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Deep “drop down” basin in the southern Dead Sea

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Abstract

The large Dead Sea graben is located within the Dead Sea fault, a plate boundary of the transform type. The graben is composed of two basins. The northern one is occupied by a lake, about 300 m deep and has a sedimentary fill of about 6 km. The southern Dead Sea basin however, is unusually deep, with about 14 km of sedimentary fill. The geometry of the southern Dead Sea basin is anomalous along the entire Dead Sea fault. We suggest that the southern Dead Sea basin was formed during the first stage of the formation of the Dead Sea fault when the tips of propagating faults, one from the collision front in the north and one from the Red Sea in the south met in this area. The fault tips overlapped and curved towards each other, isolating a block of crust and lithosphere that dropped into the mantle. Geophysical data indicate that the basin is probably bordered on all sides by vertical faults that cut deep into basement. The deep part of the southern Dead Sea basin is not a pull-apart but instead a “drop down” basin. The Salton Trough in California is probably another example of such a basin.

Keywords: Dead Sea fault; transform faults; rifting; basin formation; lithospheric delamination

1. Introduction

The Dead Sea fault spans around 1000 km (Fig. 1), from the Red Sea to the Taurus Mountains in Turkey. It is an active left lateral transform plate boundary with an extensional component, separating the Arabian Plate and the Sinai sub-plate. Activity along the fault is thought to have started in the Middle Miocene, when a transition of motion took place from opening in the Gulf of Suez to transcurrent displacement along the Dead Sea fault. The total amount of left lateral slip is estimated at about 105 km [1].

The extensional regime combined with the dominant lateral motion along the Dead Sea fault resulted in the formation of a series of deep pull-apart basins. They were formed between left-stepping fault segments of the Dead Sea fault and can be found in topographically lower areas. Marginal normal and oblique faults usually border these depressions on the western and eastern sides, while transverse or oblique normal faults define their southern and northern limits. Structural saddles typically occur between the basins where transpression

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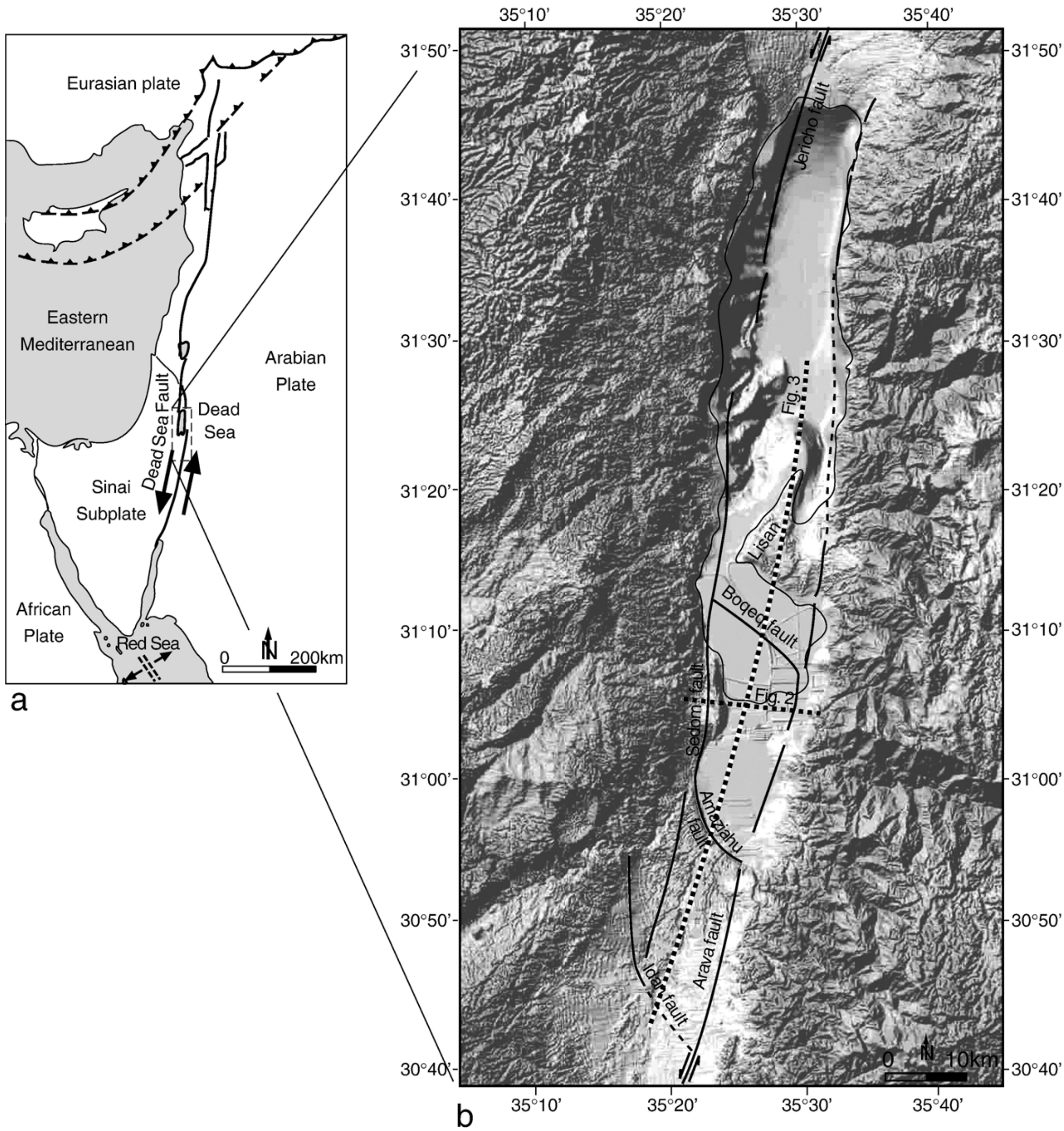

