Deformation at a strike-slip, stepover zone along the southeastern margin of the Dead Sea pullapart basin, Jordan

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Abstract. Detailed stratigraphic and structural study of the southeast Dead Sea basin along the Dead Sea Transform in Jordan was carried out in order to determine the deformation history and processes of pullapart basin formation. Fieldwork focused on mapping and collecting structural orientation data in the area of the intersection of the NE-trending, strike-slip Wadi Araba fault (WAF) and the NW-trending, dip-slip Khunayzira fault. The recent movement on the WAF shows spectacular polished fault planes, slickensides, and Riedel and conjugate Riedel shears. During the Late Quaternary the position of the WAF shifted west toward the basin. This is evident from a series of pressure ridges and exposed positive flower structures that do not deform the lacustrine deposits of the Lisan formation (63–15 ka). The Khunayzira fault makes a prominent, curvilinear 50 m-high scarp that trends SE-NW. In the study area, the scarp is highly eroded and sinuous. Slip on the Khunayzira fault branches onto four fault traces near the junction with the WAF. No cross-cutting relationship is observed between the Khunayzira and WAF. These data contradict the idea that strike-slip motion on the WAF terminates and is transferred to dip slip along the Khunayzira fault. Our data agree with the more complex model of the Dead Sea pull-apart basin, that explain the activity of the transverse faults as younger than the formation of the basin. Paleostress calculations based on fault-slip data of the WAF and the faults of the Upper Cretaceous rock show two stress fields. The first is characterized by WNW compression and NNE tension, which represent the Syrian Arc stress field. The second is characterized by NNW compression and ENE tension, which represents the Dead Sea stress field.

1 Introduction

The Dead Sea, >400 m below sea level, is an actively subsiding basin formed along the Dead Sea transform (DST) plate boundary which separates the Sinai-Palestine subplate on the

west from the Arabian plate on the east (Fig. 1). A total sinistral displacement of 107 km along the transform has occurred since the inception of the shear zone in the Miocene (e.g. Quennell, 1959; Freund et al., 1970). The DST can be divided into five major fault provinces. From south to north, these are: the Gulf of Aqaba, Wadi Araba, Jordan Valley, Yammouneh, and El Ghab (Orontes). These segments include or are separated by large morphotectonic sedimentary basins that have formed between *en echelon*, left-stepping segments of the DST. Present-day microseismicity indicates a clustering of seismic activity in these major basins (van Eck and Hofstetter, 1990). The entire length of the southern transform exhibits rift morphology due to divergent plate motion (leaky transform of Garfunkel, 1981).

The Dead Sea sedimentary basin is filled with nearly 10 km of Miocene to Holocene sediments (e.g. Garfunkel, 1997; Gardosh et al., 1997). Due to rapid subsidence of the Dead Sea basin and fluctuations of the water bodies that have filled the depression since the Pliocene, extensive outcrops of basin margin deposits are impressively exposed in wadi incisions on both sides of the Dead Sea. These sediments have recorded the ongoing deformation processes produced by transtension along the Dead Sea transform system.

Although the Dead Sea is cited as a classic example of a pull-apart basin (e.g. Wilcox et al., 1973), there remain many unresolved questions about its structural style and history, the complex relationship between active structures and reactivation of ancient structures, and the partitioning of strain. This study presents structural orientation data collected at the intersection of the strike-slip Wadi Araba (Arava) fault which bounds the southeast margin of the Dead Sea basin and the transverse, dip-slip Khunayzira (Amatzayahu) fault. The goal of this study is to resolve the local relative stress axes of lithologic units of various ages in order to understand the deformation history and process of strain transfer in an active, evolving pullapart basin.

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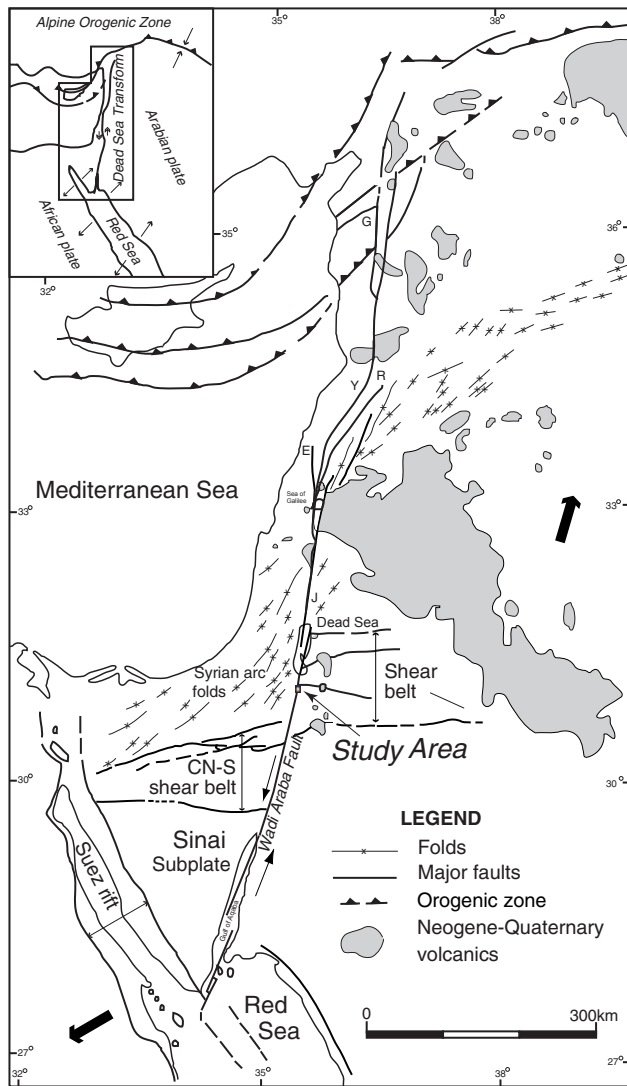
Fig. 1. The Dead Sea Transform (DST) is the plate boundary fault system that separates the Sinai and Arabian plates (after Garfunkel, 1981). G: Ghab fault, Y: Yammouneh fault, R: Rachaiya fault, E: Ed Damor fault, CN-S: Central Negev-Sinai shear belt.

