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The tectonic framework of a complex pull-apart basin: seismic reflection observations in the Sea of Galilee, Dead Sea transform

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Abstract

A multi-channel seismic reflection survey consisting of 20 lines with a total length of 180 km was conducted in the Sea of Galilee. The data provide new insights into the Pliocene–Quaternary evolution of the Kinarot–Beit–Shean pull-apart basin (KBSB) along the Dead Sea transform. Two distinct zones are defined beneath the lake: (1) a graben that underlies most of the lake, bounded by steep north–south longitudinal strike-slip faults and (2) shallow pre-rift units underlying the northwestern wider part of the lake. We suggest that before approximately 4 Ma, the KBSB grew due to northward movement of the Korazim Plateau and by crustal stretching along the rift axis. Since the Pliocene (~ 4 Ma), lateral slip has been transferred from the southern segment of the basin's western marginal fault to normal faults in the Galilee, and to the eastern margin of the Korazim Plateau by the newly formed, Almagor fault, which makes a restraining bend along the transform. N–S lithospheric stretching below the KBSB has diminished and the Korazim Plateau has changed from being a detached block to a compressional saddle. A phase of rapid subsidence, and formation of a half-graben structure in the northern part of the basin approximately 1 Ma ago was coeval with major deformation in areas adjacent to the KBSB, indicating major reorganization of the plate boundary in the region. Currently, most transform motions are probably taken up along a single fault on the eastern side of the KBSB, implying that the main trough under the Sea of Galilee is in a late stage of growth as a pull-apart.

Keywords: Pull-apart basin; Sea of Galilee; Seismic reflection; Kinematics; Plate boundary; Dead Sea transform

1. Introduction

Pull-apart basins are depressions that are bounded by sideways-stepping, strike-slip faults parallel to their length. They form where the sense of stepping or bends along the faults have the same sense as fault motion (Crowell, 1974; Garfunkel, 1981; Mann et al., 1983; Christie-Blick and Biddle, 1985). The internal structure of these basins is highly variable both in space and time owing to complex stress fields and heterogeneous crustal rheology around the termination of the delimiting faults. This complexity has led to several unresolved problems regarding the kinematics and dynamics of pull-apart basins (e.g. Rodgers, 1980;

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Garfunkel, 1981; Reches, 1987; Katzman et al., 1995; ten Brink et al., 1996). There is only rare documentation of the time-dependent deformation patterns within pull-apart basins, and the relation of these basins with the adjacent deformed structural domains.

The Neogene Dead Sea transform is characterized by a series of deep pull-apart basins (Fig. 1). These are from south to north: Gulf of Elat (Aqaba), Dead Sea, Kinarot–Beit–Shean, Hula and Ghab basins (Garfunkel and Ben-Avraham, 2001). Because these basins are located along the transform, their evolution is directly linked to geometrical changes of the plate boundary. The deep structure and history of the Kinarot–Beit–Shean basin (KBSB) in the central part of the transform (Figs. 1–3) is least understood. The presence of Neogene volcanics in, and around the basin, the uplifted and strongly fractured Korazim Plateau just north of the basin, and the faulted Galilee mountains just west of it (Fig. 2), indicate a complex tectonic history, and raise questions about the connection of these features with the development of the KBSB, and changes in the faulting pattern along the central Dead Sea transform.

To gain insight into the internal structure of the basin, and to infer its kinematic history and relations with the regional plate boundary, we carried out the first multi-channel seismic reflection survey (180 km) in the Sea of Galilee, which covers the northern part of the KBSB (Figs. 1 and 2). Our analysis of the seismic data sheds new light on the history of the basin, mainly on deformation during the Pliocene and Quaternary, and the relations of the KBSB with structures in surrounding regions. Our results have implications for understanding regional plate boundary kinematics, which has been subjected to considerable debate (Freund, 1978; Kashai and Croker, 1987; Rotstein and Bartov, 1989; Rotstein et al., 1992; Heimannn and Ron, 1993; Ben-Avraham et al., 1996), and we hope will contribute to a better understanding of the development of large pull-apart basins.

2. Geological framework

The Dead Sea transform plate boundary separates the Sinai sub-plate from the Arabian plate along an approximately north–south small circle (Garfunkel, 1981; Joffe and Garfunkel, 1987) (Fig. 1). The transform is more than 1000 km long and connects the divergent plate boundary along the Red Sea with the Alpine convergent zone in Turkey. A total left-lateral displacement of 105 km has occurred along the southern and central strands of the transform (Quenell, 1958; Freund et al., 1970), being constrained to postdate 20 Ma (Bartov et al., 1980). The average rate of slip during the last 5 Ma is estimated at 5–6 mm/year (Joffe and Garfunkel, 1987).

The deep basins developed along the southern half of the transform are considered to be pull-apart basins, because they are developed between left-stepping en echelon strike-slip faults (Garfunkel, 1981). These basins are filled by thick (7–10 km and more) Neogene–Quaternary sediments and locally also by igneous rocks, while between them are higher standing structural saddles where the fill is thin or absent (ten Brink et al., 1999). The basins and the bounding strike-slip faults are embedded in an almost continuous depression that is delimited by normal faults (Garfunkel, 1981).

The extent of the KBSB is outlined by a pronounced negative Bouguer gravity anomaly whose northern part extends all along the Sea of Galilee, but dies out under the Beteha Valley NE of the lake (Fig. 2a) (Ben-Avraham et al., 1996; ten Brink et al., 1999). The basin is approximately 60 km long, extending from the Wadi Malih area in the south to the Korazim Plateau in the north, and its width varies from 7 to 9 km (Fig. 2). Like the other basins along the Dead Sea transform, the KBSB is situated between two left stepping left-lateral strike-slip faults, which define the setting of a pull-apart basin (Fig. 2c) (Schulman, 1962; Rotstein et al., 1992), and it is delimited by normal faults that are separated from the deep part of the basin by narrow structural steps (Michelson, 1979; Schulman, 1962). The freshwater, Sea of Galilee currently covers the northern part of the basin. The lake has a N–S extent of ca. 21 km and an area of approximately 170 km^2, maximum water depth of 46 m (Fig. 3) and lake surface is at about 210 m below mean sea level (Ben-Avraham et al., 1990).

The Zemah-1 well located 3 km south of the Sea of Galilee (Fig. 3) is the only source of information on the deep stratigraphy of the KBSB. The well penetrated 4.3 km of basin-fill sequence (Marcus and Slager, 1985) and bottomed in approximately 100 m

