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The Northern end of the Dead Sea Basin: Geometry from reflection seismic evidence

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Abstract

Recently released reflection seismic lines from the Eastern side of the Jordan River north of the Dead Sea were interpreted by using borehole data and incorporated with the previously published seismic lines of the eastern side of the Jordan River. For the first time, the lines from the eastern side of the Jordan River were combined with the published reflection seismic lines from the western side of the Jordan River. In the complete cross sections, the inner deep basin is strongly asymmetric toward the Jericho Fault supporting the interpretation of this segment of the fault as the long-lived and presently active part of the Dead Sea Transform. There is no indication for a shift of the depocenter toward a hypothetical eastern major fault with time, as recently suggested. Rather, the north-eastern margin of the deep basin takes the form of a large flexure, modestly faulted. In the N–S-section along its depocenter, the floor of the basin at its northern end appears to deepen continuously by roughly 0.5 km over 10 km distance, without evidence of a transverse fault. The asymmetric and gently-dipping shape of the basin can be explained by models in which the basin is located outside the area of overlap between en-echelon strike-slip faults.

Keywords: Dead Sea Basin; Pull-apart basin; Basin asymmetry; Transform fault

1. Introduction

The Dead Sea Basin (DSB) is assumed to be one of the largest and deepest pull-apart basins in the world and considered as a classic example for such structure (Aydin and Nur, 1982; Allen and Allen, 1990). It is located within the Dead Sea Rift which is a transform type plate boundary separating the Arabian and Sinai plates while connecting the spreading zone of the Red Sea in the South to the Taurus collision zone in the north (Fig. 1A). The Dead Sea Transform is a left lateral shear, which started in the Miocene, with an accumulative lateral displacement of 105 km (Quennell, 1958; Freund et al., 1970; Garfunkel, 1981). The DSB with all its subbasins is about 150 km long and about 20 km wide. It is composed of two main segments. The northern segment is covered by a lake, while the southern is subaerial. However, the basin appears to end north of the lake in a smaller and narrower sub-basin, the Jericho/Shuna basin, which is the focus of the current investigation.

The southern Dead Sea Basin has been explored and investigated intensively over the last four decades (see

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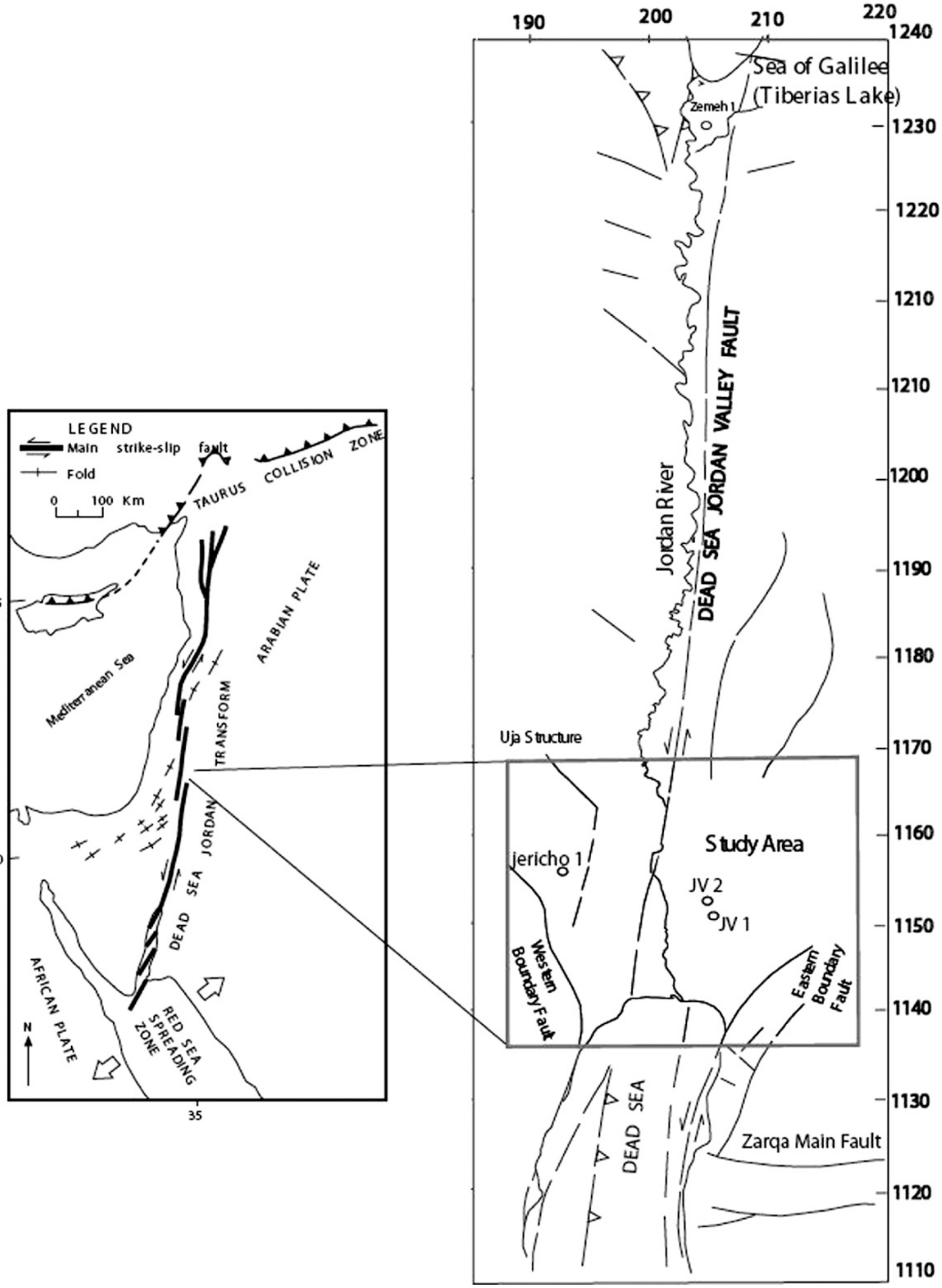

Fig. 1. (A) Outline of the Dead Sea Transform plate boundary and the main strike-slip faults (modified from Gardosh et al., 1997). (B) General tectonic structure of the northern part of the Dead Sea Basin and Jordan Valley. Location map of the study area, the boreholes, used for interpretation (JV 1 — Jordan Valley 1, JV 2 — Jordan Valley 2). Coordinates are in Cassini Palestine grid.

