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# *The structure and development of the Dead Sea basin: Recent studies*

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## ABSTRACT

**Recent studies on the evolution of the Dead Sea basin have shed light on the intricate tectonic regime of the area. Combined with newly available data from Jordan, a new picture of a symmetrical deep basin is emerging. Salt is prevalent over the entire width of the basin in the south. The original thickness of this layer was calculated to be ~2 km, but at present it does not exceed 900 m. Crustal studies indicate a difference between the southern and northern basins, which are separated by a large, normal fault. Depth to the basement in the northern basin is estimated to be 6–8 km, while that of the southern basin is 12 km. Relocation of deep earthquakes revealed that the majority of well-constrained micro-earthquakes ($M_L \leq 3.2$) occurred at depths much deeper than previously expected (20–32 km). Seismicity and the low value of regional heat flow suggest that the lower crust might be cool and brittle. A lithospheric strength profile was calculated, indicating a narrow brittle-to-ductile transition at a depth of 31 km. Uplift measurements, submersible studies, and combined geological-geophysical mapping are some of the new techniques applied to the area to solve the complex neotectonic structure. Results indicate that the southern and northern basins are both currently active. In addition to tectonics, activity is also inferred by the presence of salt diapirs, whose uplift or subsidence may be related to current motion along active faults. Discrepancies in earthquake-reoccurrence times may indicate that the main fault in the northern Dead Sea basin, the Jericho fault (also known as the Jordan fault), is segmented, or that earthquakes occur in clusters. One such segment is responsible for the formation of a small subbasin on the northwestern shore of the lake, the Qumran basin, whose complex neotectonic regime includes strike-slip, reverse and normal faulting, folding, right bending splays, and a migrating depocenter. Recent global positioning system measurements provide slip-rates of 2.6–3.8 mm/yr for the current plate motion in this area. An open crack between the seafloor and a sharp bathymetric cliff in the lake provides visual evidence for this motion, while data from shallow seismic surveys present paleoseismic information on this activity.**

**Keywords:** Dead Sea, pull-apart basins, rift valley, strike-slip fault.

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## INTRODUCTION

The Dead Sea basin (Fig. 1) has been a focus for scientific studies since the middle of the nineteenth century. Early bathymetric soundings of the northern part of the Dead Sea were collected in several expeditions as early as the first half of the nineteenth century (Lynch, 1849; Eriksen, 1989). Modern marine geophysical surveys began in the second half of the twentieth century and included bathymetry, heat flow, magnetics, gravity, seismic refraction, and single and multichannel seismic reflection profiling (e.g., Neev and Emery, 1967). Several maps of the fault pattern of the Dead Sea basin were published simultaneously with the collection of the geophysical data, followed by models of the active tectonic processes in this area (Neev and Hall, 1979). These maps and models were modified with time as more data were collected.

Geophysical research conducted in the Dead Sea through to the mid-1990s was summarized by Ben-Avraham (1997) and Niemi and Ben-Avraham (1997). Bathymetry and single channel Sparker seismic data (Neev and Hall, 1979) indicate that the basin is a fault-bounded depression with deformation taking place mainly along transverse and longitudinal faults. Sediments in the center of the basin are largely undeformed, except in the area east of the central axis of the basin (the Arnon sink), where differential subsidence is thought to be presently occurring (Neev and Hall, 1979; Ben-Avraham et al., 1993). A gradual decrease in the Bouguer gravity anomaly from both ends of the basin led ten Brink et al. (1993) to suggest that the basin sags toward its deepest part in the center. These data also suggest that passive collapse into the deepening graben may have occurred in the past and that the Moho is not significantly elevated under the basin, with deformation being limited to the crust.

Magnetic studies (Neev and Hall, 1979; Frieslander and Ben-Avraham, 1989) show that anomalies extend uninterrupted from the western land into the basin, while the magnetic contours are discontinuous across the eastern margin of the basin. This result was interpreted as meaning that faulting on the western margin of the basin has been mostly normal, with strike-slip motion occurring on the eastern side for the most part. High-resolution, 3.5-kHz seismic data was used to map out the Western Intrabasinal fault, thought to be the main active fault in the Dead Sea lake (Ben-Avraham et al., 1993), and slumping, thought to be a result of the 1927 Jericho earthquake (Niemi and Ben-Avraham, 1994).

In addition, low values of surface heat flow (40 mWm$^{-2}$; Ben-Avraham et al., 1978) indicate a brittle crust and are thus consistent with earthquake data, which suggest a brittle-ductile transition at ~31 km (Aldersons et al., 2003). Therefore, most of the deformation is probably confined to the upper brittle crust (although basin-related deformation must include at least part of the semi-brittle to ductile crust).

Since the previous compilation was published (Ben-Avraham, 1997), new studies have shed light on the tectonics, seismicity, and geology of the region. Results of these new studies are presented here, with the intention of summarizing and updating the state of current knowledge of the tectonics of the Dead Sea basin. Due to its unique environment, the area has attracted scientists from around the world, all with the hope of understanding basin-forming processes.

## THE LARGE-SCALE STRUCTURE OF THE DEAD SEA BASIN

### Seismicity

#### *Teleseismic P-wave Tomography*

New findings of the structure of the crust and upper mantle across the Dead Sea basin were obtained as a result of a large project spanning Israel and the entire Dead Sea fault (Hofstetter et al., 2000). The study was carried out by applying P and PKP wave-relative travel-time-residual inversions of 612 teleseisms, which were recorded by the seismic networks of Israel and Jordan. In addition, Bouguer gravity anomalies were used to independently examine the structure of the crust and upper mantle.

Seismic stations within the Dead Sea fault recorded positive travel-time residuals (summation of all anomalies seen by the rays extending from the bottom of the model to the top), with the largest occurring in the southern Dead Sea basin. In addition, the Dead Sea basin is also characterized by the largest negative velocity anomaly (over 12%). The location of this anomaly is in good agreement with the location of the positive travel-time-residual anomaly.

In contrast to the pronounced negative velocity anomaly in the center of the southern Dead Sea basin, velocity anomalies are minimal (slightly negative, but close to zero) on both the northern and southern sides of this area. Salt, despite having a relatively low mass density, usually exhibits a high-seismic velocity comparable to dolomite (Dobrin, 1952). One would thus expect a small anomaly, if at all, for a station located above a salt dome such as Mount Sedom. However, the fact that both travel-time residuals and velocity anomalies within the basin indicate the presence of a slow material relative to the ambient material excludes salt as a main component of the basin fill. This is in agreement with the findings of the refraction study (Ginzburg and Ben-Avraham, 1997; see below), which showed that, except for two prominent salt diapirs (Lisan and Ein Gedi), the layer of salt is relatively thin, as well as with new multichannel seismic data from both sides of the border (Al-Zoubi et al., 2002)

A positive velocity anomaly in the northern Dead Sea basin was attributed to small changes of the depth of the Moho discontinuity. Qualitative estimations of this uplift, based on the inversion of teleseismic and relative travel-time anomalies, suggest that a relatively small elevation of less than 3 km can explain this positive anomaly. Ginzburg and Ben-Avraham (1997) calculated a difference in the depth to the basement between the northern and southern basins of ~6 km from seismic refraction data (see below). However, the refraction stations were located at the center of the fault valley, while the seismic stations are at the sides of the fault valley.

