-early Mesozoic rifting of Gondwana until the formation of the present-day passive margins (Garfunkel, 1998; Walley, 1998). This sharp margin is characterized by a narrow shelf (0–3 km wide) and a steep slope (~10°) with mountain ridges extending westward close to the shore. Elongated ridges and scars run sub-parallel to the base of the slope, marking the surface expression of deformations in the upper-Messinian to recent sedimentary section

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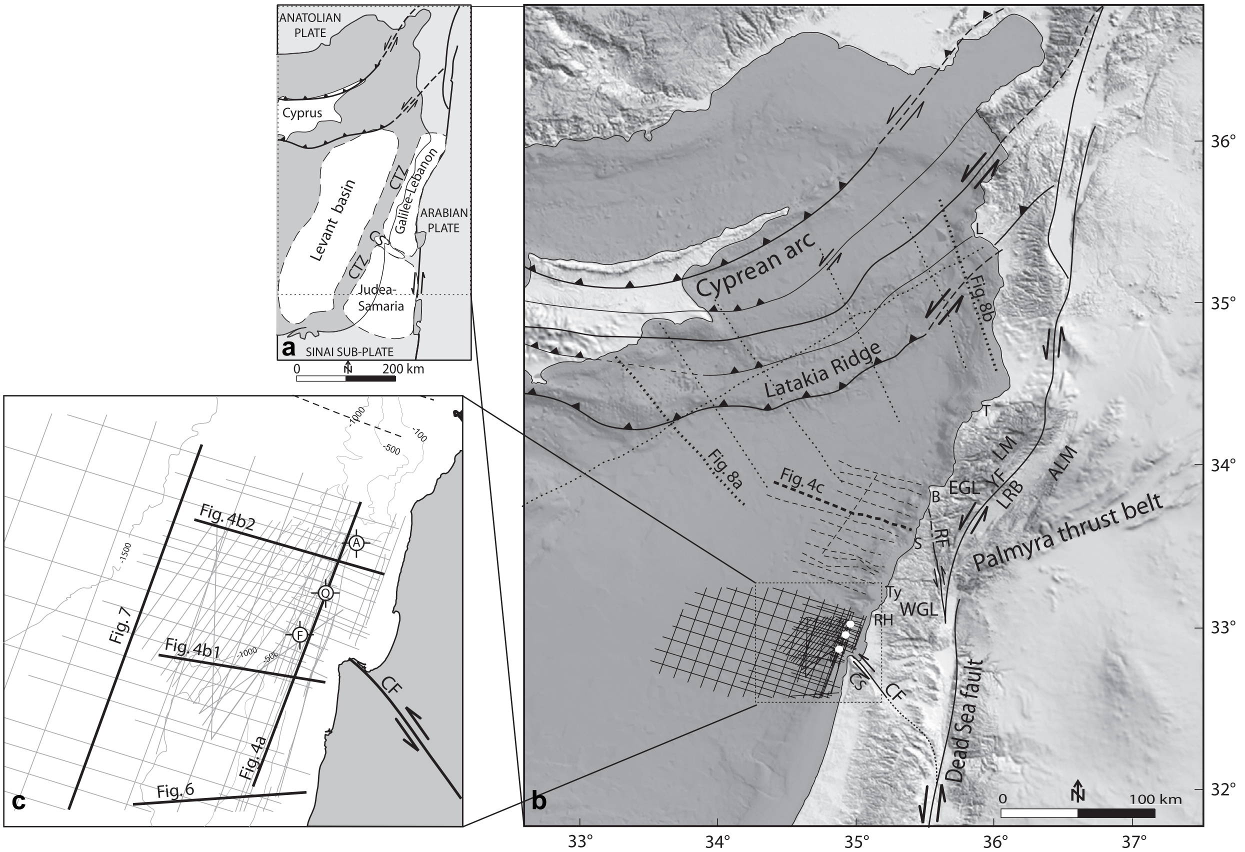

Fig. 1. Location maps of the study area. (a) Schematic distribution of terranes with distinct crustal structure in the eastern Mediterranean (modified after Ben-Avraham and Ginzburg, 1990). (b) Location of seismic surveys and wells used in this study on DTM showing major tectonic elements. Elements of the Cyprean arc are marked after Ben-Avraham et al. (1995). Seismic profiles interpreted in the present study are marked by solid black lines (multi-channel) and dashed lines (single-channel). Additional profiles examined are marked by dotted lines (Kogan and Stenin, 1994). Thick lines indicate profiles presented in the forthcoming figures. White dots indicate location of wells used in the seismic analysis. (c) Enlargement of seismic location map offshore northern Israel on a generalized bathymetric map. Three wells were drilled on the continental shelf: F = Foxtrot, Q = Qishon Yam 1, A = Asher Yam 1. DTM courtesy of John K. Hall. Abbreviations: CS = Carmel Structure, CF = Carmel Fault, CTZ = Crustal Transition Zone, RH = Rosh Haniqra, RF = Roum Fault, WGL = Western Galilee-Lebanon province, EGL = Eastern Galilee-Lebanon province, LRB = Lebanese Restraining Bend, YF = Yammouneh Fault, LM = Lebanon Mountains, ALM = Anti-Lebanon Mountains, Ty = Tyre, S = Sidon, B = Beirut, T = Tripoli, L = Latakia.

(Ben-Avraham et al., 2006). Several studies have indicated that the continental-oceanic crustal transition in this area is abrupt and located beneath the continental slope (Ben-Avraham and Ginzburg, 1986; Ginzburg and Ben-Avraham, 1987; Ben-Avraham et al., 2002). Onland, topography of Galilee-Lebanon, a segment of the African-Sinai plate, is anomalously high (∼3100 m) and deformed, as a result of transpressional stresses along a right-step of the sinistral Dead Sea fault plate boundary. Segev et al. (2003) have shown that this area onland is characterized by a prominent positive isostatic anomaly, which is not compensated at depth. In contrast to the dynamic tectonic appearance onland and along the continental margin, bathymetry of the Levant basin offshore Galilee-Lebanon is smooth and subsurface reflectors appear regular and are almost unaffected by the intense deformation onland. However, these onland-offshore tectonic interactions have hardly been studied in this area due to the small number of offshore surveys.

The recent structural evolution of the continental margin of Galilee-Lebanon is predominantly controlled by motion along the Dead Sea fault system (Fig. 1). About 105 km of sinistral displacement has occurred along this system since its initiation in the mid-Miocene (e.g., Freund et al., 1968; Garfunkel, 1981). East of Galilee-Lebanon, the Dead Sea fault system branches off into a number of sub-parallel and divergent faults (Beydoun, 1977; Walley, 1988). Most of the motion in this area is accommodated by the NNE trending Yammouneh fault (Walley, 1998), which lies along the Lebanese restraining bend. Two other major branches are the NW trending Carmel fault (northern Israel) and further north, the NNW trending Roum fault (southern Lebanon). These faults extend from the Dead Sea fault westwards towards the Levant continental margin, and together with the Palmyra thrust belt which lies east of the Dead Sea fault, accommodate some of the motion.

The seismically active Carmel fault is one of the main tectonic elements along the eastern Mediterranean continental margin. Despite the large number of studies which have focused on its marine continuation (e.g. Ginzburg et al., 1975; Neev et al., 1976; Ben-Avraham and Hall, 1977; Kafri and Folkman, 1981; Garfunkel and Almagor, 1985; Ben-Gai and Ben-Avraham, 1995), the trend of the fault offshore and nature of deformations along it are still highly debated (Fig. 2). One study, that of Garfunkel and Almagor (1985), suggested that offshore northern Israel the Carmel fault curves northwards and continues along the southern Lebanese continental slope, up to Tyre. However, the tectonic relationship between the Carmel fault and its surroundings offshore Lebanon is not clear, i.e. the relations between the sharp continental margin at depth, the highly deformed area onland and the tectonically calm Levant basin to the west.

This paper presents the results of a comprehensive geophysical study of the central Levant margin and in particular, the marine continuation of the Carmel fault. Results of this study agree with the suggestion of Garfunkel and Almagor (1985) for the trend of the fault offshore. The present study shows that this fault is part of a *fault zone* which continues along the base of the Lebanese continental slope, reactivating the crustal transition zone. The Carmel fault zone marks the deformation front for activity onland (uplift of the Lebanese thrust belt) and on the continental shelf. As such, it acts as a *tectonic isolator* between Galilee-Lebanon and the adjacent Levant basin.

2. Data

2.1. Study area

The study area is located offshore northern Israel and southern Lebanon (Galilee-Lebanon). Additional information from the northeastern Levant basin, between Cyprus and Syria was also examined (Fig. 1). In terms of crustal structure, the investigated area covers the continental-oceanic transition zone of Galilee-Lebanon and its adjacent section of the Levant basin. In particular, the area of interaction between the offshore extension of the Carmel fault and the structures of western Galilee were analyzed in higher resolution. Both the shallow and the deep structure of the continental margin were examined using a combination of various data sources (below).

2.2. Data

Data used in this study consisted mainly of interpretation of multi and single-channel seismic reflection profiles collected along 4150 km and 850 km of ship track respectively, during