Fig. 1. A DTM image of the Dead Sea basin. Major faults are shown. The Dead Sea basin is divided into two sub-basins, which are separated by the Lisan Peninsula — a large buried salt diapir. The two basins are thought to be divided by a large oblique normal fault, the Boqeq fault. The two main strands of the Dead Sea fault in this area are the Jericho fault, which borders the northern sub-basin on the west and the Arava fault, which borders the southern sub-basin on the east. The "drop down" basin is bounded by the Boqeq fault in the north, the Amazyahu fault in the south, the Sedom fault in the west and the Ghor Safi fault, which does not extend to the surface, in the east. The Ghor Safi fault is located slightly west of the Arava fault. Dotted lines mark the locations of the geological cross sections and gravity models in Fig. 2. The location of the Dead Sea basin within the Dead Sea fault is shown in the inset.

often takes place. Lengths of the individual pull-apart basins range from 15 km to 50 km and they are 5–20 km wide, while their depths range between 3 and 8 km. The crystalline basement underlying the larger pull-aparts is thinner than normal, which accounts for basin subsidence.

A notable exception is the southern basin of the Dead Sea graben. Here, seismic refraction and reflection profiles and gravity data indicate that the basin is 12–15 km deep with a ratio of width/depth of less than 1. This unusual situation is unique to the entire length of the Dead Sea fault. In this paper we present a model for the formation of the southern Dead Sea basin and suggest that the southern Dead Sea basin was formed during the first stage of the formation of the Dead Sea fault when the tips of propagating faults, one from the collision front in the north and one from the Red Sea in the south met in this area.

2. Dead Sea basin

The Dead Sea, with a water level at about 417 m below sea level, is situated within a large pull-apart, the Dead Sea basin, that formed along the Dead Sea fault continental transform. Almost 150 km in length, this is one of the largest pull-aparts known on Earth. Understanding its structure and evolution is thus important for understanding large pull-aparts elsewhere on Earth.

The Dead Sea basin is divided into two sub-basins, which are evident in the deep structure and are separated by the Lisan Peninsula — a large buried salt diapir (Fig. 1). The two basins are thought to be divided by a large oblique normal fault [2]. The two main strands of the Dead Sea fault in this area are the Jericho fault, which borders the northern sub-basin on the west and the Arava fault, which borders the southern sub-basin on the east [3]. The two faults overlap in the central part of the Dead Sea basin and in the northern part of the southern sub-basin, which are bordered by the two en echelon strike–slip faults. Today, the northern basin is occupied by a lake, about 300 m deep, while the southern basin is sub-aerial.

Gravity data indicate a large negative anomaly, the largest in the Middle East, over the Lisan Peninsula and the southern sub-basin [4,5], where the main faults overlap. The gravity data also indicate that the basin is narrow (7–10 km), although the surface expression of the basin is wider at its center (about 16 km) and covers the entire width of the transform valley due to the presence of shallower blocks that dip towards the basin. The Bouguer anomaly along the axis of the basin decreases from both the northern and southern ends towards the center. This has led to the proposal [4] that the basin gradually sags toward the center and is not bounded by faults at its narrow ends. Modeling of the gravity data has suggested that the southern part of the northern sub-basin has about 9 km of sedimentary fill, overlying a layer, about 7 km thick, of Mesozoic carbonate platform rocks [4]. South of the Lisan Peninsula at the northern part of the southern sub-basin the gravity modeling suggests a similar basin. Later gravity modeling [6] has suggested that the deepest part of the basin is centered under the Lisan Peninsula where the basin is about 10 km thick. Magnetic modeling had suggested about 6 km of sedimentary fill overlying about 7 km of Mesozoic carbonates in the northern sub-basin [7].

