Anatomy of the Dead Sea transform: Does it reflect continuous changes in plate motion?

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ABSTRACT

A new gravity map of the southern half of the Dead Sea transform offers the first regional view of the anatomy of this plate boundary. Interpreted together with auxiliary seismic and well data, the map reveals a string of subsurface basins of widely varying size, shape, and depth along the plate boundary and relatively short (25–55 km) and discontinuous fault segments. We argue that this structure is a result of continuous small changes in relative plate motion. However, several segments must have ruptured simultaneously to produce the inferred maximum magnitude of historical earthquakes.

INTRODUCTION

The Dead Sea transform plate boundary offers a unique opportunity to study crustal and upper mantle deformation associated with strike-slip motion because of the simple and well-exposed pretransform geology and the slow (<10 mm/yr) relative plate motion (Garfunkel et al., 1981). This plate boundary separates the Arabian plate from the African plate and connects the Red Sea spreading center with the collisional belt of southern Turkey (Fig. 1). The well-developed Rift Valley, as wide as 25 km, and partially below sea level, straddles the southern half of the transform and is the focus of our study. Although many studies utilizing outcrop geology, oil exploration wells, and seismic reflection data have been conducted (e.g., Ben-Avraham et al., 1996; Garfunkel et al., 1981; Heimann and Ron, 1993; Horowitz, 1987; Neev and Hall, 1979; Rotstein et al., 1991, 1992; Shaliv et al., 1991; ten Brink et al., 1993), it was impossible to obtain a complete view of this plate boundary, because the international border between Jordan and Israel is within the Rift Valley. The gravity map presented here (Fig. 1) offers the first complete regional view of the anatomy of the plate boundary. The making of the map is the result of a cooperative project approved as part of the peace treaty between Jordan and Israel. The map is based on ~40 000 gravity stations which, within the Rift Valley, are mostly distributed at a spacing of ≤0.5 km. The stations were measured over the years by the Natural Resources Authority, Jordan, the Geophysical Institute of Israel, and there are additional marine surveys of the Dead Sea and the Sea of Galilee (ten Brink et al., 1993; Ben-Avraham et al., 1996). The databases of Israel and Jordan were mutually tied by measurements made at the Aqaba-Elat and the Bet-Shean border crossings. The data were tied to an absolute gravity base station 9002 in Amman, and were reduced according to the 1971 reference ellipsoid.

OBSERVATIONS

The gravity field, which is indicative of density variations of subsurface rocks, is a powerful tool to map in detail the anatomy of this plate boundary, especially when combined with analysis of seismic reflection and well data (Fig. 1). Basins, generated as a result of the relative plate motion and fault geometry, are detected in the gravity field because of the low density of their fill (2000–2200 kg/m^3) relative to the surrounding rocks (2500–2670 kg/m^3) (ten Brink et al., 1993; Rybakov et al., 1998). The locations and shapes of small basins are used to delineate fault segments assuming that vertical strain develops along irregularities in strike-slip fault systems (Bilham and King, 1989; ten Brink et al., 1996). Multichannel seismic reflection data (from the national archives of Jordan and Israel; e.g., Bartov et al., 1998; Frieslander et al., 1995, 1996; Gardosh et al., 1997; Kasahi and Croker, 1987; Neev and Hall, 1979; Rotstein and Bartov, 1989; Rotstein et al., 1991, 1992; Shtivelman et al., 1998; ten Brink and Ben-Avraham, 1989; Y. Ben-Gai and M. Rezhnikov, 1997, written commun.; and Fig. 2) which cross the majority of these faults were examined to verify their locations. These data were collected in support of oil and water explorations by the Geophysical Institute of Israel and by oil exploration companies during the past 30 yr. Line spacing on the Israel side of the rift valley is often ~5 km between the Sea of Galilee and Elat. Similar coverage on the Jordanian side is limited to the central and southern Dead Sea basin. The areal coverage and orientation of the seismic lines were limited by the presence of the international border in the middle of the Rift Valley.