### *Strength of the Lower Crust under the Dead Sea Basin*

A recent reevaluation of local seismicity of the Dead Sea basin for the period of 1984–1997 (Aldersons et al., 2003) revealed that the majority of well-constrained micro-earthquakes ($M_L \leq 3.2$) occurred at depths much deeper than previously expected. These micro-earthquakes display continuous focal depths down to the Moho, located at a depth of 32 km, while the upper mantle appeared to be aseismic during the 14-yr data period (Fig. 2). Sixty percent of the earthquakes nucleated at depths of 20–32 km and more than 40 percent occurred at depths shallower than that of peak seismicity, situated at 20 km (an upper bound uncertainty of ±5 km was estimated for depths greater than 20 km, but depth mislocations did not exceed ±2 km for most earthquakes). This implies that the lower crust (20–32 km) is significantly strong under the Dead Sea basin. These findings are important due to the fact that while deep-rooted earthquakes have been documented in rift zones (such as the East African Rift, e.g., Shudofsky et al., 1987; and the Baikal Rift system, Déverchère et al., 2001), lower crustal seismicity is still debated for the Dead Sea fault system (which is a transform valley and not a classic rift).

A lithospheric strength profile was also calculated. Based on a surface heat flow of 40 $mWm^{-2}$ (Ben-Avraham et al., 1978) and assuming a quartz-depleted lower crust, a narrow brittle to ductile transition is thought to occur in the crust around 380 °C at a depth of 31 km. The low value of the regional surface heat flow indicates that the lower crust might be cool and brittle. If brittle behavior is likely to be the dominant deformation mechanism in the lower crust of the basin, strong earthquakes should also nucleate in the lower crust, not just micro-earthquakes. However, due to the long recurrence interval of strong earthquakes in the Dead Sea (Shapira, 1997), several centuries of monitoring might be required before valid statistics would allow a reliable assessment of this likely possibility.

For the upper mantle, the brittle-to-ductile transition occurs in the model at 490 °C and at 44 km depth. However, the absence of microseismicity in the upper mantle remains problematic. If the lower crust of the Dead Sea is cool and brittle, then the upper mantle should also be in a seismogenic state, but it appears to be aseismic during the 14-yr data period. Aldersons et al. (2003) argue that the high strength of the mantle is the reason for the scarcity of earthquakes below the Moho. If this is the case, the upper mantle would not be aseismic, but nucleation of earthquakes would be difficult, leading to long recurrence intervals. In the case of the Dead Sea basin, decoupling between the crust and the mantle was not found to be a likely mechanism for explaining the absence of earthquakes in the upper mantle. Results of the above study point toward a mechanically coupled crust-mantle system.

## Seismic Refraction

A wide-angle seismic reflection-refraction experiment involving the use of 9 ocean bottom seismometers (OBS), placed at the bottom of the Dead Sea, and 11 portable seismic land stations was conducted along a north-south profile in the lake of the northern basin and adjacent land area (Ginzburg and Ben-Avraham, 1997).

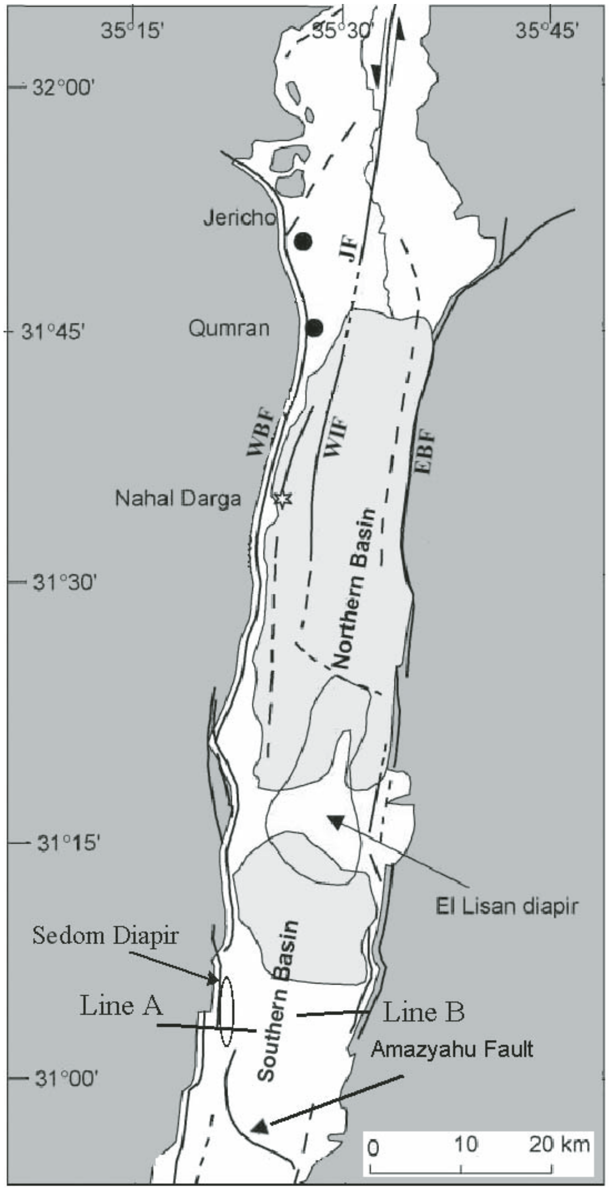

Figure 1. The Dead Sea basin showing the location of main faults and subbasins (after Lubberts and Ben-Avraham, 2002). Box indicates location of Figure 6. Lines A and B indicate the location of the profiles shown in Figure 3. JF—Jericho fault (dashed where inferred); WBF—Western Boundary fault; EBF—Eastern Boundary fault; WIF—Western Intrabasinal fault. Star marks the epicenter of the 1927 Jericho earthquake.

The profile revealed a structure that shows a considerable difference between the northern and southern basins. The two areas are separated by a major basement fault with a downthrow to the south of ~4–5 km. This faulting and intense sedimentation resulted in the deposition of a 6–8 km-thick sedimentary sequence in the northern Dead Sea basin and a 12-km-thick sedimentary sequence in the southern basin. The differences between north and south may indicate that the northern basin is younger than the southern one or that greater subsidence was prevalent in the southern basin. These data do not support the idea of a gradual sagging of the basin from north and south toward its center (as proposed by ten Brink et al., 1993).

Analysis of the recorded seismograms indicated the presence of two large Pliocene salt diapirs in the young basin fill (Fig. 3). The southern diapir was interpreted as being part of the Lisan diapir. Other than these two salt diapirs, it would seem that the refraction indicates that little salt is present in the fill of the Dead Sea basin. This is in excellent agreement with the findings of Hofstetter et al. (2000), which were based on seismic tomography (see above).

## THE INTERNAL STRUCTURE OF THE DEAD SEA BASIN

### Results from Seismic Reflection Studies across the Southern Dead Sea Basin

The Dead Sea basin is divided more-or-less down the center by the international border between Israel and Jordan. Despite the numerous studies (gravity, magnetics, and seismicity) carried out by both countries, interpretation and synthesis of these data have been handicapped by the fact that all of the surveys on either side terminated short of the border, with no tie between them. In addition, raw data was not exchanged between the two nations. The recent exchange of seismic profiles helped bridge the gap in information and shed light on extensional processes involved in the formation of the basin (Al-Zoubi and ten Brink, 2002; Al-Zoubi et al., 2002).