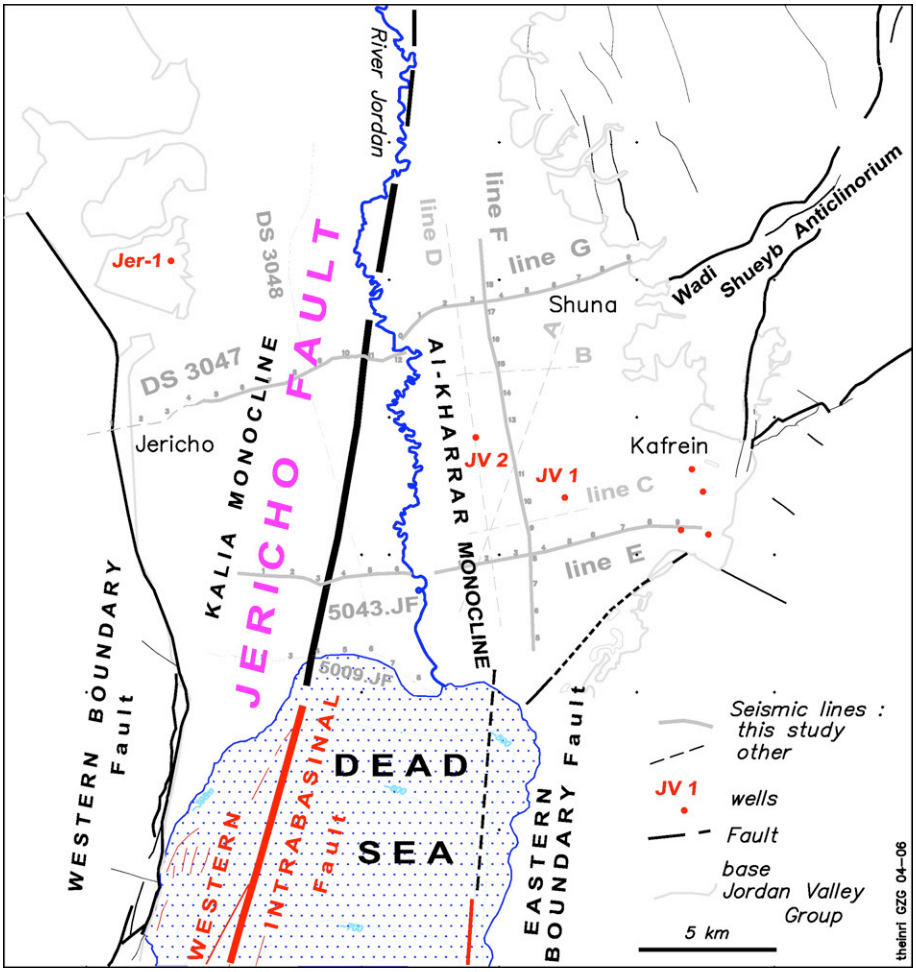

Fig. 2. Schematic structural map of the study area. The base of Jordan Valley Group outcrop (gray line) shows the limits of the lower Jordan Valley syntectonic depositional system. Dark gray lines (line E, Fig. 4; line F, Fig. 5; line G, Fig. 6; line 5043.JF, Fig. 7 left; line DS 3047, Fig. 8 left): seismic lines used in this study. Light gray lines (lines A, B, C and D): other seismic lines used for interpretation but not shown. Wells Jer-1, Jericho 1, JV 1 and JV 2 are deep wells. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Horowitz, 2001 and references therein), whereas the structure of the northern basin and its transition to the Jericho/Shuna basin are still not clear due to lesser interest from the oil industry. Some geophysical work has been carried out separately on the eastern (Natural Resources Authority) and the western (Geophysical Institute of Israel) sides of the Jordan River of the northern end of the Dead Sea Basin. Herein, some of the existing reflection seismic data from Jordan side have been used, seeking to clarify the subsurface structures within the basin. The geophysical data supplemented by limited deep boreholes data provide valuable information about the architecture of the study area. However, the interpretation and synthesis of this data has been limited by the fact that all of the surveys on both sides terminate short of the international border. In order to bridge this gap of information four fair-to-good quality seismic time sections close to the northern end of the north basin of the Dead Sea, two from each side of the Jordan River, were joined and interpreted (Fig. 2). Although they were acquired by different techniques, and there is a gap of 800 m to 1 km between them, the basin fill reflections could be accurately correlated as shown below. A review of the main tectonic elements of the Jericho–Shuna basin and the basin fill stratigraphy is presented.

2. Geological setting of the study area

The study area is located in the transition zone between the Dead Sea Basin and the Jordan Valley's depression. In general, the area is 50 km long and 20 km wide. It has been studied by numerous researchers (Picard, 1931; Quennell, 1958; Freund et al., 1970; Garfunkel, 1981; Rotstein et al., 1991; ten Brink et al., 1999; Belitzky, 2002). Picard (1931) was the first to describe the depression as a Rift Valley bordered by two faults. The western boundary fault was noted as the oldest tectonic element within the study area. This fault lies along the western side of the Dead Sea Basin's margin and curves to the northwest away from the rift relaying with the Uja (Flexure) structure (Fig. 1B). According to seismic data from south east of Jericho, the transform fault lies in the middle of the Jericho Basin, which forms a 1 km wide zone of intense deformation with in the syntectonic sediments (Rotstein et al., 1991). The main strike-slip fault continues N–NE from the Dead Sea to the Sea of Galilee (Tiberias Lake) and lies to the west of the study area (Garfunkel, 1981; Ten Brink et al., 1999). The eastern boundary fault of the Dead Sea Basin extends from the northeastern corner of the Dead Sea and appears to bend to the east (Bender, 1968, 1974, Fig. 1B), where only normal throw is evident. In the Jordan Valley, the transcurrent displacements only took place along a single strike-slip fault zone, without a deep pull-apart basin as in the Dead Sea Basin.

The sedimentary section of the study area is subdivided into two parts; the Pre-rift section from Paleozoic to Early Tertiary age and the syn-rift (syntectonic) section of Miocene to recent age. Three relatively deep boreholes were drilled in the study area. Jericho 1 is the deepest borehole, located in the Pre-rift Senonian chalk/chert on the western side of the Jordan Valley (Fig. 2) and reaching Oxfordian limestone/shale at 1644 m depth, whereas the Jordan River 1 (JV 1), drilled in 1959 presented 100 m of Pleistocene rift sediments to reach top Jurassic (Fig. 3). The Jordan Valley 2 (JV 2) borehole penetrated about 1400 m, where the top of the Early Cretaceous was found. The top 560 m of this well were interpreted by us as Tertiary to recent syntectonic sediments deposited on the western flank of the Al-Kharrar Monocline (Fig. 3: Al-Zoubi et al., 2006).

The syntectonic eastern basin fill of the Jericho–Shuna Basin is dipping to the west, starting with gentle 3 to 5° on the eastern side and then increasing to more than 15° over the N–S-trending Al-Kharrar Monocline (Fig. 2; Al-Zoubi et al., 2006). The basin configuration further west and its relationship to the above-mentioned major steep strike-slip fault (Jordan Valley Fault, Garfunkel, 1981; Kashai and Croker, 1987; Main Fault Zone, Rotstein et al., 1991) is controversial. In the western side of the basin the buried Kalia Monocline (Fig. 2) parallels this segment of the fault indicative of local transpressive motion as are earthquake first-motion analyses (Rotstein et al., 1991). The earlier studies assumed the basin west of the Jericho Fault to be shallow and the seismically imaged Kalia structure to be composed of Cretaceous and Jurassic strata. Yet, Shamir et al. (2005), based on there recent high resolution seismic lines on the western side of the Jordan River argue the syntectonic basin east and west of the Jericho Fault to be much deeper than thought before. They also note that reflectivity patterns show substantial involvement of (Pliocene?) salt in the structural development on either side. A major fault east of the Jordan River is suggested by them to control subsidence of this deep basin since Pleistocene. A localized transcurrent shear along the Jericho Fault is postulated to have switched to delocalized deformation distributed on an array of smaller faults along the transform. The chief aim of the present study is to examine this hypothesis.