2 Tectonic setting

The Dead Sea transform (DST) is a 1100 km-long plate boundary that connects Red Sea spreading in the south with continental collision in the Taurus-Zagros mountain belt and eastward escape of the Anatolian plate in the north (Fig. 1). The Red Sea spreading rate at the latitude of the Nubian-Sinai-Arabia triple junction is estimated as 9 mm/yr directed along N25-30°E (Courtillot et al., 1987). Estimated geologic slip rate of 6–10 mm/yr for the DST is based on a cumulative offset of 107 km of Miocene and older rocks (e.g. Zak and Freund, 1966; Freund et al., 1970). The commencement of displacement along the DST, based on equal displacement of Precambrian contacts and 20 Ma basaltic dikes, (Bartov et al., 1980; Eyal et al., 1981) did not occur before the intrusion of the dikes. Hence, the mean rate of slip along the southern segment of the DST is in the order of 5.5 mm/yr. Based on

an airphoto reconnaissance of the DST and earthquake catalogue information, Garfunkel et al. (1981) suggested that present-day slip rate has been slower (1.5–3.5 mm/yr) when compared to Plio-Pleistocene rates. A recent study of offset alluvial fans near Ar-Risha (Ginat et al., 1998) estimate long term slip rates between 3.0–7.5 mm/yr since the late Pliocene-early Pleistocene. However, at that location, only relative age control was used. Recent work on offset alluvial fan surfaces and drainages along the northern Wadi Araba fault indicates a minimum 4.7±1.3 mm/yr slip rate since 15 ka (Zhang, 1998; Niemi et al., 2001). Klinger et al. (2000) reports a late Quaternary slip rate of the northern Wadi Araba fault of 3–7 mm/yr based on cosmogenically dated displaced surfaces of the Wadi Dahal alluvial fan.

Chu and Gordon (1998) considered the azimuth of the DST unreliable for plate motion reconstruction between Arabia and Nubia (AR:NU). The strike of the DST and the transform-normal extension are two components of the AR:NU slip vector. In the region south of the Dead Sea, three distinct sets of fault trends have been mapped (e.g. Gulf of Aqaba, Ben-Avraham, 1985; Dead Sea, ten-Brink and Ben-Avraham, 1989). The major, strike-slip faults trends N15-20°E, the basin-bounding normal faults are subparallel to the strike-slip faults, and several transverse dip-slip or oblique-slip faults trend approximately N50-60°W. At the Dead Sea, the transform strike bends 10° to the west and the character of the DST continues to change northward from strike slip to oblique slip and dip slip.

The pull-apart basin model describes the formation of sedimentary basins between *en enchelon* strike-slip faults by extension directed parallel to the strike of the transform (Wilcox et al., 1973; Crowell, 1974; Aydin and Nur, 1982). Katzman et al. (1994) and ten-Brink et al. (1996) using 3-D boundary element models of pure, strike-slip faults arranged in an *en enchelon* pattern show that fault normal extension and the formation of a full graben is a product of fault interaction in the overlap zone. Subsidence extends outside the overlap zone and is seen as asymmetrical (half graben) with uplift manifested at the fault tips. Oblique opening (~10% of strike-slip motion) produces similar features over a wider zone of subsidence.

Further complications in interpreting the DST crustal deformation may be due to stress field fluctuations. Eyal (1996) postulated that the present stress field fluctuates between the Syrian Arc fold belt (WNW shortening, NNE extension) and a Dead Sea transform (NNW shortening, ENE extension) depending on the seismic cycle of large DST earthquakes. Al-Diabat (1999) suggested a similar bimodal stress field system based on fault slip data collected east of the DST. These data oppose the prevailing clay model experiments by Wilcox et al. (1973) that suggest *en enchelon* folds develop early in the shear process. Other models suggest the Syria Arc fold belt formed prior to the inception of the DST (Eyal and Reches, 1983). It is evident from these examples that additional data are need in order to understand the neotectonic behavior of faults within the Dead Sea basin.

In this study we present structural orientation data from
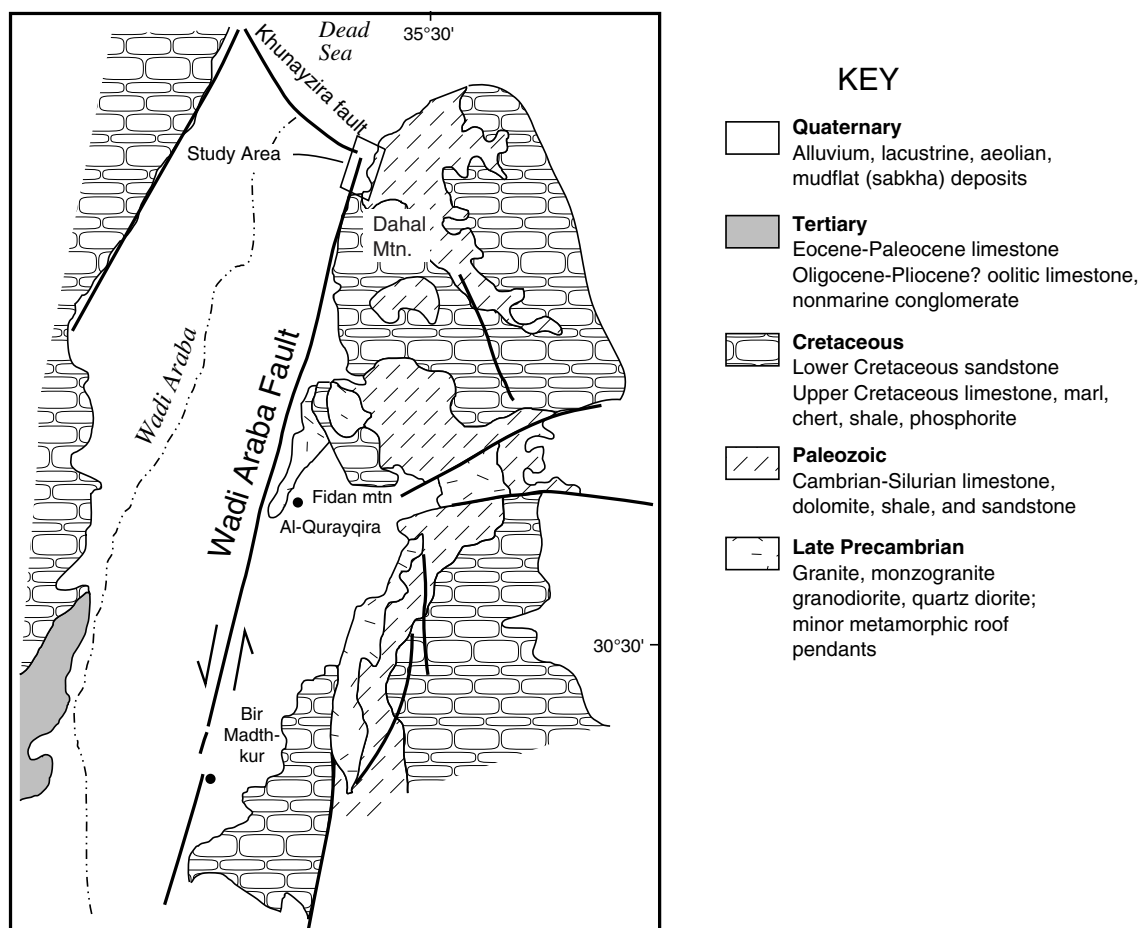
Fig. 2. Generalized geologic map of Wadi Araba showing juxtaposition of different bedrock lithologies across the valley. The Wadi Araba fault is an active, strike-slip fault of the DST. The study area is located at the intersection of the Wadi Araba fault and the Khunayzira normal fault. Map modified after Bender, 1975.