In order to obtain more direct evidence on the thickness and structure of the sedimentary section in the Dead Sea basin, a seismic wide angle reflection/refraction profile was measured along the basin [2]. The results indicate that the basement lies at a relatively shallow depth (6–8 km) under the northern sub-basin. South of the northern sub-basin a major fault affecting the basement was detected. It downthrows the basement and the overlying Cretaceous and pre-Cretaceous sediments to the south by about 4–5 km and forms the northern boundary of the southern sub-basin. The faulting was followed by the deposition of over 8 km of Pliocene to Recent sediments resulting in a 14 km thick sequence in the northern part of the southern sub-basin of the Dead Sea. The sedimentary basin in this area is therefore exceptionally deep with well defined boundary faults. In the following sections we describe the structure and architecture of this basin and suggest that it was formed as a “drop down” basin during early stages of the evolution of the Dead Sea fault.

3. “Drop down” basin

The northern portion of the southern sub-basin of the Dead Sea is bordered on all sides by vertical faults. We refer to it as a “drop down” basin. Strands of the Dead Sea faults are located on the east and west [8–10]. These are the Sedom fault on the west and Ghor Safi fault on the east. Fault plane solutions indicate that both faults are strike–slip in this area [11]. As a result the basin here is symmetric with an original shape of a full-graben. The basin has widened with time by the collapse and tilting of blocks from the eastern and western margins. An en echelon arrangement of the main faults with a full-graben configuration of the basin in-between is quite rare along the Dead Sea fault. The only other two places are the Aragonese Deep at the central part of Gulf of Aqaba [12] and the southern Sea of Galilee at the central part of the Kinneret–Bet Shean basin [13]. In most other cases the basins are asymmetrical with the main strand of the transform occurring on one side, while the other is bounded mainly by normal faults [14,15].

The transverse faults within the basin are less clear. The Amazyahu fault on the southern margin of the “drop down” basin is of particular interest. The trace of this fault is expressed on the surface as an easily recognized escarpment in the southern sub-basin of the Dead Sea. When the first north–south seismic reflection line was shot across this fault, not only was interest raised but it also led to new models about the nature of transverse faulting in the Dead Sea basin. In turn, the Amazyahu fault has also served as a model for transverse faulting in pull-apart basins elsewhere. These models describe it as a major listric fault which reaches the basement. The interpretation of the Amazyahu fault as a listric fault was first proposed by Arbenz [16] and was adopted by later works [8,17,18]. As a result, this part of the basin was assumed to grow with time in a north–south direction. In a more recent work [19] it has been suggested that lower crustal thinning occurred in the Dead Sea due to lower crustal flow.

The type of faulting along the Amazyahu fault was determined previously solely by the interpretation of seismic reflection sections, which in these cases were in the time domain. The results of processing recent seismic reflection data across the Amazyahu fault using advanced techniques shed new light on the nature of the fault [20]. The pre-stack depth migration that was used gives a much better definition of the faults and better continuity of the pre-fill reflections, thus enabling the study of the basement faulting and its role in the internal structure of the basin. It indicates that the Amazyahu fault, which was previously interpreted as a listric fault, is a deep basement fault. Ginzburg et al. [20] also noted that the Boqeq fault, at the northern margin of the “drop down” basin, cuts through the deeper part of the young fill and the Cretaceous and older beds, probably to the crystalline basement.

In order to understand the nature of the “drop down” basin and the bordering faults, we have constructed two geological cross sections, east–west and north–south, using the most recent seismic reflection profiles from the area, the north–south seismic refraction profile within the basin [2], drill hole data and gravity data. An early version of the east–west section was published previously [9]. However these authors did not take into account the seismic refraction data and used an older gravity compilation. We recalculated this section (Fig. 2) using the seismic refraction data and the latest gravity compilation [6] from the region. The north–south cross section, which was constructed during this study for the first time, shows the main features of the “drop down” basin (Fig. 3). It is based on pre-stack depth migration seismic reflection profiles, as well as on the seismic refraction and gravity data. It shows that the area of the “drop down” basin is the deepest part of the Dead Sea basin and not the area of the Lisan diapir, as previously suggested [6]. It also indicates the sharp north and south boundaries of the “drop down” basin, where deep basement faults, the Boqeq fault and Amazyahu fault, are located.