3. Reflection seismic data acquisition

A dense grid of seismic reflection profiles was collected in the Jordan side of the study area, during the 1980s in support of oil exploration. There were several difficulties in acquiring good quality seismic data especially at greater depths due to the near-surface conditions (up to several hundreds of meters of unconsolidated sediments at shallow depths). The narrow geometry of the basin, which governs the direction, is more of a problem to shallow data. The most restricting factor regarding the quality of the data is the narrow E–W geometry, since the seismic survey did not cross the international border, which lies in the middle of the valley. The average distance between the rim escarpment and the international border is only about 4–6 km. The seismic lines were recorded using 48 channels and the more recent lines using 96 channels. Vibrators were used as the energy source for all the lines. Most of the lines in the study area were carried out using 30 m geophones group interval and vibration points at 60 m interval, which yielded only 24 folds. The source sweep of 10–60 Hz was used for a maximum length of 5 s. The maximum (asymmetric) spread employed in the study area reached 2985 m. All the lines have been processed to a datum of −400 m below sea level applying automatic statics and most were wave-equation migrated. In general, the penetration depth that could be obtained in the seismic survey is estimated to be roughly equal to the maximum spread length. Therefore, we expected geological information down to a depth of 2000–4000 m. However, in our interpretation we used only the upper part of the sections where seismic information and well data warranted a realistic interpretation. The seismic line from the eastern side of the Jordan River was tied to the published seismic lines from the western side, as presented by Rotstein et al. (1991)

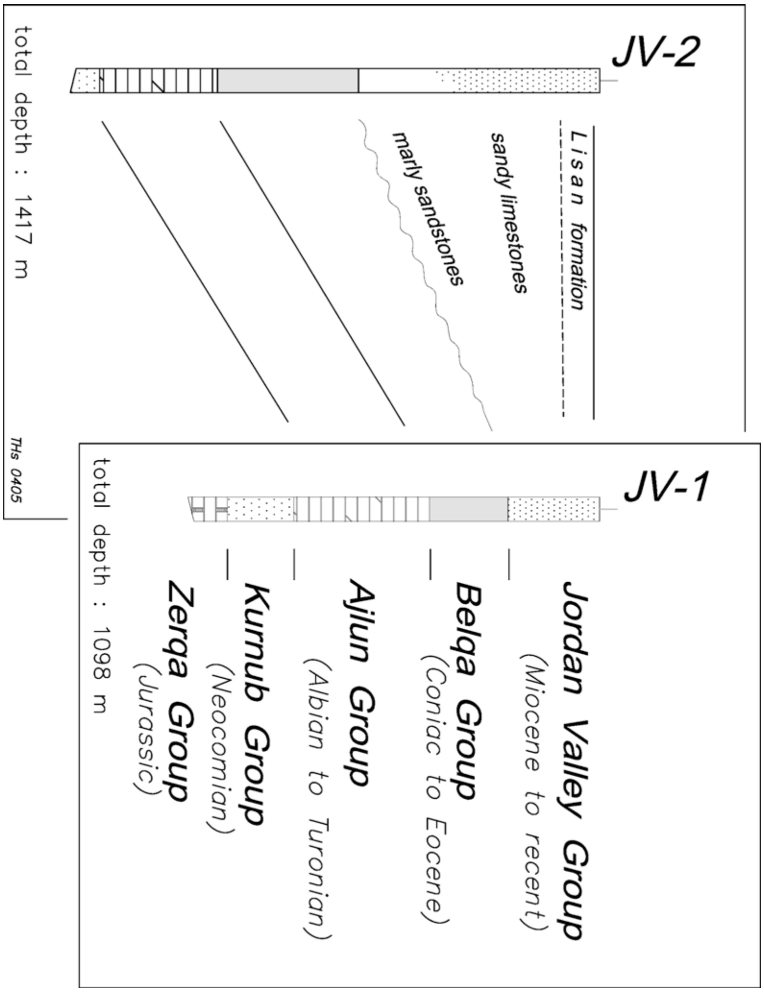

Fig. 3. Condensed stratigraphic columns and sketched correlation of boreholes JV-1 (Bender, 1968) and JV-2 (after H. Rabi, NRA, unpublished report, 1992) (for well locations see Figs. 1 and 2). Generalized lithologies are as follows: top Jurassic in JV-1 = 70 m dolomites, some sandstones and shale; Kurnub: variegated sand stone, lignite traces, some shale; Ajlun: limestones, marls; Belqa: chalks with conspicuous cherts, phosphatic chalks, marls and limestone; post-Eocene in JV-1 = 276 m of syn-rift lacustrine marls, clays and evaporites, intercalations of sandstone and conglomerates; post-Eocene in JV-2 (on top of comp act chalks containing chert nodules) = 120 m of friable sandstone with streaks of marl followed by 30 m of plastic marl (‘marly sandstone unit’), 60 m of limestones with fossiliferous intercalations of unknown significance (fossiliferous limestone unit), 245 m of sandy limestone with gravel interbeds and also some marl (sandy limestone/marl unit), 70 m of marls and marly limestones (interpreted here as Lisan Formation), about 30 m of sand and gravel (Al-Zoubi et al., 2006).

and Shamir et al. (2005). All sections have been processed to a datum of −400 m b.s.l.

4. Interpretation of recently released reflection lines

Line E (Fig. 4) is notable for a very clear angular seismic unconformity at the base of the syntectonic sediments (R1). It illustrates not only the truncation of the older deposits (X=km 3 to 6.5) but also the onlap of the younger strata (X=km 1.5 to 6). The angular relations within this section indicate that the initial basin subsidence was accompanied by tilting of the older, e.g., Cretaceous strata in the margins of the Dead Sea Basin. Some of the erosion in this margin may be due to the lowering of the base-level. However, an unknown part of erosion particularly in the eastern part of the section must be older than the Dead Sea basin subsidence, as erosion of the marine platform carbonates started as early as the emergence of the Syrian Arc structures at the end of the Eocene (Horowitz, 2001). Subsequently, the basin widened and the onlapping syntectonic sediments buried the truncated Cretaceous strata. This widened late basin is probably the Transform Jordan Valley Fault (Garfunkel, 1997).