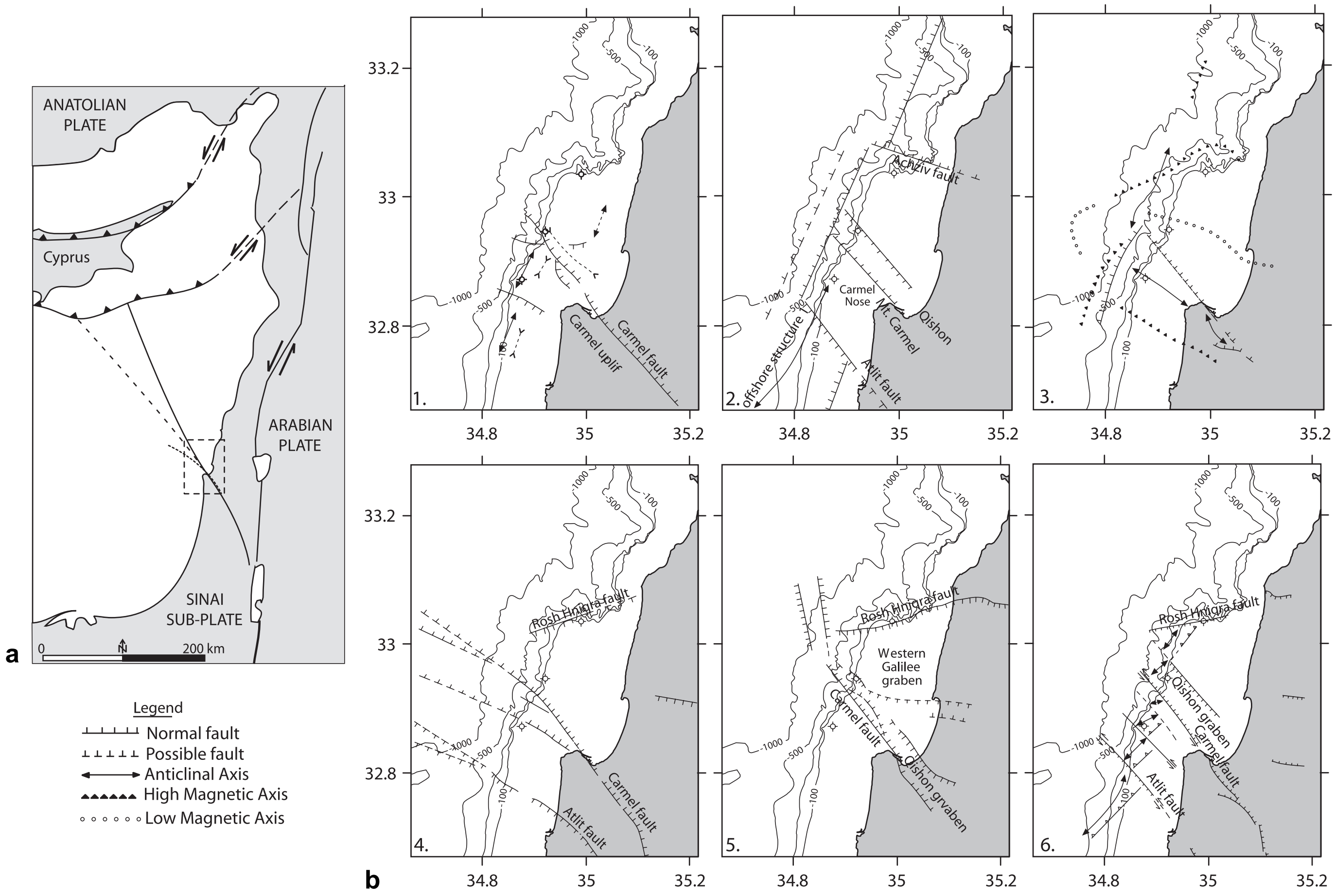

Fig. 2. Comparison between the main interpretations suggested for the trend of the marine continuation of the Carmel fault. (a) Map that summarizes the suggestions for the Carmel fault in the Levant basin. Solid line – Abdel Aal et al. (2000), dashed lines – Ben-Avraham et al. (1988), and dotted line- after Hofstetter et al. (1996) based on earthquake data. (b) Summary of six interpretations of seismic surveys for the trend of the Carmel fault and other faults on the continental margin. The main controversy is centered on the area from the edge of the continental shelf basinwards. 1. Ginzburg et al., 1975; 2. Neev et al., 1976; 3. Ben-Avraham and Hall, 1977; 4. Kafri and Folkman, 1981; 5. Garfunkel and Almagor, 1985; and 6. Ben-Gai and Ben-Avraham, 1995.

five geophysical surveys offshore the Levant continental margin (location maps in Figs. 1b,c). These surveys were controlled by three deep wells (Qishon Yam 1, Asher Yam 1 and Foxtrot) located on the continental shelf of northern Israel. An additional seismic study comprising ∼1100 km between Cyprus and Syria (Kogan and Stenin, 1994) was used to examine the NE corner of the Levant basin. Previous interpretations of refraction, magnetic and gravity data were used in this study to obtain an image of the deep crustal structure (e.g. Ben-Avraham et al., 2002, and references therein). Earthquake data was compiled from the Iris database (IRIS, 2005) as well as from previous studies (e.g. Salamon et al., 2003) to provide a regional map of recent tectonic activity of the Levant basin and its margins (Fig. 3). Bathymetry was obtained from previous surveys (Ginzburg and Ben-Avraham, 1986; Hall, 1994; Ifremer, 2005).

3. Results

3.1. Bathymetry

Morphology of the present day continental margin of northern Israel and southern Lebanon is characterized by a sharp transition separating the elevated area onland from the deep marine basin (Fig. 1). Offshore the Carmel structure and western Galilee the continental shelf broadens anomalously to ∼15 km, and progressively narrows from ∼3 km offshore Rosh Haniqra until it virtually disappears off Beirut. The continental slope is steep (about 10°), irregular and deeply cut by numerous canyons. Close to the base of the continental slope, elongated hummocky ridges and scars appear on the seafloor, sub-parallel to the slope. Further to the west, bathymetry of the continental rise is generally smooth and featureless, deepening towards the NW, apart from a few bathymetric steps lying sub-parallel to the slope.

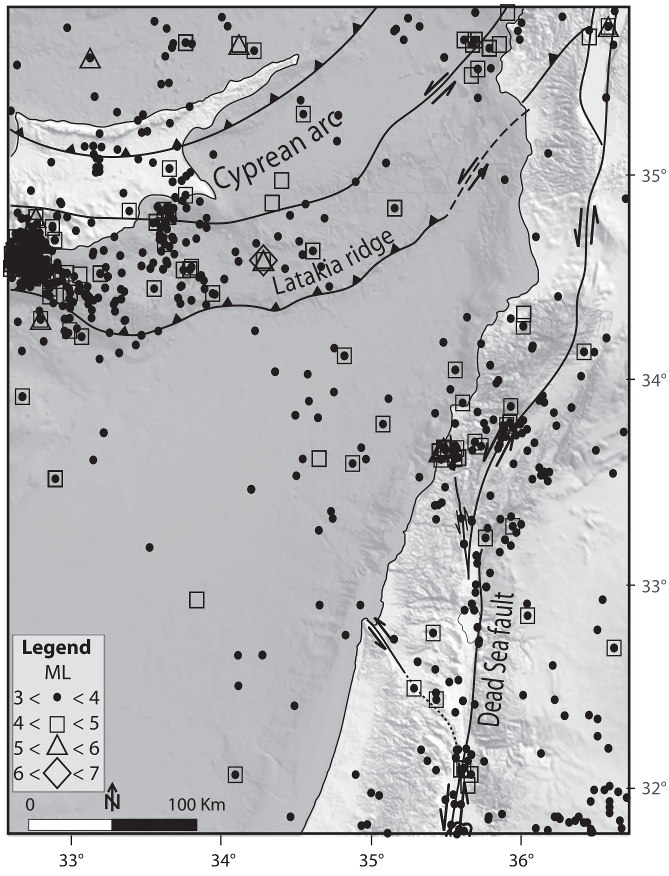

Fig. 3. Regional map of recent seismic activity (>3 ML) in the Levant basin and its margins, between the years 1990 and 2005 (after IRIS, 2005), plotted on DTM showing the major tectonic elements in the area.

3.2. Sediments

Seismic data shows that the area is comprised of three major sedimentary units ranging from the present until Jurassic times, i.e. Plio-Pleistocene, Messinian, and pre-Messinian (Fig. 4a). These sequences are separated by two regional unconformities. Nile derived Plio-Pleistocene sediments, which cover most of the study area, comprise the uppermost sedimentary unit. Under the continental rise this unit is relatively thin (∼0.5 km) with high frequency thinly spaced reflectors deformed in short wavelength folds (Fig. 4c). Close to the base of the continental slope the Plio-Pleistocene unit generally thickens towards the east, directly above a landward thinning of the Messinian evaporitic sediments (Figs. 4b,c). In this area these two units are highly deformed by folds and numerous faults, which trend parallel to the continental slope. On the continental shelf and slope, the Plio-Pleistocene unit is thin and cut by young canyons truncating the sedimentary record. A local thickening of this unit on the continental shelf occurs over the western Galilee graben, between two elevated structures that extend from land offshore – the Carmel in the south and Rosh Haniqra in the north (Fig. 4a).

One of the most prominent units in the study area is the Messinian evaporitic sequence, which underlies much of the Levant basin (Fig. 4). This unit is bounded between two erosional unconformities from above and below. These unconformities, termed M (top Messinian) and N (base Messinian) respectively, serve as seismic markers throughout the entire eastern Mediterranean. Under the basin, the thickness of the Messinian unit is generally constant (∼1200 m). Close to the base of the continental slope this unit thins until it disappears, mostly due to shallowing of the N reflector (Fig. 4b). This landward wedging is accompanied by numerous faults and possible diapirism (Fig. 4c). The M reflector, which also marks the base of the overlaying Plio-Pleistocene unit, is generally horizontal in the basin and becomes irregular close to the base of the continental slope. The Messinian unit is absent from the continental shelf.

The pre-Messinian unit (Fig. 4) is composed of Jurassic to Eocene sediments and covers most of the Levant basin and margins. Reflectors within this unit appear generally smooth under the continental rise, deepening basinwards with long wavelength undulations (Fig. 4b2). Under the continental shelf and slope this unit is folded as part of the Syrian arc fold system (Ben-Gai and Ben-Avraham, 1995). Additional young and more local compressional structures, accompanied by deep rooted faults, are evident along the continental slope from offshore the Carmel structure up to Tyre (Fig. 4b).

3.3. Structures on the continental shelf

The narrow continental shelf of southern Lebanon is composed of a thin Plio-Pleistocene cover which overlies Cretaceous units. At the shelf edge, basinwards tilting shelf marginal wedges were reported by Ben-Avraham et al. (2006) in places where the Plio-Pleistocene cover was not removed by the incision of young submarine canyons (Figs. 4c and 5a). Further to the south, offshore Galilee the structure changes and a sharp widening of the continental shelf from 3 to 15 km occurs. In this area, the shelf is disrupted by two elongated and elevated Mesozoic structures, the Rosh Haniqra and Carmel structures, which extend from onland and almost converge at the shelf edge. Upon these structures, the Plio-Pleistocene cover almost disappears, as is evident from drillholes (Foxtrot and Asher Yam 1) and seismic data (Fig. 4a). Between these structures, Plio-Pleistocene fill of the Western Galilee Graben (Garfunkel and Almagor, 1985) reaches thickness of 1180 m as revealed by the Qishon Yam 1 well (Schattner et al., 2006). Some of the E-W trending faults that deform the western Galilee onland (e.g. Freund, 1970) can be traced offshore, into the Western Galilee Graben; in particular, the Central Galilee Escarpment (CGE on Figs. 4a and 5) which divides the northern and southern Galilee. The western extent of this graben structure is delimited on the shelf edge by a fault zone, which is discussed below (fault set II). The E-W faults within the graben are also truncated and are not evident in the sedimentary section further to the west, beneath the continental rise.

3.4. Active faulting along the continental margin

Results of this study indicate that a continuous fault zone (marked on Figs. 4 and 5 as FZ) deforms the continental margin from offshore the Carmel structure, and along the Lebanese continental slope up to Beirut. This zone is comprised of four sub-parallel deep rooted faults. Variations in the trend of the fault zone and structures observed along its axis enable its division into three segments (Fig. 5b). The first and southernmost segment continues the northwest trend of the Carmel fault (also termed Yagur fault) from onland, across the continental shelf of northern Israel, up to its edge. This fault is the principal component of the fault zone, and has been previously interpreted as the marine continuation of the Carmel fault (e.g. Ben-Gai and Ben-Avraham, 1995). Displacements along the Carmel fault in this segment are a combination of sinistral strike-slip and dip-slip between the uplifted marine extension of the Carmel structure in the south and the down-thrown Western Galilee Graben in the north. The southernmost fault of the system is the Atlit fault that delimits the uplifted Carmel structure from the south. In between these two major faults, two additional faults (Tira and Dado faults, Figs. 4a and 5a) cut through the Carmel structure and dissect a NNE trending Syrian arc anticline on the continental shelf (Ben-Gai and Ben-Avraham, 1995). Although less prominent than the Carmel fault, recent geological mapping onland also show evidence for the Atlit, Tira and Dado faults in the coastal area (Segev, personal communication).