The “drop down” basin is bordered, though, by deep vertical faults on all sides, the Boqeq fault in the north, the Amazyahu fault in the south, the Sedom fault in the west and the Ghor Safi fault, which does not extend to the surface, in the east (Figs. 2 and 3). As a result the basin is symmetrical both in east–west and north–south directions. At the surface the basin is about 30 km long and about 18 km wide; however, at the sub-bottom it is about 20 km long and 13 km wide.

3D gravity modeling has been carried out on the basis of the constructed geological models (Figs. 2 and 3) using the GSFC (*Geological Space Field Calculation*) program [21]. Seismic velocities were converted to densities using known relationships [22]. The models in Figs. 2 and 3 suggest that the large negative gravity anomaly of the Dead Sea is the result of the large sedimentary fill in the “drop down” basin and the salt diapir of the Lisan Peninsula.

An interesting feature is the relation between the Sedom fault on the west and the Amazyahu fault on the south. In their analysis of the faults in this region Larsen et al. [10] have shown that the two faults are probably connected. This means that the western strand of the Dead Sea fault bends to the east at the southern boundary of the “drop down” basin. The western margin of the basin is indeed quite similar to the southern margin (Figs. 2 and 3).

Results of analyses of earthquake data have led to significant findings on the deep structure of the basin. Hofstetter et al. [23] have studied the crustal and upper mantle structure across the Dead Sea rift and Israel from teleseismic P-wave tomography and gravity data. They showed that the southern Dead Sea basin is characterized by the largest decrease of velocity, in both upper and lower crustal layers, due to the infilling of light material relative to the surrounding material. Aldersons et al. [24] studied the local seismicity of the Dead Sea basin for the period 1984–1997. Sixty percent of well-constrained microearthquakes ($ML \leq 3.2$) nucleated at depths of 20–32 km and more than 40% occurred below the depth of peak seismicity situated at 20 km. The deeper events are located in the area of the “drop down” basin. The lower crustal seismicity in the Dead Sea basin is supported by earlier findings of very low heat flow in the area. The average measured heat flow in