clastic and chemical sediments along the southeast margin of the Dead Sea pullapart basin at a critical stepover fault location. We use the structural orientation data in units of various ages to test whether data of the deformation history shows two overlapping coeval stress fields.
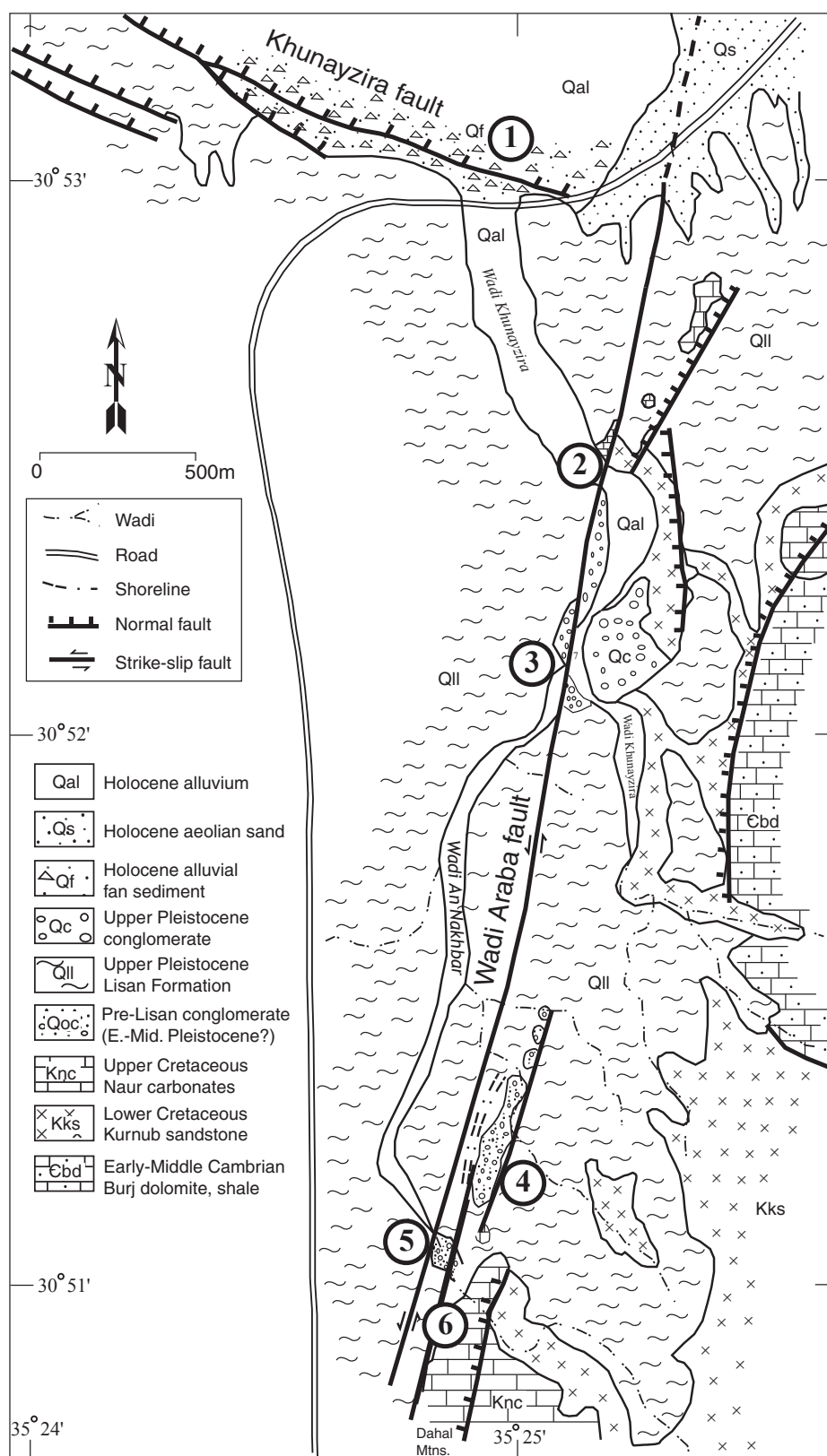
3 Study area

The study area is located southeast of the Dead Sea at the intersection of the Khunayzira (Amatzayahu) dip-slip fault and the Wadi Araba strike-slip fault in Jordan (Fig. 2). This location was selected because of its potential to yield information on the geometric relationships at a step-over zone in a pullapart basin. Stream incisions and artificial exposures make the stratigraphic units and structures accessible for structural analyses. Two major streams cross the study area, the Wadi Khunayzira and Wadi An Nakhbar (Fig. 3). These streams have deep canyons along which the rocks and the faults are well exposed.

Previous studies of the southeastern area of the Dead Sea are included in regional studies of the DST rift valley. Gar-

funkel et al. (1981) and Galli (1999) mapped the active late Quaternary faults along the Dead Sea-Jordan transform from air photos. The Wadi Araba fault (WAF) and regional geology in the study area was also mapped (Tarawneh, 1992) as part of the Jordanian National Resource Authority 1:50 000 scale geologic mapping program (Fig. 2).