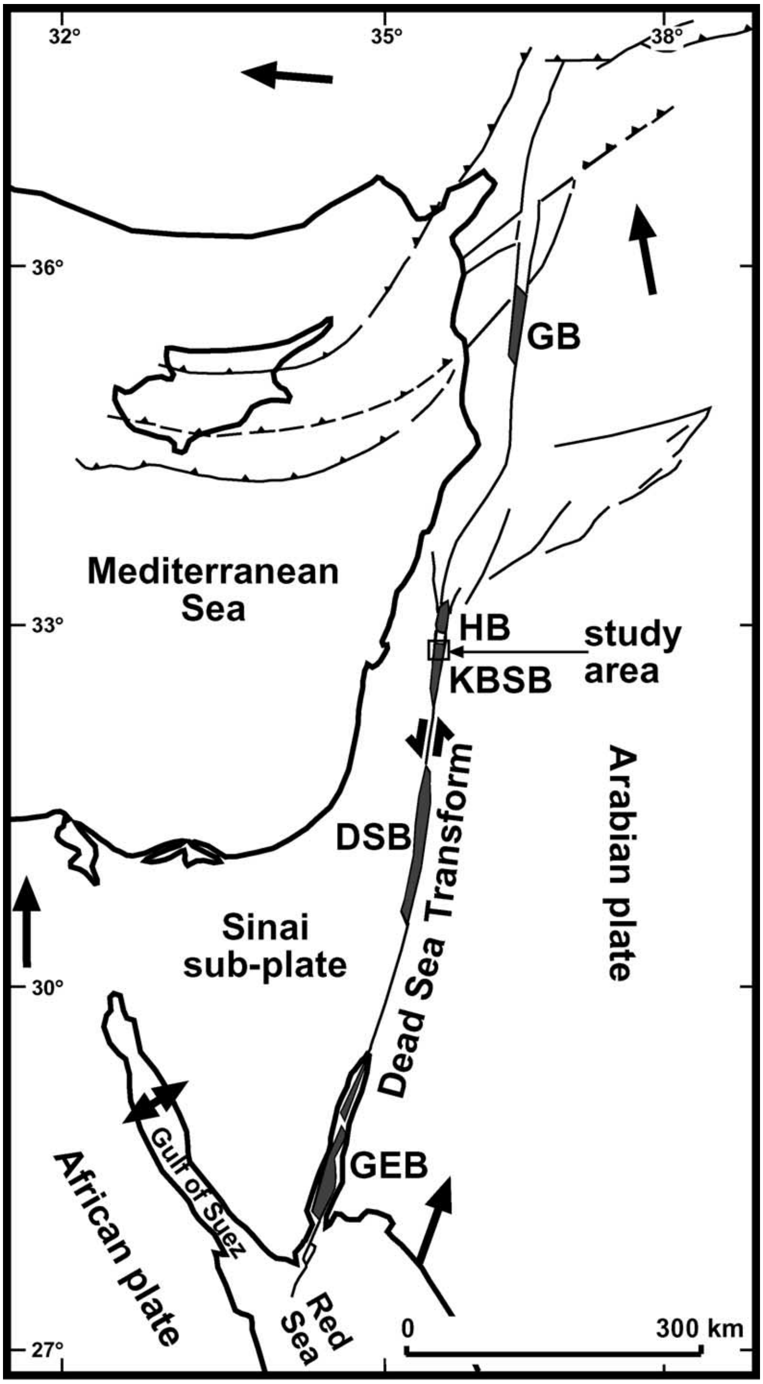


Fig. 1. Map showing the Dead Sea transform (DST) and basins along it (after Garfunkel and Ben-Avraham, 2001). GEB—Gulf of Elat (Aqaba) basin, DSB—Dead Sea basin, KBSB—Kinarot–Beit–Shean basin, HB—Hula basin, GB—Ghab basin. Heavy arrows indicate generalized plate motions (from McClusky et al., 2000). The study area is marked in the inset.

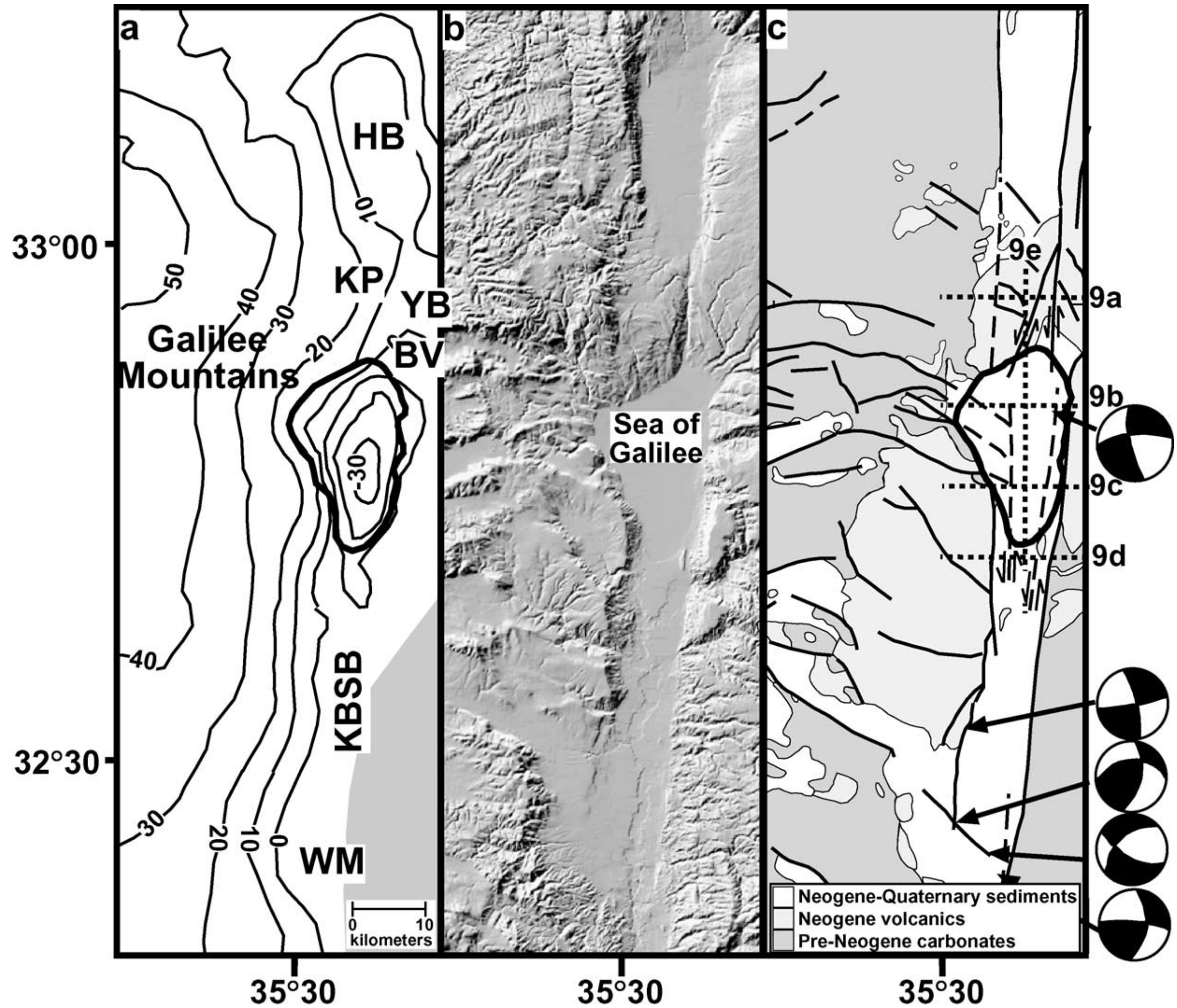


Fig. 2. (a) Residual Bouguer gravity map of the central Dead Sea transform region. WM—Wadi Malih, KBSB—Kinarot–Beit–Shean basin, KP—Korazim Plateau, HB—Hula basin, YB—Yahudia Block, BV—Beteha Valley (after Ben-Avraham et al., 1996; ten Brink et al., 1999). (b) Digital terrain model map of the same region depicting the major morphological elements (Hall, 1993). (c) Compiled geologic map of the region (after Schulman, 1962; Saltzman, 1964; Michelson, 1979; Belitzky, 1987; Heimannn, 1990). Focal mechanism solutions are after van Eck and Hofstetter (1990) and Hofstetter et al. (1996). The dotted lines are locations of cross-sections in Fig. 9.

of Middle Miocene fluvial and lacustrine sediments. Interpretation of gravity data suggests that there is at least another 1 km of additional low-density basin fill (Ben-Avraham et al., 1996). The thick Miocene sequence in the basin in comparison to the margins indicates that the KBSB formed during the initial phase of transform motion in the early Miocene (20–17 Ma; Garfunkel, 1989). The Middle Miocene sequence is overlain by approximately 1100 m of 8–6-Ma-old evaporites and volcanics, followed by 5.5–3.5-Ma-old lacustrine beds, and 670 m of basalt flows, that occur all around the Sea of Galilee (Heimannn et al., 1996). The Late Pliocene and Early Quaternary sediments in the well are 480 m thick, and commonly dip tens of degrees at exposures on the basin floor to a distance of some 10 km south of the Sea of Galilee