Seismic reflection data from Israel and Jordan have led to a more complete picture of the tectonic regime in the southern Dead Sea basin. Correlation of the three major sedimentary sequences that form the basin fill (Miocene clastics, Pliocene salt, and Pleistocene-Holocene clastics and evaporites; as defined by Zak and Freund, 1981) allowed for sequences to be mapped across the entire width of the southern Dead Sea basin for the first time (Fig. 4; Al-Zoubi et al., 2002). The data reveal that all three major structural steps known to exist on the western side of the basin (the rim block, intermediate block, and deep block) are also found in the east, indicating that the southern Dead Sea basin is a full graben. The very thin Miocene fill and lack of Pliocene salt in the eastern intermediate block suggests that the Ghor-Safi fault was initiated earlier than the Sedom fault.

The current data seem to resolve the controversy over the distribution and amount of rock salt present in the eastern part of the southern Dead Sea basin. While previous estimates of the thickness of Pliocene evaporates for this part of the basin ranged from 4 to 5 km to a very thin layer of salt, if at all, the new interpretation clearly shows that salt is present over the entire width of the basin (Fig. 4), but does not exceed 900 m in thickness. The data also indicate that in this area salt flowed upward from the deep basin throughout the Pleistocene as suggested by Gardosh et al. (1997). More recently, a number of techniques were applied to the Sedom Diapir to reconstruct the topographic rise and its relation to lake level variations during the late Pleistocene and Holocene (Weinberger et al., this volume). Data examined include angular and erosional unconformities, thickness variations, caprock formation, chemistry and isotope composition of lacustrine aragonite, cave morphology, precise leveling, and satellite geodesy.

### *Lower Crustal Flow and the Role of Shear in Basin Subsidence*

The seismic profiles from the southern basin of the Dead Sea show gradual thickening of the basin from south to north without major vertical offsets in either the basin fill or the underlying strata. The geometry of the strata indicates a southward expansion of symmetrical subsidence. Based on the newly available data, Al-Zoubi and ten Brink (2002) proposed that the observed subsidence is due to necking of the lower crust over a longer area than defined by brittle deformation. Lower crustal flow may be driven by the thinning of the brittle overburden in the central part of the basin and possibly by thinning of the lower crust in response to north-south stretching. The authors also suggested that lateral shear along the Dead Sea transform increases the likelihood that lower crustal flow is a significant factor in the subsidence of the Dead Sea basin.

Thinning by ductile deformation provides a viable mechanism for observed regional subsidence (Al-Zoubi and ten Brink, 2002). Large-scale subsidence (5–6 km depth) with little attendant brittle deformation in the southern Dead Sea basin was interpreted as indicating thinning due to lower crustal flow. Along-axis flow within the lower crust could be induced by the reduction of overburden pressure in the central Dead Sea basin, where brittle extensional deformation is observed. The authors further suggested that lower crustal flow facilitated by shear may be a viable mechanism to enlarge basins and modify other topographic features even in the absence of underlying thermal anomalies. However, their model contradicts the observations of Aldersons et al. (2003), whose results indicate the presence of a strong, brittle lower crust.

### *The Lisan Diapir*

The release of data from the Jordanian side has also allowed imaging of the Lisan diapir—a large salt diapir underneath the Lisan Peninsula (Fig. 1). The size of the diapir was determined to be 13 × 10 km, with an average thickness of 6 km (Al-Zoubi and ten Brink, 2001). The diapir started rising during the early to middle Pleistocene as this section of the basin underwent rapid subsidence and significant extension of the brittle overburden. Regional extension of the overburden and underlying salt caused differential loading, which in turn caused the initiation of the rise of the diapir. During the middle to late Pleistocene, the diapir pierced through the extensionally thinned overburden as indicated by rim synclines, which attest to rapid salt withdrawal from the surrounding regions. There are also indications that the diapir is still rising intermittently (Al-Zoubi and ten Brink, 2001),

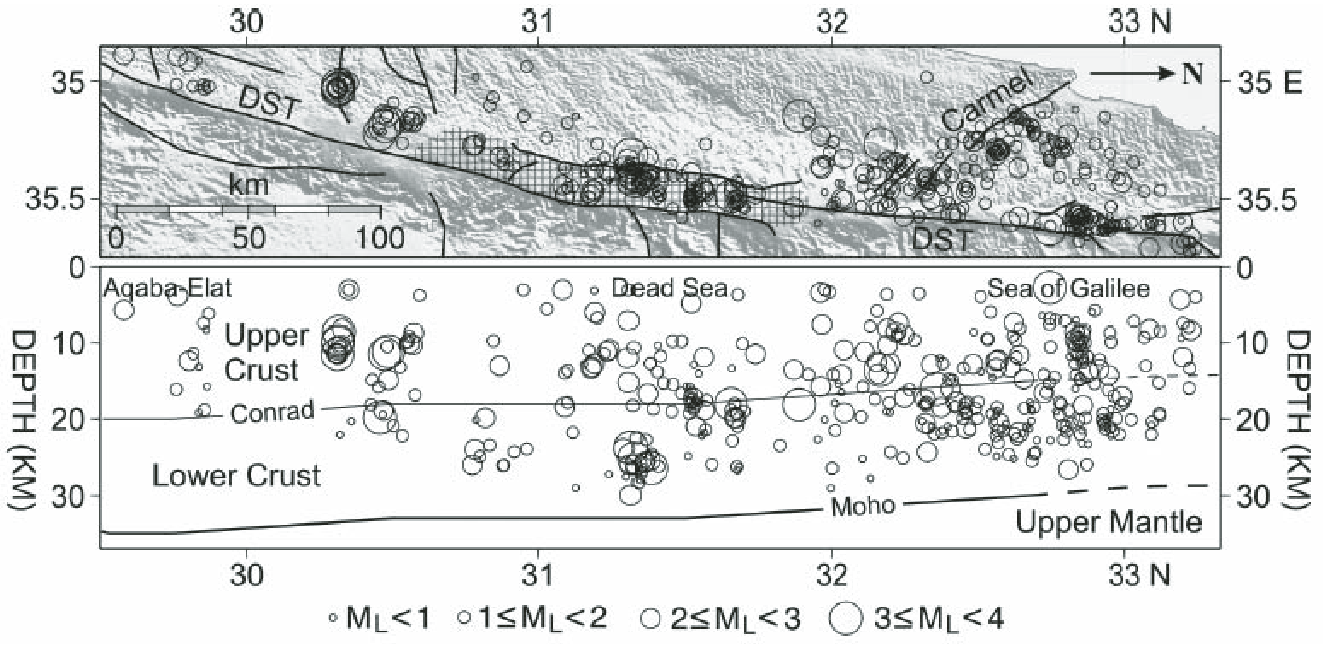

Figure 2. Depth section of well-constrained seismicity (410 earthquakes, 1984–1997, after Aldersons et al., 2001) along the Dead Sea transform (DST) from Aqaba-Elat to the Sea of Galilee (after Aldersons et al., 2003). The square grid fill defines the Dead Sea basin on the map. Conrad and Moho discontinuities from Ginzburg et al. (1981).