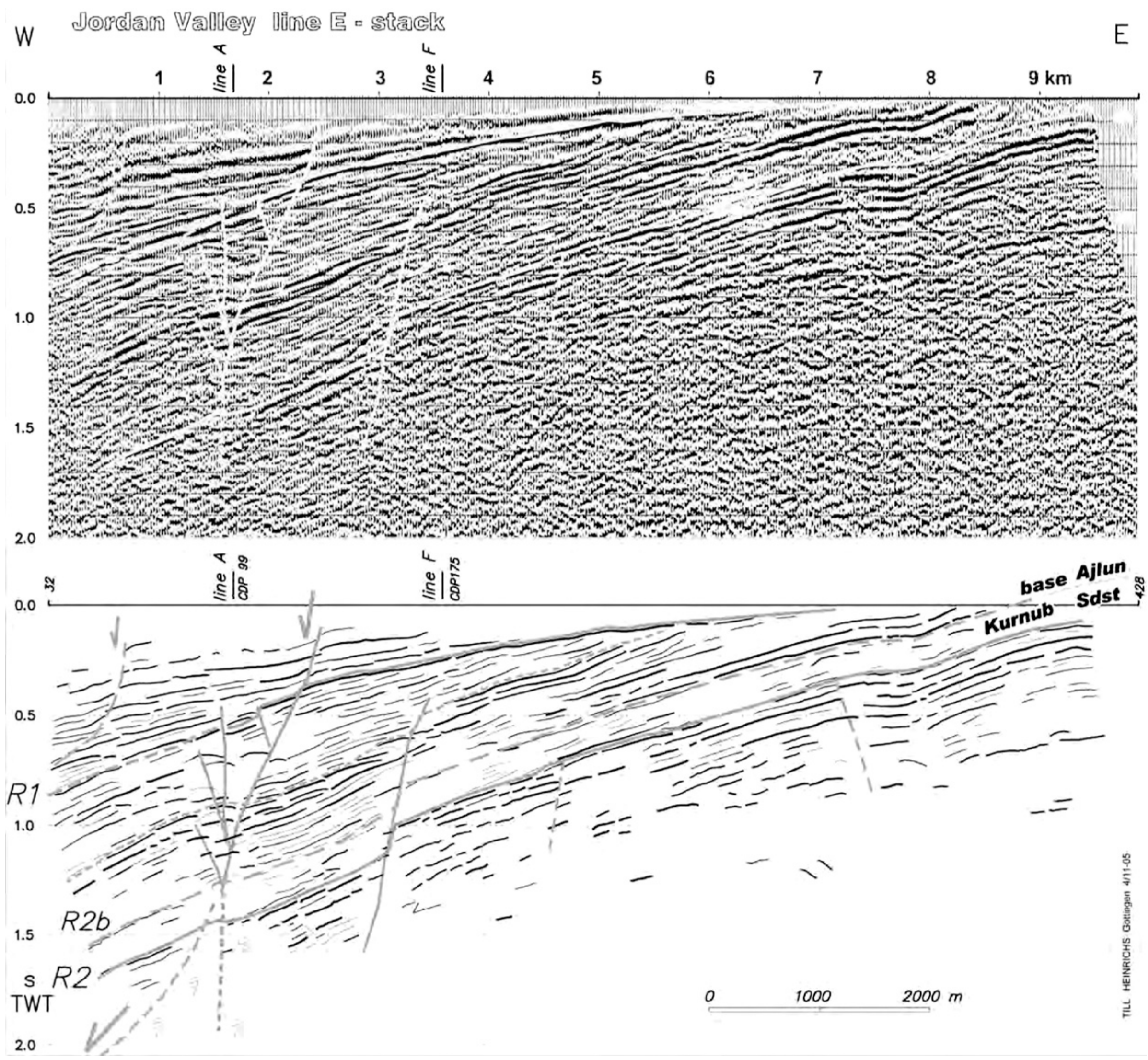

Fig. 4. Seismic line E. Top: original section down to 2 s TWT, stack; bottom: interpreted digital line drawing; R1: seismic unconformity at the base of Jordan Valley Group; R2b: characteristic seismic reflectivity near base of Ajlun Group; R2: base of Kurnub Group, sub-Cretaceous seismic unconformity. Stratigraphic interpretation is based on outcrop and shallow wells (cf. Fig. 2) near the eastern end of line E and on well JV 1.

Apart from links with wells JV 1 and JV 2 (Fig. 3) via seismic lines C and D (Al-Zoubi et al., 2006) the stratigraphic interpretation of the Cretaceous platform cover is controlled by outcrop of the Kurnub and lower Ajlun Groups just beyond the eastern end of line E. These stratigraphic units can be traced by shallow wells beneath the Jordan Valley Group deposits (Fig. 2). The uppermost formation of the Ajlun Group may be represented by the bundle of three or so strong reflectors (km 4 to 5, 0.3 to 0.4 s; km 1.5 to 3, 1 to 0.7 s and possibly 0 to 1 km, 1.25 to 1.1 s). If so, then reflectivity should be due to the massive and well-layered limestones of the Wadi As-Sir Formation. This unit may be followed into the reflector package C of line 5043.JF (Fig. 7; left part). The overlying, less reflective Balqa' Group of flint-bearing chalks, limestones and marls seems to attain a somewhat increased thickness compared to the average sequence exposed further east. Therefore, it may be possible that relics, for example, of Oligocene strata are preserved in the down warped part of the platform sequence buried underneath the syntectonic deposits.

Line F (Fig. 5) links the southern line E to the northern line G in addition to the links provided by line D (for location see Fig. 2). It confirms earlier interpretations (Al-Zoubi et al., 2006) by clearly imaging the wide-spanning Syrian Arc structures that

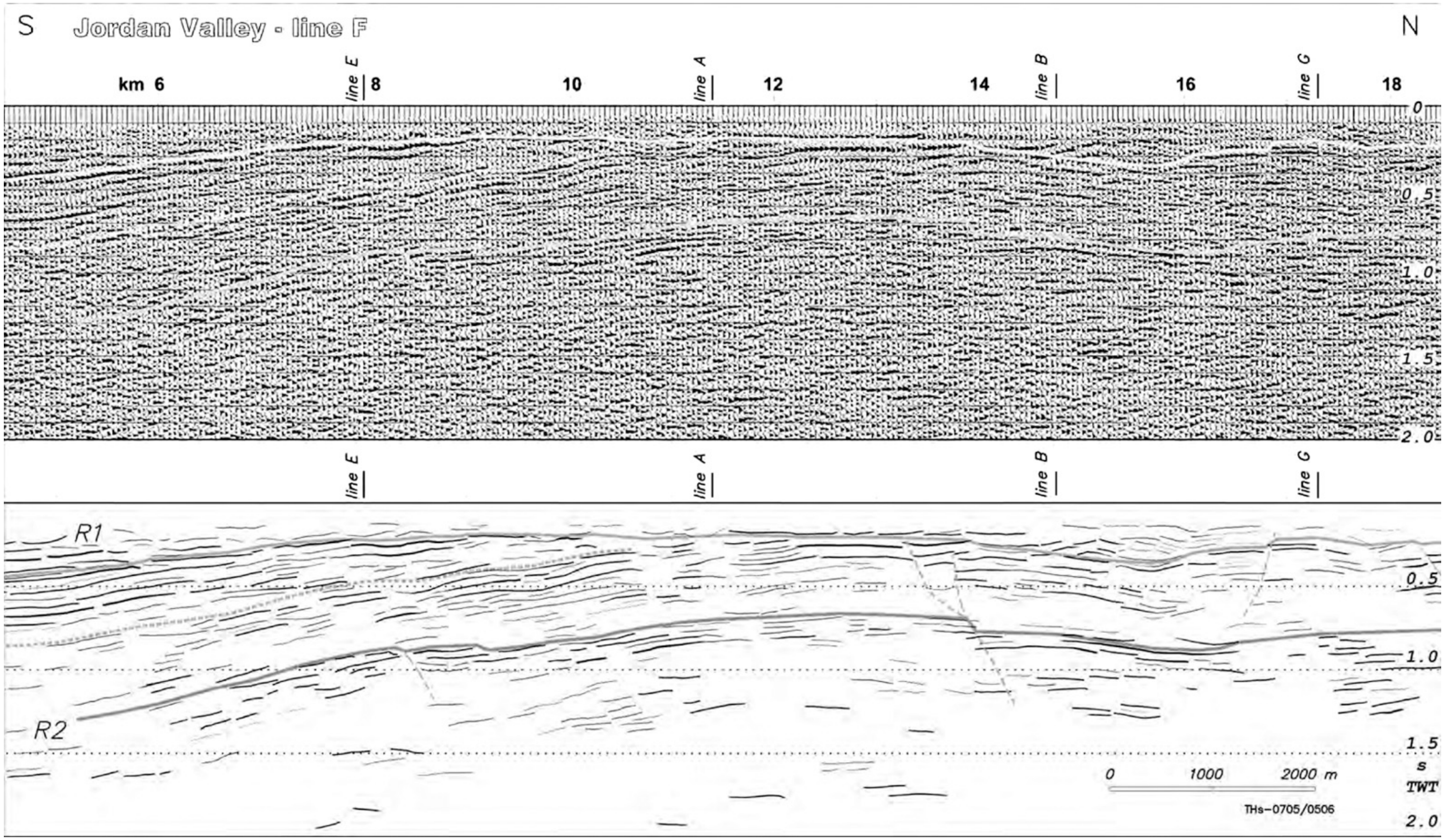

Fig. 5. Seismic line F. Top: original section down to 2 s TWT, with wave equation migration applied. Bottom: interpreted digital line drawing; symbols are as in Fig. 3; dashed line is estimated top of Ajlun Group (top Turonian). Major structure is Wadi Shueyb Anticlinorium. Note truncations of Cretaceous between km 8 and 14.