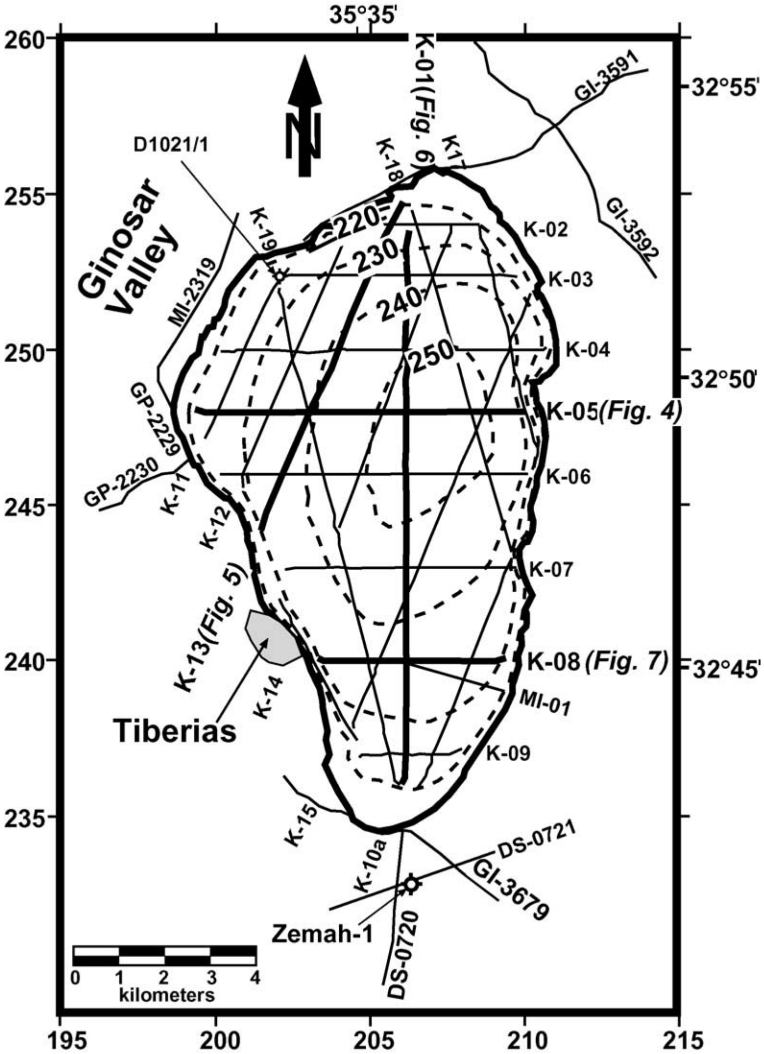


Fig. 3. Location of onshore and offshore seismic reflection profiles. Profiles GI-3591 and GI-3592 are from Rotstein and Bartov (1989). Profiles DS-0720 and DS-0720 south of the lake were re-processed from data of the Israeli oil company. Profile GI-3679 was re-processed and modified after Rotstein et al. (1992). The thick lines designate profiles presented in this paper. The dashed lines are bathymetry (m below mean sea level) (after Ben-Avraham et al., 1990). The map coordinates are of the Israeli grid.

(Heimannn and Braun, 2000). These deformed and relatively shallow sediments indicate that in this area, basin subsidence was slow, and that locally, the basin fill was even uplifted and eroded.

The pronounced negative Bouguer gravity anomaly over the Sea of Galilee was previously interpreted to show that the low-density basin fill thickens from ca. 5 km under Zemah-1 well to ca. 7 km under the center of the lake (Ben-Avraham et al., 1996). These are minimum estimates because effects of compaction with depth were not taken into account. The pattern of the gravity anomaly further shows that the basin-fill ends abruptly just south of the Korazim Plateau (Fig. 2a). Short wavelength magnetic anomalies over the Sea of Galilee (Ginzburg and Ben-Avraham, 1986) show that shallow basalt bodies underlie its marginal parts. These are interpreted to consist of downfaulted Pliocene basalt.

Comparison of the Jurassic–Cretaceous section north of the lake, in Korazim Plateau (Fleischer, 1968) with the coeval facies on the western side of the transform shows that the Korazim Plateau was displaced some 60 km northward relative to the western side of the transform (Freund et al., 1970). This indicates that a large part of the transform offset was accommodated on a fault on the west of this plateau. However, the lack of a morphological expression, or through-going N–S fracture in the basalt argues against significant lateral motion along the western side of plateau in the last 4 Ma. The counter-clockwise rotation of the Pliocene basalt on numerous oblique slip faults (Heimannn and Ron, 1993) and the lack of similar deformation west of the Plateau (Ron et al., 1984) also indicate that in the last few million years this block was structurally detached from the western side of the transform.

3. Acquisition and processing of seismic data

In 1997, a seismic reflection survey was carried out in the Sea of Galilee, consisting of 20 lines with a total length of 180 km (Fig. 3). The system was composed of a 48-channel, 600-m-long hydrophone streamer. The source of energy was a single 400 in.^{3} water gun with pressure of 1820 psi. Recording length was 4 s and sampling rate was 2 ms. Navigation during acquisition was controlled by a global positioning system (GPS) in autonomous mode. Additional onshore profiles were carried along the northwestern margins of the lake (Fig. 3), in order to link the onshore and offshore data. Some older multi-channel profiles carried out south of the lake (Marcus and Slager, 1985; Rotstein et al., 1992) were re-processed so that the interpreted stratigraphy in the Zemah-1 borehole and the new offshore seismic profiles could be linked. The seismic profiles carried out by Rotstein and Bartov (1989) in the Korazim Plateau, north of the lake were also linked to the new profiles. All land data of the various vintages were acquired with a Vibroseis source.

Due to the configuration of the marine acquisition system, subsurface coverage could not be obtained closer to the shoreline than 500 to 800 m. The lack of boreholes within the sediments underlying the lake and the relatively short seismic streamer reduced velocity resolution at depth, thus, making the time to depth conversion in the basin-fill formations extremely difficult. However, the shallow sections in most parts of the lake are expected to portray a gradual increase in velocities downward due to compaction of unconsolidated clastic sediments. The water depth dictated the periodicity of multiple reflections. These were removed relatively easily by pre- and post-stack predictive deconvolution.

4. Stratigraphy and faults in the northern KBSB

The seismic reflection survey imaged a well-bedded series that extends to variable depths, reaching a maximum of 2600 ms (~ 3 km) two-way travel time (TWT) overlying nonreflective rocks. To facilitate interpretation, seven reflectors based on amplitude strength were picked and mapped in the basin fill. The reflectors tie across all the seismic cross-sections, apart from reflector KIN-1 that appears only below the northwestern part of the lake. Apart from reflectors KIN-2 and KIN-4, the designation assigns only relative ages to the reflectors, as the absolute age could not be determined in the absence of relevant geological data. The age of these two reflectors is based on indirect geological evidence from the surroundings of the lake. The structure under the lake defines two distinct zones: (a) an approximately 20 km long N–S trending trough delimited by ca. N–S striking faults that extends under the length of the lake and (b) a less depressed marginal zone under the NW part of the lake.

Reflector KIN-1 was traced only in the northwestern marginal zone where it forms the base of the fill. It was recognized based on seismic velocity contrast and limited constraints from shallow water wells in the area. Its depth ranges from 350 to 1500 ms TWT (Figs. 4 and 5). Extrapolation of onshore seismic profiles and magnetic anomalies and interpretation of data from wells indicates that this reflector most likely represents the top of Cretaceous carbonates of the Judea and Mount Scopus Groups. This reflector is offset vertically by up to 200 ms by a system of WNW trending faults (Fig. 5), and on the east it is truncated by the western marginal fault of the basin.

Reflector KIN-2 is close to the base of the bedded series in the main trough under the lake, and can be recognized in the entire trough (Figs. 4, 6 and 7).