At the edge of the continental shelf, the second segment of the fault zone changes its trend progressively to the north (Fig. 5b). The ca. 10 km wide fault zone cuts through the continental slope of northern Israel, with the southernmost (Atlit) and northernmost (Carmel) faults becoming the westernmost and easternmost, respectively (Fig. 5a). The Dado fault, which now delimits the Carmel structure on the west, exhibits a positive flower structure which represents transpressional motion (Fig. 4b1). Further to the west the Tira and Atlit faults show a gentler flower structure slightly dipping eastwards, signifying a general E-W compressional component. The easternmost fault (the Carmel fault), which delimits the Western Galilee Graben on the west, does not exhibit noticeable compressional features, but rather a sharp transition indicative of strike-slip motion (Fig. 4b2). North of Rosh Haniqra, where the continental shelf narrows abruptly, the fault zone is located in the basin itself. In this area the fault zone cuts a number of submarine alluvial fans (Fig. 5a). Displacements in this part of the segment, which extends up to offshore Sidon, are mainly the result of strike-slip motion.

The third and northernmost segment of the fault zone displaces the uplifted Lebanese continental margin in the east relative to the adjacent Levant basin in the west (Fig. 5). In this segment the fault zone runs north-northeast along the base of the Lebanese continental slope, from Sidon at least until offshore Beirut. Displacements are exhibited by tectonic boudinage along a NNE axis, which are expressed on the bathymetry by elongated and narrow ridges (Fig. 5a). In the subsurface, these boudinage are distinguished from each other by deep rooted faults, which comprise the main fault zone (Fig. 4c). The interlaying sediments are left folded but not faulted. Displacements resulting in the formation of the elongated folds are mainly strike-slip with a NW-SE compressional component.

In addition to the fault zone described above, the upper sedimentary column (Messinian and Plio-Pleistocene) and the bathymetry along the base of the continental slope are affected by numerous slope parallel growth faults (marked on profiles of Fig. 4 with gray lines). These deformations were described south of the Carmel structure (termed 'Disturbed Zone' by Tibor and Ben-Avraham, 1992) as well as north of it (termed 'Deformation Belt' by Ben-Avraham et al., 2006) as resulting from salt tectonic processes (DB – marked on Fig. 5a by a dark gray strip). Spatially, the area deformed by these growth faults is delimited in the east by the base of the continental slope, while the western border of this strip is irregular. Along the base of the Lebanese continental slope the northern segment of the fault zone coincides spatially with the growth faults of the 'Deformation Belt'. In this area the western border of the 'Deformation Belt' is smoother (width varies between 35 km in the south and 15 km in the north).

West of the 'Deformation Belt' and the northern segment of the fault zone, the picture changes significantly. The bathymetry of the continental rise is generally smooth and almost

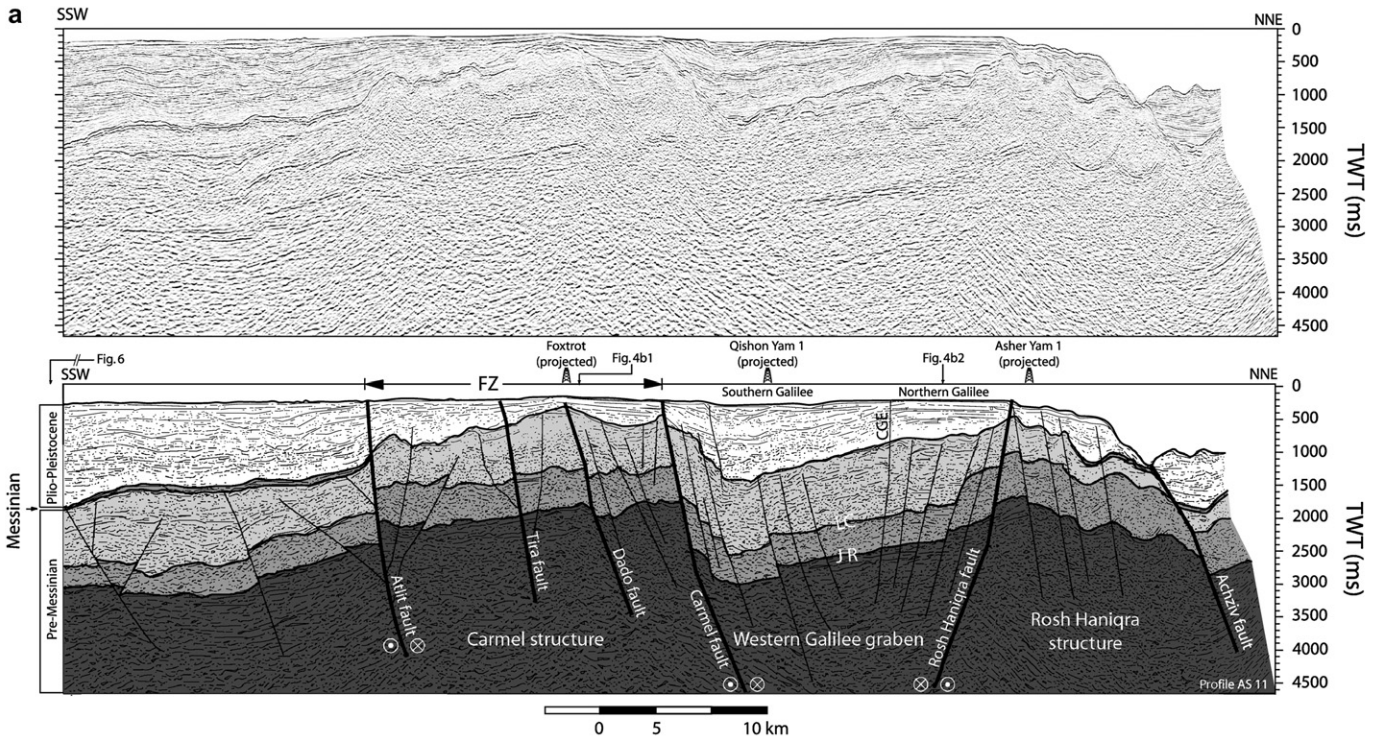

Fig. 4. Four representative seismic profiles (in time domain) from the three segments of the major fault zone mapped in this study. FZ marks the extent of the fault zone discussed in text. Well location is projected. Main tectonic faults are marked by heavy black lines (fault set II in text), minor by thin black lines. Salt tectonic growth faults are marked by gray lines (fault set I in text). Location of wells and crossing profiles presented in other figures is marked above the interpreted section. For location map see Fig. 1. (a) NNE-SSW trending multi-channel profile AS-11 located along the continental shelf showing the two elevated structures, Carmel and Rosh Haniqra, separated by the Western Galilee Graben. This profile crosses the southernmost segment of the fault zone (FZ), whose northern bounding fault was previously interpreted as the marine continuation of the Carmel fault (e.g. Garfunkel and Almagor, 1985). Differences between the northern and southern Galilee continue from onland into the Western Galilee Graben offshore, divided by the Central Galilee Escarpment (CGE). (b) The central segment of the fault zone, represented by two E-W trending multi-channel seismic profiles extending from the continental shelf basinwards. 1. Profile AS-22 showing how the Carmel structure on the east is bounded by the fault zone (FZ). At the edge of the continental shelf a positive flower structure manifests the westward transpressional indentation of the Carmel structure against the fault zone. Note that this profile is located south of the Carmel fault. 2. Profile AS-8 showing the truncation of the Western Galilee Graben by the fault zone (FZ), which extends from the continental slope to the basin. East of the fault zone the Rosh Haniqra fault marks the northern extent of the Western Galilee Graben (see map in Fig. 5). (c) E-W trending single-channel seismic profile 6, which extends from the Lebanese continental margin into the basin, representing the northern segment of the fault zone. The fault zone is manifested by high angled faults, which fold and delimit the sedimentary units between them, and may represent the near-surface expression of a narrow strike-slip flower structure. East of the FZ, landward thickening of the Plio-Pleistocene unit is evident above thinning of the Messinian unit from below. West of the fault zone, the sedimentary section appears generally horizontal indicating tectonic quiescence. Local undulations and small bathymetric steps in the Plio-Pleistocene section indicate their basinwards drag by the Messinian evaporites from below. Abbreviations: FZ = Fault Zone, M = Top Messinian, N = Base Messinian, LC = Lower Cretaceous (upper Aptian), JR = Upper Jurassic, CGE = Central Galilee Escarpment, D = possible Diapirs.

featureless except for a few submarine channels and minor bathymetric steps (Fig. 5a). Plio-Pleistocene sediments are slightly undulating (Fig. 4c). Close to the surface a few growth fault are present resulting in the formation of these steps. This relative tectonic quiescence is also observed in the deeper subsurface. The top Messinian reflector (M) appears generally horizontal with local undulations in the west while the base of the Messinian evaporite sequence (N) slopes basinwards (Fig. 4c).

4. Discussion

This study examines the tectonic relations across the Levant continental margin. In order to understand the tectonic differences between the highly deformed area onland and the relatively featureless Levant basin the continental slope and its base were analyzed in high resolution. At the base of the continental slope the upper section of the sedimentary column is deformed and forms a belt that becomes narrower to the north (Ben-Avraham et al., 2006). This trend is accompanied by progressive narrowing of the continental shelf, steepening of the continental slope and accentuation northwards of the onland relief.

4.1. Onland and on the continental slope — northern Israel and southern Lebanon

The highly deformed Galilee-Lebanon area can be divided into two provinces, east and west of the Roum fault (marked on Figs. 1b and 5a as EGL and WGL — Eastern and Western Galilee-Lebanon Provinces respectively). The eastern province is comprised of a highly elevated area of the Lebanon — Anti-Lebanon Mountains, separated by the Bekka valley.