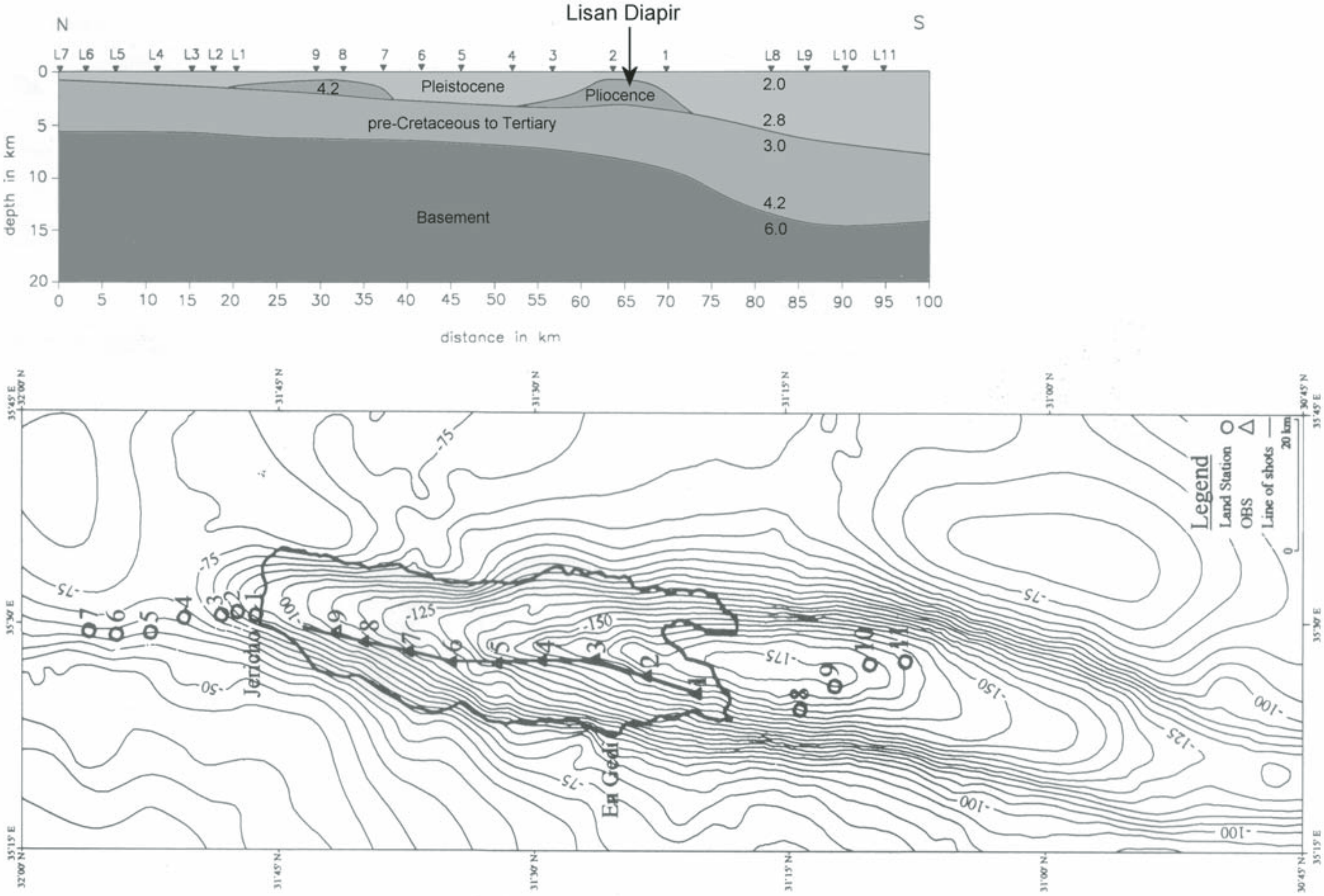

Figure 3. Top: Velocity-depth section along Dead Sea from north of the northern basin, to the southern basin, based on the seismic refraction experiment (after Ginzburg and Ben-Avraham, 1997). The 2.0 km/s velocity represents the Pleistocene fill of the basin. The 4.2 km/s velocity is associated with Pliocene evaporites. The 6.0 km/s velocity represents the top of the crystalline basement, while the overlying 3.0–3.8 km/s is associated with the Tertiary to pre-Cretaceous sediments. Bottom: Map of the profile showing the location of the ocean bottom seismometers (OBS) and land stations (Ibid).

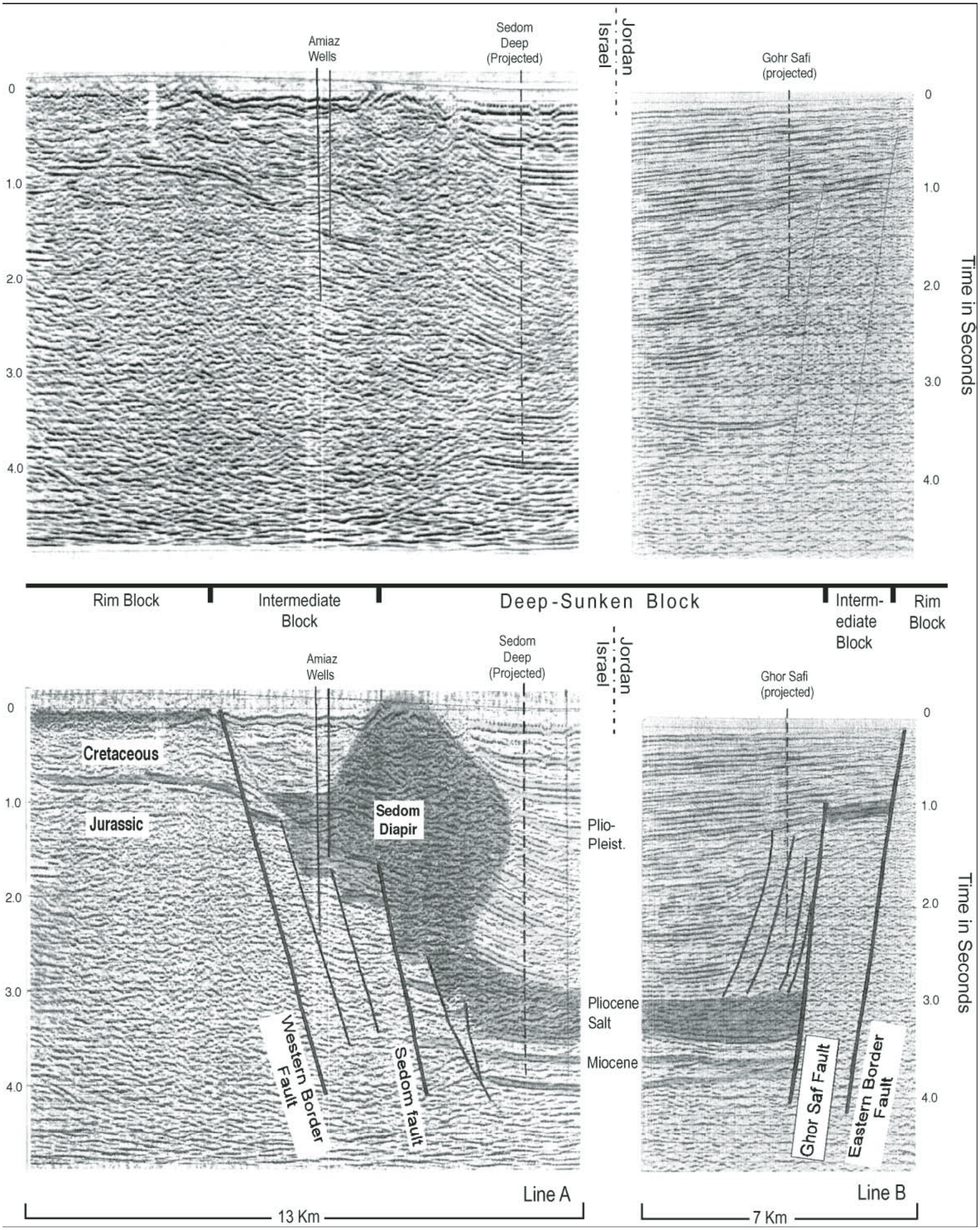

Figure 4. Top: Seismic time lines from the southern Dead Sea basin. Line A—Western side; line B—Eastern side. Bottom: Interpretation showing the main structural elements on both sides of the southern Dead Sea basin: rim blocks, intermediate blocks, deep sunken block, and the faults that separate them. The Sedom Deep-1 is projected into line A to a position that fit the stratigraphy of the deep block (after Al-Zoubi et al., 2002). See Figure 1 for location.