The Rift Valley from the Gulf of Aqaba (Elat) to about 90 km northward is occupied by three basins that become successively narrower and shallower to the north. They include the Aqaba (Elat) basin, which extends from the offshore, the newly discovered Timna (Qa-Taba) basin, which is offset en echelon from the Aqaba basin, and a string of basins, which we name the Gharandal basin. The basins are oriented diagonally to the axis of the Rift Valley, an arrangement similar to that in the Gulf of Aqaba (Ben-Avraham et al., 1979). Intermittent morphological expressions of an active fault (Garfunkel et al., 1981) and a 1-km-wide fault zone identified in high-resolution seismic profiles (Shtivelman et al., 1998) are coincident with our fault locations based on gravity. Two-dimensional gravity modeling of the Timna basin indicates that it is 1300 m deep (Fig. 2C).

The next 150 km of Rift Valley to the north are occupied by a large negative gravity (maximum of –132 mgal) that represents the Dead Sea basin. The transition from the Gharandal basin to the Dead Sea basin is characterized by a gravity high, which corresponds to a topographic saddle between the northern and southern Arava (Araba) Valley. Deformation in this area may be complicated by an east-west–oriented fault, which intersects the valley from the west. The Dead Sea basin appears to be divided into segments 20–30 km long, and seismic reflection profiles (Frieslander et al., 1996; Gardosh et al., 1997; ten Brink and Ben-Avraham, 1989; Fig. 1) confirm the existence of diagonal cross-basinal normal and listric faults. The 6.5-km-deep Sedom-Deep well (Fig. 1) did not reach the base of the basin fill (Gardosh et al., 1997) and gravity models indicate a maximum of ~10 km of basin fill under the Lisan subbasin (ten Brink et al., 1993).

The character of the plate boundary changes north of the Dead Sea. A shallow (~800 m deep) asymmetric basin, which we name the Jericho basin, plunges westward (Fig. 2A) and terminates against a west-dipping strike-slip