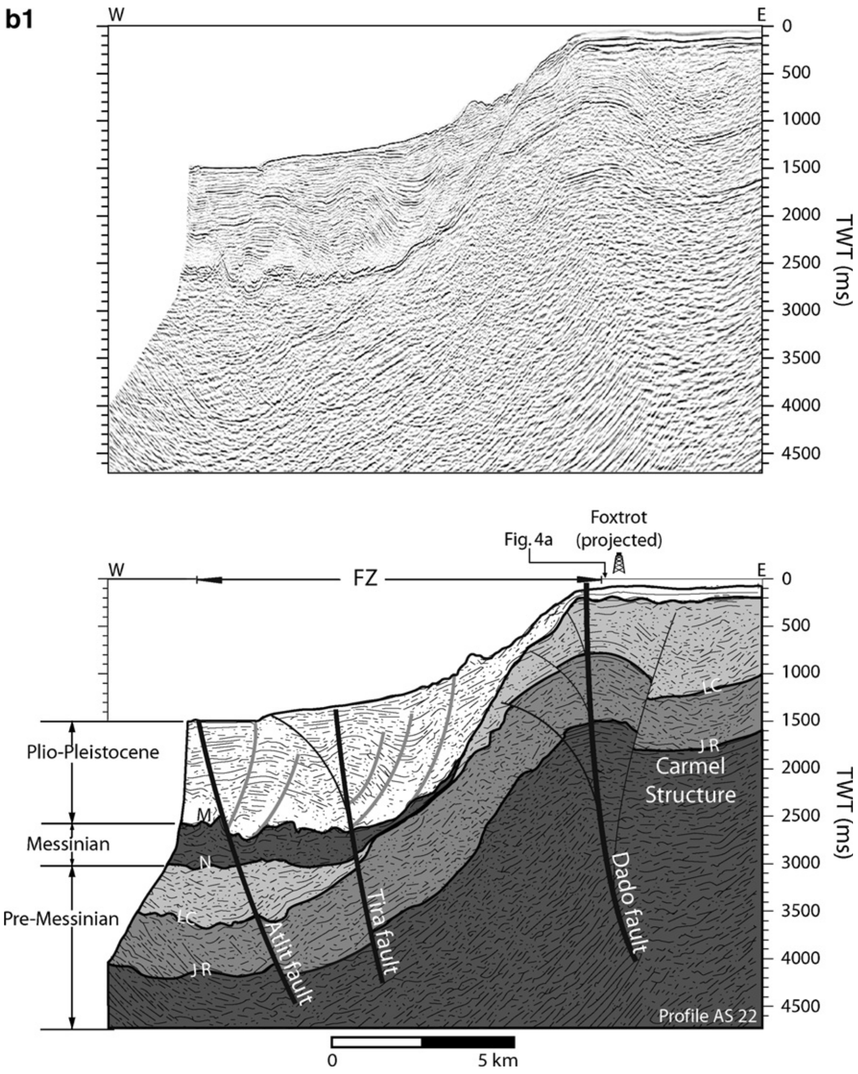

Fig. 4 (*Continued*)

These features are located along the N30°E trending Yammouneh fault, to the east and north of the Roum fault. The western province exhibits a topographically lower area, which continues southwards into the Galilee (e.g. Walley, 1998), between the Roum fault and the Levant continental margin. The eastern and western provinces show continuation of surface-related geomorphologic characteristics, but remain distinguished from each other regarding their tectonic style. In the eastern province, a combination of the slight rotational (6° counterclockwise) sinistral N-S movement along the Yammouneh fault caused a wide zone of crustal overlap of the Arabian plate and Sinai sub-plate (Freund and Tarling, 1979) along the Lebanese restraining bend (LRB in Fig. 1b). This overlap resulted in the uplift of the NNE-SSW trending Lebanon and Anti-Lebanon Mountains, which exhibit a large positive isostatic anomaly (Segev et al., 2003). Further northwest, Daeron et al. (2004) suggested that the Lebanon Mountains are pushed against the ESE dipping "Beirut-Tripoli thrust" that comprises the offshore prolongation of the Roum fault.

The western Galilee-Lebanon province reacts differently to the stresses resulting from movements along the Lebanese restraining bend (Fig. 5a). Deformations in this province are mainly internal and do not exceed its boundaries: the Roum fault in the east and north (Ron, 1987; Walley, 1998), and the Carmel fault zone in the south (Ginzburg and Ben-Avraham, 1992; Rotstein et al., 1993; Achmon and Ben-Avraham, 1997). In this area the topography is less prominent than in the eastern province, becoming progressively lower towards the Galilee, in the south. Internal deformations are manifested by a counterclockwise rotation of faulted blocks in Lebanon and northern Galilee (Freund, 1970; Freund and Tarling, 1979), which are delimited by second order southwest trending dextral faults (Ron, 1987; Walley, 1998). The southern Galilee exhibits a general N-S fan-like widening, which grows smaller from the east, along the Dead Sea fault, to nearly zero along the Levant margin (Freund, 1970). To the west, deformations of the western province of Galilee-Lebanon extend to the coastal area (Garfunkel and Almagor, 1985), and are manifested on the continental shelf by two

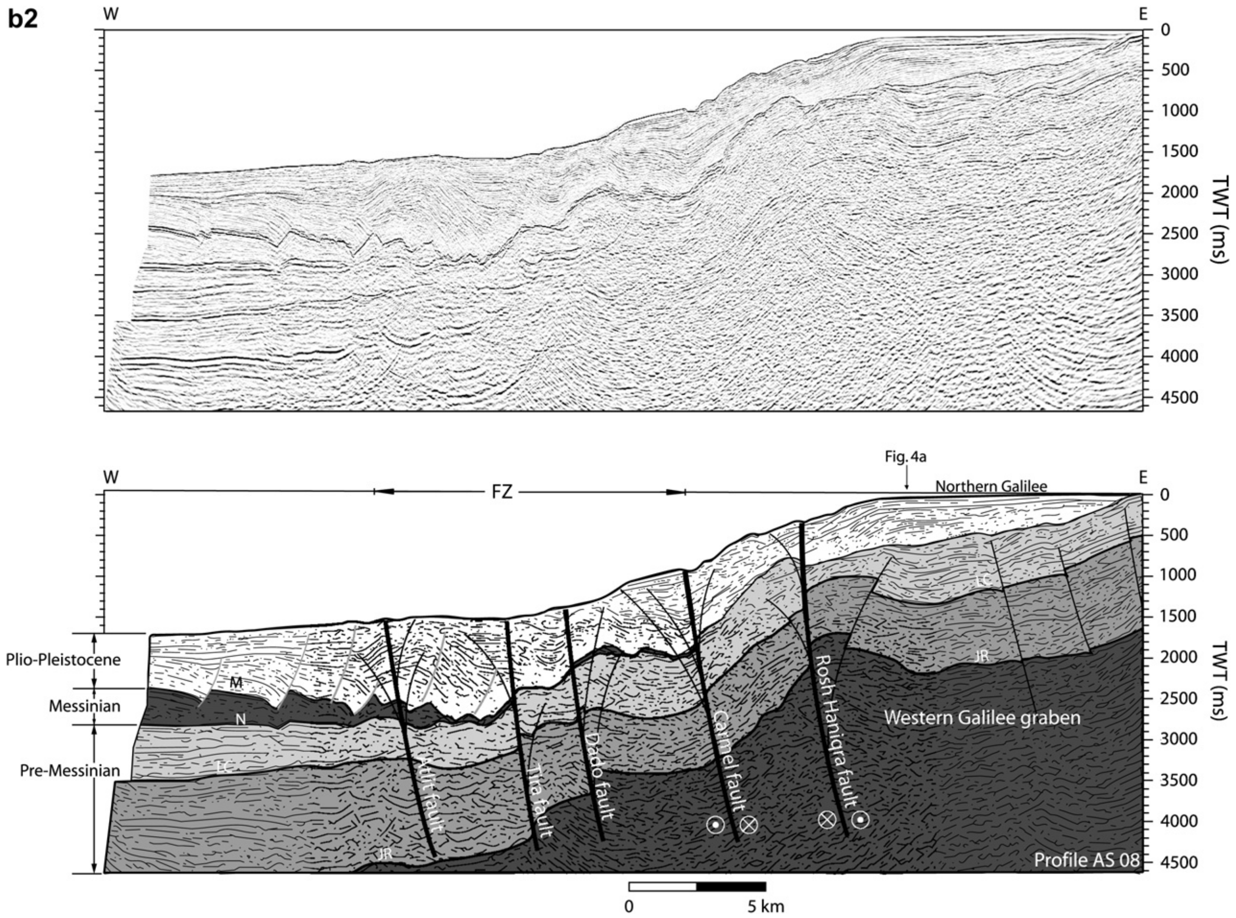

Fig. 4 (*Continued*)

main features. First, offshore southern Lebanon, shelf marginal wedges are tilted basinwards, probably due to tectonic forces (Ben-Avraham et al., 2006). Second, further to the south the uplifted Rosh Haniqra structure projects seawards and together with the uplifted Carmel structure, delimits the Western Galilee Graben (Figs. 4a and 5a) (Garfunkel and Almagor, 1985).

While the previous studies discussed above present a complex picture of deformations onland, our data show that beyond the fault zone, offshore, there is no evidence for major tectonic activity. This fault zone (marked as FZ on Fig. 5) delimits the western province of Galilee-Lebanon in the west similar to the way that the Roum fault delimits the eastern province. Patterns of deformation change sharply from the eastern to the western Galilee-Lebanon provinces across the Roum fault. The prominent structural differences between the western province and the Levant basin occur across the marine continuation of the Carmel fault (the fault zone). However, the transition between activity to quiescence does not occur along the continental slope, as would be expected, but along the fault zone further to the west. In the area, where the continental shelf widens, some of the E-W trending faults that deform the western Galilee onland can be traced offshore. Still, their extent is limited to the shelf. This may be explained by the sharp continental-oceanic transition zone which is present at depth (Ben-Avraham et al., 2002) which acts as a rheological border for the western Galilee-Lebanon province, as modeled by Ben-Avraham and Lyakhovsky (1992).

4.2. Active faulting along the base of the continental slope

Results indicate that two sets of faults are active in a narrow belt along the continental slope of northern Israel and at the base of the slope off southern Lebanon, up to offshore Beirut. The first set of faults (fault set I, marked by gray lines on Figs. 4 and 6) consists of shallow halokinetic-driven growth faults that deform the Messinian to recent section. The second and more dominant set (fault set II, black lines on Figs. 4 and 6) contains deeply rooted high angle faults, which represent the fault zone (FZ on Figs. 4–6).

4.2.1. Fault set I – salt tectonics

Along the base of the continental slope of southern Lebanon the upper sedimentary sequence, from the Messinian to the present, is deformed in a belt that extends from Tyre to Beirut (Ben-Avraham et al., 2006) (gray area marked by DB on Fig. 5a). In this ‘Deformation Belt’ the upper plastic Plio-Pleistocene sediments thicken landwards, producing