although interferometric synthetic aperture radar (InSAR) measurements show that some areas of the Lisan Peninsula are subsiding, while others are being uplifted (Baer et al., 2002). Deformation associated with the edge of the salt, previously interpreted as the Boqeq diagonal fault (crossing the basin in a NW-SE direction, Ben-Avraham et al., 1990), was reinterpreted according to the newly released seismic sections as representing the edge of the Lisan salt diapir, rather than a deep rooted fault in the basin fill (Al-Zoubi and ten Brink, 2001). Hence, according to the new interpretation, there is no diagonal fault cutting the Pleistocene section between the Sedom and Lisan diapirs.

The location of the Lisan diapir within a sunken block of the Dead Sea basin was explained by a model of diapiric formation during extension in accordance with the model proposed by Vendeville and Jackson (1992). According to this model, a diapir develops where the overburden was thinned relative to the surrounding areas, provided the overburden is not too rigid and the viscosity of the salt not too great as to resist the rise. These conditions are met in the Dead Sea. The Lisan diapir developed faster than the Sedom diapir to the west due to higher N-S extension rates along the long axis of the basin.

Seismic data and gravity models indicate the basin reaches a depth of ~8.5 km under the Lisan diapir. This is ~1.5 km shallower than previously suggested. Gravity also indicates that thinning of the salt is more gradual to the north than to the south.

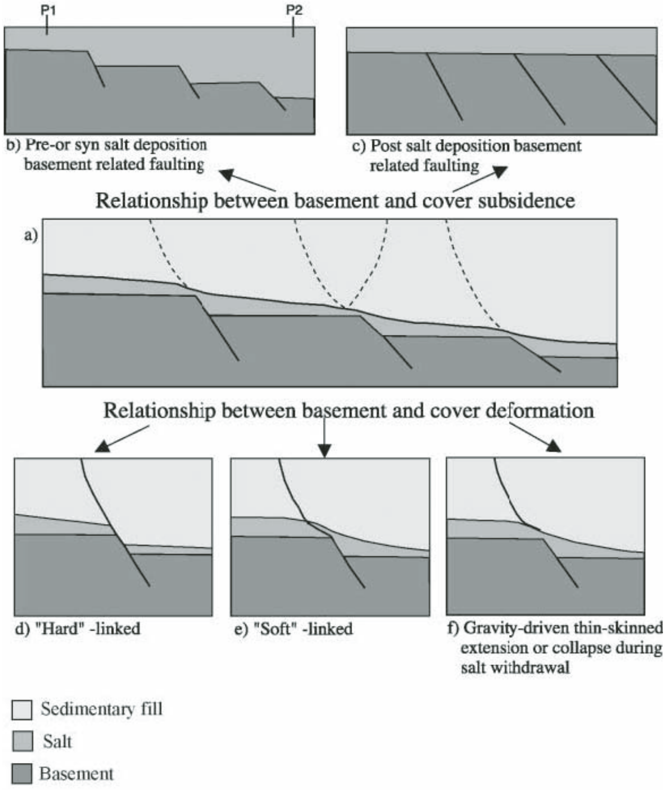

Figure 5. Interpreted behavior of salt. (A) Present geometry across a basin. Variations in cover thickness can be caused by (B) salt withdrawal as a result of differential pressure between two points (marked P1 and P2) or (C) basement faulting, causing thickness variations seen in the cover. The ability of salt to act as a décollement (detachment plane) means that deformation of the overburden could be interpreted in different ways: (1) it is directly coupled to basement faults (below seismic resolution) and hence, undergoes deformation as a result of activity; (2) deformation is caused by basement faulting with salt acting as a décollement zone, or (3) gravity driven extension or collapse due to salt withdrawal with the top salt surface acting as a detachment plane causes the observed deformation (after Larsen et al., 2002).

### *Salt Tectonics*

A comprehensive study based on seismic cross section and borehole data from the western side of the southern Dead Sea basin was carried out in order to investigate the relationship between halokinetic features and major faults in the area (Larsen et al., 2002). The study was aimed at answering the question as to whether basement faulting preceded or followed salt deposition.

According to their study, a thick layer of salt (~2 km), which comprises the Sedom Formation, was most likely deposited during and after basement faulting and not before (Fig. 5). Furthermore, they also suggest that the listric Amazyahu fault may have developed as a result of gravity driven extension or collapse due to salt withdrawal, with the top salt acting as a detachment plane. Subsidence and rotation along this fault seem to have started in the early Pleistocene and most likely induced antithetic faulting, which in turn later generated graben features in the shallow section. This rotational movement, along with the removal of salt into diapirs in the north (creating a space for deposition) may have led to the migration of the local depocenter toward the southeast, while regionally the main depocenter migrated to the northeast (e.g., Zak and Freund, 1981; ten Brink and Ben-Avraham, 1989). In addition, it was found that the Sedom fault has experienced strike-slip movements as well as normal faulting.

### *Tectonic Evolution of the Qumran Basin from 3.5-kHz Seismic Profiles*

The recent tectonic structure of the northwestern margin of the Dead Sea basin was examined using high-resolution 3.5-kHz seismic reflection profiles collected in 1984 in two different surveys (Lubberts and Ben-Avraham, 2002). The first survey (the western margin survey) focused on the shallow platform margin and was conducted in shallow water (part of which is exposed today due to dropping lake levels). Lines 0.25–3 km long and spaced 250 m apart were collected in water between 1 and 60 m deep perpendicular to the shoreline of the lake, with almost E-W orientation. The second survey collected high-resolution seismic and bathymetric data from water depths between 60 and 320 m at the time of the survey. This survey was collected along E-W and NNE-SSW oriented lines. Parameters used for these surveys were summarized by Ben-Avraham (1997).