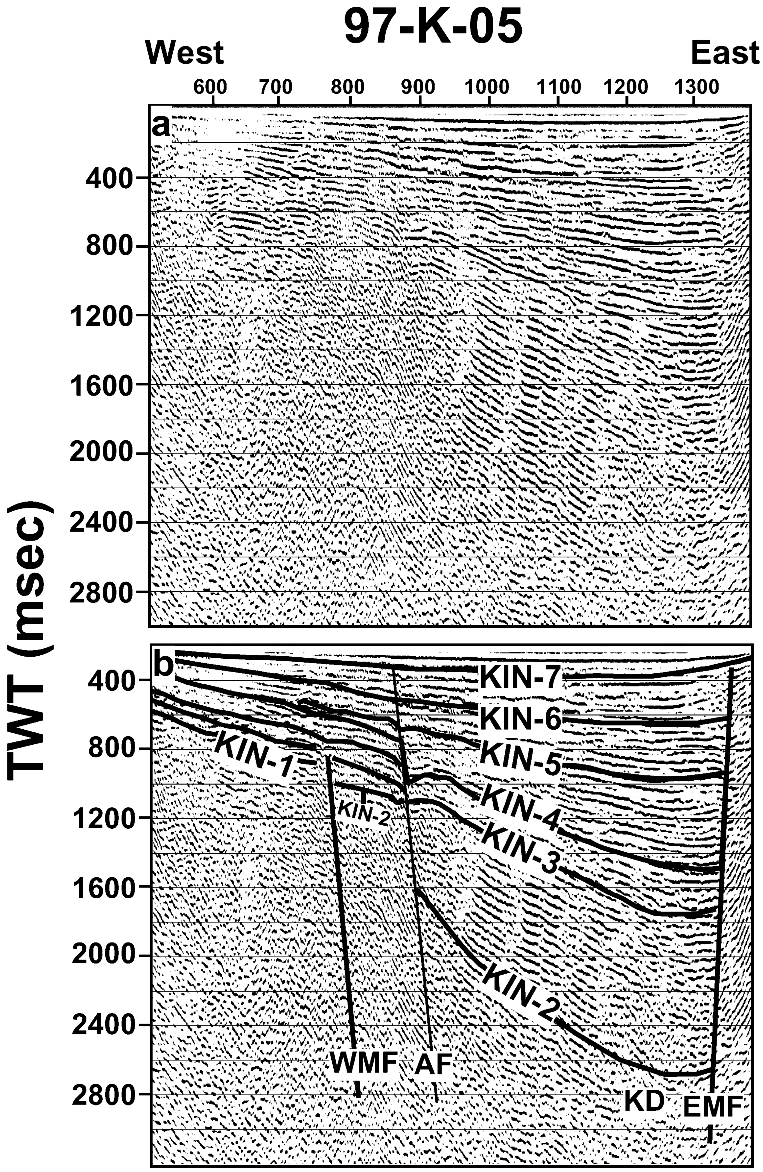


Fig. 4. Seismic reflection profile K-05 in the northern part of the lake. WMF—western marginal fault, AF—Almagor fault, KD—Kursi depression, EMF—eastern marginal fault.

Correlation of data from our survey with seismic reflection lines through the Zemah-1 well just south of the lake (Rotstein et al., 1992) shows that this reflector is correlated with the top of the Cover Basalt unit (at a depth of about 500 ms TWT). Given the age of this basalt (Heimannn et al., 1996), the entire reflective fill imaged by our seismic survey in the main trough under the lake is younger than 4 Ma. In the main trough, reflector KIN-2 reaches a maximum depth of 2600 ms TWT below the lake floor (Fig. 4), which corresponds to a depth of about 3 km, assuming plausible seismic wave velocities in these sediments. Thus, in post-Cover Basalt times, the Sea of Galilee subsided by ca. 2.5 km relative to the area south of the

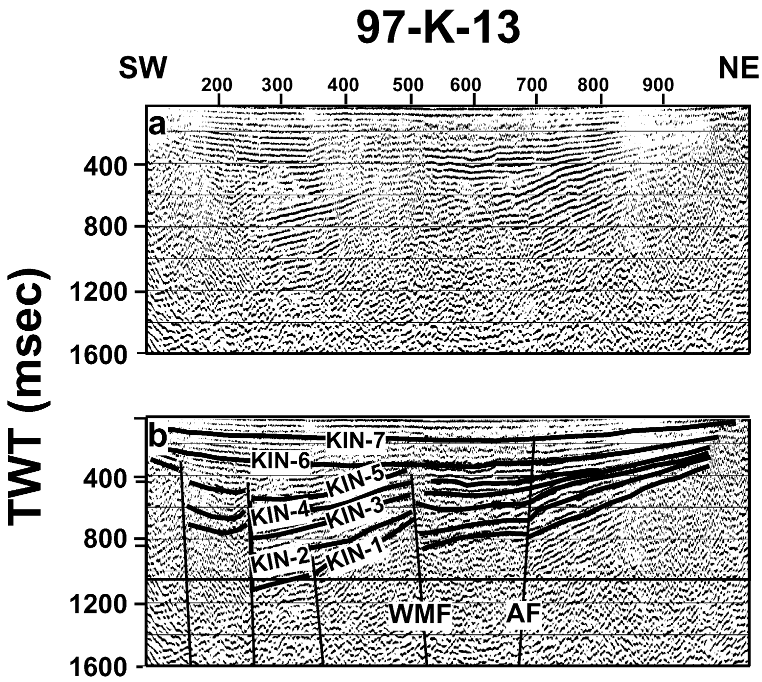


Fig. 5. Seismic reflection profile K-13 in the northwestern part of the lake. WMF—western marginal fault, AF—Almagor fault.

lake, where the coeval fill is much thinner and Early Quaternary and Late Pliocene sediments are even exposed.

4.1. Basin marginal faults

Similar to the other pull-apart basins along the Dead Sea transform, the structure of the young trough beneath the Sea of Galilee is dominated by ca. N–S trending longitudinal faults, separated by narrow steps from the normal fault on the east and west that control the onshore morphological boundaries of the basin (Garfunkel, 1981; Figs. 8 and 9). The eastern marginal fault, which is approximately parallel to longitude 208 (Israel grid), can be traced all along the eastern side of the lake, about 2 km west of the Haon fault (Fig. 8). It seems to die out in the north, as it cannot be recognized along strike onshore in the Beteha Valley. The western marginal fault, close to longitude 204 (Israel grid), is prominent along the southern part of the deep trough to about latitude 243 (Israel grid), opposite the town of Tiberias. Farther north, it forms the eastern boundary of the fault system of the NW marginal zone, and is less distinct on the seismic profiles. Northward, this fault projects to the 10–15° trending Almagor fault on the eastern side of the Korazim Plateau (Belitzky, 1987).

Faults that delimit the basin in the north or south were not observed on the seismic images. However, the existence of the northern transverse fault, which separates the KBSB from the Korazim Plateau, is inferred indirectly from the seismic data (Fig. 9e). In the northern KBSB, the minimum depth of the KIN-2 reflector (Pliocene basalt) is 3 km and gravity models suggest that the minimum depth of the Neogene–Cretaceous unconformity is 7 km (Ben-Avraham et al., 1996). Data from boreholes in the southern Korazim Plateau indicate that the Pliocene basalt and the unconformity between the Neogene clastic units and the Cretaceous carbonate units are at a depth of a few tens of meters and a few hundreds of meters, respectively (Fleischer, 1968). The sharp gradients of the magnetic field (Ginzburg and Ben-Avraham, 1986), the Bouguer gravity field (Ben-Avraham et al., 1996) and bathymetry (Ben-Avraham et al., 1990) indicate that this fault has an east–northeast strike,