The Wadi Araba valley floor is an area of badland topography. Most of this area is covered by the easily eroded, flat-lying lacustrine sediments (including marl and clastic sections) of the Upper Pleistocene Lisan Formation. The study area is located at the margin of the Lake Lisan which covered a large area of the Dead Sea rift during the Late Quaternary, ca. 63–15 ka (Kaufman et al., 1992). Base level lowering of the Wadi Araba drainage has been controlled by changes in the lake level of the Dead Sea and the Late Pleistocene precursor, Lake Lisan. The Dahal mountains are the bare bedrock region east of Wadi Araba fault. High relief is marked by elevation that ranges from 170 m below the mean sea level (MSL) to 408 m above MSL. The bedrock has been strongly dissected by headward erosion of the major drainages.

Fig. 3. Geologic map of the study area constructed from interpretation of 1:10 000 scale black-n-white air photos from 1978 and field mapping.
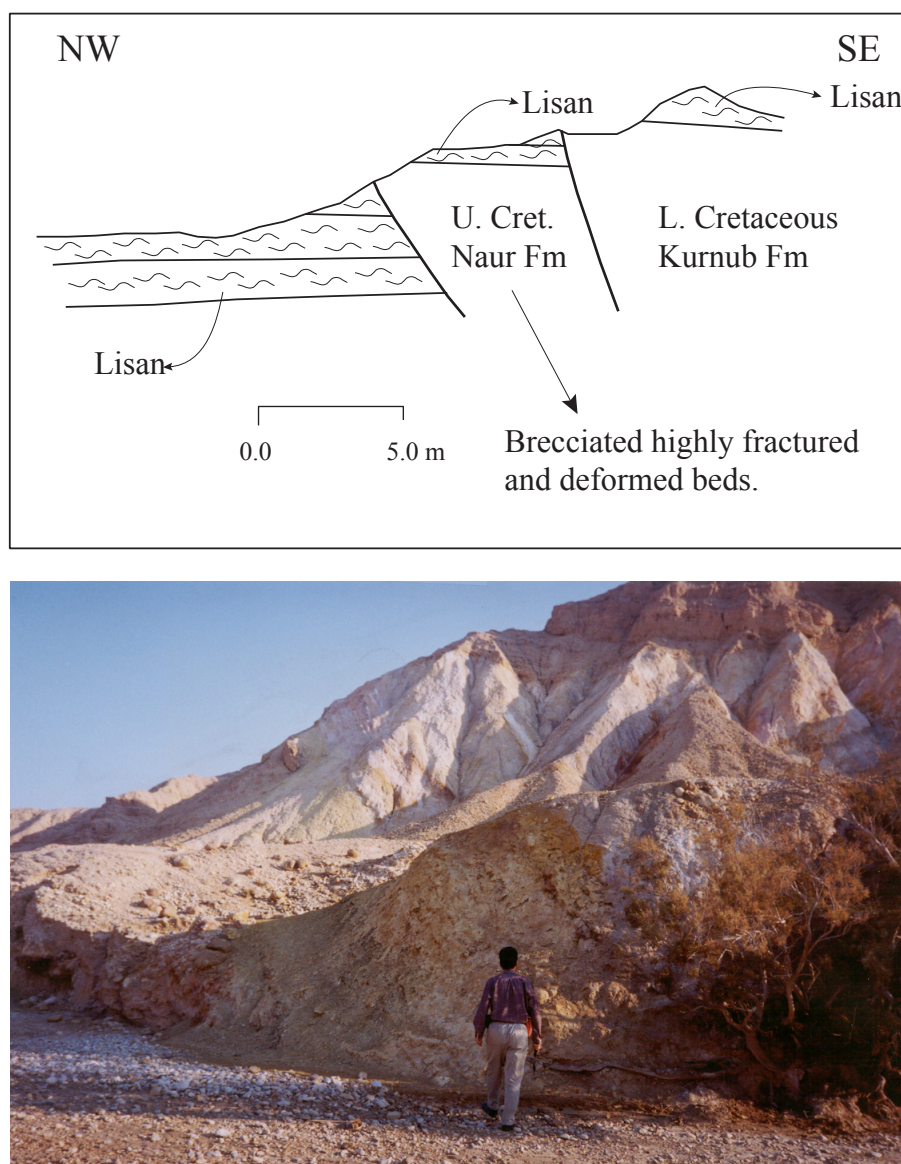
Fig. 4. (a) On the northern bank of Wadi Khunayzira, the transform is seen as a reverse fault with Lower Cretaceous (Kurnub Fm) sandstone upthrown relative to the Upper Cretaceous (Naur Fm) carbonates in the hanging wall. The Naur formation is highly fractured and the faults offset the Upper Pleistocene Lisan Formation. **(b)** Photograph of the structure viewed toward the north. Man standing in the foreground for scale. Location 2 on the geologic map of Fig. 3.

4   Stratigraphy

The stratigraphic section in the study area is composed of three dominant units:

(1) bedrock of Upper Cambrian and Cretaceous limestone, shale and sandstone,

(2) Quaternary lacustrine deposits of the Lisan Formation, and

(3) Quaternary alluvial fan deposits of Pleistocene and Holocene age (Fig. 3).

The Burj Formation is a dolomite and shale sequence of late Middle Cambrian to early Late Cambrian age. The formation outcrops in the northeastern corner of the study area in a structurally uplifted block. The Kurnub Sandstone Group is of Early Cretaceous age and outcrops along the eastern side of lower Wadi Khunayzira and in the southeastern area (Fig. 4). The Naur Limestone Formation is Cenomanian in age. Two small outcrops are found in the study area (Figs. 3, 4). In the southern area along Wadi An Nakhbar, steeply dipping limestone beds here represents the extension of deformed Dahal mountains that extend to the south. The second outcrop is located in the northeastern corner of the study area as a down-thrown fault block.

Conglomerates of probable Pleistocene age are found along the fault zone. At the Wadi An Nakhbar exposure

Fig. 5. DST on the northern bank of the Wadi An Nakhbar forms a 50–70 cm wide, zone of fault gouge that offsets the cemented pre-Lisan conglomerate. The fault extends into the wadi bed. Clasts are oriented long axis parallel to fault strike. Location 5 on the geologic map of Fig. 3.

Fig. 6. A prominent pressure ridge formed of Pre-Lisan Pleistocene conglomerate. Two former shorelines of the Lisan Lake are seen as notches in the western side of the pressure ridge. View toward the north. Location 4 on the geologic map of Fig. 3.