Three different structural areas were mapped from the western margin survey (Fig. 6). The first area (1 in Fig. 6A) was interpreted as a 3-km-long, 0.5-km-wide, NNE-trending zone of

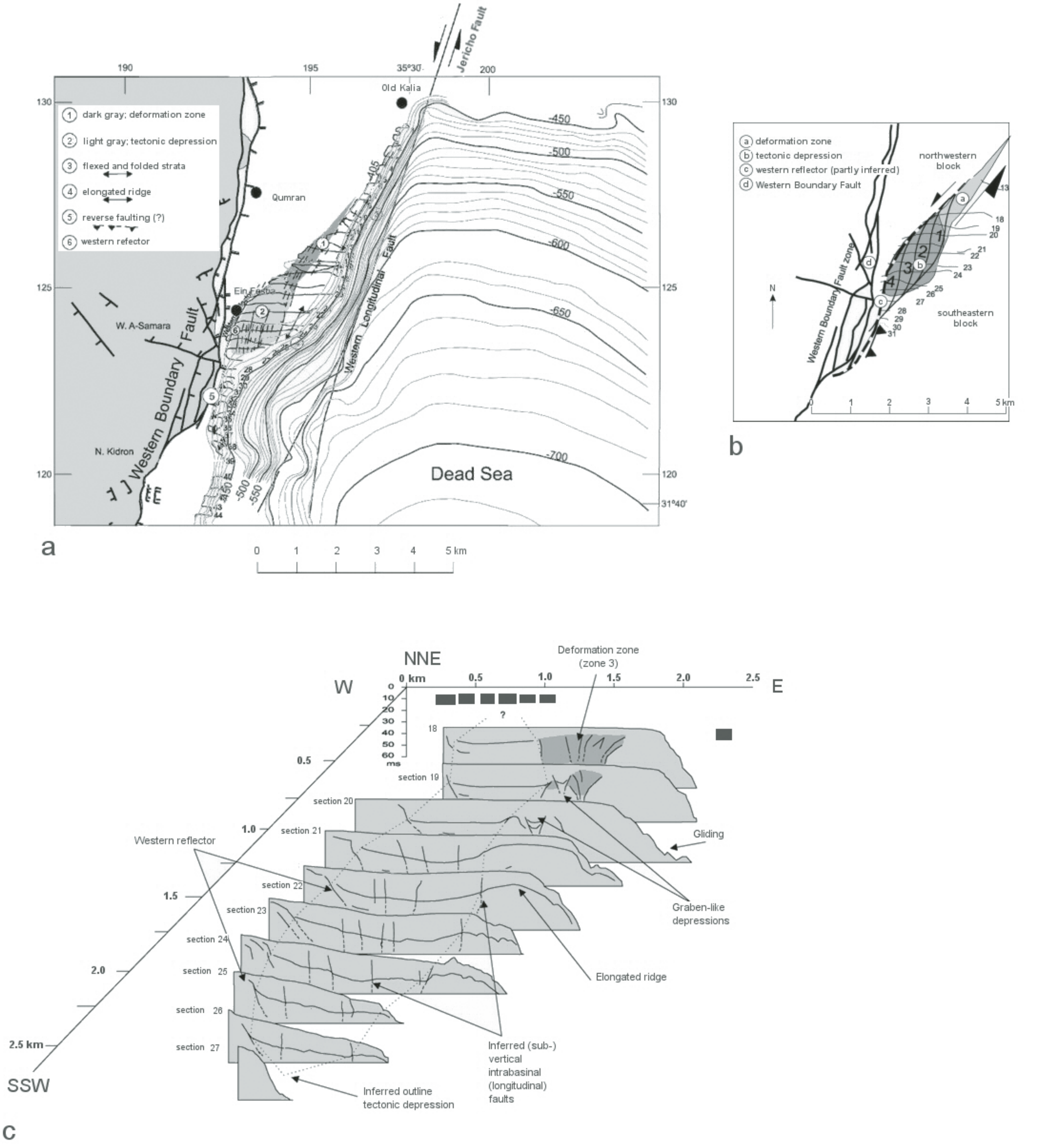

Figure 6. Structural features of the Qumran basin (from Lubberts and Ben-Avraham, 2002). (A) Bathymetry of the northwestern shoulder of the Dead Sea along with location map of 3.5-kHz seismic lines used for the study. Bathymetry calculated from the 3.5-kHz seismic lines. The dark gray area between 125°N and 127°N marks an area of strong tectonic deformation. The light gray area between 123°N and 125°N marks a tectonic depression. (B) Schematic evolution of the tectonic depression (Qumran basin) when depicted as a releasing-bend pull-apart. Its orientation relative to the Western Boundary fault suggests different absolute magnitudes of horizontal displacement for opposing structural blocks (indicated by the length of the strike-slip arrows). (C) Geometry of the Qumran basin synthesized from the interpretation of 3.5-kHz seismic sections. The inferred outline of the tectonic basin is marked by a broken line. The dark gray area marks the deformation zone located northeast of the depression. A fault bounds the depression to the west (marked Western Reflector). Also marked are an elongate ridge that bounds the depression to the east, inferred (sub) vertical faults that cut the depression in longitudinal direction, and graben-like depressions along the northeastern boundary of the depression. The structural basement of the tectonic depression is not penetrated acoustically.

deformation, marked by faulted, folded, and intensely deformed strata. This area gradually merges into the second structural zone (2 in Fig. 6A), which is characterized by a tectonic depression, termed the Qumran basin. The depression ends abruptly where the marginal slope steepens dramatically from 1.4° to ~9° over 250 m and transforms into the third structural area (5 in Fig. 6A), which is characterized by reverse faulting and folding (tectonic setting is summarized in Fig. 6B).

The newly discovered Qumran basin is 2 km long, 1 km wide, and at least 30–40 m deep (Lubberts and Ben-Avraham, 2002). It is asymmetrical longitudinally, with its axis plunging ~0.8°. In the transverse direction, the depression is symmetrical in the north to weakly asymmetric in the south, suggesting stronger subsidence along the eastern side of the basin (Fig. 6C).

The study speculates that both the narrow zone of intense deformation and the Qumran basin originate from strike-slip motion along right-bending faults that splay off from the Jericho (or Jordan) fault, which is considered to be the strike-slip master fault delimiting the active Dead Sea basin on the west. Fault interaction between the Jericho fault and the normal faults bounding the transform valley (the Western Boundary fault) was used to explain the origin of the right bending splays. The widening of the basin head toward the south could result from the successive formation of secondary right bending splays to the north, as the active depocenter of the Dead Sea basin migrates northward with time.

### *GPS Measurements*

With increased availability of satellite data, global positioning system (GPS) measurements have been widely applied to the Dead Sea fault. Based on three years of continuous GPS measurements, (1996–1999), the current displacement across the Dead Sea fault was calculated (Pe'eri et al., 2002b). Analysis of the data provided an estimate of 2.6 ± 1.1 mm/yr, confirming what was deduced from geological and seismological evidence—that the boundary between the African plate and Sinai subplate is currently active.

However, these values are slightly low in comparison to other, more global measurements, which found a rate of 5.8 ± 1 mm/yr left-lateral slip on the southern Dead Sea fault (McClusky et al., 2003). The possibly higher rate determined in comparison with regional GPS studies could reflect an active opening of the Gulf of Suez estimated at ~1 mm/yr (Steckler et al. 1998), which would add an additional component to the calculated global slip rate (and thus increasing it). GPS data are not yet sufficient to justify this conclusion.

A more recent study (Wdowinski et al., 2004) calculated the slip rate along the Dead Sea fault as 2.8–3.8 mm/yr for a period spanning seven years between 1996 and 2002. While their estimate is closer to the one derived by McClusky et al. (2003), they attribute the differences in slip rates between the different studies to the different methodology used in each study and the timescale of observations. The exclusion of measurement stations from the data contributes to a higher estimate of 3.2–4.2 mm/yr.

It should be pointed out that geological estimates based on processes during the last 25 million years (e.g., Garfunkel, 1981) indicate a slip-rate ranging from 6 to 10 mm/yr but are thought to be overestimated according to Wdowinski et al. (2004). According to Klinger et al. (2000), geomorphological studies of the fault system in Israel indicate a rate of 4 ± 2 mm/yr since the late Pleistocene, which is much closer to the observed rates from GPS measurements.