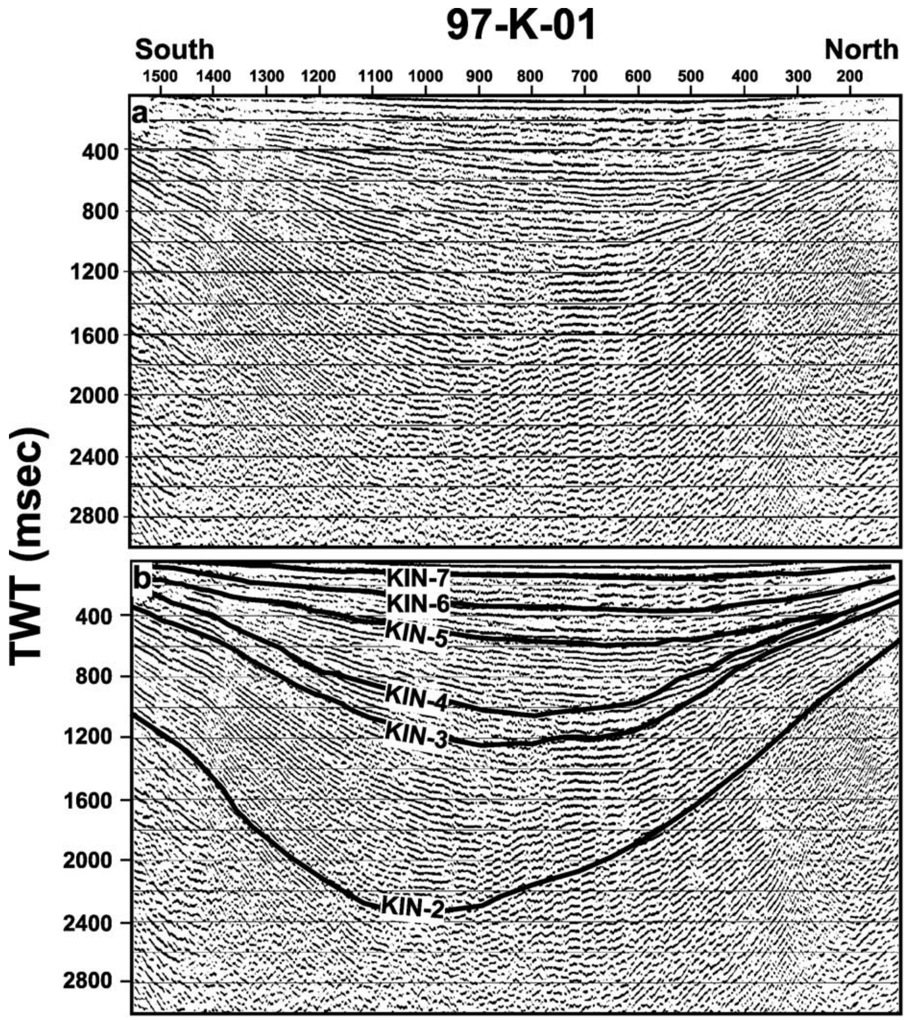


Fig. 6. Seismic reflection profile K-01 to the length of the lake.

and it is located along the northwestern shores of the lake (Fig. 8), where shallow water limitations disabled coverage by the seismic system. The proposed fault (termed here Kfar–Nahum fault; KNF in Fig. 8) has a minimum vertical offset of 4.5 km (Fig. 9e), out of which at least 2.5 km of displacement are post-Pliocene. Normal faulting on the Kfar–Nahum fault implies approximately 1.5 km of lateral displacement along the western side of plateau, assuming a fault angle of 60° and 2.5 km of subsidence. Due to the lack of coverage by our seismic survey, we could not examine the relation between the Kfar–Nahum fault, and the western marginal fault, or the Almagor fault.

4.2. Main trough

The internal structure of the trough is defined primarily by flexing of its fill that reflects syn-sedimentary differential subsidence of the basin floor. Only minor faults, with small vertical displacements were imaged within the trough. In a N–S section, the beds dip from the margins of the trough towards a broad depression under the central part of the lake (Fig. 6). In E–W cross-sections, the trough is rather symmetrical in the south (Fig. 7), but under the middle and northern parts of the lake, the bedding outlines an east plunging asymmetrical NE–SW

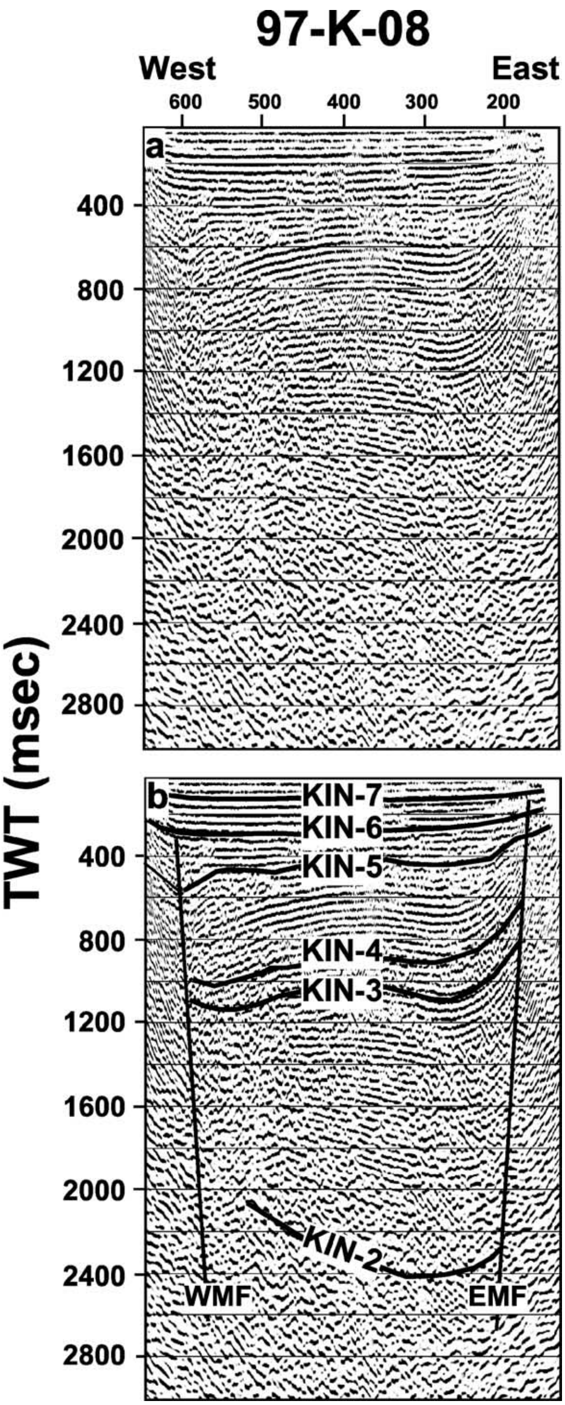


Fig. 7. Seismic reflection profile K-08 in the southern part of the lake. WMF—western marginal fault, EMF—eastern marginal fault.

trending half-graben (Fig. 4). The basin depocenter is designated as the Kursi depression and is located under the deepest part of the lake floor (Figs. 8 and 10). Here, the trough has an asymmetrical cross-section, with its deepest area close to its eastern margin, where reflector KIN-2 is about 2.5 km deeper than near the southern part of the lake. This structural relief broadly agrees with the estimate, based on gravity anomalies, that under the lake the basin fill is some 2 km thicker than near Zemah-1 south of the lake (Ben-Avraham et al., 1996). However, the deepest part of young trough is located a few kilometers north of the gravity minimum (Figs. 8 and 10).

The units between the various reflectors thin towards the less depressed parts of the trough, but the thickness variations are much more accentuated above reflector KIN-4 than below it (Fig. 10). All reflectors are clearly ruptured by the eastern marginal fault, but reflectors KIN-5 to KIN-7 overlap the western fault (Figs. 4, 5 and 7), indicating that activity on this fault became slow. The depth of reflector KIN-7 varies from 75 ms TWT near the lake margins to nearly 200 ms TWT under the Kursi depression. Its estimated age is between 10 and 50 ka, based on its depth, assuming a seismic wave velocity of 1.6 km/s for the uppermost, unconsolidated sediments and a sedimentation rate of 3–6 mm/year (Thompson et al., 1985).