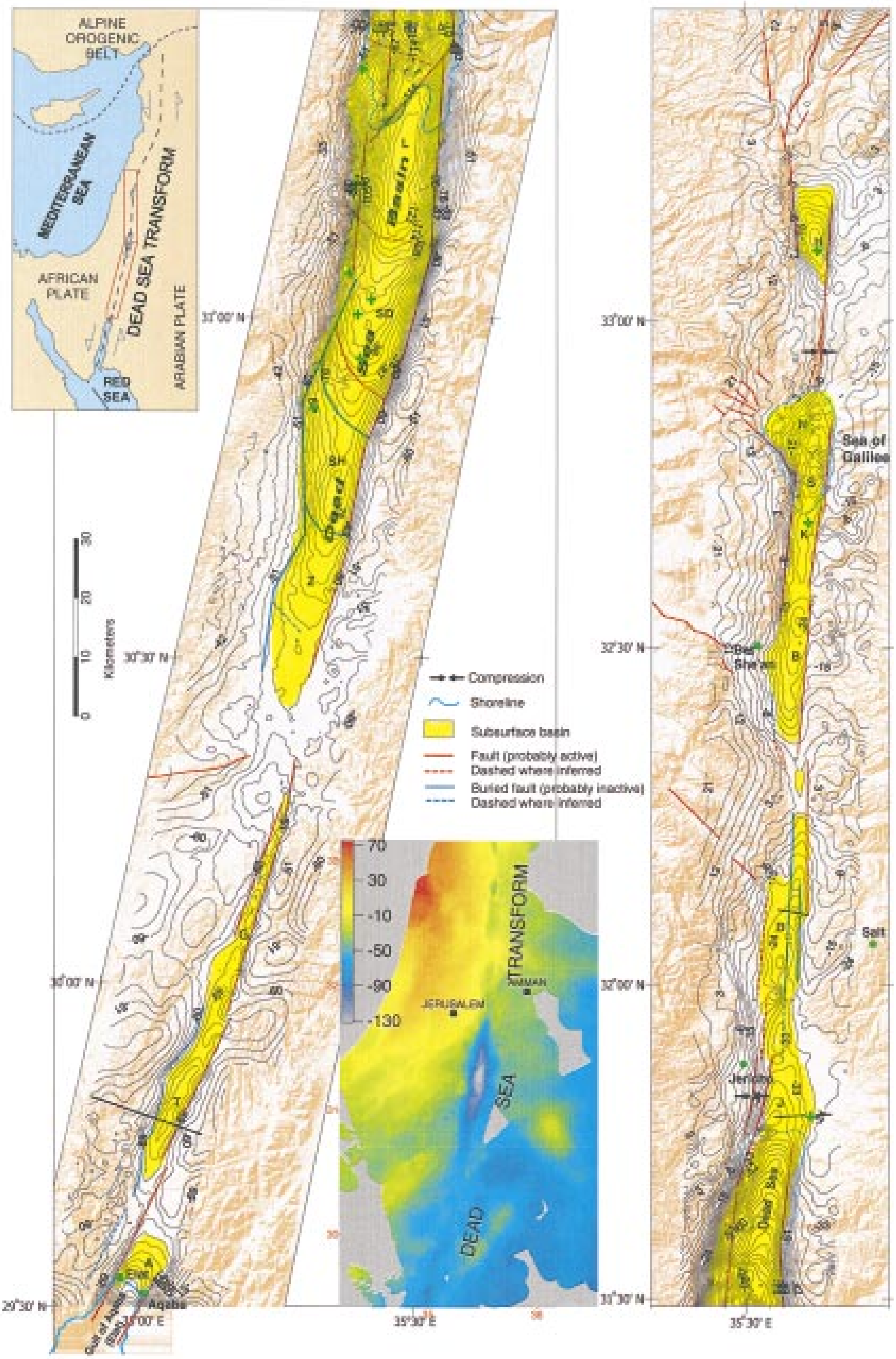

Figure 1. Bouguer gravity anomaly map of Dead Sea transform, Jordan and Israel, corrected with density of 2670 kg/m^3. Contour interval is 3 mGal. Terrain correction was calculated from digital terrain model (DTM) (Hall, 1993) with 25 m grid using in-house code. Background: Shaded relief topography from DTM. Black lines: Locations of profiles in Figure 2. Abbreviated basin names: A, Aqaba (Elat); B, Bet Shean; D, Damia; G, Gharandal; H, Hula; J, Jericho; K, Kinarot (Bakura); N, S, northern and southern Sea of Galilee; T, Timna (Qa'Taba). Dead Sea basin is further divided into following subbasins (ten Brink and Ben-Avraham, 1989; Bartov et al., 1998): Z, Zofar; SH, Shezaf; SD, Sedom; L, Lisan; and Dead Sea. Green crosses are oil exploration wells, from north to south: Notera (in H), Zemah (in K), Jordan Valley-1 (in J), Ein-Gedi on Dead Sea shore, Amiaz-1, Sedom-1, Melekh-Sedom, Sedom Deep, and Amaziahu (in Sd), and Arava-1 (in SH). Top inset is simplified plate geometry and location of maps. Bottom inset is regional Bouguer gravity map of Israel and Jordan.

fault (Rotstein et al., 1991). A buried monocline parallels this segment of the fault on the west and is indicative of local transpressive motion (Rotstein et al., 1991). A shallow (~250 m deep) basin (Fig. 2B), which we name the Damia basin, occupies the central Jordan River valley. The shape of the basin in the gravity map is complex, and seismic reflection data show several parallel faults at the edge and within the basin. The central faults are buried under a few hundred meters of sediments (Fig. 2B), although surface geological evidence and abrupt stream-course changes suggest recent activity (Garfunkel et al., 1981). The Bet Shean basin to the north plunges asymmetrically toward the east (Shaliv et al., 1991; M. Gardosh, 1998, personal commun.). The narrow (~6 km) and long symmetric Kinarot (Bakura) basin (Rotstein et al., 1992) occupies the upper Jordan River valley and extends into the southern Sea of Galilee (Ben-Avraham et al., 1996; Y. Ben-Gai and M. Rezhnikov, 1997, written commun.). The presence of many gabbro and basalt layers within the 4.25-km-thick basin fill in the Zemah well (Marcus and Slager, 1985) explains the small gravity anomaly over this basin.

Gravity modeling and seismic reflection data suggest that the northern part of the Sea of Galilee is occupied by an asymmetric basin plunging to the southeast, and the basin does not appear to be associated with a simple north-south strike-slip fault (Ben-Avraham et al., 1996; Y. Ben-Gai and M. Rezhnikov, 1997, written commun.). Seismic reflection data (Rotstein and Bartov, 1989) and geological studies (e.g., Heimann and Ron, 1993) indicate that the plate boundary is reestablished as a strike-slip fault with a slight compression north of the Sea of Galilee. A left stepover of faults generates the classical pull-apart Hula basin, where 2.8 km of alternating lake beds and volcanic flows have been drilled (Heimann and Steinitz, 1989).