### *Remote Sensing*

Remote sensing has shown great potential as a tool for carrying out comprehensive research of the Dead Sea region. Two different studies have examined the Sedom salt diapir located on the western shoulder of the southern Dead Sea basin. The first study used an airborne hyperspectral sensor (the German DAIS [Digital Airborne Imaging Spectrometer]) to remotely sense the lithological surface structure of the Sedom diapir (Zock, 2000). This pioneering investigation showed the potential to distinguish between different strata purely on the basis of the reflection spectra from lithology. This was found to be a reliable indicator of the depositional conditions for different strata and could provide a tool for interpreting lithological discontinuities that were caused by local tectonics.

The second study, which focused on the current uplift of the Sedom diapir and its internal deformation, was carried out using InSAR (Pe'eri et al., 2001). The calculated uplift rates show that the salt diapir is divided into two sections with each section having a different uplift rate. Measurements were found to be 8.3 ± 0.3 and 6.9 ± 0.3 mm/yr for the northern and southern blocks, respectively (Fig. 7) (Pe'eri et al., 2004). The uncertainty of ± 0.3 was estimated using a root-mean-square method on all the pixel values around each block's uplift center (Pe'eri et al., 2004). In addition, direct measurements using InSAR show that the salt budget of the diapir is 48,000 ± 16,000 $m^3$/yr. GPS and leveling were used as reference measurements in the study. A special geodetic network was constructed to provide the high-vertical accuracy required by these investigations. The three years (2000–2002) of leveling measurements are in good correlation with the InSAR results. The diapir deformation was modeled (Pe'eri et al., 2002a) by simulating the salt flow as a viscous fluid passing through two vertical pipes with an elliptical cross-section. Viscosity ($3.9 \times 10^{19}$ poise to $4.64 \times 10^{19}$ poise) and salt budget (35,578 $m^3$/yr ± 3,063 $m^3$/yr) were calculated from the model. The calculated salt budget is in good agreement with the direct measurements. In addition, the division of the diapir into two blocks may be associated with local tectonics. Analysis of seismic lines from the southern Dead Sea indicates that the deformation pattern of the diapir is driven not just by the passive rise of salt, but is influenced also by tectonic processes. A detailed study on the history of the Sedom diapir and its uplift rates is presented by Weinberger et al. (this volume).

### *Evidence of Neotectonic Activity and Life*

One of the most unique studies carried out in the Dead Sea was aimed at evaluating recent tectonic activity of the Western

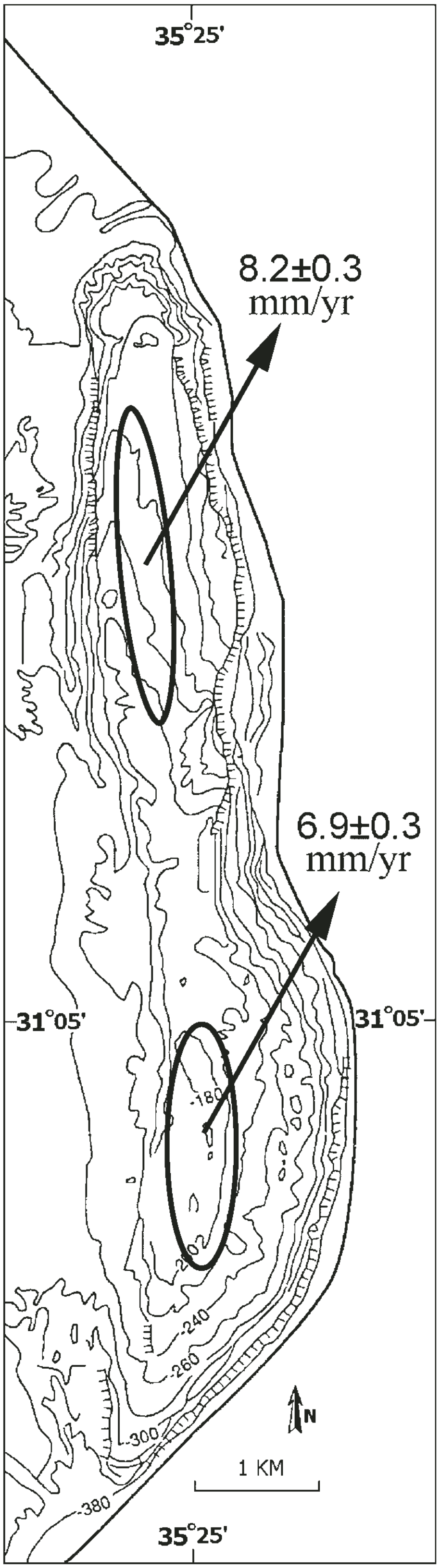

Figure 7. Simplified topographic map of the Mount Sedom salt diapir (see Figure 1 for location), showing the division into two separate blocks and their respective uplift rates (after Frumkin, 1996).

Intrabasinal fault, thought to be the main longitudinal fault representing the active plate boundary in the Dead Sea (the marine extension of the Jericho fault). This fault is located along the bathymetric scarp of the western shoulder of the lake (Neev and Hall, 1979). For two weeks in December 1999, a two-man submersible, the *Delta*, was brought to the lake for an archaeological and geological survey (Lazar and Ben-Avraham, 2002). A total of 35 dives were made, lasting between 20 min and 2 h. Visibility was around 6 m and fairly uniform throughout all locations and depths. In general, the seafloor is flat and covered with salt. The submersible study was followed by a high-resolution seismic chirp survey, used to correlate the underwater images with tectonic features (Fig. 8A, B, and C).

The dives were made in water depths ranging from 20 m to 250 m below Dead Sea level and were limited to the northwestern corner. Dives centered on the western shore encountered a sharp bathymetric cliff. This cliff was interpreted as being part of the same escarpment mapped as the main active longitudinal fault (Fig. 8A; the Western Intrabasinal fault). At the base of this escarpment, the contact between the seafloor and fault scarp (expressed as a sharp vertical cliff) was open (i.e., an open crack ~15 cm wide) suggesting either seepage of fresher water (thus dissolving the salt above it) or oblique motion (resulting in the formation of an open crack). In deeper waters (> ~100 m) the escarpment is "stepped" with vertical offsets of up to 10 m. Along the scarp, evidence of slumping was also observed, as well as areas where the salt has been chipped away exposing underlying, partly deformed, laminated marl. This was also interpreted as evidence for motion along the scarp due to the fact that only shaking of the wall could provide an explanation for the lack of salt in some areas but not others.

The high salt concentration makes it almost impossible for life to survive in the waters of the Dead Sea. However, halophilic microorganisms have been known to exist and have even been monitored in this harsh environment (Oren, 1997; Madigan and Oren, 1999). It has always been thought that these life forms were dependant on surface algae, and were dormant in the lake in recent years due to the increasing salt concentration caused by the lack of a supply of fresh water (Oren, 1997). One of the most exciting discoveries of this study were suspected colonies of these halobacteria living and thriving on the salt itself at all water depths, even at of 100 m below the surface of the Dead Sea (560 m below mean sea level at the time), where no light can filter through the water. These red patches were observed mainly close to zones of intense faulting, near the fault, and on top of small mounds near faulted areas. However, only a detailed sampling study will determine whether the red color indicates the presence of bacteria or the result of inorganic mineralization brought to the surface via seepages from below.