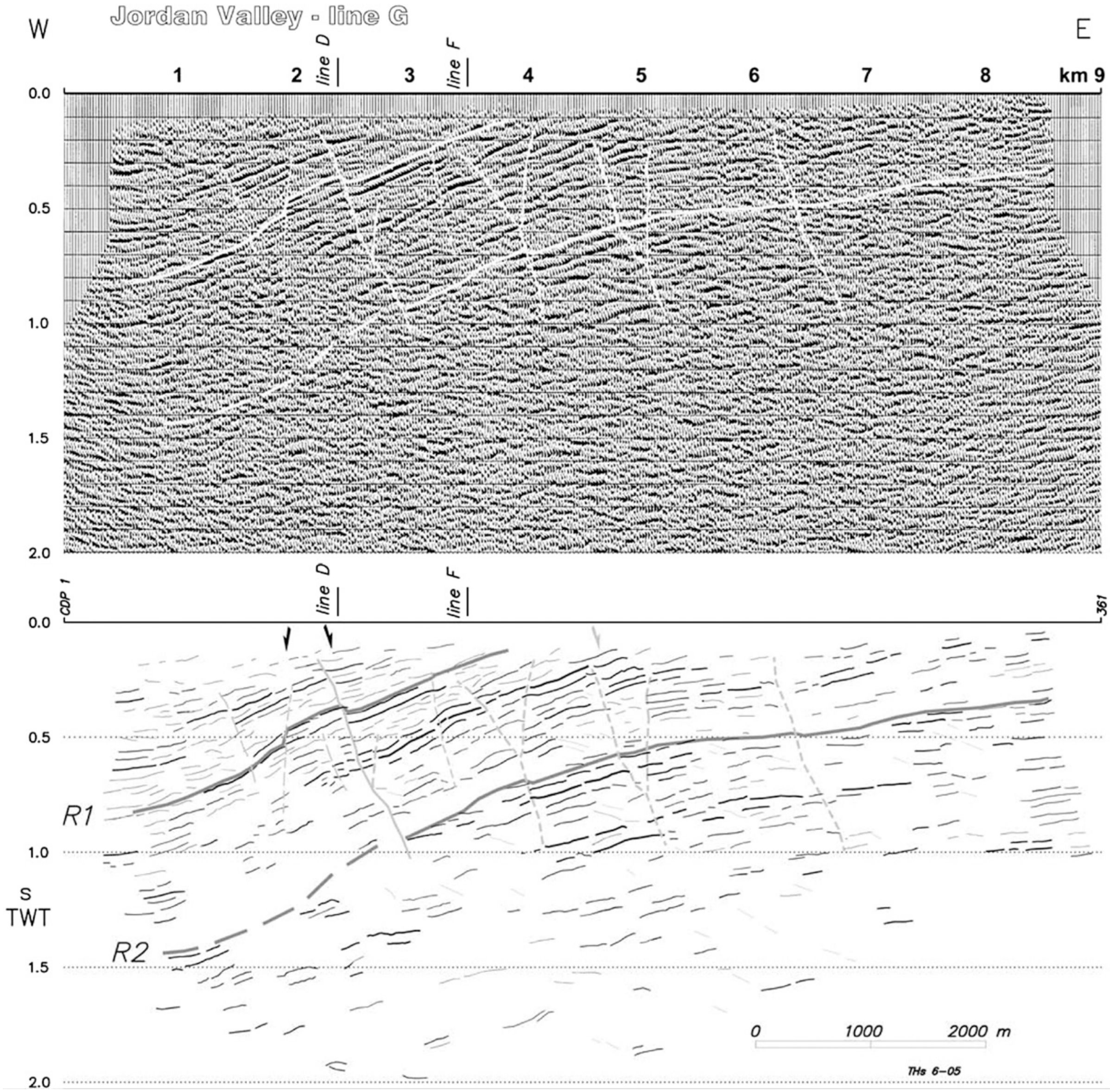

Fig. 6. Seismic line G. Top: original section down to 2 s TWT, WE migration. Bottom: interpreted digital line drawing. Symbols are as in Fig. 3.

continue from the lower slopes of the Transjordanian Mountains south-westwards plunging beneath the syntectonic sediments. In particular, the Wadi Shueyb Anticlinorium flanked by synclines is imaged well (Fig. 2). The top and the flanks of the anticlinorium are marked by truncations defining the unconformity at the base of the syntectonic strata.

Line G (Fig. 6) runs from Shuna in the east to close to the Jordan River in the west. The stratigraphic interpretation of the sub-Cretaceous unconformity is partially based on the low link with deep well JV 2 along line D. But this correlation is strengthened by carrying the base of Cretaceous horizon from the mapped structures and structure contour constructions considerably east of Shuna into the section. The base of the syntectonic sediments is defined by onlapping reflectors (km 1 to 3, 0.8 to 0.3 s), and also by the horizon in the crossing lines F and D.

Fault indications are weak; some may point to antithetic normal offsets, and also a few are synthetic normal. The general structure is one of a Monocline developing from a shallow dipping shelf (5 to 9 km) westwards into a steeper limb (1 to 4 km). Flattening of this limb westward may be a tromp d'oeil because of potential migration artefacts in the margin of the section and also because the trace of the line turns south in the last kilometer (cf. Fig. 2), a point that will be clarified in the composite section below.

5. Geometry from combined reflection lines

By combining the reflection seismic line 5043.JF (Shamir et al., 2005) with seismic line E on the eastern side of the Jordan River (Fig. 4), for the first time a complete cross-section of the sub-Jordan Valley part of the northern end of the Dead Sea Basin can be presented (Fig. 7). Section 5043.JF (Shamir et al., 2005) had to be suitably transformed as to show angular relations of reflectors more clearly. However, compared with the eastern side of the Jordan River section, both sections being stacks should be geometrically compatible. In the eastern side of the Jordan River control of stratigraphy in general and the post-Eocene unconformable base of syntectonic sediments in particular, are provided by ties with deep wells JV 1 and JV 2 (Fig. 3), via reflection lines D (not shown) and F (Fig. 5). The correlation with outcrop geology on the eastern ends of the profiles (Al-Zoubi et al., 2006) has been considered.

In the following we carried the stratigraphic interpretation from the steep monoclinal limb of the seismic line E (Fig. 4) over into the high-resolution seismic line in the western side of the Jordan River section 5043.JF. The correlation relies on the continuity in the attitudes of the reflectors in both sections (Fig. 7). However, we noted that the well-defined basal syntectonic unconformity of section E runs into the reflector package D (Fig. 7: line 5043.JF) of the western side of the Jordan River section. The package D marks as noted by Shamir et al. (2005) a pronounced change in character of reflectivity and an unconformable contact at the top high-frequency reflections believed to indicate finely bedded strata of an open lake, below thick bedded units. By contrast, we interpret this as a paraconformable interface representing the basin ward extension of the post-Eocene unconformity observed on the slope and shoulder of the basin. Deeper reflector package C may correspond (arrow between sections in Fig. 7) to the bundle of strong reflectors at the top of the Ajlun Group in the eastern side of the Jordan River (line E: Fig. 7). Here high reflectivity is likely to be due to the massive and well-layered limestones of the Wadi As-Sir Formation. Other high-reflectivity units are likely to represent well-bedded limestone units of the Ajlun Group and may be followed into reflector packages A and B of line 5043.JF (Fig. 7). Finally, the unconformity at 2.2 s TWT, 5–6 km noted by Shamir et al. (2005) can be linked to the sub-Cretaceous unconformity (Kurnub Group base) in the eastern side of the Jordan River (Fig. 7).