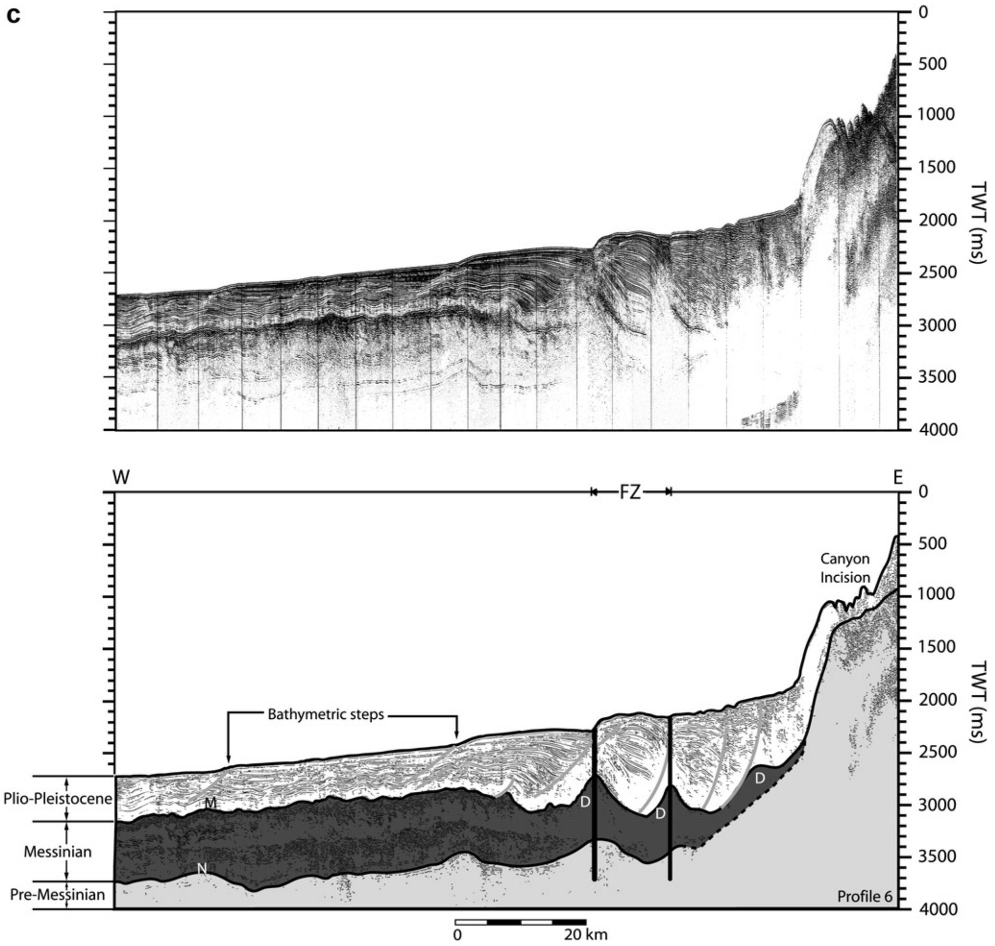

Fig. 4 (*Continued*)

a pressure gradient upon the underlying viscous Messinian evaporites, which thin landwards (Fig. 4c). As a result, the Messinian evaporites become unstable, fail to support the overburden and flow basinwards, dragging the Plio-Pleistocene sediments with them (Raft-Tectonics, e.g. Duval et al., 1992). Consequently, the plastic Plio-Pleistocene sediments undergo pure shear, expressed by the presence of landward dipping growth faults. These faults may allow for the upward flow of evaporites forming diapirs. Blocks between the growth faults are mostly tilted to the east, i.e. landwards. These salt tectonic deformations are limited laterally (east-west) by the second set of faults which is discussed below (fault set II – light gray area marked by FZ on Fig. 5a).

Deformation of the Plio-Pleistocene and Messinian sediments which form the 'Disturbed Zone' south of the Carmel structure (Tibor and Ben-Avraham, 1992) was attributed to salt tectonics. In contrast to the clear lateral borders of the 'Deformation Belt' north of Tyre, in the south the western border of the salt-driven deformations is more diffused and less defined (DB on Fig. 5a). These differences are the result of activity along the central and northern segments of the fault zone combined with the salt-driven growth faults from Tyre northwards. South of the Carmel structure interactions between the Plio-Pleistocene and the Messinian sediments are less affected by tectonic elements, with activity occurring solely along the growth faults (Fig. 5a and 6).

4.2.2. Fault set II – Carmel fault zone

Along the continental margin, from the Carmel structure northwards, a set of four deeply-rooted sub-parallel high-angle faults, which comprise the main fault zone, was found in the seismic data. Variations in type and orientation of meso-scale structures along these faults allowed the division of the fault zone into three consecutive segments (Fig. 5b). On the continental shelf the four faults were identified in previous studies up to its edge (Ben-Gai and Ben-Avraham, 1995). However, seismic analysis conducted in the present study shows that these faults can be traced beyond this point, sub-parallel to each other and therefore, are referred to as belonging to a single system of faults. Sinistral motion is evident along the components of the southern segment of the fault zone as displacements of Mesozoic units, which compose the Carmel structure (Fig. 4a).

The question of the continuation of the Carmel fault zone beyond the edge of the continental shelf has been the center of dispute in previous studies (Fig. 2b). According to the dense network of seismic lines used in the present study, at the shelf edge the fault zone almost converges with the orientation of the continental slope and continues along its trend northwards.

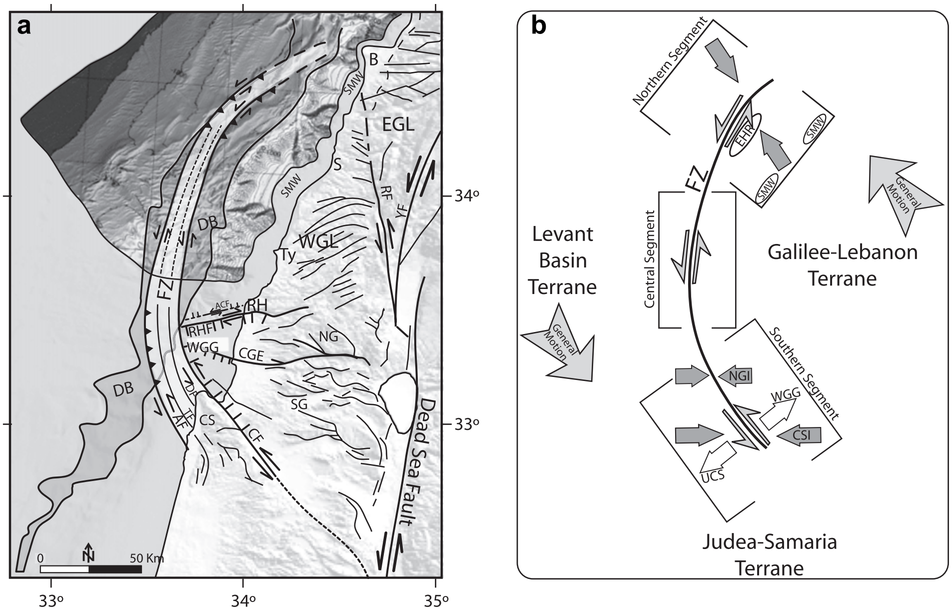

Fig. 5. The marine continuation of the Carmel fault zone and its structural relations to other major tectonic features in the area (marked by FZ on a light gray strip in this figure and by FZ in Figs. 4, 8 and 9). (a) Base map is comprised of the DTM and multibeam data collected during SHALIMAR survey (Ifremer, 2005). Altering sense of motion is marked along the FZ. 'Deformation Belt' (DB) is marked after Ben-Avraham et al. (2006). Rosh Haniqra fault (RHF), which delimits the Western Galilee Graben (WGG) from the north, extends from onland to the continental shelf until it is truncated by the FZ at the shelf edge. Central Galilee Escarpment (CGE), which marks the boundary between northern and southern Galilee onland (after Matmon et al., 2003) extends to the shelf edge, also truncated by the FZ. Elongated ridges and scars are evident along the northern FZ segment. These ridges are truncated offshore Tyre (Ty), as a result of activity along the central FZ segment. Extent of the 'Deformation Belt' (DB, dark gray strip) is marked after Ben-Avraham et al. (2006). (b) Schematic illustration of the altering sense of movement along the three segments of the FZ, between the three crustal terranes (Galilee-Lebanon, Judea-Samaria and Levant basin). A general sinistral sense of motion along the FZ is inferred by movement along its land segment, structures along its trend, and the prevailing stress regime (i.e. Giannerini et al., 1988). In the southern segments gray arrows mark the westwards Indentation of the Carmel Structure (CSI) and the Northern Galilee Indentation (NGI). White arrows indicate extension between the Western Galilee Graben (WGG) and the Uplifted Carmel Structure (UCS). In the northern segment gray arrows represent the non-coaxial compression manifested on the bathymetry (a) as Elongated Hummocky ridges (EHR). Abbreviations: FZ = Fault Zone, RHF = Rosh Haniqra Fault, CF = Carmel Fault, AF = Atlit Fault, DF = Dado Fault, TF = Tira Fault, RF = Roum Fault, YF = Yammouneh Fault, CS = Carmel Structure, WGG = Western Galilee Graben, CGE = Central Galilee Escarpment, SMW = tilted Shelf Marginal Wedges, WGL = Western Galilee-Lebanon province, EGL = Eastern Galilee-Lebanon province, Ty = Tyre, S = Sidon, B = Beirut, SG = Southern Galilee, NG = Northern Galilee, CSI = Carmel Structure Indentation, NGI = Northern Galilee Indentation, UCS = Uplifted Carmel Structure, EHR = Elongated Hummocky ridges.

Offshore Tyre (central segment), the continental slope trends more to the NE while the fault zone trends to the north (Fig. 5). There, the fault zone cut the seafloor west of the base of the continental slope. Along this entire segment, orientation of compressional fold axis are parallel to the trend of the fault zone. Offshore the Carmel structure, these folds were interpreted as the outcome of movement along a shore parallel transpressional fault which appears as a positive flower structure (interpretation suggested by Steve Tobias, 1999, personal comm.). The present study, which examined the same data together with additional surveys, shows that the faults along the continental slope (central segment) continue the ones from the southern segment, on the continental shelf. Therefore, the folds at the edge of the Carmel structure are interpreted as a transpressional westwards indentation of the structure (Fig. 5b), which results from a progressive bend of the fault zone from northwest to north.

In the northern part of this segment (central segment), roughly offshore Tyre, the trace of the fault zone no longer follows the continental slope but rather runs along its base. Garfunkel (1984), who studied the occurrence of 'Tyre disturbance' in this area explained this by salt tectonic processes, but assumed that deeply rooted faults are present below the disturbance. These faults, however, were never demonstrated. Our data shows that in this area the faults of set II cut diagonally through set I, separating the 'Disturbed Zone' in the south from the 'Deformation Belt' in the north (discussed above) (FZ and DB on Fig. 5a). This diagonal cut is evident by the change in deformations of the Plio-Pleistocene section and the bathymetry. In this segment disturbances are pronounced and diffused due to the differences in strike between fault set I and fault set II.

In the northern segment of the fault zone, from offshore Sidon up to Beirut, high angle faults cut through the sedimentary column sub-parallel to the base of the continental slope (Fig. 4c). Ben-Avraham and Ginzburg (1986) interpreted one of these faults as a clear vertical strike-slip fault with different sequences of sub-bottom reflectors on both sides. Regional seismic analysis carried out in the present study shows that these sequences are the narrow and elongated folds, which appear between the high-angle faults of set II and are exhibited on the bathymetry as long hummocky ridges (Fig. 5). Motion along these faults occurs simultaneously with the halokinetic faults of set I within the 'Deformation Belt'. In this segment both fault sets follow, more-or-less the same strike and hence, deformations in this area are distinguishable in contrast to the diffused deformations in the central segment. The sub-vertical appearance of fault set I and the sharp western border of the belt formed by one of its strands, indicates that this set is dominant.

Occurrence of these structures in the northern segment of the fault zone can not be explained solely by simple strike-slip displacements along the base of the continental slope. Formation of elongated folds requires stronger non-coaxial stresses than expected along a shear zone. These folds are therefore interpreted as resulting from an asymmetric sense-of-shear along the fault zone (Fig. 5b). At the head of the continental slope Ben-Avraham et al. (2006) showed the existence of shelf marginal wedges which are tilted basinwards (Fig. 5a). The tilt was suggested to be controlled by post sedimentation tectonic activity. Moreover, according to results of the present study the presence of these structures, together with the elongated ridges, suggests that movement along this segment of the fault zone is transpressional.