In the same area, differences in salt crystal size were observed in the vicinity of lineaments interpreted as faults. It is possible that less-saline water from surrounding aquifers is flowing through the inclined layers, accumulating pressure, which eventually leads to its seepage through cracks and faults in the bottom of the lake (Yechieli and Gat, 1997). Such seepage could slow down crystallization processes, leading to larger, coarser crystals along the scarp. This decrease in local water salinity may provide an explanation for the abundance of suspected red halobacteria by creating a friendlier environment for them to thrive in. Such seepage is thought to be tectonically controlled, once again indicating active faulting in the northern Dead Sea basin.

## DISCUSSION

New geophysical data from the Dead Sea basin provides important information on tectonic processes, which shape and control the entire area. Regional cooperation has opened up a wealth of opportunities for joint research, which has just begun to provide information on the basin as a whole.

### The Deep Structure of the Dead Sea Basin

The exchange of data between Jordan and Israel has led to the combination of networks for earthquake monitoring (seismic stations). Results of this cooperation have led to significant findings on the deep structure of the basin. Earthquake data suggests that the southern Dead Sea basin is characterized by the largest increase in teleseismic travel-time residuals in the region (Hofstetter et al., 2000). This is probably due to the infilling of light material (sediments) relative to the surrounding material, which is also supported by the seismic refraction data. Analysis of micro-earthquake data has also led to the conclusion that 60% of micro-earthquakes nucleate at depths of 20–30 km (Aldersons et al., 2003)—far deeper than what was expected in comparison with other transforms and pull-aparts worldwide, suggesting a brittle lower crust. In addition, a more detailed lithospheric strength profile was calculated from this data indicating a narrow brittle-to-ductile transition at a depth of 31 km.

As an alternative solution to a brittle lower crust, a model recently developed by Al-Zoubi and ten Brink (2002) suggests that crustal flow might well be a viable deformation mechanism in the lower crust of the Dead Sea basin. However, the relocation of earthquake epicenters mentioned above, indicate that the lower crust is probably brittle (Aldersons et al., 2003). The new model of Al-Zoubi and ten Brink (2002) corresponds with the model based on gravity results proposed by ten Brink et al. (1993), which shows a gentle sagging of the northern and southern ends of the Dead Sea toward the center of the basin and points to crustal flow. However, refraction studies (e.g., Ginzburg and Ben-Avraham, 1997) indicate a sharp step between the southern and northern basins. This sharp step seems to be in keeping with a brittle lower crust, which is more easily broken and faulted. Seeing as gravity methods do not always pick-up the location of faults, the refraction data seem more reliable and hence, the brittle lower crust model more viable.

### Recent Activity

Information on the shallow structure indicates that tectonics is still shaping the basin, controlling and dominating processes

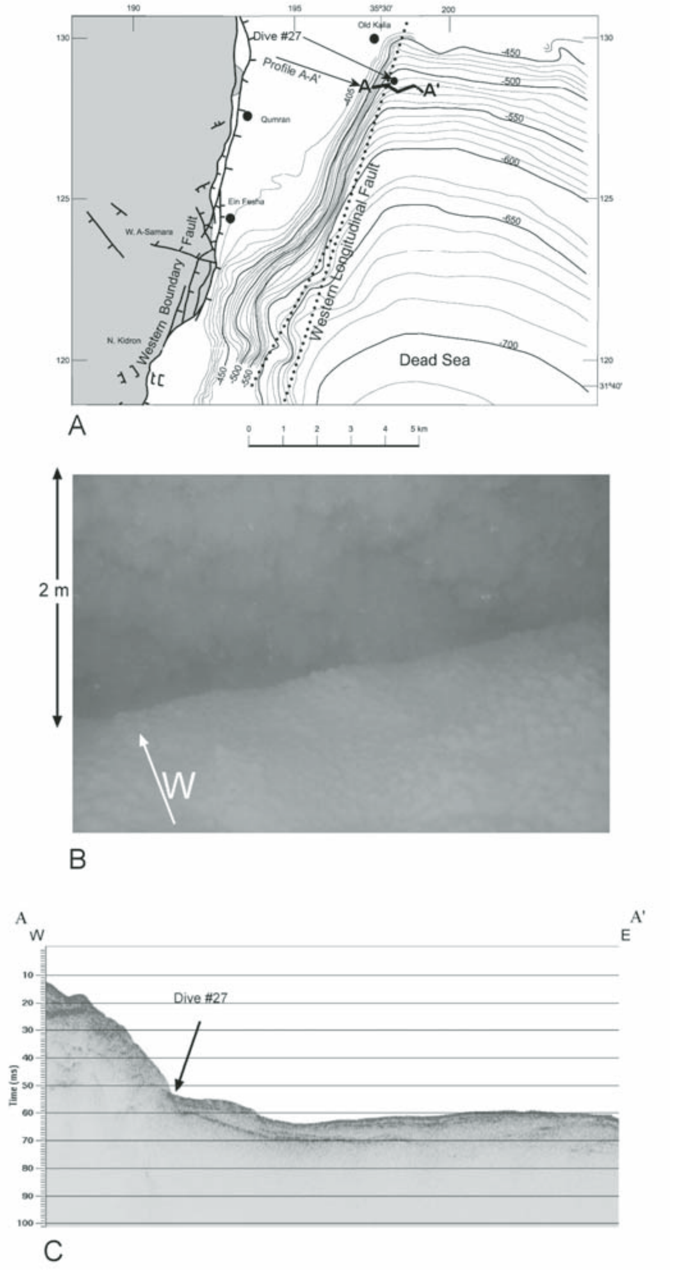

Figure 8. The Western Intrabasinal fault. (A) Location map of submersible dive #27 (black dot) and line A–A′ from the chirp survey along with the bathymetric map of the northern Dead Sea basin, based on Neev and Hall (1979). Location of Western Intrabasinal fault, which diverges into two faults to the south, is marked by dotted lines. (B) The underwater expression of the Jericho fault at a water depth of 100 m as recorded in dive #27. An open crack (~15 cm) between the cliff and seafloor is visible and could indicate water seepages through an active fault. (C) High-resolution chirp seismic profile A–A′ showing the location of the fault and dive #27. The contact between the seafloor and the slope corresponds with the underwater expression of the Jericho fault (after Lazar and Ben-Avraham, 2002).

in the lake. Activity in the northwestern corner of the lake was inferred from visual evidence collected by the submarine campaign (Lazar and Ben-Avraham, 2002). Faults were suspected in areas where differences in salt crystal size and red halobacteria were observed. Seepage of water through cracks would slow down crystallization processes and reduce local water salinity, thus creating a friendlier environment for the bacteria to thrive in. Such seepage is thought to be tectonically controlled.

Indications for recent activity within the Dead Sea basin present an interesting picture. Earthquake return intervals calculated for these studies differ from those obtained in other studies, which could indicate that either earthquakes in the area are clustered or that activity on the Jericho fault is not spatially distributed in a uniform way. These recent findings seem to be in good correlation with Niemi and Ben-Avraham (1997), who divided the marine extension of the Jericho fault into different segments. These segments are not always activated at the same time and seismic energy can be transmitted along all of the segments or along a selected few. Thus, studies carried out in different areas of the Dead Sea basin can show differences in earthquake return rates. Much work still needs to be done in order to fully understand the mechanisms at work in the Dead Sea basin. However, continuous regional cooperation has provided vital information, allowing researchers to obtain a more complete image of the basin and the tectonic processes which formed it and continue to form it.

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