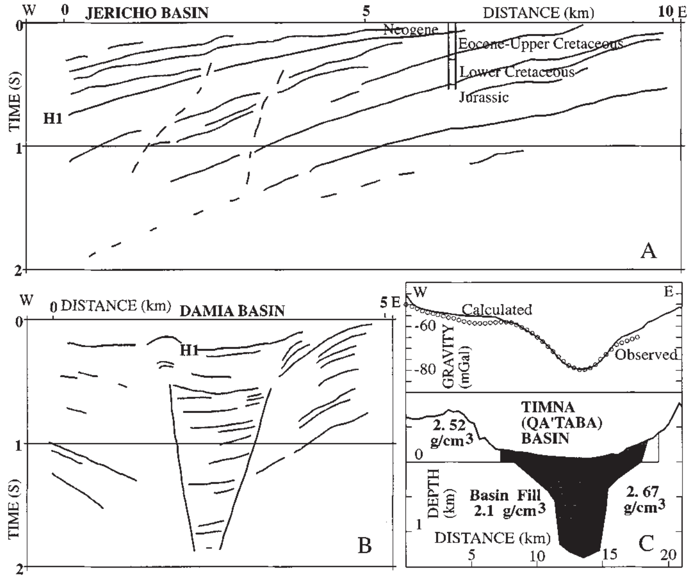

Figure 2. Line drawings of seismic reflection profiles crossing (A) Jericho basin and (B) Damia basin. H1: Base of rift fill, which at Jordan Valley-1 well occurs at 276 m depth. C: Two-dimensional gravity model across Timna (Qa'Taba) basin. There are no coincident seismic lines there. See Figure 1 for location.

DISCUSSION

Our interpretation of fault locations based on the gravity and aided by seismic reflection data indicates that the motion along this 420-km-long plate boundary is accommodated by at least 15 separate fault segments with segment lengths varying between 25 and 55 km. More fault segments are shown buried on seismic reflection profiles and do not offset or perturb the upper sedimentary section (e.g., Frieslander et al., 1995, 1996; ten Brink and Ben-Avraham, 1989), indicating that they are no longer active. Strike-slip faults tend to smooth themselves as they mature; i.e., the geometrical complexity of strike-slip faults should decrease with increasing cumulative strike-slip offset (Wesnousky, 1988). The cumulative offset of 105 km along the Dead Sea transform is expected to be accommodated by a single smoothed 420-km-long fault segment (Stirling et al., 1996; Wesnousky, 1988). The observations of a large number of basins and of numerous and overlapping fault segments along the Dead Sea plate boundary suggest a continuous adjustment to changes in the relative plate motion. A continuous adjustment of the plate boundary is to be expected, considering that the pole of rotation between Arabia and Africa is close to the Dead Sea plate boundary and may have been getting closer with time (Chu and Gordon, 1998).

Alternatively, it could be argued that the basins developed before the Dead Sea fault system smoothed itself, and that structural response of the uppermost crust may remain complex despite a smooth slip at depth. Earthquake data from the region do not have sufficient resolution to locate the faults at depth. However, other lines of evidence indicate a dynamically changing plate boundary with time.

1. An extinct fault trace, associated with an inactive anticline at Zemah well, was observed in seismic reflection profiles in the Kinarot basin (Rotstein et al., 1992). The extinct fault and anticline are oriented northeast, whereas the active eastern boundary fault trends north-south. The absence of sediment accumulation in the Zemah well between 2 Ma and 60 ka (Horowitz, 1989) led Rotstein et al. (1992) to conclude that the basin underwent compression and shortening during that period due to a change in the geometry of the transform.

2. Paleomagnetic data and K-Ar dates from basalt flows and sedimentary strata between the Sea of Galilee and the Hula basin show that transpressive deformation started there only ca. 0.9 Ma (Heimann and Ron, 1993).

3. An extensive analysis of stress indicators in Israel, Jordan, and Sinai suggests spatial and temporal fluctuations in the stress field direction since the formation of the Dead Sea transform in the Miocene (Eyal, 1996).