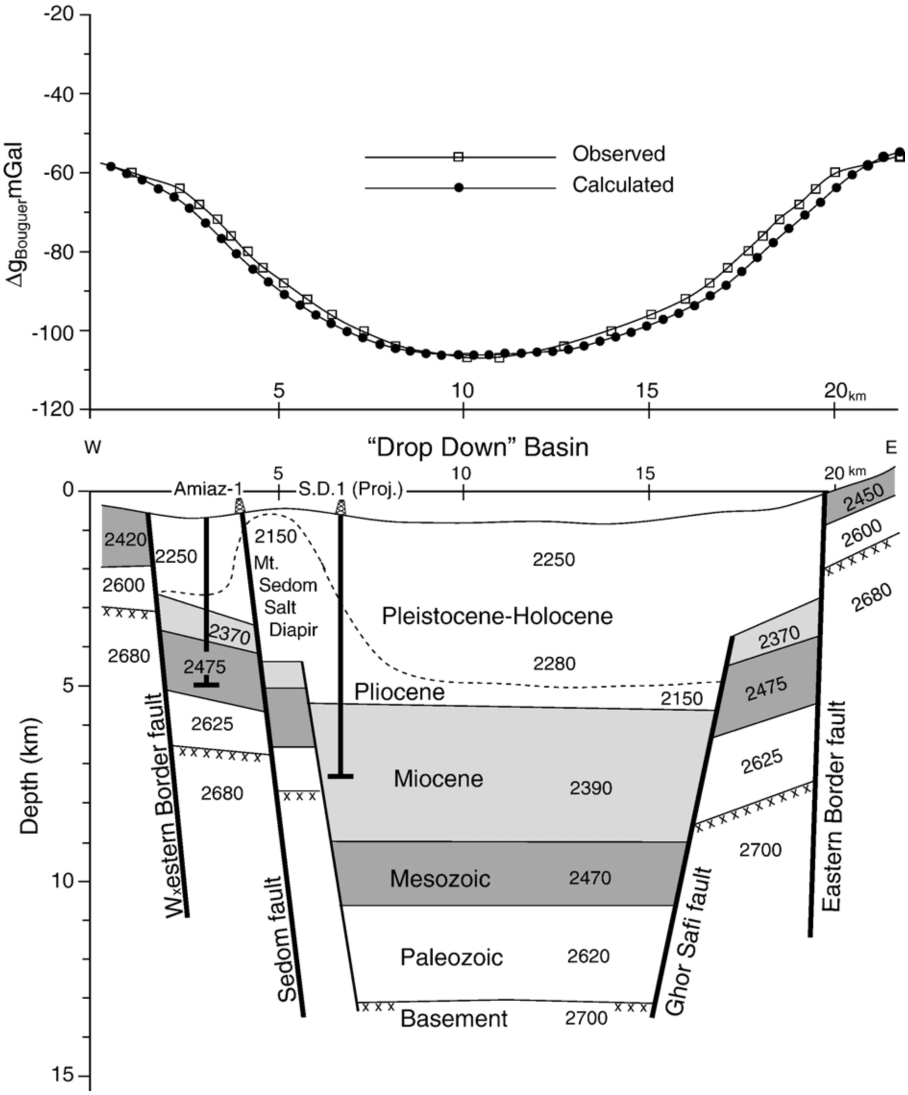

Fig. 2. East–west geological cross section through the "drop down" basin. The section is based on seismic reflection, seismic refraction and drill hole data. Numbers are densities in kg m^{-3}. Gravity models are shown on top. S.D. Sedom Deep drill hole. An early version of this section was published previously [9]. However it did not take in account the seismic refraction data and used an older gravity compilation. The section shown in this figure was recalculated using the seismic refraction data and the latest gravity compilation [6] from the region. The "drop down" basin is bordered by deep vertical faults of the Sedom fault in the west and the Ghor Safi fault, which does not extend to the surface, in the east.

the northern Dead Sea basin is 38 mW m^{-2} [25, 26] and it is 42 mW m^{-2} [27] west of the basin. The low value of the regional surface heat flow is a good indication that the lower crust might be cool and brittle here.

4. Formation of the "drop down" basin

The "drop down" basin is a unique basin along the entire Dead Sea fault. Its origin must be linked somehow with the processes that have led to the formation of the Dead Sea fault itself. The origin of the Dead Sea fault was the topic of several studies. Earlier models [28,29] have suggested that the rifting activity along the Dead Sea fault propagated from the northern Red Sea in the south to the north. Indeed, at the southern part of the Dead Sea fault, within the Gulf of Aqaba, geophysical data indicate that seafloor spreading processes propagate from the Red Sea northward [30]. More recent studies, however, have suggested that stresses generated at the collision belt along the Taurus Mountains are responsible for the formation of the Dead Sea fault. Based on analysis of crustal structure variations in the