(Figs. 3, 5) the angular, poorly sorted gravel and cobbles are in angular unconformable contact with the overlying, horizonally bedded Lisan Formation. These pre-Lisan gravels are highly deformed; bedding attitudes change rapidly within a short distance. They might be deposited in a narrow, pull-

apart basin formed along the WAF and were deformed later by the movement along the WAF. At another location the Pre-Lisan conglomerates form a prominent pressure ridge (Figs. 6, 7). These deposits have been beveled by lake terraces with two former shorelines evident on the western side

Fig. 7. The conglomerates (possibly of middle to early late Pleistocene age?) of this pressure ridge are well rounded, well sorted gravel that is strongly cemented and highly fractured. The fractures are filled with calcite. View toward the northeast. Location 4 on the geologic map of Fig. 3.

of the ridge. At this location, the pre-Lisan conglomerates are well rounded, well sorted, and well cemented. The unit contains numerous calcite-filled fractures.

The upper Pleistocene Lisan Formation unconformably overlies the Kurnub Sandstone and the pre-Lisan conglomerate. At least three different facies of Lisan formation are present in the outcrop: a deep-water facies composed of thinly laminated marl and gypsum, a beach facies composed of calcarenite and oolitic sandstone with interbeds of well-rounded pebbles and cobbles, and a fan-delta facies composed of graded beds of coarse sand and gravel.

Post-Lisan conglomerate is exposed in a small outcrop at the intersection of the Wadi Khunayzira and the Wadi An Nakhbar. Other recent sediments are differentiated into alluvium and aeolian sands. These deposits are concentrated at the mouth and in the channel and tributaries of Wadi Khunayzira. Alluvial fan deposits of sand and gravel at the base of the Khunayzira escarpment are capped by a thin soil. Aeolian coarse- to medium-grained sand derived from the local bedrock blankets the eastern side of the ghor.

5 Structures

5.1 Wadi Araba fault (WAF)

In the southern end of the study area, the WAF has clear geomorphic expression with offset stream channels and alluvial fan surfaces, shutter ridges, and sag depressions. In the deep canyons of Wadi Khunayzira and Wadi An Nakhbar, the WAF plane is well exposed, cutting the Lisan and post-Lisan conglomerates. Striations were well developed on the polished pebbles (Fig. 8). The fault plane in the exposure of the Wadi An Nakhbar wall (Fig. 3, Location 5) has an attitude of N15°E, 80E. Striations plunge 15° to the N15°E. The eastern block was down faulted. Within the fault zone, a Riedel shear strikes due north and dips 60°E.

A series of pressure ridges formed along right-stepping fault traces were mapped along an eastern strand of WAF. The largest pressure ridge is cored by pre-Lisan conglomerate and measures 300 m in length (Fig. 3, Location 4; Fig. 6). Other smaller, rounded, and isolated pressure ridges are located along the fault trend and disappeared gradually to the north. These ridges must have formed small islands close to the shore of the Lisan Lake. These ridges represent an old trace of the WAF, the recently active WAF is located west of the pressure ridges.

Fig. 8. Highly polished cobble along the fault plane shows several generations of slickenlines with strike-slip and dip-slip components.

Fig. 9. Exposure of the DST fault plane along Wadi An Nakhbar viewed toward the east. The fault cuts the Upper Pleistocene conglomerate. Location 3 on the geologic map of Fig. 3.

At the intersection of the Wadi An Nakhbar and the Wadi Khunayzira (Location 3 on Fig. 3), the WAF zone is well exposed. For part of its distance, the fault crosses the Wadi floor and forms a 50–70 cm-wide dike that is filled with oriented clasts in a well-cemented conglomerate. Here the WAF has an attitude of N15°E, 80°SE. Several meters to the north, the WAF has the attitude of N15°E, 75°SE with well-developed, striations on pebble surfaces that plunge 25°, S20°W (Fig. 9). A prominent Riedel shear marked by cemented fault gouge strikes N-S, 70°W and intersects the WAF at this location. In the southern bank of Wadi Khunyzira, the two strands of the WAF exhibit normal separation (Fig. 10). The attitude of the fault plane is N15°E, 80° NE and the striations plunge 20° toward the S05°W. The eastern block was down faulted. The vertical throw across this fault is 4 m as observed from

the offset of a gravel bed. Using the triangle method, the horizontal displacement is calculated to be 8 m.

The straight western bank of the Wadi Khunayzira between Location 2 and 3 on Fig. 3 is formed by the N5°W, 80°NE-trending exposed plane of a Riedel shear. Slickensides are poorly developed and striations are difficult to measure. At the same place a conjugate Riedel shear strikes N50°E, 55°NW.

At Location 2 (Fig. 3), the WAF shows reverse separation; the Lower Cretaceous Kurnub FM sandstone is upthrown relative to the Upper Cretaceous Naur Fm carbonates (Fig. 4). Lower and Upper Cretaceous rocks are highly fractured and brecciated. The neighboring and the overlying Lisan beds are in apparent buttress unconformable contact with the deformed bedrock. Farther to the north, where the WAF is ex-

Fig. 10. The DST forms a 2.5 m wide zone that strikes N15°E, 80°NE. Slickensides observed on the polished clasts of the fault plane plunge 20° to the S5°W. The vertical, normal throw of this fault is 4 m. Location 3 on the geologic map of Fig. 3.
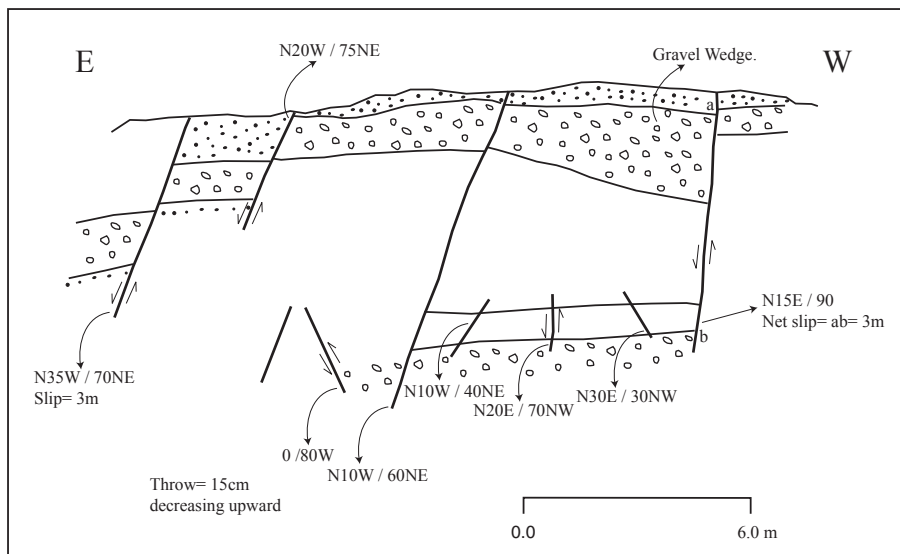
Fig. 11. Sketch map of deformation within the Lisan formation exposed along the eastern trace of the DST just south of the pressure ridge. Location 6 on geologic map. The Lisan formation at this outcrop is predominately nearshore and deltaic facies with distinct horizons of well-rounded gravel and cobbles.

posed as a wall that strikes N20°E, 85°NW with slip directed 25°, S30°W. At the same outcrop Riedel shears (N05°E, 80°NW) and conjugate Riedel shears (N60°W, 25°SW) were measured.