4.2.3. Lack of evidence for the Carmel fault zone in the Levant basin

In spite of the extensive research which focused on the offshore continuation of the Carmel fault (Fig. 2a), there is general agreement for its trend and nature of movement only up to the edge of the continental shelf of northern Israel, i.e. the first and southernmost segment of the fault zone described above. Analysis of seismic activity during the years 1900–1991 was interpreted by Salamon et al. (1996). They proposed that the northern border of the Sinai sub-plate is located in the Levant basin, where the Carmel fault projects westwards, and curves southwards towards the head of Suez Canal in the Mediterranean. However, they state that this border could not be delineated exactly, due to the low level of seismicity in the NE region of the eastern Mediterranean basin. Hofstetter et al. (1996) showed that onland, the Carmel fault is seismically active but that this activity becomes diffused towards the basin. According to their study the offshore extension of this fault generally trends WNW into the basin.

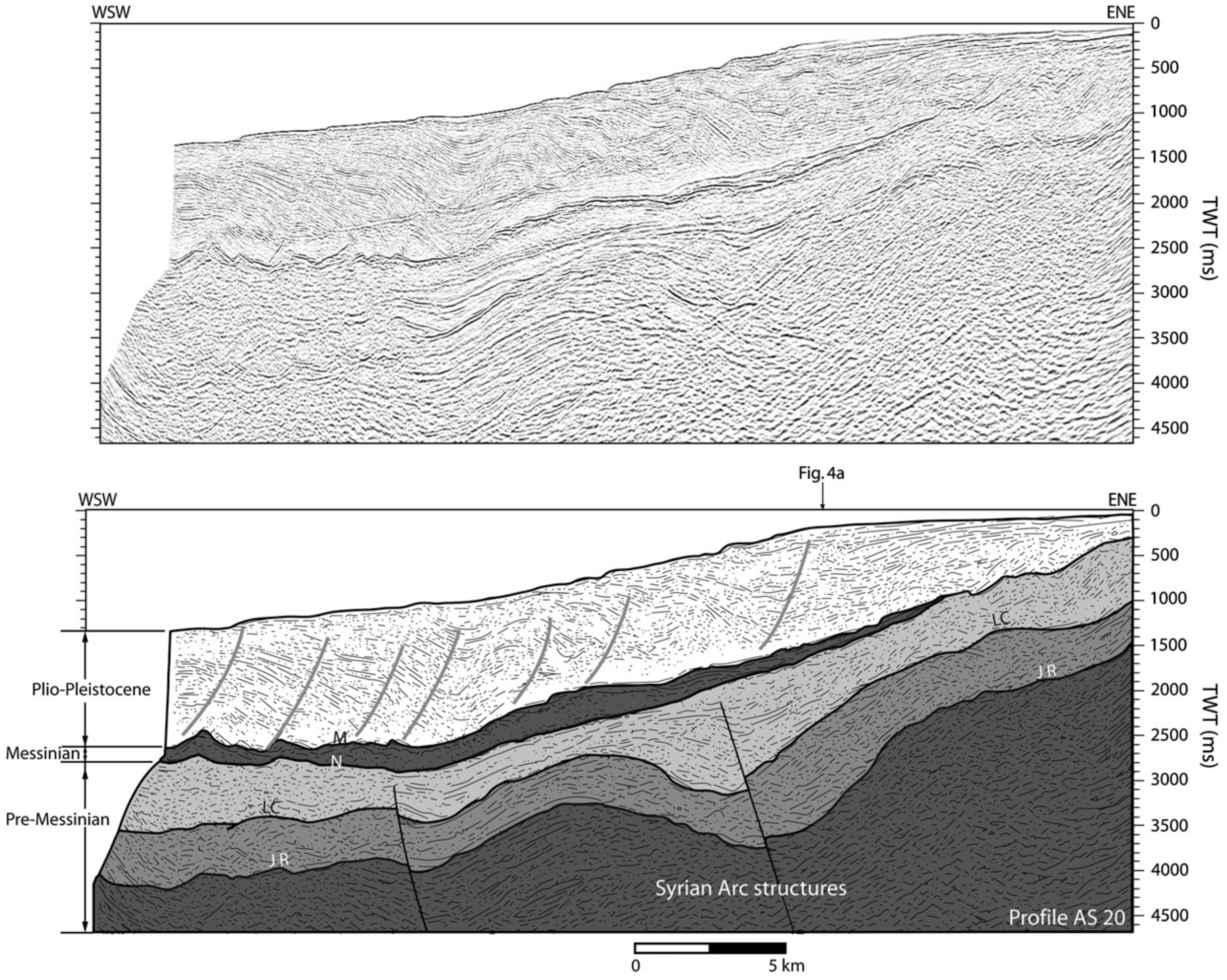

Fig. 6. ENE-WSW trending multi-channel seismic profile AS-20, located ∼10 km south of the Carmel structure showing a regular continental margin with no evidence for faulting along the marine continuation of the Carmel fault zone (e.g. Figs. 4b1 and 4b2). Older faults within the deeper section (thin black lines), between structures of the late Cretaceous Syrian arc folds, are not evident in the younger Messinian and Plio-Pleistocene units. A large number of growth faults disturb the Plio-Pleistocene unit, driven by salt tectonic processes (fault set I, marked by gray lines).

In order to examine these suggestions all available seismic data from the continental margin of Galilee-Lebanon and the Levant basin was analyzed. Results indicate that no significant fault exists in this area continuing the southern segment of the fault zone westwards. Only slight deformations are exhibited in the Plio-Pleistocene section, resulting from salt tectonics (Fig. 7). In addition, tectonic quiescence was recognized to the northwest (Fig. 8a), indicating that no major fault occurs west of the central and northern segments. On the other hand, a well developed fault zone is located along the continental slope of the northern Levant, offshore Syria (Fig. 8b) (see below).

Abdel Aal et al. (2000) presented a schematic sketch of a fault extending from the Levant continental margin towards the Cyprean arc (Fig. 2a). They located this fault between the Roum and Carmel fault and it is not clear which of them they addressed. To examine the possibility that the marine continuation of the Carmel fault zone extends towards the Cyprean arc, the present study reexamined previously published seismic data collected between the Levant margin and Cyprus (Fig. 8, Kogan and Stenin, 1994). Particular attention was paid to the region outside the boundaries of our data, specifically south of the Latakia ridge, which is considered to be the southernmost border of the Cyprean arc (e.g. Ben-Avraham et al., 1988; Kempler and Garfunkel, 1994; Ben-Avraham et al., 1995). Seismic data show that the upper kilometers of the sedimentary section between the Latakia ridge and the western border of the supposed marine continuation of the Carmel fault (the fault zone) are not dissected by any major fault (Fig. 8a). Horizons within this section appear to be more-or-less continuous and rather horizontal. Furthermore, most of the seismic activity in the vicinity of the eastern Cyprean arc is concentrated along the arc itself and not in the Levant basin (Fig. 3).

4.2.4. *Large scale faulting along the Levant continental margin — north of the Carmel structure*

The combination of data presented in this study, between the Levant continental margin and the Cyprean arc, shows that the three segments of the fault zone presented here compose the marine continuation of the Carmel fault zone (FZ on Fig. 9). This zone extends from the continental slope of northern Israel, along the slope of southern Lebanon and up to Beirut, in three consecutive segments (Fig. 5b). Motion along this fault system displaces the western province of Galilee-Lebanon onland (which consists of continental crust) against the oceanic crust of the Levant basin (Fig. 9b). Furthermore, analysis of the entire dataset shows that there is no major faulting: (1) west or south of the southern segment of the fault zone; (2) west of the ‘Deformation Belt’; or (3) in the vicinity of the eastern Cyprean arc.

Variations in trend and structures along the three segments of the marine continuation of the Carmel fault zone reflect the differential motion between the western Galilee-Lebanon province and the Levant basin (Fig. 5b). These variations are: (1) NNE trending dip-slip displacements across the southern segment, with a sinistral component to the NW between the uplifted Carmel structure in the south and the downfaulted Western Galilee Graben north of it; (2) relatively pure shear with minor compressional evidence along the central segment, between the western Galilee-Lebanon province and the Levant basin; and (3) non-coaxial shortening of the NNE-SSW trending folds along the northern segment, within the ‘Deformation Belt’ (DB on Figs. 5a and 9a), with possible slight reverse faulting at the base of the continental slope, exhibited by the tilted shelf marginal wedges (SMW on Fig. 9a). The combination of these features indicates that the overall displacement along the entire fault system is mainly oblique sinistral transpression. This is supported by fault simulations carried out by

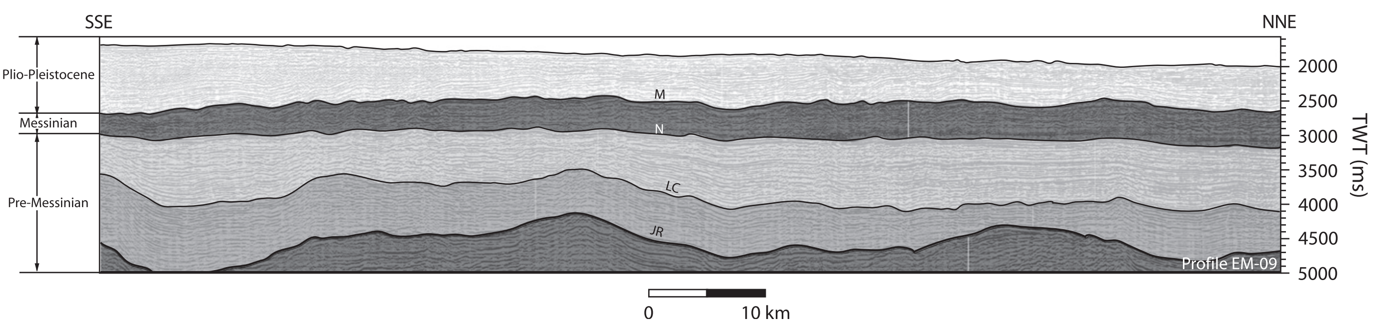

Fig. 7. NNE-SSW trending multi-channel seismic profile EM-83-9. Subsurface reflectors within the Levant basin are horizontal and show no evidence for tectonic faulting.