According to our interpretation, the well-resolved reflections beneath reflector package D (Fig. 7) image the Late Cretaceous to Eocene well-layered marine platform carbonates characteristic of the regional cover sequence on the Arabian plate. Shamir et al. (2005) interpreted these reflection packages (chronostratigraphic horizons A to D) as a deep part of the northern Dead Sea Basin.

About 8 to 9 km further north, the combined seismic lines G (Fig. 6) from the eastern side of the Jordan River and DS3047 from the western side of the Jordan River (Rotstein et al., 1991) show an even narrower and shallower syntectonic basin (Fig. 8) with a maximum depth of 0.9 s TWT (roughly 1.1 to 1. 5 km). The deep basin is asymmetric towards the Jericho Fault too, west of the Jericho Fault crossing line DS3047. Fleischer and Gafsou (2006) give top Turonian at about −2000 m b.s.l. (equivalent to ca. 0.8 s TWT) where the seismic image shows reflector onlap. Flexer et al. (1989) have demonstrated the systematic onlap of the Senonian onto the post-Turonian synsedimentary Syrian Arc structures around the Judea Arch. Such an onlap seems to be imaged in DS3047 (8 to 10 km, 0.5 to 0.8 s TWT) very well because the seismic line here provides nearly a dip section (open arrows in Fig. 7, West of Jericho Fault). The Kalia monocline structure is rather not asyngenetic with the Dead Sea deformation, but to a greater extent related to the older episodes of Syrian Arc folding. Thus, for the West of the Jericho Fault block we have adopted the base of the post-Eocene to be higher in the section as interpreted by Kashai and Croker (1987) who estimated it at 0.5 s TWT near km 10 (Fig. 8, dotted line). The Dead Sea deformation immediate subsidence west of the Jericho Fault is argued to be comparatively small which underscores the asymmetry of the deep basin east of Jericho Fault.

Concluding that, the combined seismic sections show the deep inner basin of the Dead Sea is delimited at its northern end by the Jericho Fault in the west segment of the Dead Sea Jordan Valley Fault and a monoclinal flexure in the eastern side. In its southern part, this monocline is associated with an unnamed fault which seems to represent a northern continuation of the Eastern intrabasinal fault (Eastern Boundary Fault, Fig. 1) taken to coincide with the eastern steep slope of the North Basin of the Dead Sea (Neev and Hall, 1979). This deep inner basin is nested in the wider and shallower Jericho–Shuna Basin, conforming to the Transform Jordan Valley Fault (Garfunkel, 1997) observed all along the

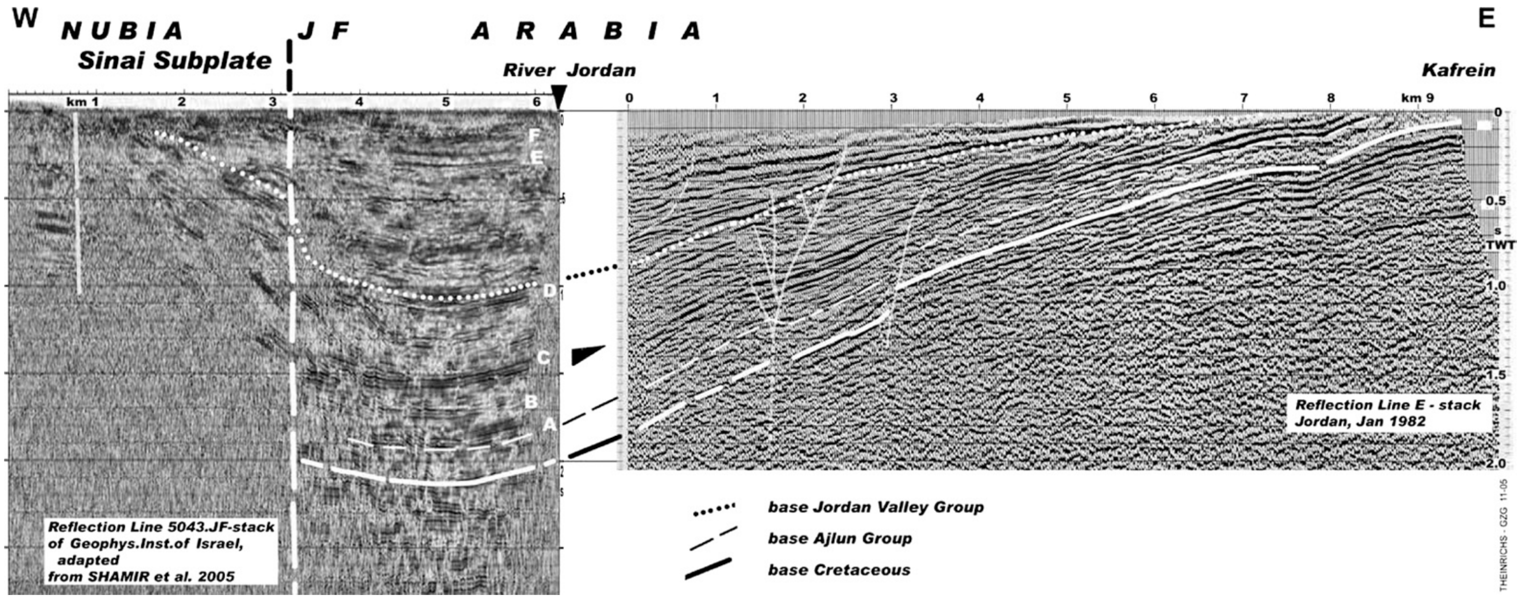

Fig. 7. Combined reflection seismic lines G (Jordan side) and 5043.JF (adapted from Shamir et al., 2005). Scales of published Section 5043 were fitted to the Jordanian section. Note: both sections are unmigrated stacks. The gap between the lines amounts to 750 m near Jordan river. JF — Jericho Fault segment of the Dead Sea Transform. Dotted line: base of syntectonic sediments. Wide dashed line: base of Ajlun Group (Albian to Turonian). Continuous line: sub-Cretaceous unconformity at base Kurnub Group (Neokomian). Stratigraphic interpretation near E-end of line is based on shallow wells south of Kafrin (red dots in Fig. 2) and on a nearby outcrop.