North of the Khunayzira fault, the topography is gentler and there are no deep valleys to expose clear fault planes. The WAF trace can be delineated in the field and on the aerial photographs as a linear depression and as an abrupt change in the topographic elevation across the fault trace. At the northern end of the study area, where Holocene alluvial and dune sand cover the bedrock, it is difficult to delineate the fault trace, but Galli (1999) traced the WAF north of the study area.

5.2 Khunayzira Fault

The Khunayzira fault makes a prominent, curvilinear, 50 m-high scarp that trends SE-NW. The base of the scarp is straighter at the northwestern end indicating higher rate of subsidence (Garfunkel et al, 1981). In the study area, the scarp is highly eroded and sinuous. The single fault scarp in the west branches in the study area to form four fault traces. The most active fault trace is the northern one that can be traced onto the recent fan of Wadi Khunayzira as a low scarp and line of vegetation. It is difficult to determine if this fault branch abuts the WAF, because it is covered by Holocene alluvial and dune sand or it may die out toward the southeast and does not cut the WAF (Location 1, Fig. 3). Detailed measurement of fractures along the Khunyzira scarp does not

Table 1. Orientation data used in paleostress calculation

T1: Attitudes of fault planes and their slickensides of the sinistral Wadi Araba fault	
Fault plane	Slickensides
N15E, 80SE	15, N15E
N10E, 80SE	10, S10W
N15E, 75SE	25, S20W
N15E, 80NE	20, S05W
N20E, 85NW	25, S30W

T2: Attitudes of fault planes in the Upper Cretaceous rocks		
Fault plane		Slickensides
N85E, 90	(D)	15, N85E
N60E, 70NW	(D)	20, N55E
N65W, 75NE	(S)	05, S75E
N30E, 60NE	(S)	05, S50W
N75W, 60NE	(S)	00, S70E
N05E, 75SE	(S)	15, N-S
N60W, 60NE	(S)	15, N60W
N70E, 85NW	(D)	20, S70W
N50W, 65NE	(S)	10, S60E
N60W, 55NE	(S)	50, N20E
N80W, 60SW	(S)	30, S80W
N90E, 90	(D)	30, S80W
N90E, 70S	(D)	10, S80W
00 70E	(S)	20, N10E
N70E, 60SE	(D)	20, S50W
N80W, 70NE	(S)	15, N90E
N80W, 70NE	(S)	00, S80E
00 75W	(S)	50, S

(S): Sinistral fault
(D): Dextral fault

show major normal faults. The dominating fractures are normal faults with only a few centimeters throw. The average strike of these fractures is N30°W, 80°NE. One fault with a 1 m offset strikes N70°W, 60°NE.

5.3 Other structures

In addition to the previously described structures, other structures are found in the study area. In Wadi An Nakhbar, 200 m east of the WAF, a set of faults cut the Lisan beds (Location 6, Fig. 3; Fig. 11). The fault set consists of three main faults and many subsidiary faults. The western strand is parallel to the WAF (N15°E, 90) with a vertical throw of 3 m. The middle strand shows no vertical separation and has an attitude of N10°W, 60°NE. The eastern strand strikes N35°W, 70°NE and has a normal separation of 3 m. Strike-slip movement along these faults is evident by the mismatch of stratigraphic thickness of gravels across the western fault strand. No slickensides are preserved in the fine-grained and friable sediment. These faults are likely part of a negative flower structure formed along another strand of the WAF.

In Wadi Khunayzira, 50 m east of its intersection with Wadi An Nakhbar, a few strike-slip faults cut the post-Lisan conglomerate. The major three faults have the attitudes of N15°W, 85°NE (parallel to the WAF), N05°E, 80°SE and N10°W, 70°NE (represent Riedel shears). And northeast of the lower course of Wadi Khunyzira, a remnant of Upper Cretaceous limestone is surrounded by Lisan sediments as a prominent pressure ridge (Fig. 3). The general trend of this ridge is N15°E. The rocks are highly fractured. The fault plane is marked with slickenlines. In the Cambrian sandstone, east of the mapped area, three sets of vertical fractures were measured with a major strike direction of N90°E and minor joint sets that strike N30°E and N30°W.

6 Paleostress

The attitude of the fault planes and striations on slickenside surfaces were measured for the WAF and the faults in the Upper Cretaceous rocks (Table 1). Upper Cretaceous rocks were chosen because they show well-developed slickensides with striations. Fault slip data for both the Lisan beds and Upper Cretaceous beds were limited due to the limited outcrop of the Upper Cretaceous rocks and due to the fact that, the WAF plane is exposed in few locations when it is intersected by the wadi courses. The fault slip data were used in kinematic and dynamic analyses (Angelier 1990; 1994) to determine the mean principal stress directions before and during the formation of the Dead Sea transform. The data were processed using the computer program "Tensor" developed by Delvaux (1993). Structural orientation data collected from the Upper Cretaceous rocks yielded a maximum compressive stress direction WNW and a maximum tension direction of NNE (Fig. 12). These trends coincide with the Syrian Arc stress field (Fig. 1; Eyal, 1996). Deformation of the Lisan formation yielded a maximum compressive stress oriented NNW and a maximum tension oriented ENE (Fig. 13). These trends coincide with formation of the WAF in the Dead Sea stress field (Eyal, 1996). Fig. (12) also shows a clear trend of the Dead Sea system superimposed on the Syrian Arc system. Separating the data of Fig. (12) gives two distinct systems, the Dead Sea system (Fig. 14) and the Syrian Arc system (Fig. 15).