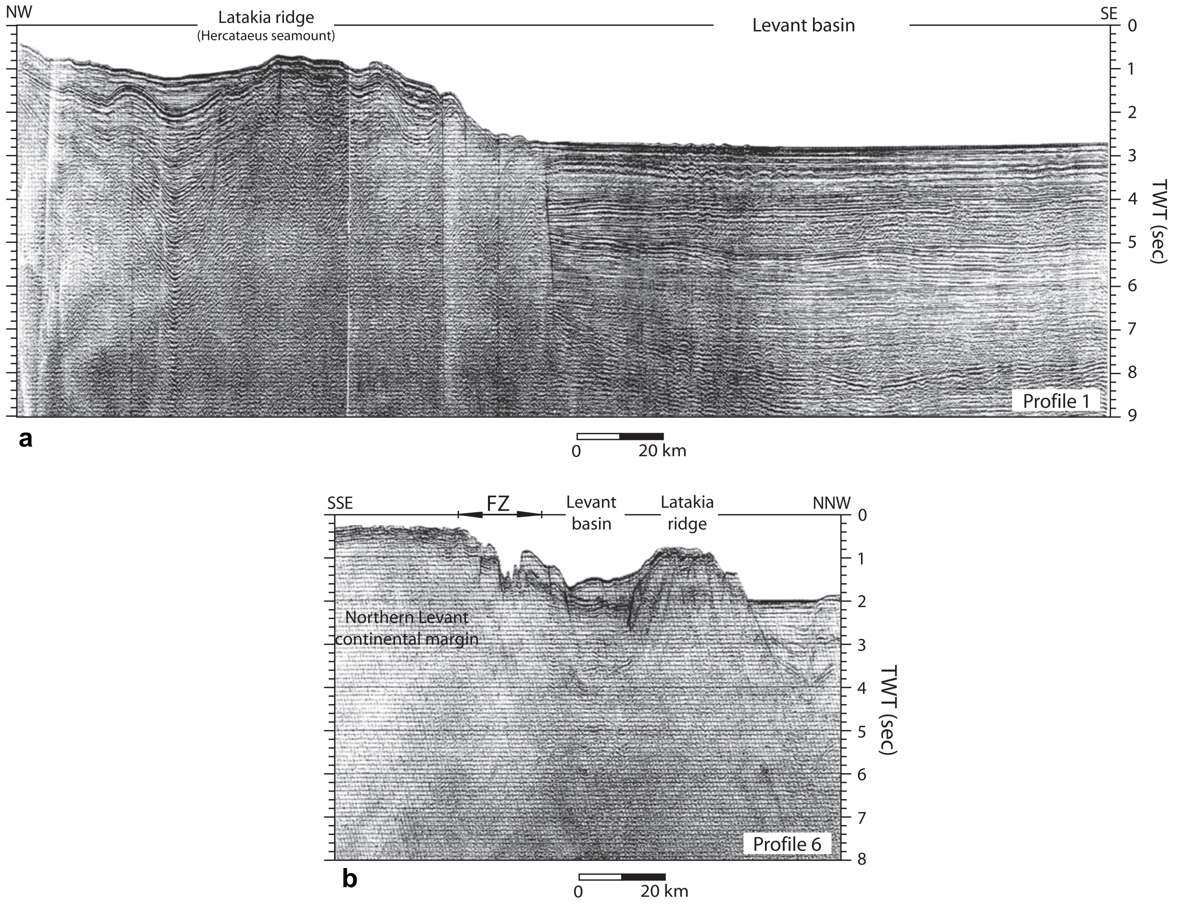

Fig. 8. Two NNW-SSE trending seismic profiles crossing the northeastern corner of the Levant basin (after Kogan and Stenin, 1994). For location see Fig. 1. (a) Profile 1 extends from the Hercataeus seamount across Latakia ridge into the Levant basin. Reflectors within the basin are generally horizontal to depth of ~8 s, and show no evidence for major faulting. (b) Profile 6 extends from Latakia basin in the north across Latakia ridge to the northern Levant continental shelf. A fault zone (FZ) is evident along the continental slope, also suggested by Darkal et al. (1990).

Ben-Avraham and Lyakhovsky (1992). They suggested that the area between the Roum and Carmel faults onland (the western province of Galilee-Lebanon) accommodates part of the displacements from the Dead Sea fault. Motion is transferred up to the continental margin where it is then channeled northwards by the sharp continental-oceanic crustal transition (discussed below). This motion is interpreted here as a general NNW push of the western Galilee-Lebanon province onland by the Lebanese Restraining Bend (LRB on Fig. 9a) against the Levant basin, inducing transtensional stresses on the southern segment of the marine continuation of the Carmel fault (Fig. 9b).

One question that needs to be addressed is the temporal relations between the two fault sets (I and II). Spatially, these faults overlap only in the area north of the Carmel structure (Fig. 9a). Fault set I (attributed to salt tectonics) results from the interactions between Plio-Pleistocene Nile derived sediments and the underlying Messinian evaporites. The Messinian event provides a maximum age constraint for the deformations. Since these deformations depend on loading of the upper Plio-Pleistocene unit − the maximum age must be younger and attributed to the period when there were just enough sediment to produce differential loading on the evaporites. Recent activity along the Carmel fault zone (Fault set II), as a branch of the Dead Sea fault, is estimated to have begun in the mid-late Miocene, with most of the activity that shaped the present landscape occurring since the Pleistocene (Achmon and Ben-Avraham, 1997). Hence, the two fault sets, which represent two independent processes, were (and still are) active during the same time frame. Nevertheless, while the salt tectonic deformations (set I) are affected by activity along the Carmel fault zone (north of the Carmel structure), they do not represent a deep rooted tectonic element as suggested in previous studies (e.g. Neev et al., 1985).

4.3. Crust of the Levant basin and its margin

The large-scale geometry of the marine continuation of the Carmel fault zone is constrained by surface geology as well as seismic reflection data that image the upper kilometers of sediments. This fault is a branch of the Dead Sea fault plate boundary and therefore could represent a deep rooted displacement. Johnson and Kattan (2001) described a similar fault zone that exhibits variations in trend and structures along its axis in the southwestern Arabian-Nubian shield. According to their study these variations, which are represented by a combination of flattening, extension, sinistral horizontal simple

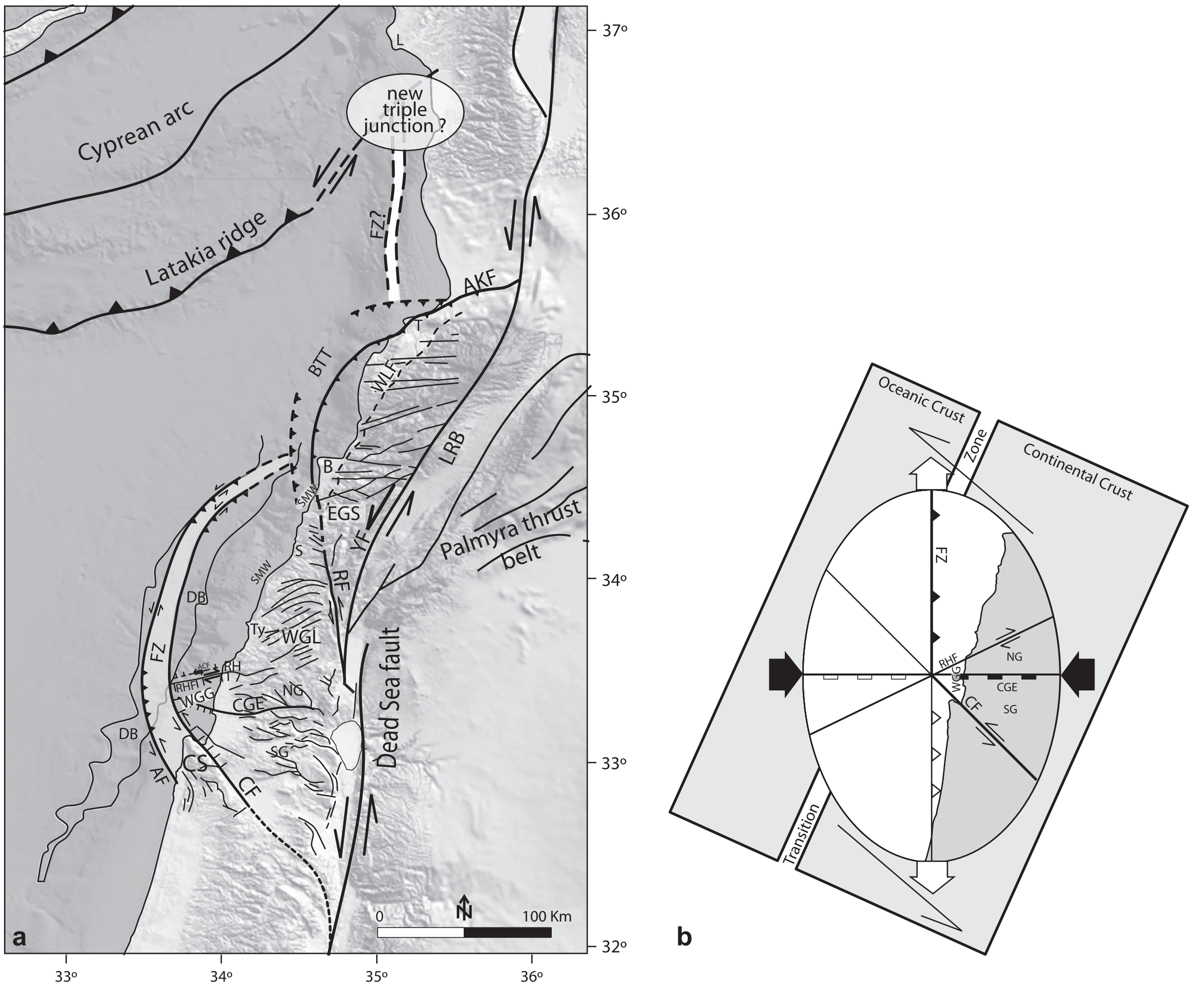

Fig. 9. (a) Map summarizing the main tectonic elements as interpreted in the present study, combined with results of previous studies. The marine continuation of the Carmel fault zone (FZ-light gray strip) trends along the Levant continental margin from the Carmel Structure (CS) northwards. In this area the shallow sedimentary sequence is affected both by the FZ (fault set II) and by salt tectonic processes in the 'Deformation Belt' (DB, fault set I). South of the FZ, the borders of the DB are more irregular. A general northwestwards motion of the Western Galilee province (WGL) is manifested by westward indentation of the Galilee, and compressional features along the northern segment of the FZ. Spatial distribution of basinwards tilted Shelf Marginal Wedges (SMW) is marked according to Ben-Avraham et al. (2006). From Beirut (B) northwards, the 'Beirut-Tripoli thrust' (BTT, marked after Daeron et al., 2001), continues onland along the Akkar Fault (AF) and bounding the Western Lebanon Flexure (WLF) onland (marked after Walley, 1998). Further northwards faulting along the Syrian continental slope is marked in accordance with the seismic data (Fig. 8) and Darkal et al. (1990). A possible location of a forming triple junction is marked between the faulting along the Levant continental margin and the Latakia ridge of the Cyprean arc (also suggested by Butler et al., 1998). (b) Strain ellipse illustrating the northwestward push of Western Galilee-Lebanon province (WGL) along the Carmel Fault Zone (FZ), which is guided by the abrupt crustal transition zone. N-S widening of the southern Galilee (SG), between the Central Galilee Escarpment (CGE) and the Carmel fault (CF), occurs along with E-W compression and arching of the northern Galilee (NG) against the FZ offshore. Open triangles and rectangles indicate sense of motion which is not evident in the data, because of the different crustal terrane in the west (Levant basin) and in the south (Judea-Samaria). Abbreviations: FZ = Fault Zone, RHF = Rosh Haniqra Fault, CF = Carmel Fault, AF = Atlit Fault, YF = Yammouneh Fault, RF = Roum Fault, DB = Deformation Belt, BTT = Beirut-Tripoli Thrust, AF = Akkar Fault, CS = Carmel Structure, WGG = Western Galilee Graben, CGE = Central Galilee Escarpment, SMW = tilted Shelf Marginal Wedges, WGL = Western Galilee-Lebanon province, EGL = Eastern Galilee-Lebanon province, SG = Southern Galilee, NG = Northern Galilee, WLF = Western Lebanon Flecture, LRB = Lebanese Restraining Bend, Ty = Tyre, S = Sidon, B = Beirut, T = Tripoli, L = Latakia, CSI = Carmel Structure Indentation, NGI = Northern Galilee Indentation, UCS = Uplifted Carmel Structure, EHR = Elongated Hummocky ridges.

shear and finite strain variations are the result of oblique transpression, similar to that found in the present study for the different segments of the Carmel fault. This type of motion was also predicted by mathematical modeling (e.g. Dewey et al., 1998). Johnson and Kattan (2001) related the complex nature the fault zone in their study area to its location between different crustal terranes. Another comparable tectonic setting was reported by Attoh et al. (2004) for the Romanche fault zone, along the continental margin of West Africa.