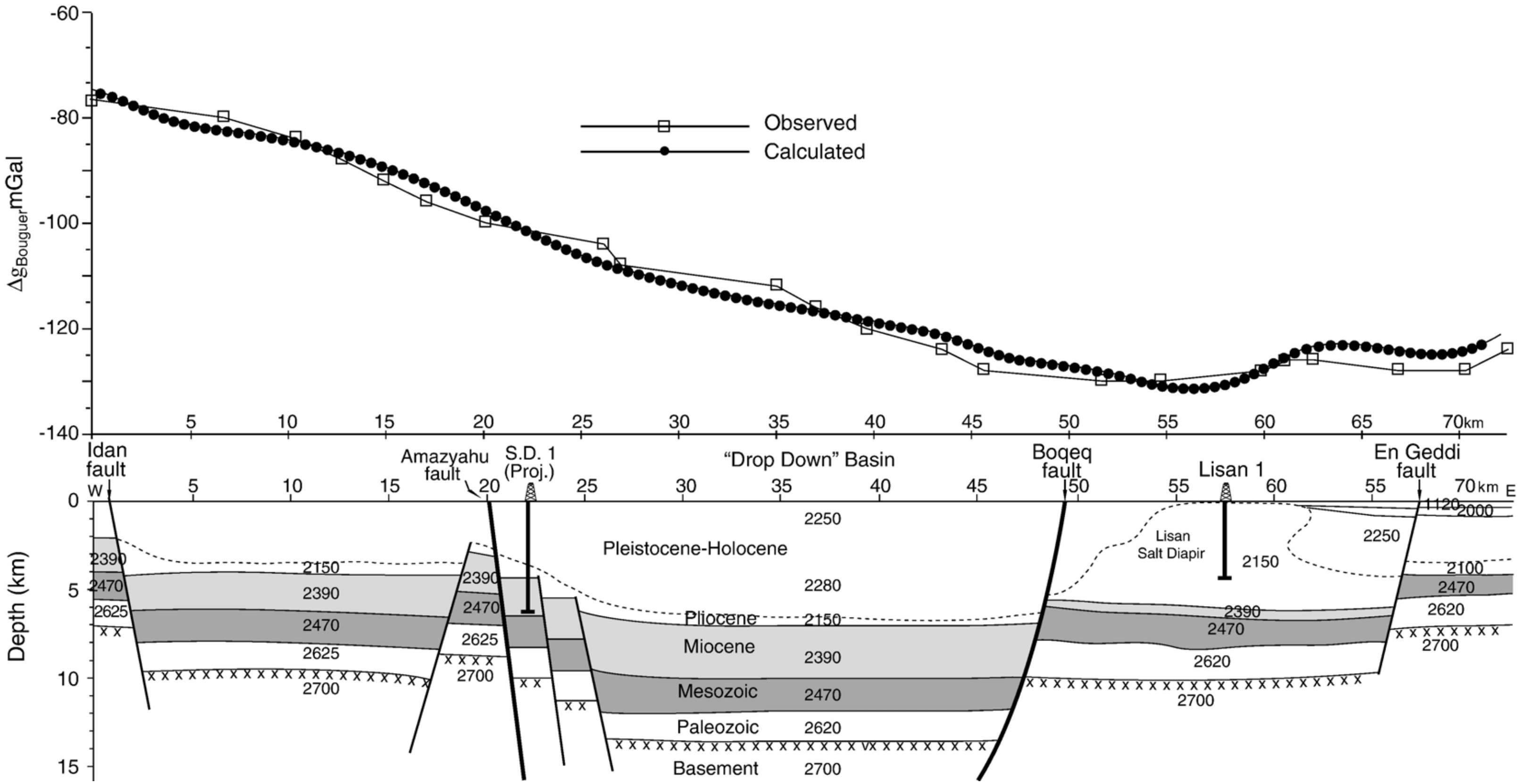

Fig. 3. North–south geological cross section through the "drop down" basin. The section is based on pre-stack depth migration seismic reflection profiles, as well as on the seismic refraction, gravity and drill hole data. The section shows that the area of the "drop down" basin is the deepest part of the Dead Sea basin. It is bordered by deep vertical faults, the Boqeq fault in the north, the Amazyahu fault in the south. Numbers are densities in kg m^{-3}. Gravity models are shown on top. S.D. Sedom Deep drill hole.

eastern Mediterranean, it was suggested that the initial cracking of the crust and faulting activity started in the collision zone in the north and propagated southward [31]. A simulation of faulting processes along the northern Dead Sea fault and the Levant margin [32] suggested that the formation of the Dead Sea fault could be explained as a result of simultaneous propagation from the north and south.

A more elaborate numerical simulation [33] of the propagation of faulting activity along the entire Dead Sea fault took into consideration both the opening of the Red Sea in the south and the collisional processes in the Taurus Mountains in the north. This mathematical model of the evolution of the Dead Sea fault suggests that it was created as a result of the propagation of two fracture zones at its northern and southern ends towards each other. The faulting, according to this model, started due to the collision of Arabia and Eurasia in the Miocene [34] and the strike–slip motion along the East Anatolian fault. It propagated from the north to the south. The collision at the northern part of the Arabian plate also caused a dramatic change of the stress field around the northern Red Sea. As a result, rifting activity changed its direction of propagation from the Gulf of Suez into the Gulf of Aqaba and a new transform plate boundary was created. The simulation suggested that the Dead Sea fault is made of two different fault zones which later on were combined into one feature.

The simulation of Lyakhovsky et al. [33] outlines only the general trend of the Dead Sea fault. We suggest that the tips of the two propagating rifts met in the area of the southern sub-basin of the Dead Sea (Fig. 4). After slightly overlapping each other, the southward propagating fault veered eastward to intersect the northward propagating fault, which itself turned westward toward the southward propagating fault. The result was the isolation of a piece of lithosphere by nearly vertical faults around its entire periphery. The relatively heavy piece of lithosphere, then supported by only weak fault frictional stresses around its circumference, was able to sink into the underlying asthenosphere, creating the deep "drop down" basin at the surface. Crack propagation studies [35] show that overlapping crack tips tend to turn towards each other as apparently occurred at the deep "drop down" basin. Recent thermo-mechanical modeling [36] has shown that in the initially cold lithosphere expected at the Dead Sea fault, shear deformation localized in a 20–40 km wide zone where temperature-controlled mantle strength is minimal. It was further suggested that the resulting mechanically weak decoupling zone extends sub-vertically through the entire lithosphere and that one or two major faults at the top of this zone take up most of the transform displacement.