7 Discussion

The area southeast of the Dead Sea was chosen for detailed structural analysis in order to understand the step-over from strike slip to dip slip in the Dead Sea pull-apart basin. The location of the active strand of the WAF has migrated westward during the late Quaternary. The older, pre-Lake Lisan (>63 ka) fault trace lies along a series of pressure ridges. Some of these ridges would have formed islands in the Lisan Lake and are geomorphically modified by lake terrace shorelines. Pre-Lisan conglomerate accumulated in a tectonically controlled, subsiding basin formed along an older trace of the WAF. Another old fault trace can be traced north of Wadi
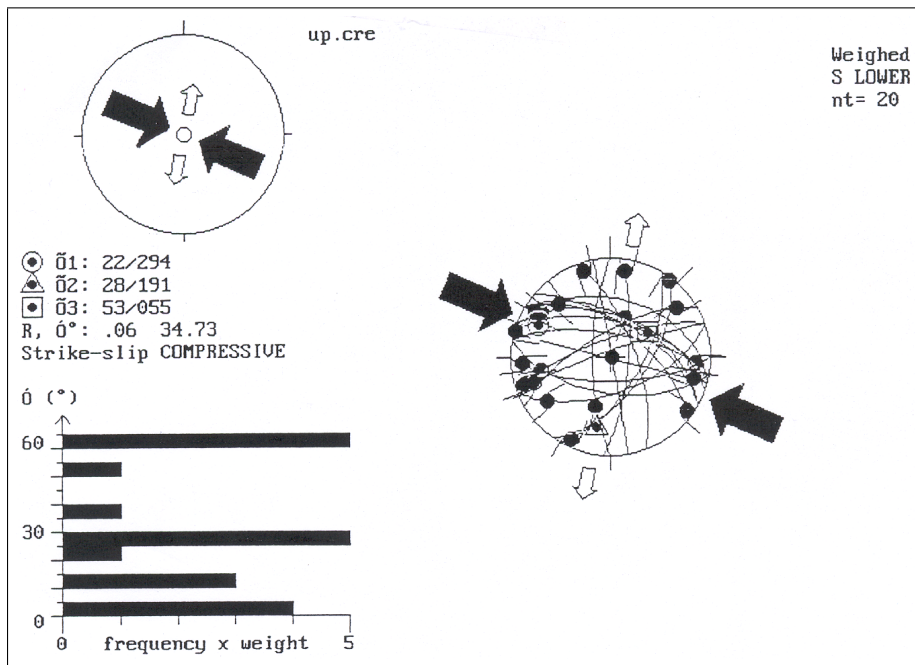
Fig. 12. Stereonet projection of fault slip orientation data from the Upper Cretaceous Naur Formation.
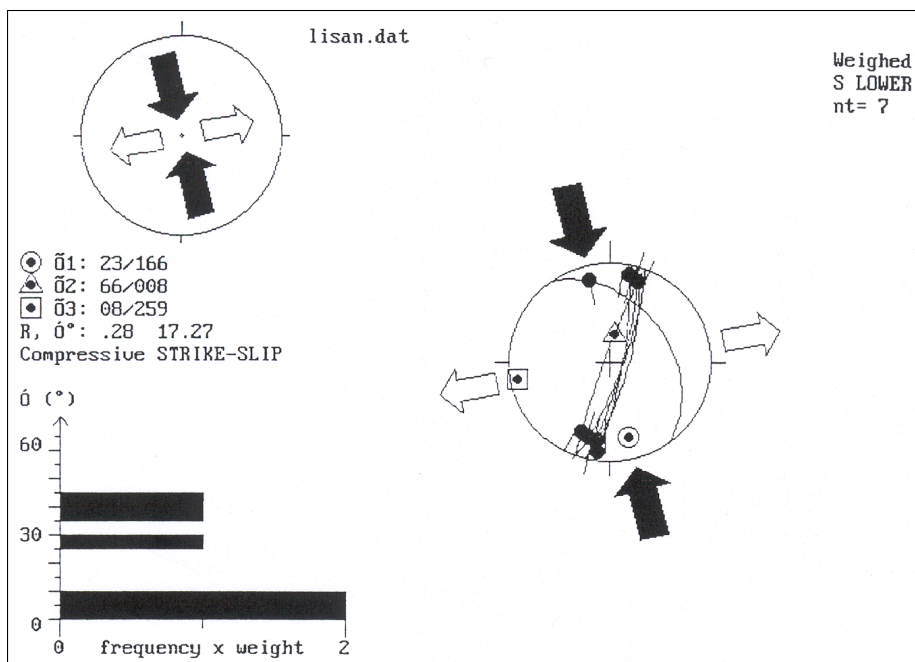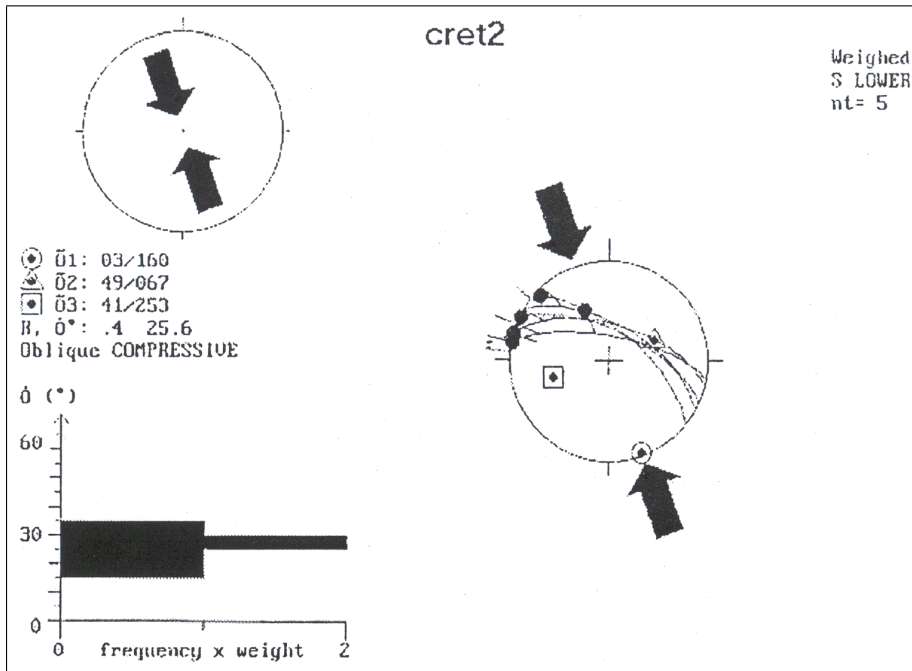

Fig. 13. Stereonet projection of fault slip orientation data from the Lisan Formation.