The N–S trending Jordan fault on the eastern side of the Korazim Plateau has a distinct morphologic expression and its ongoing activity is documented by a 2.1-m sinstral displacement of a crusader fortress near the northern part of the Korazim Plateau (Ellenblum et al., 1998) and offset of a drainage system just north of the Sea of Galilee (Marco et al., 2000). The fault forms a sharp boundary between the Pliocene, Cover Basalt unit on the west (Korazim Plateau) and younger basalts on the east (Golan Heights) (Fig. 9a). Under the lake, the Jordan fault is observed in seismic line K-3, but its southern continuation disappears somewhere between latitudes 250 and 253 (Fig. 8). The seismic images indicate that on the ground surface, the Jordan fault and the eastern marginal fault are not continuous and the Beteha Valley is located within the en echelon jog formed between the two faults (Fig. 8). However, gravity data indicate that there is no deep basin under the Beteha Valley (Ben-Avraham et al., 1996), and therefore, it is proposed that at moderate depth, the Jordan fault and the eastern

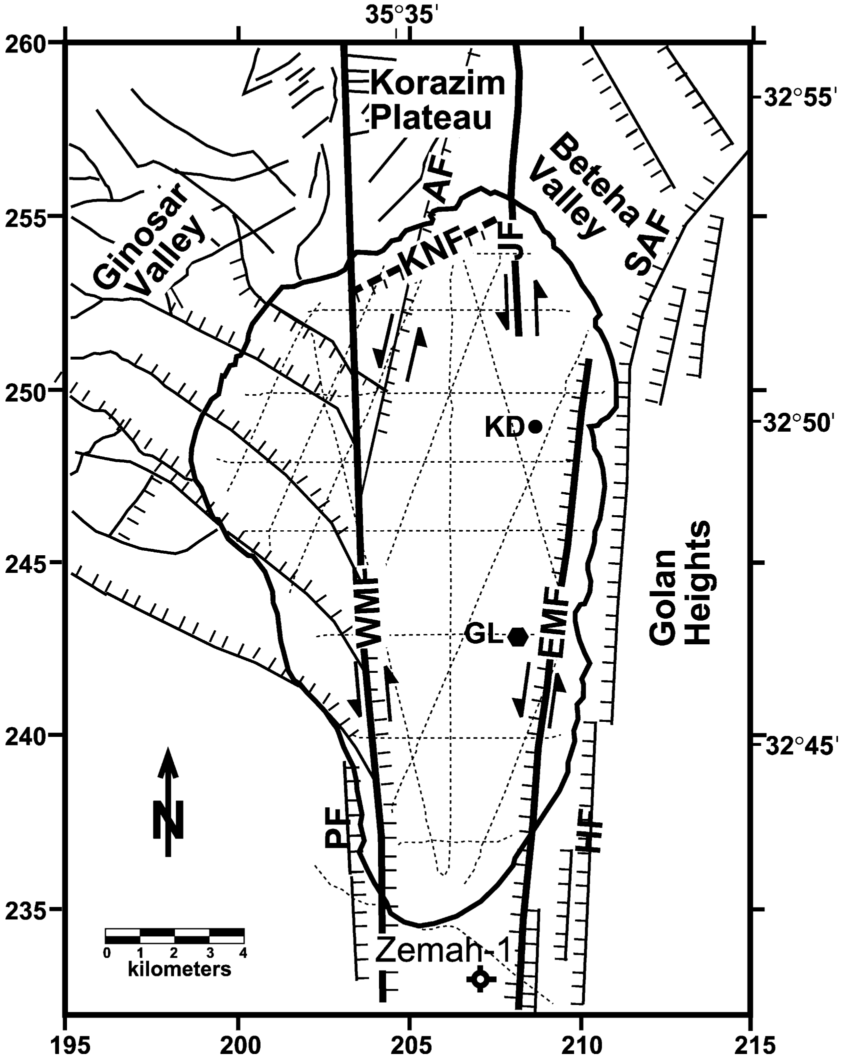
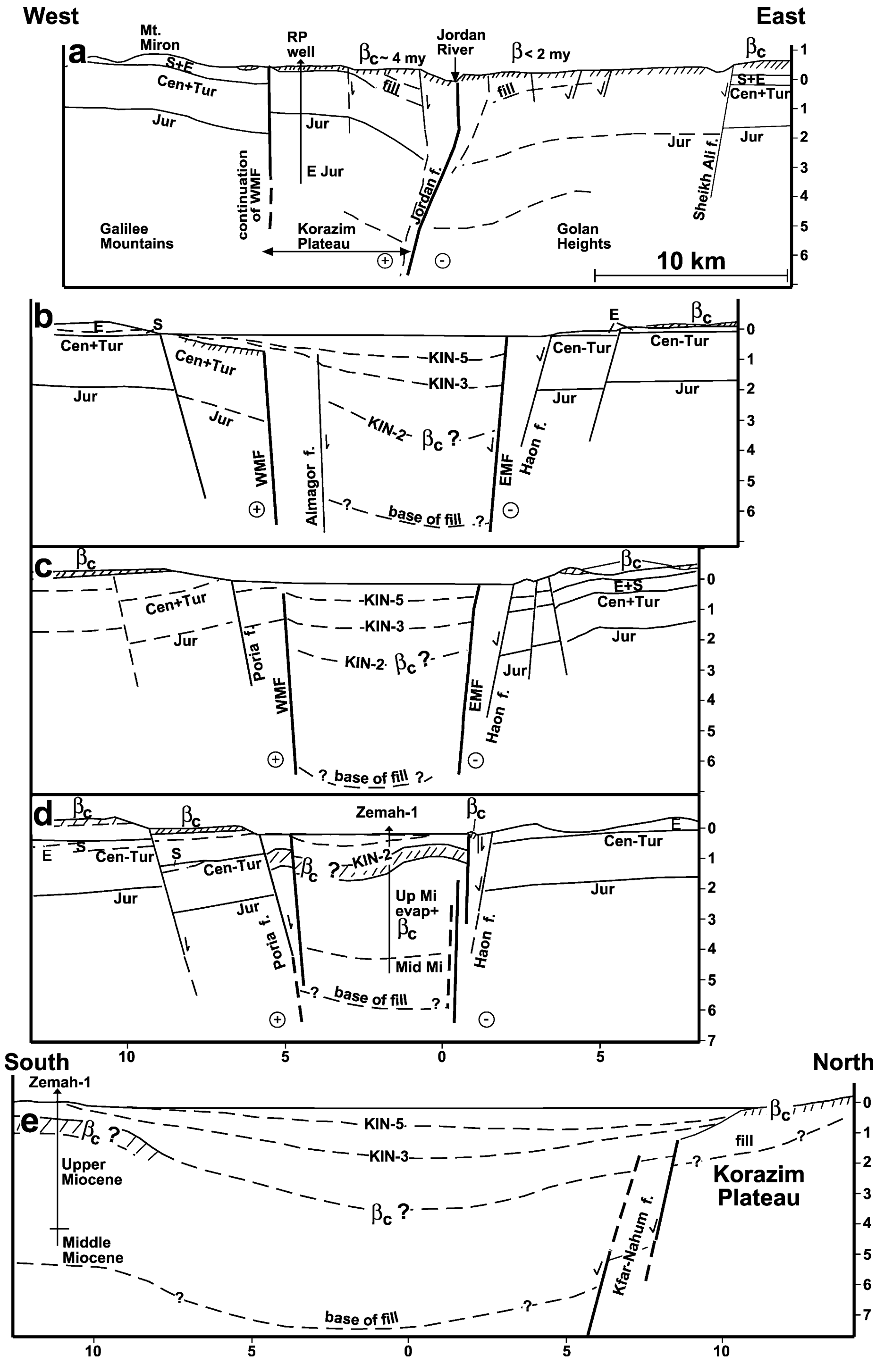


Fig. 8. The major faults in the northern Kinarot–Beit–Shean basin. PF—Poria fault, HF—Haon fault, WMF—western marginal fault, EMF—eastern marginal fault, KNF—Kfar–Nahum fault, AF—Almagor fault, SAF—Sheikh–Ali fault, KD—Kursi depression, GL—gravity low (after Ben-Avraham et al., 1996). Faults from the onshore are after Saltzman (1964), Michelson (1979), Belitzky (1987) and Heimannn (1990).

marginal fault merge, permitting slip to be transferred between the faults.