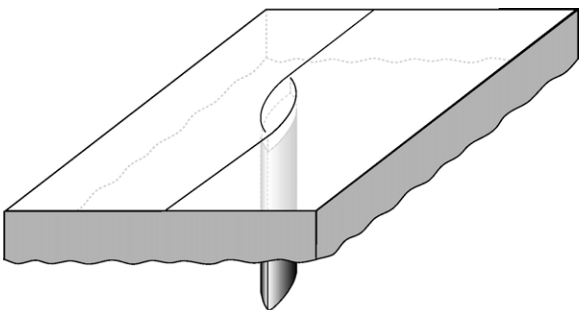

Fig. 4. Conceptual model of the "drop down" basin. The propagating cracks from the Taurus collision zone in the north and the Red Sea in the south met in the Dead Sea area and isolated a piece of lithosphere that has dropped down into the asthenosphere.

A simple force balance on the isolated piece of lithosphere shows that the coefficient of friction f on the circumferential vertical faults must be less than

$$lw\alpha\Delta T/d(l+w)$$

where l and w are the length and width of the isolated piece of lithosphere of assumed rectangular cross-section, d is lithosphere thickness, α is the coefficient of thermal expansion, and ΔT is the average temperature deficit of the lithosphere with respect to the underlying asthenosphere. The quantities l and w are several tens of kilometers, d is about 100 km, α is about 0.003 K^{-1}, and ΔT is several hundred kelvins. The coefficient of friction on the boundary faults must be less than a few tenths.

For 8 km drop down, the lithosphere of the Dead Sea must have been far from isostatic equilibrium. If isostasy prevailed at the time of crack propagation then an isolated column of lithosphere would not sink. It is hard to tell what was the state of isostasy at the time of formation of the "drop down" basin, however several lines of evidence suggest that the region could be uncompensated isostatically.

The magnetic anomaly map of the region (Fig. 5) shows large anomalies. This suggests great variability in the lithology of the crust. The largest anomaly here is the Hebron magnetic anomaly [37,38]. The interpretation of Rybakov et al. [37] suggests a large basic magmatic body of unknown age penetrating the Permo-Triassic sediments in the Hebron area (marked as H in Fig. 5). The estimated depth of the top of the magmatic body is about 3.5–4 km below sea level, i.e., quite shallow within the upper crust. Such large crustal variability at shallow depth suggests that the crust in the Dead Sea

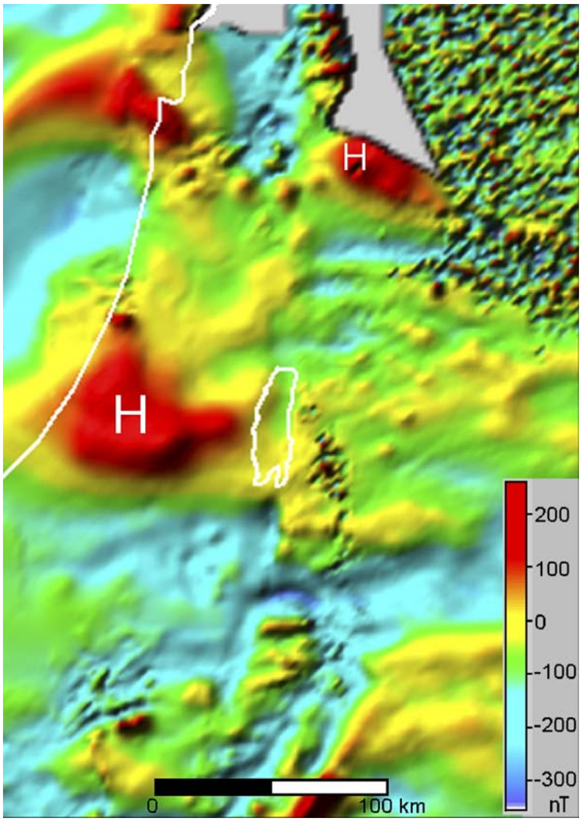

Fig. 5. Color shadow magnetic anomaly map of the central Dead Sea fault and adjacent areas (modified after [53]). The largest anomaly here is the Hebron magnetic anomaly (marked in H). Please note that the eastern edge of the anomaly is shifted ~100 km due to the lateral motion along the Dead Sea fault [38]. The magnetic pattern suggests large lithological variability at shallow crustal depths.

region at the time of crack propagation could have been out of isostatic equilibrium.

ten Brink et al. [39] analyzed the morphology and the crustal structure beneath the transform using gravity and topography profiles perpendicular to the transform. They concluded that at present the Dead Sea fault is not compensated isostatically and discussed several options that could explain the strong negative topography and ongoing sedimentation in the Dead Sea basin. One of the possible mechanisms is related to the loading of a heavy intrusion with density ~3300 kg m^{-3} located at a depth between 20 and 30 km in the lower crust.