Khunayzira as an Upper Cretaceous pressure ridge. In each case, the Holocene active fault is located west of the older trace.

This study is the first to delineate the exact location of the WAF in this area. The main WAF is associated, as other strike-slip faults, with both Riedel and conjugate Riedel shears. Their orientations relative to the main fault is 10–20° for the Riedel shears and 65°–75° for the conjugate Riedel, which corresponds to the Riedel model in both experiments and earthquake faults (Tchalenko and Ambraseys, 1970).

The WAF continues to the north of the study area. There is no indication that it terminates in this area and the strike-slip movement changes into dip-slip movements along the Khunayzira fault. The later fault dies out into four traces before it connects the WAF. No crosscutting relationship is observed between the two faults. These observations are not in agreement with the interpretation of Garfunkel (1981) that the Khunayzira fault represents the southern boundary of the Dead Sea pull-apart basin, where the eastern strike-slip fault terminates and the western one takes over. This result is in accordance with the postulation of ten Brink and Ben Avraham (1989) and Kashai and Croker (1987). These authors suggested that the transverse faults in the Dead Sea basin (Iddan, Amatzyahu (Khunayzira), Boqeq and Ein Gedi faults)

Fig. 14. Stereonet projection of fault slip orientation from the Upper Cretaceous Naur formation showing the Dead Sea paleostress system.
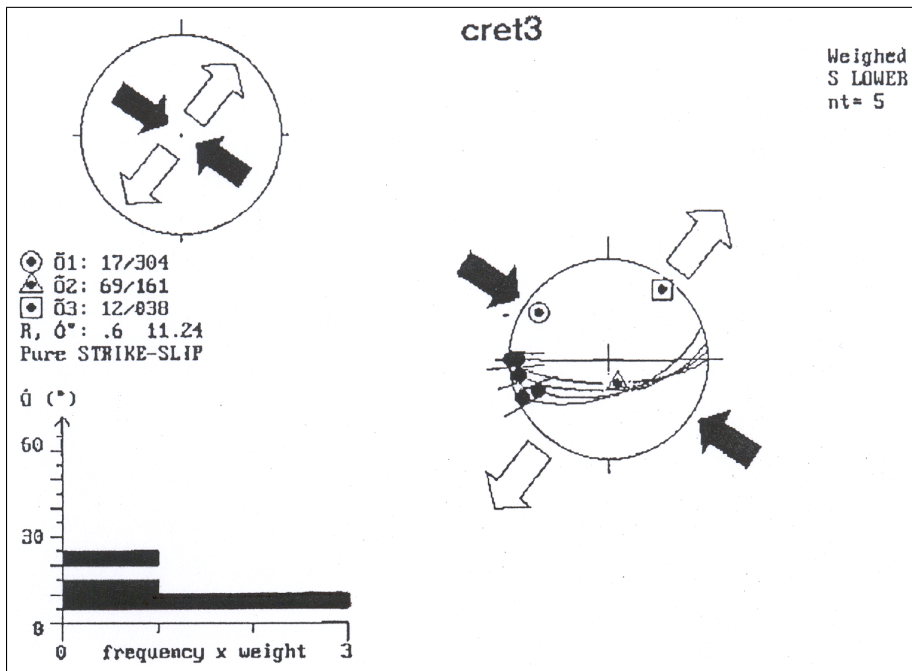
Fig. 15. Stereonet projection of fault slip orientation from the Upper Cretaceous Naur formation showing the Syrian Arc paleostress system.

are younger than the two strands of the transform and that they were active after the formation of the basin. ten Brink and Ben Avraham (1989) suggested that the northern propagation of the southern fault (WAF) coincides with the northward migration of activity on transverse faults. This model corroborates an earlier suggestion of a northward migration of the depocenter of the Dead Sea basin proposed by Zak and Freund (1981).

Detailed study of the Bir Zreir pull-apart basin in eastern Sinai by Eyal et al. (1986) showed that both the western and

eastern NNE-trending, major strike-slip faults continue beyond the oblique fault that connects them along the southern boundary of the pull-apart. Sand-silicone model experiments of oblique rifting by Tron and Brun (1991) showed that at high obliquity angles, deformation is partitioned between two distinct sets of oblique-slip and strike-slip fault trends. Sandbox analog models of pull-apart basins by McClay and Dooley (1995) and Dooley and McClay (1997) showed that the sidewall faults of the pull-apart basins show changes in kinematics from dominantly dip-slip extension in their cen-

tral section to oblique slip and strike slip at either end where they merge with the principal deformation zone. These authors compare their analog models with natural examples of pull-apart basins, including the Dead Sea and show many strong similarities in structural geometries and stratal architectures. These models are a reasonable fit for development of active faults mapped along the southern DST, and support partitioning of strain onto transform-parallel normal faults proposed by Ben-Avraham and Zoback (1992). Transform normal extension may better explain the formation of basins along the DST than the classic pull-apart basin model.

8 Conclusions

Study of the neotectonic structures exposed in the Dead Sea basin can reveal much about the deformation processes that operate in the uppermost crust and the formation of transtensional basins. The stratigraphic section in the study area is composed of three dominant units:

(1) Cambrian and Cretaceous limestone, shale, and sandstone,

(2) Quaternary lacustrine deposits of the Lisan Formation, and

(3) Quaternary alluvial fan deposits of Pleistocene and Holocene age.

The oldest rocks in the study area are the Cambrian Burj formation, the Lower Cretaceous Kurnub sandstone, and the Upper Cretaceous limestones. Fracture orientation data indicate that these rocks have been folded and uplifted during an early phase of tectonic deformation when the transform plate boundary was formed in the Miocene. The Cretaceous rocks also core pressure ridges within the present stress regime. Unconformably overlying the Paleozoic and Mesozoic bedrock are tilted Pleistocene fluvial gravels. These conglomerates may correlate to the Samra Formation (350 to 116 ka; Kaufman et al., 1992). The contact of the flat-lying Late Pleistocene lacustrine deposits of the Lisan Formation with the older units forms both buttress and angular unconformities. Fault slip data indicate the maximum principal stress is oriented NNW-SSE and minimum principal stress is directed ENE-WSW for post-Lisan deformation.

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