4.3. Northwestern zone

The structure under the northwestern part of the lake differs markedly from that of the main trough to the east. First, the reflective fill is considerably thinner than in the deep basin. Secondly, this area is crossed by several WNW–ESE trending faults, which are the continuation of the fault system on the adjacent Ginosar Valley (Saltzman, 1964) (Fig. 8). The onshore faults displace the Cover Basalt and their offsets are directly expressed in the topography (Saltzman, 1964; Matmon et al., 1999). The NW trend of these faults forms a large angle with the strike of the transform, which has led to destruction of the escarpment on the western margin of the


West
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KIN-3
KIN-2
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Almagor f.
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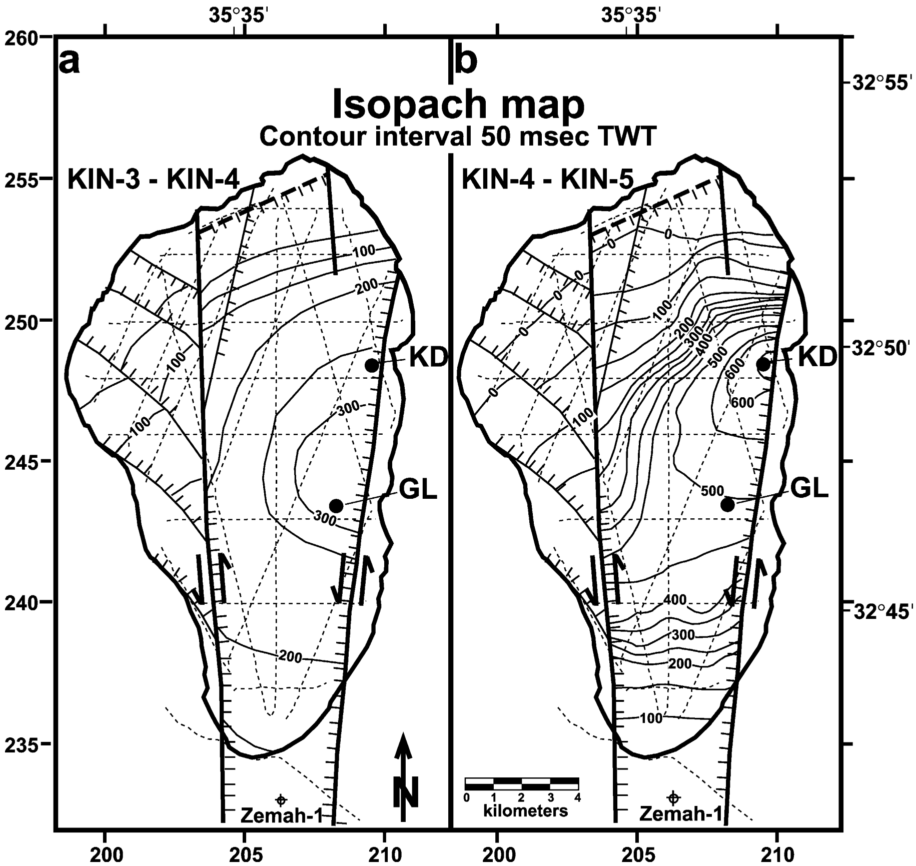

Fig. 10. Two-way travel time isopach map of: (a) the interval between reflectors KIN-3 and KIN-4. (b) The interval between reflectors KIN-4 and KIN-5, which designates a subsidence event with a depocenter at the Kursi depression (KD). GL is the location of the most negative Bouguer gravity anomaly in the basin (Ben-Avraham et al., 1996).

basin. The eastward termination of these faults along the western marginal fault and the post-Pliocene vertical displacement on these faults indicate that these faults branch out of the western marginal fault and transfer slip. This is consistent with field evidence, which indicates a few hundred meters of left-lateral slip on these normal faults, just west of the lake (Saltzman, 1964).

These faults form the eastern part of a ca. 15 km wide (in N–S direction) faulted zone that extends westward as far as the Mediterranean coastal plain, changing its strike to close to E–W in the Galilee Mountains (Fig. 2), where vertical fault offsets reach 500 m and more. As these faults displace the Cover Basalt where present, and are very well expressed in the topography, they must have been active in the past few million years (Matmon et al., 1999, 2000). Moreover, a study of the cosmogenic isotope content in one of the fault surfaces demonstrates Holocene motion (Gran et al., 2001).

Fig. 9. Geological cross-sections (locations shown in Fig. 2c): (a) through the Korazim Plateau. Data from Picard (1956), Fleischer (1968), Rotstein and Bartov (1989) and Rosh-Pina-1 borehole. Jur—Jurassic, Cen + Tur—Cenomanian + Turonian, S + E—Senonian + Eocene, β_c—Pliocene Cover Basalt; (b) through the northern part of the lake; (c) through the southern part of the lake; (d) through the Zemah structure, south of the lake; (e) from Korazim Plateau in the north to Zemah in the south.

5. Discussion

The sedimentary structure and fault geometry inferred from the results of the new seismic survey provide the basis for a new interpretation for the evolution of the KBSB and the associated kinematics of the plate boundary zone in the region. Structures under the Sea of Galilee and in the adjacent areas record the modification of a pre-existing pull-apart basin that resulted from rearrangement of the main faults along a part of the Dead Sea transform. We find that the configuration of the major strike-slip fault strands along the KBSB has changed considerably with time.

The young trough underlying most of the lake area is a box-shaped pull-apart basin that developed between left stepping en echelon faults as a direct consequence of the left-lateral motion along the Dead Sea transform. As in other basins along the Dead Sea transform, longitudinal faults along the margins of the trough are very prominent, but the fill of the trough is downflexed and has only minor faults with small vertical offsets. Another features similar to those of other Dead Sea transform basins are the normal faults on the exterior part of the basin (Haon and Poriya faults—Figs. 8 and 9). These faults express a small component of transtension that leads to opening of a new area, which provides the space for growth of the basin (Garfunkel, 1981; McClay and Dooley, 1995; Dooley and McClay, 1997). The marginal strike-slip faults are prominent features, but only a few connecting transverse faults at the terminations of the basins have been identified along the Dead Sea transform (Arbenz, 1984; Ben-Avraham and Garfunkel, 1986; Garfunkel and Ben-Avraham, 1996; Brew et al., 2001). Transverse faults have the essential role of allowing the pull-apart basin to grow and become longer as the lateral transform motion proceeds, so they are expected to occur in all basins. Although transverse faults were not directly observed in the seismic images, the proposed Kfar–Nahum fault (KNF in Fig. 8) probably defines the northern margin of the KBSB (Fig. 9e). The lack of a major transverse fault underneath the southern part of the lake supports the notion that the deep trough under the northern part of the lake is part of the larger KBSB and not a separate basin.