A subsequent study of the lithosphere structure, isostasy and gravity field [40] revealed that most of the sedimentary basins along the Dead Sea transform are out of isostatic compensation. The same is true for the northern part of Israel (Galilee) and Lebanon, where the crust is significantly thinner than typical continental crust. Thus, it is possible that in the Miocene when the "drop down" basin formed, the area was not in isostatic equilibrium.

An interesting observation is that in the area of the "drop down" basin the trend of the Dead Sea fault changes from NNE to N–S quite sharply. This supports the suggestion that the two cracks propagating from north and south actually collided in this area and that the piece of lithosphere isolated by the two major faults eventually fell down into the asthenosphere and created the "drop down" basin.

This means that the "drop down" basin was the first basin formed along the Dead Sea fault. Only later did other pull-apart basins develop along its entire length due to the transform motion. The "drop down" basin itself was further modified due to that motion. Alternative models to the "drop down" model have been previously proposed. The most popular is the drip model. The negative buoyancy of a drip that forms near the Earth's surface exerts a downward pull, resulting in surface subsidence. This mechanism has been the subject of considerable interest in tectonics and geodynamics (e.g., [41] and ref. therein). Lustrino [42] suggested that recycling of lower crust (coupled with lithospheric mantle) can explain several geochemical peculiarities relatively common in low-volume intraplate igneous rocks (ocean island basalts and intracontinental rocks), oceanic and continental flood basalts and mid-ocean ridge basalts (MORB). Saleeby and Foster [41] and Zandt et al. [43] suggested that the present-day surface subsidence of the southern Sierra Nevada Mountains in California is driven by flow into the mantle of downwelling (drip) beneath the adjacent Great Valley. This model is also supported by seismic refraction data presented by Yan et al. [44]. Molnar and Jones [45] analyzed the conditions for the convective removal of mantle lithosphere and concluded that the high strength of cold mantle minerals does not prohibit drip formation. These models, primarily developed for large scale features in southern California, do not require deep vertical faults around the subsided area, such as the case in the southern Dead Sea. On the other hand, they assume the existence of heavy rocks of eclogitic composition in the lower crust which might not be the case for the Dead Sea region.

Recently Sobolev et al. [36] and Petrunin and Sobolev [46] presented results of a three-dimensional thermo-mechanical model of a pull-apart basin formed at an overstepping of an active continental transform fault such as the Dead Sea basin. They adopted the classical scheme of pull-apart basin formation and demonstrated that the major parameter controlling basin length, thickness of sediments and deformation pattern beneath the basin is the thickness of the brittle layer. Their closest fit to the Dead Sea parameters was obtained with a model surface heat flow of 60 mW m^{-2}. They also state that no pull-apart type of deformation would occur in a cold lithosphere with a heat flow below 50 mW m^{-2} due to mechanical attachment of the lower crust and strong mantle lithosphere. However, the average measured surface heat flow at the Dead Sea basin is less than 40 mW m^{-2} [25], well below the heat flow required for the model. The low surface heat flow values along the Dead Sea transform are also supported by the depth distribution of local seismicity [24]. Additional shortcomings of the classical pull-apart model are the absence of a significant normal component of displacement along the faults that form the sedimentary basin and the fact that only part of the Dead Sea basin is unusually deep.

Features similar to the “drop down” basin in the Dead Sea may exist along other large continental transforms. A possible example is the Salton Trough at the southern San Andreas fault, north of the Gulf of California. This is the deepest basin along the entire San Andreas fault system, including the Gulf of California with about 12 km of fill [47]. The Salton Trough area is located where the Gulf of California depression meets the San Andreas fault. At this location the San Andreas fault bends westward [48]. Recent studies [49–51] indicate that by 6.5–6.3 Ma, a sudden onset of Pacific–North American plate-boundary motion took place within the Gulf of California. Prior to this period all of the dextral displacement between the Pacific and North American plates was accommodated outside of the gulf region [52]. The breakup of Baja California from the continent probably propagated from south to north. We suggest that when the new crack in the lithosphere met the San Andreas fault at the Salton Trough area, a piece of lithosphere was isolated and then detached and fell into the asthenosphere to form a “drop down” basin, a situation similar to the one at the southern Dead Sea basin.

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