4. Well data (see Fig. 1 for location) show variable and asynchronous sediment accumulation rates among basins of the Rift Valley. The accumulation must at least partly reflect basin subsidence because an accommodation space had to be present for thousands of meters to accumulate in these small continental basins (Horowitz, 1987). Accumulation rates during the Miocene were high in the Kinarot basin and in the southern part of the Dead Sea basin (Horowitz, 1987), but the Hula basin was a structural high until 4 Ma (Heimann and Steinitz, 1989). Palynostratigraphy of the wells indicates unusually high accumulation rates between 2.3 and 1.8 Ma and during the past 250 k.y. in the Dead Sea basin (Horowitz, 1989). In the Hula basin, the accumulation rate increased gradually after 3 Ma, and jumped significantly only during the past 70 k.y. In the Kinarot basin, rates were high from 2.2 to 2 Ma, but negligible ever since (Horowitz, 1989). Similar information is not available from other basins.

5. The subsidence of the Dead Sea basin appears to have migrated with time from south to north. Well (Horowitz, 1987; Gardosh et al., 1997) and outcrop (Bartov et al., 1998) data suggest that the Miocene depocenter was probably centered in the Shezaf subbasin (>2000 m thick), included the Zofar and Sedom subbasins, but did not extend as far north as the Ein-Gedi well (Fig. 1). The Pliocene evaporitic Sedom Formation, 1300 m thick in the Sedom Deep well (Gardosh et al., 1997), forms salt diapirs in the Sedom and Lisan subbasins and probably farther north (Neev and Hall, 1979), but is not found in the Arava-1 well (Horowitz, 1987), and no evidence for halokinesis is found on seismic lines south of 30°55′ (ten Brink and Ben-Avraham, 1989). The Pliocene-Pleistocene lacustrine Kuntila Member in the Zofar subbasin is at a depth similar to that outside the basin, but is 530 m deeper in the Arava-1 well farther north (Bartov et al., 1998). The Pleistocene section is only ~40 m thick in Arava-1 well (Horowitz, 1987), but is 3800 m thick in the Sedom Deep well (Gardosh et al., 1997). The lowest elevation of the basin is currently at the Dead Sea, at 720 m below msl.

6. Seismic stratigraphic analysis indicates that the initiation of activity on the diagonal basin-crossing faults of the Dead Sea basin migrated northward with time, and that the shallow sequence of the Shezaf subbasin thickens

gradually northward (ten Brink and Ben-Avraham, 1989). The western boundary fault in that area is buried under 1.4 s of sediments, suggesting that it has not been active for some time (ten Brink and Ben-Avraham, 1989).

If we accept that the segmented nature of the fault system reflects the present plate boundary geometry, we could argue that it is due to highly oblique transtension, because physical models of oblique strike-slip motion produce multiple highly oblique short fault segments (Tron and Brun, 1991). However, with the exception of the southern Arava valley and the Gulf of Aqaba farther south (Ben-Avraham et al., 1979), fault orientations deviate both clockwise and counterclockwise from that of the plate boundary, whereas the faults in physical models are oriented either clockwise or counterclockwise to the direction of motion, but not in mixed directions (Tron and Brun, 1991).

Analysis of historical records suggests a maximum local magnitude, $M_L = 7.3$, which, using the local relationship, $\log L = 0.5\ M_L - 1.6$, corresponds to a maximum rupture length of 115 km (Ben-Menahem, 1991). The corresponding moment magnitude, $M_w = 7.3$, is larger than expected from the rupture of a single fault (Stirling et al., 1996). Hence, few fault segments were likely moving simultaneously during a single earthquake, possibly in a manner similar to that observed during the Landers earthquake in California (Hauksson et al., 1993). A section of 115 km corresponds to the distance from the southern end of the Dead Sea basin (lat 30°28″) to the northern end of the Lisan peninsula (lat 31°28″), where there is a possible jog from the eastern to the western side of the Dead Sea. Another possible section extends from the northern end of the Dead Sea to the northern end of the Sea of Galilee.

CONCLUSIONS

A new Bouguer gravity anomaly map of the Dead Sea rift reveals numerous basins of various sizes and shapes occupying the Rift Valley. We interpret this structure to represent a plate boundary comprising numerous and short fault segments. We argue that this fault geometry is due to a continuous adjustment of the plate boundary to small changes in the relative plate motion between Africa and Arabia, and review other lines of evidence that suggest a dynamically changing plate boundary with time. The map presented here underscores the merits of international scientific cooperation in the Middle East and should serve as a framework for additional research on the anatomy and mechanics of this transform plate boundary.

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