Prior to the extrusion of the Cover Basalt in the Pliocene (4–5 Ma), significant lateral motion took place on a fault along the western side of the Korazim Plateau that continued southward along the western margin of the KBSB (Figs. 2c and 8). This fault controlled basin development as a pull-apart, and during this time, the Korazim Plateau was a detached block between the two parallel transform faults (Fig. 11a). Reflectors KIN-5 to KIN-7, which cover the western marginal fault under the northwestern part of the lake (Figs. 4 and 5), indicate that activity on the

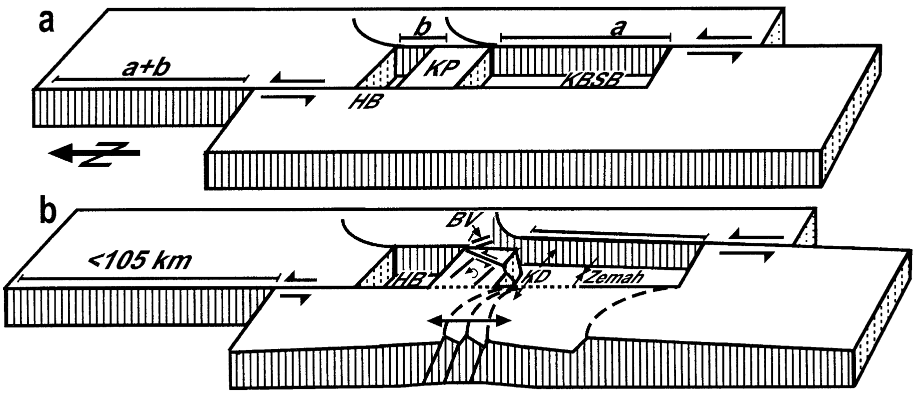

Fig. 11. A general kinematic model for the Kinarot–Beit–Shean basin. (a) The KBSB formed due to an en echelon jog between two segments of the transform prior to 17 Ma ago due to northward motion of the Korazim Plateau (KP). (b) Branching of the western transform fault in the northern KBSB occurred in the Pliocene. A major reorganization of the plate boundary that took place approximately 1 Ma ago resulted in subsidence in the northeastern KBSB (KD) and a coeval compression in the Zemah area, south of the lake. KBSB—Kinarot–Beit–Shean basin, KD—Kursi depression, KP—Korazim Plateau, HB—Hula basin, BV—Beteha Valley.

northern strand (bounding Korazim Plateau) has diminished. This has shifted part of the lateral slip out of the southern strand of the western marginal fault into branching normal faults in the Galilee. Some of the slips have also been transferred northward to the eastern part of the Korazim Plateau through the newly formed Almagor fault, which makes a restraining bend (Fig. 8). The Korazim Plateau, which was a detached block, has become a compressional saddle with the new fault configuration.

Apart from the relative motion between the Korazim Plateau and the Sinai sub-plate, motion between the Arabian plate and Korazim Plateau also led to the formation of the 22-km-long Hula basin (HB in Fig. 11). A thick sequence of fluvial and lacustrine sediments, which underlies 8.8 Ma basalt at a depth of 2400 m in the Notera-3 drillhole (Heimannn and Steinitz, 1989) suggests to us that the formation of the Hula basin was possibly coeval with the formation of the KBSB. This scenario is consistent with the model of Katzman et al. (1995) where two depressions separated by an elevated structure form when spacing between two parallel *en echelon* strike-slip faults is relatively small, and the overlap is relatively large.

The normal faults that branch out of the western marginal fault under the NW sector of the lake imply that some of the lateral slips along the Dead Sea transform north of the Sea of Galilee are diffuse, and therefore that the lateral offset is less than south of the lake. This is consistent with structural considerations from the northern Dead Sea transform in Lebanon and Syria (Freund et al., 1970; Walley, 1988, 1998). The normal faults in the Galilee strike at a high angle to the transform and therefore their activity causes some N–S extension of the area that may amount to 1–2 km (Freund, 1970). If the lateral offset along the southern part of the transform was 30 km since the Pliocene (Joffe and Garfunkel, 1987), then N–S extension in the Galilee can account for 3–6% of the 105-km left-lateral slip being diverted away from the transform in this area. Splaying of faults out of the transform farther north in Lebanon and Syria may account for the smaller offset in the northernmost part of the transform where the front of ophiolite nappes appears to be offset 70–80 km left laterally (Freund, 1970; Al-Maleh et al., 1992).

Reflector KIN-4 represents the major subsidence horizon in the northern part of the basin (Figs. 4 and 10). In the south of the lake, in the Zemah area, this reflector is deformed and indicates some transpression (Rotstein et al., 1992). Onshore geologic evidence shows that this transpression attained its peak approximately 1 Ma ago (Braun, 1990). The asymmetric subsidence pattern, and formation of a half-graben structure in the northern part of the basin (Figs. 4, 9b and 10) is consistent with the idea that it was controlled by a different fault configuration in comparison with the pre-Pliocene configuration. During the same time, a pull-apart developed under the southern part of the Sea of Galilee where the two strike-slip faults were active.

During that period (~ 1 Ma ago), some other major deformation events occurred in domains adjacent to the KBSB (Fig. 11b). These are the rotation of blocks within the Korazim Plateau (Heimannn and Ron, 1993), normal faulting in the Yahudia Block (YB in Fig. 2a; Hurwitz et al., 2000) and major subsidence in the Hula basin (HB in Fig. 2a; Heimannn, 1990). All these suggest that the major phase of subsidence in the northern KBSB was closely linked to deformation in adjacent areas and major changes in the geometry of the plate boundary in the region. The pattern of deformation during this event indicates the termination of N–S crustal extension at ca. 1 Ma in the KBSB, consistent with the low heat flow (36.5 mW m^{-2}) in the Zemah-1 well (Levitte et al., 1984).

Reflectors KIN-6 to KIN-7 in the uppermost part of the fill of the Sea of Galilee depression are not visibly offset by the fault along the NW portion of the lake. Seismicity in this region (van Eck and Hofstetter, 1990; Ben-Menahem, 1991), vertical offset of the uppermost sediment under the lake (Ben-Avraham et al., 1986), prominent escarpments along the southwestern shores of the lake, and the evidence of Holocene motion on one of the major faults across the central Galilee (Gran et al., 2001) suggest to us that the southern segment of the western marginal fault is still active. The ongoing seismic activity on the Jordan fault and rupturing of the eastern marginal fault by the uppermost reflectors raises the possibility that at present, most transform movements in this area are taken up along a single fault. If this is the case, it signifies the rearrangement of lateral motion and complete transfer to the eastern side of the KBSB. If further transform motion is now concentrated mainly on the eastern side of the basin, this implies termination of its growth as a pull-apart. A similar scenario for the extinction of pull-apart basins by localizing strike-slip motion to one side was proposed for the Haiyuan fault zone in northwestern China (Zhang et al., 1989).

6. Conclusions

Our multi-channel seismic reflection survey conducted in the Sea of Galilee provides new insights into the evolution of the Kinarot–Beit–Shean pull-apart basin (KBSB) and the associated changes in the geometry of the plate boundary zone in the area since the Pliocene. Our kinematic analysis emphasizes the role of plate boundary rearrangement, and the evolution of large pull-apart basins along its axis. The major conclusions of this study are:

1. Two distinct structural zones underlie the lake: (a) a N–S trending trough delimited by steep longitudinal strike-slip marginal faults accommodated with marginal normal faults, indicating a small component of transtension and (b) a marginal zone under the NW part of the lake, where pre-rift units are located at shallow depths.
2. The structure of the plate boundary in the region was drastically modified approximately 4 Ma ago. Prior to approximately 4 Ma ago the KBSB grew by northward movement of the detached Korazim Plateau and crustal stretching along the rift axis. Since the Pliocene, lateral slip has been transferred from the southern segment of the western marginal fault to a system of normal faults in the Galilee, and to the eastern side of the Korazim Plateau by the Almagor fault, which delimits a restraining bend along the transform.
3. The 1–2 km of N–S extension along normal faults in the Galilee since the Pliocene (Freund, 1970) implies that 3–6% of the lateral slip has been diffused away from the transform along the KBSB.
4. Rapid subsidence was centered in the northeastern part of the basin approximately 1 Ma ago and indicates major reorganization of the plate boundary zone in the region. That event was coeval with major deformation in domains adjacent to the KBSB. The pattern of deformation is consistent with termination of N–S crustal extension underneath the KBSB.
5. If the Jordan fault (north of the lake) and the eastern marginal fault of the basin are continuous at moderate depth, it implies that most transform motions are currently taken up along a single fault on the eastern side of the KBSB. This would imply that the main trough under the Sea of Galilee is in its final stage of growth as a pull-apart.
6. As in all studied pull-apart basins, the major obstacle for a more comprehensive analysis of the KBSB kinematics is its three-dimensional configuration. A major effort should be devoted to characterize the geometry of faults at depth.

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