Similarly, the Carmel fault zone is located between three units that differ in their crustal makeup. Ben-Avraham and Ginzburg (1990) divided the area onland into two main crustal provinces north and south of the Carmel fault, based on seismic refraction data (Fig. 1a). To the south, the crust of Judea-Samaria is clearly thicker than that of Galilee-Lebanon (~30 km as opposed to ~23 km) and exhibits a different internal structure. These two units are comprised of continental crust. Gravity, magnetic and earthquake data support this division (Ginzburg and Ben-Avraham, 1986; Rybakov et al., 1997; Hofstetter et al., 2000). According to earthquake data Hofstetter et al. (1996) showed that the southern unit is stable and aseismic, whereas the northern one is characterized by a wide area of diffused seismic activity (Fig. 3). To the west a third crustal unit, which is underlined by oceanic crust, was defined – the Levant basin (Ben-Avraham and Ginzburg, 1990).

A sharp crustal transition between the continental Galilee-Lebanon terrane and the oceanic Levant basin is located below the continental slope (Ginzburg and Ben-Avraham, 1986; Ben-Avraham et al., 2002). This sharp transition marks the boundary between areas of significant differences in crustal strength. According to the present study, the marine continuation of the Carmel fault zone developed into this boundary, propagating to the north as supported by numerical models for the region (Ben-Avraham and Lyakhovsky, 1992). At greater depths, this fault zone may extend through the crustal transition zone as a vertical structure, reflecting oblique sideways movement of Galilee-Lebanon past the Levant basin. However, the accentuated bathymetric relief across the Galilee-Lebanon continental margin along with the elevated continental shelf and the tilted shelf marginal wedges indicate a more feasible possibility. These features suggest that the Galilee-Lebanon terrane forms a thrust of crustal-scale, over the hanging wall of the fault zone. Seeing as thrusting and compression were described in the area (along the Lebanese restraining bend, Walley, 1998; and the Palmyra thrust belt, Chaimov et al., 1990) this phenomenon is not unexpected in this region.

4.4. Tectonic implications

A large debate exists in the literature regarding the partitioning of movement between branches of the Dead Sea fault system and their relation to the Levant continental margin, and the Cyprean arc. Direction of maximum principal stresses (Reches, 1987; Giannerini et al., 1988) and calculations of ideal plate motion in this area (Westaway, 2003) indicate that motion between the African and Arabian plates should have been accommodated along the Roum fault on a trajectory that crosses the NE Levant basin from Beirut to eastern Cyprus. However, data examined in the present study did not find evidence for large scale faulting in the NE Levant basin, between the Levant margin and the eastern Cyprean arc. A possible explanation for this could arise from the structure of the different crustal provinces in the study area. The sharp rheological contrast that exists between the weaker continental crust of the Levant margin and the stronger oceanic crust underlying the Levant basin resists any fracturing initiated onland. Given this rheological contrast, Westaway (2003) explained the contradiction between the ideal plate motion he found and the observed one by the weaker nature of the continental crust which provided a pathway of less resistance for the development of the Dead Sea fault north of Beirut.

Further northwards, several deformations along the continental margin were initiated by activity onland, but are not evident in the Levant basin. In the vicinity of Beirut, the Roum fault reaches the Mediterranean coast (e.g. Butler et al., 1997). Offshore, Daeron et al. (2004) mapped its marine continuation as a bow shaped compressional feature that meets the Levant coast once again further northwards, south of Tripoli, coinciding with the Akkar fault (Walley, 1988) (AF on Fig. 9a). This offshore feature, termed the ‘Beirut-Tripoli Thrust’ (Daeron et al., 2004) (BTT on Fig. 9a), delimits the Lebanon Mountains in the northwest and was suggested to dip ESE as a typical thrust wedge (Tapponnier et al., 2004) under the Western Lebanon Flexure (Walley, 1998) (WLF on Fig. 9a). From Tripoli northwards, Darkal et al. (1990) explained the steep continental slope by a N-S trending fault that reaches offshore Latakia in the north. This fault is evident in Fig. 8b, as well as by a sharp gradient along the same strike, in the depth of the top basement (Rybakov and Segev, 2004 and references therein). This indicates that active tectonics occur along the Levant continental margin north of the marine continuation of the Carmel fault zone mapped in the present study. These activities extend to offshore Latakia, at the southern front of the eastern Cyprean arc plate boundary (Fig. 9a), and may coincide with a vertical hinge zone along the northern Levant margin as suggested by Ben-Avraham (1978).

4.4.1. Implications on the deformations onland

Displacement along the Lebanese restraining bend is manifested by the elevated Lebanon and anti-Lebanon mountains (the eastern Galilee-Lebanon province). While the marine continuation of the Carmel fault zone isolates the Levant basin from the deformations onland, some of them are absorbed by the western Galilee-Lebanon province before they reach the continental margin. Re-evaluation of the deformations onland, in view of the new findings offshore, indicates that some of these displacements are absorbed by internal deformations of the western province of Galilee-Lebanon, between the Roum and Carmel faults, and the continental margin (Fig. 9b). These internal deformations are manifested by a general N-S widening (Freund, 1970) and subsidence (Matmon et al., 2003) of Southern Galilee onland (SG on Fig. 9b), between the Central Galilee Escarpment (CGE) and the Carmel fault zone (CFS) in the south. In the Northern Galilee (NG) general E-W compression (Ron and Eyal, 1985) resulted in the formation of a wide arch (Matmon et al., 2003) that continues offshore as the Western Galilee Graben (Garfunkel and Almagor, 1985). On the continental shelf, data show that the northern and southern parts of the Galilee province are still distinguishable (Fig. 4a) up to the edge of the shelf, where they are truncated by the central segment of the Carmel fault zone (Fig. 9a). Further northwards, in southern Lebanon, internal deformations of the area are manifested by counterclockwise rotated blocks (e.g., Freund and Tarling, 1979), delimited by second order SW-NE trending dextral faults (e.g., Ron, 1987), which may extend to the narrow continental shelf.

Additional data from earthquake studies show that clusters of events are rather diffused in southern Lebanon and less indicative of plate boundaries (Salamon et al., 2003; Badawy and Horvath, 1999). An up-to-date map of seismic events, between the years 1990–2005 (IRIS, 2005) (Fig. 3), shows that ca. 45% of the events in the area are shallower than 20 km and only ca. 18% of them are larger than 4 ML. The combination of these deformations onland, together with reconstructions of the regional stress field (Reches, 1987; Giannerini et al., 1988) and the new data offshore suggest that there is a decrease in the degree of deformation from the eastern Galilee-Lebanon province to the Levant basin. This decrease is not gradual but rather sharp, occurring across the Roum fault in the east and the marine continuation of the Carmel fault zone along the Levant continental margin. In-between these boundaries the western province of Galilee-Lebanon is being sheared in a general NW-SE direction, pushed against the marine continuation of the Carmel fault zone, and acts as a buffer that attenuates transform of energy from the Dead Sea fault to the continental margin (Fig. 9b). Consequently, possible thrusting may occur on the Levant continental margin only north of the western Galilee-Lebanon buffer, along the 'Beirut-Tripoli thrust'.

4.4.2. Reactivation of the old continental margin

Results of this study indicate that the strike of the marine continuation of the Carmel fault zone is channeled along the sharp rheological boundary produced by the abrupt continental-oceanic crustal transition. The effect of this sharp boundary on the Roum fault is different: in the southeast, where this fault branches from the Dead Sea fault, it exhibits sinistral displacements (e.g. Butler et al., 1997). As it approaches the Mediterranean coast, the strike-slip motion fades out and is transferred to reverse faulting on the continental margin (Daeron et al., 2004). The transitional section of the Roum fault, in the coastal area, behaves as a hinge joint, which exhibits limited displacements on the surface. The possible change in characteristics along the Roum fault may be the reason for some controversies in the literature regarding the amount of slip along different sections of the fault and its specific location near the Levant continental margin. On the whole, the extensive faulting along the marine continuation of the Carmel fault zone, together with the indications for the 'Beirut-Tripoli thrust' suggest that the sharp passive continental margin not only reshapes the course of major faults onland, but is also reactivated as these faults are channeled along its trend.

In the east, the northern segment of the Dead Sea fault forms a braided fault system displacing the Arabian plate in respect to the Sinai sub-plate (e.g., Garfunkel, 1981) (Fig. 9a). Most of the motion, ca. 47 km of the left-lateral slip, is accommodated by the Yammouneh fault, which runs between the Lebanon and anti-Lebanon mountains (e.g., Walley, 1998). The remainder of the 100–105 km of motion reported on the southern segment of the Dead Sea fault is distributed between several branches of the fault east and west of the Yammouneh fault. To the east, the Palmyra thrust belt absorbs ca. 20 km of northward motion by shortening (Chaimov et al., 1990; Gomez et al., 2001; Zanchi et al., 2002). To the west the Roum fault displays ca. 8 km of sinistral displacement (Walley, 1998). Finally, the sinistral component of movement along the Carmel fault onland was estimated at ca. 4 km (Freund, 1970). The active nature of the continental margin north of the Carmel structure, as mapped in the present study, insinuates that some of the missing kilometers of displacement from the southern Dead Sea fault may be channeled through the marine continuation of the Carmel fault zone, towards offshore Latakia. In this area, interactions between the reactivated continental margin and the Latakia ridge may signify the initiation of a new triple junction (as suggested by Butler et al., 1998).

5. Conclusions

The tectonic regime presented in this study indicates that the seismically active Carmel fault zone continues along the Levant continental margin, from the Carmel structure in the south until south of Beirut. This system is accompanied by a second set of faults, which can be found along the base of the continental slope in most areas of the eastern Levant, and is attributed to salt tectonic processes. The Carmel fault zone follows the sharp crustal transition zone and reactivates the continental margin. As such, the continental margin north of the Carmel structure should be considered an active margin. Deformations from the Lebanese restraining bend are partially absorbed by the western Galilee-Lebanon province, but probably do not affect the Levant basin. This is due to the rheological discontinuity across the marine continuation of the Carmel fault zone, which acts as a tectonic isolator in the region. Evidence for activity found in this and previous studies suggests that the active continental margin extends up to Latakia ridge initiating a new triple junction in the eastern Cyprean arc.

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