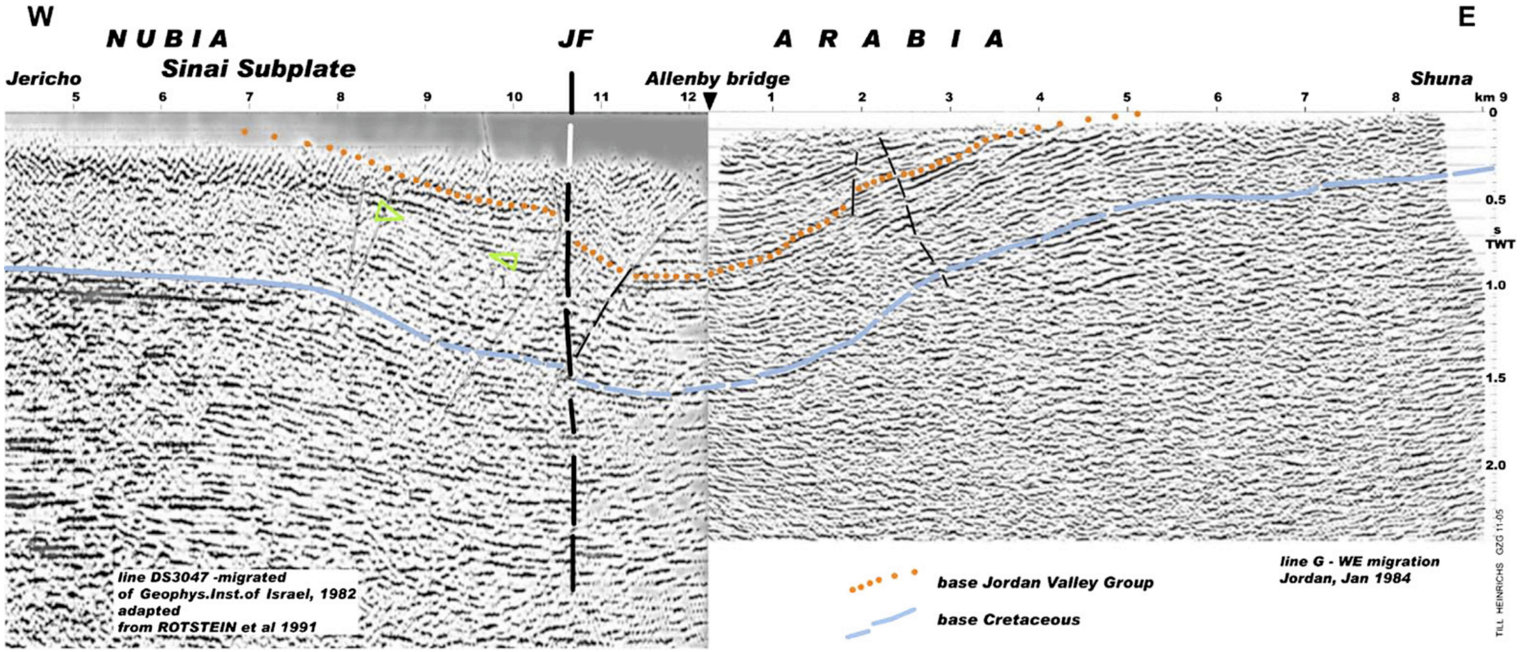

Fig. 8. Combined reflection seismic lines E (Jordan side) and of DS3047 (1982; adapted from Rotstein et al., 1991). JF: Jordan (Jericho) Fault. Light gray faults: interpretation by Rotstein et al. (1991). Black faults: interpretation in this study. Dotted line — base of syntectonic sediments, in Jordan controlled by links with deep well JV 2 and JV 1 via reflection lines D and C (Al-Zoubi et al., 2006), whereas west of Jericho Fault this base is taken from Kashai and Croker (1987, Fig. 10). Green open arrows point to seismic unconformity that may represent onlap of Senonian on top Turonian, see text for discussion. Blue line: sub-Cretaceous unconformity, carried over into eastern margin of this line from mapped structure E of Shuna (Heinrichs, unpublished; Shawabkeh, 2001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

southern Dead Sea Transform (DST). The inner deep basin between the Dead Sea Northern shore and Jericho–Shuna is strongly asymmetric toward the Jericho Fault underscoring the dominant role of this fault in basin development. There is no evidence for a major Eastern fault controlling the post −5 m/year sedimentation as postulated by Shamir et al. (2005). In the sections at about 5 km north of the Dead Sea; the inner Dead Sea Basin proper has narrowed to about 6.5 km (Fig. 7) as compared to 8 km at the Jordan River Delta. In sections 12 km north of the northern shore the inner basin has further narrowed to about 5 km width (Fig. 8).

The longitudinal gradient of the basin floor is estimated next. The maximum depth reached by the northern Dead Sea Basin in line 5043.JF amounts to only 1.1 s TWT (roughly 1.55 to 1.65 km). In the composite sections Jericho–Shuna the maximum depth is estimated at 0.9 s (1.25 to 1.35 km) using reflector package D in line 5009.JF (Shamir et al., 2005) where the maximum depth of the syntectonic basin beneath the Jordan River Delta reaches 1.2 s (1.68–1.8 km). Therefore, the basin axis seems to plunge continuously toward the south by about 0.5 km over 10 km with no indications of a transverse fault. A gentle southward plunge without breaks by transverse faults is also supported by the southern 5 km part of section DS3048 (Rotstein et al., 1991) trending NNW and nearly covering the gap between 5034.JF and 5009.JF east of the Jericho Fault (Fig. 2).

6. Discussion and conclusions

Based solely on the reflection characteristics the sequence of high-resolution reflectors east of the Jericho Fault was interpreted as a northern extension of the Dead Sea Basin reaching to 2.5 s TWT, (~2.5–3 km depth), and possibly beyond (Shamir et al., 2005). However, as discussed above, the lack of borehole control in the deep basin may be overcome by correlating the western side sections with the eastern side sections that are controlled by deep and shallow wells and by ties to outcrop geology in the Transjordanian mountain foothills. It is concluded that the sedimentary cover sequence of the Arabian plate can be followed from outcrop in the E dipping into the basin and into the Jericho Fault where the base of the syntectonic sediments reaches its maximum depth at about 1 s TWT below ground.

The Dead Sea Basin's depocenter was claimed to be shifting toward a hypothetical major post-Miocene eastern fault becoming active in the course of a post-horizon-D (Delocalization of Transform Motion) (Shamir et al., 2005). Yet, the present data do not support a shift of the depocenter away from an inactivation Jericho Fault nor the major eastern fault is evident from the available seismic sections. Assuming a major fault hidden in the 800 m gap of the southern composite section, down throwing the pre-Pliocene sequence therefore, the Cretaceous correlations becoming obsolete is unlikely. There would be a strongly asymmetric basin leaning against the Jericho Fault with the depocenter remaining close to it through post-horizon-D times. So the Jericho Fault appears to continue acting as a major control of subsidence in this part of the Dead Sea Basin.

Asymmetric basin geometry is common to many major transcurrent faults. In general, this indicates an active control of the growth of pull-apart structures by the respective fault (e.g., Ben-Avraham and Garfunkel, 1986). Alternatively, Ben-Avraham (1992) suggested that it was due to near-field stresses deviating from the intra-plate stresses such that the extension is perpendicular to the transform strike.

Katzman et al. (1995) and ten Brink et al. (1996) showed that asymmetric basins with gentle longitudinal plunge are manifestations of pull-apart basins outside the zone of overlap between the en-echelon faults and no extension is required. These authors used a boundary-element technique to model the three-dimensional crustal deformation of a deep pull-apart basin as a result of relative plate motion along en-echelon faults. The brittle upper crust was modelled as an elastic block, cut by two en-echelon semi-infinite vertical faults (Fig. 9a). The plate motion effect was imposed as a horizontal displacement everywhere at the bottom of the elastic block except in a stress-free shear zone in the vicinity of the fault zones. The width of the shear zone and the amount of overlap between the en-echelon basin-bounding faults were varied. Their model results indicated that as the width of the shear zone increases, the basin becomes more elongate along the faults (Katzman et al., 1995). Subsidence between the en-echelon faults was shown to be symmetric producing full-graben profiles, but subsidence outside the area of overlap between faults is asymmetric producing half-graben profiles (Fig. 9b). These models also indicate that the block enclosed between overlapping weak faults is deformed almost in pure shear by lengthening along the y-axis and by contracting in both the vertical (subsidence) and the fault-perpendicular (x-direction) axes (ten Brink et al., 1996). Using a 2-D boundary-element model, Aydin and Schultz (1989) also produced fault-normal extension in the region of overlapping strike-slip faults. Therefore, the half graben shape of the

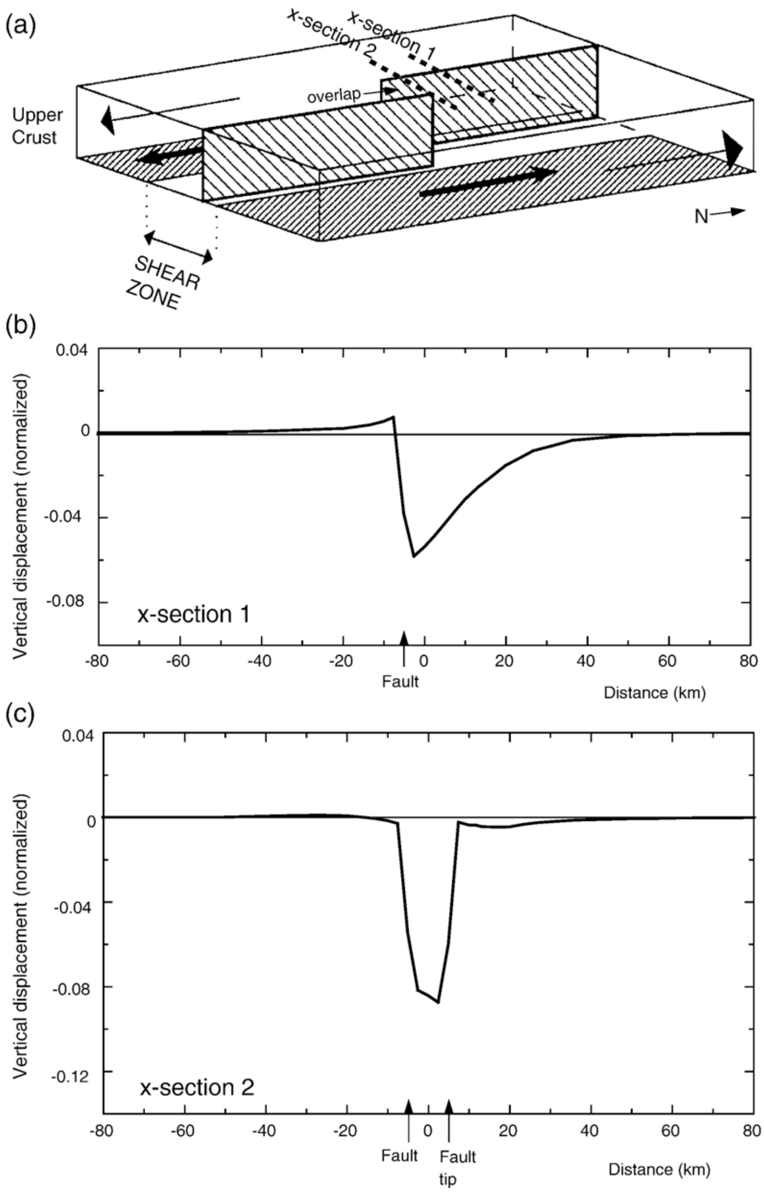

Fig. 9. (a) Boundary-element model geometry used to generate cross-sections 1 and 2 (after ten Brink et al., 1996). The model consists of two weak faults arranged en-echelon within an elastic medium. The block is subjected to left-lateral motion on the sidewalls and the bottom wall, with the exception of a 40-km wide zone below the faults that is free to deform. The en-echelon faults are spaced 10 km apart and overlap by 20 km. (b) Predicted surface deformation across the two faults at the tip of the eastern fault. (c) Predicted surface deformation 10 km north of the tip of the eastern fault.

northern Dead Sea Basin is interpreted to be the result of a single fault, i.e., the Jericho fault continuing north from the Dead Sea, whereas in the Dead Sea itself symmetric subsidence (ten-Brink and Ben-Avraham, 1989; Al-Zoubi et al., 2002) is produced by overlapping faults (Katzman et al., 1995), and there is no need to invoke extension in the northern Dead Sea Basin.

The current study does not aim to discuss the detailed fault kinematics, but to fit our observations into the regional fault pattern around the Dead Sea Basin. According to Niemi and Ben-Avraham (1997), in a study of the recent active subaquatic faults, the Jordan (Jericho) Fault continues into the Dead Sea north basin for about 15 km with characteristics of transcurrent slip where it is replaced by NNE to NNW trending segments of the western intrabasinal fault system with apparently normal throws. The transcurrent character of these segments is blurred due to large subsidence of the

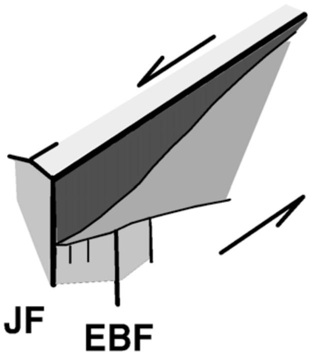

Fig. 10. Conceptual sketch of the structural control on subsidence at the northern end of Dead Sea Basin. JF: Jericho Fault. EBS: Eastern Boundary Fault. Finite normal displacements (subsidence) are largest adjacent to Jericho Fault, diminishing northward and eastward across basin; EBF dies out north of the lake.

central north Basin destabilizing the uppermost crust; consequently the normal faulting became the predominant deformation mode in a marginal fault network. This is in line with the findings of Sagy et al. (2003) analyzing the marginal deformation belt along the western Dead Sea pull apart (including the Western Boundary Fault). However, at depth left-lateral slip continuity in the region as indicated by the July 1927, M7.1 earthquake, the epicenter is placed close to the western intrabasinal Fault System (Shapira et al., 1993).

Though the precise geometry of the DSB ultimate northern tip remains to be established, our observations suggest the Eastern Boundary Fault (EBF) dies out northward and on the NE side of the basin bordered by the above flexure, e.g., where only normal displacements are seen (Fig. 10). Further south the EBF links via the Ghor Safi Fault (dominantly normal? or mixed normal transcurrent) to the Wadi Araba Fault, which takes over the transcurrent displacement south of the DSB again.

Comparison with analogue models of long and small pull-apart structures in a brittle crust on a thick ductile basement (Smit, 2005) reveals interesting resemblances as well as differences. First, the pull-apart basins with small stepovers compared to crustal thickness (ca. 1/3 in the case of the DSB), whilst bounded by overlapping transcurrent faults along their longitudinal margins, are rather ended by flexural tips than by transverse normal faults. This is exactly what we deduce from the composite seismic sections across the northern end of the Dead Sea Basin. However, the model illustrates ample development of Riedel shears at acute angles to the transcurrent faults and during further deformation some of the Riedel shears seem to grow into oblique transverse normal faults controlling the depocenter of the basin. However, such oblique transverse faults have yet to be identified in the Jericho/Shuna basin. There may be a suggestion of such a fault just south of the Jordan River Delta by a cluster of small events during the February 2004 earthquake on a suspected NW-trending cross-fault with hypocenter depths of ca. 13 km (mixed normal and transcurrent motions, Shamir et al., 2005). Yet, gravimetry gives no hint to any significant normal displacement there (Ten Brink et al., 1999) nor does the structure of the young sediments (cf. Niemi and Ben-Avraham, 1997). Such faults may be veiled by thick Pliocene salt deposits (Neev and Hall, 1979).

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