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A Review of Gravity and Magnetic Studies in the Jordan Dead Sea Transform Zone

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Abstract

The geodynamic evolution of the Dead Sea Transform (DST) remains one of the most contentious issues of the eastern Mediterranean tectonics. Therefore, wide-ranging geophysical surveys have been carried out over five decades to fill the gap of geological information existing in the region. The collected data sets allowed new models to be constructed, improving the knowledge of the crustal and lithospheric structure of the DST, and the reformulation of its complex tectonic history. In this context, the contribution of gravity and magnetic investigations deserves, with no doubt, a review on both large and small scales. The potential data were employed to interpret the evolution of the Dead Sea basin, delineating the crustal and upper mantle structure and modelling the density distribution of the sediments. The crystalline basement structure and magmatic intrusions were investigated, and underground structures of salt diapirs were explained and sinkhole hazards were detected along the Dead Sea coast. In order to produce the first comprehensive compilation of gravity and magnetic studies in the Jordan DST zone, all available potential field data were combined and revised. The main features of the potential fields resulting from these surveys were described, and the qualitative and quantitative interpretations proposed by several authors were abridged. The information presented by this paper will help interested geoscientists, in different geological fields, with their regional and local studies in the Jordan DST zone region. The compilation of geophysical observations presented here may also facilitate the understanding of similar transform systems elsewhere.

Keywords: Dead Sea Transform, gravity data, magnetic data, gravity and magnetic anomaly fields, interpretative models.

1. Introduction

The Dead Sea Transform, also known as the Dead Sea rift, is a major continental fracture zone that separates the Arabian plate and the Sinai- Palestine plate (Figure 1). It extends over a distance of more than 1000 km, linking the Zagros-Taurus convergence zone in the north with the Red Sea in the south, where seafloor spreading takes place (Garfunkel, 1981). The geology and tectonics of the transform fault are largely affected and controlled by the geodynamic processes acting in the Red Sea region which have resulted in its opening (Girdler, 1990 and references therein). Continental transform faults, such as the Dead Sea fault system, involve complex structural and sedimentary regimes related to the active transform displacement along fault segments (Garfunkel and Freund, 1981; Kashai and Croker, 1987; Ben-Avraham and ten Brink, 1989; Beydoun, 1999; Smit et al., 2009; Ben-Avraham and Katsman, 2015).

Integrated geophysical methods are important approaches to study the distribution of rocks, to identify their types and to determine the associated structural features. Past potential field investigations, especially gravity and magnetic methods of the Jordan DST zone, have contributed significantly to understanding the structural framework and lithologies of the region and indicate a complex tectonic history. They were important tools for giving a geological picture about the subsurface structure and the geometry of the DST pull-apart basins (Ginzburg and Ben-Avraham, 1986; Frieslander and Ben-Avraham, 1989; Batayneh, et al., 1995; Ben-Avraham et al., 1996; ten Brink et al., 1993, 1999; Ben-Avraham and Schubert, 2006; Eppelbaum et al., 2007; Segev et al., 2018) the depth of basement, the dimensions of magmatic intrusions, and volcanic centres (Folkman and Bein, 1978; Folkman and Ginzburg, 1981; El-Isa and Kharabsheh, 1983; Gvirtzman and Weinberger, 1994; El-Kelani et al., 1998; Rybakov et al., 1999b; Segev et al., 1999; Rybakov et al., 2000; Eppelbaum et al., 2004; Rybakov and Segev, 2004; Tašárová et al., 2006; Rybakov et al., 2011; Segev and Rybakov, 2011; Schattner et al., 2019).

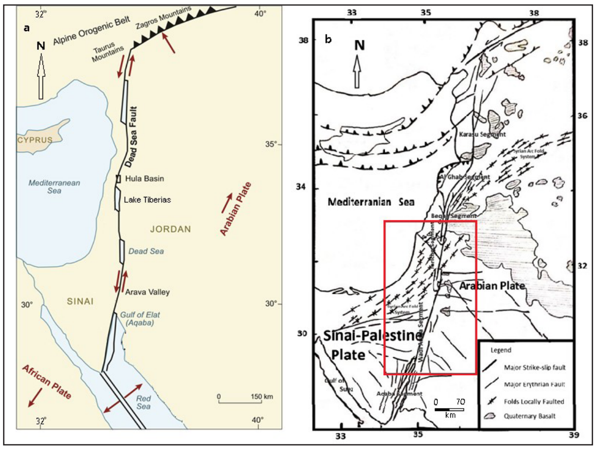

Figure 1. a. Map of the DST showing general relative plate motion from the opening of the Red Sea in the south to the Zagros-Taurus Mountains in the north (modified after Ben-Avraham et al., 2008). **b.** Regional tectonics of the Jordan Dead Sea Transform zone (modified after El-Isa, 2017), the red rectangle indicates the study area of this work.

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Also, the potential data were employed in for modelling the crustal and upper mantle structure, and the lateral and depth density distributions in the crust (Ginzburg and Makris, 1979; Folkman, 1981; ten Brink et al., 1990; Hofstetter et al., 2000; Al-Zoubi and Ben-Avraham, 2002; Götze et al., 2002; El-Kelani, 2006; Segev et al., 2006; Al-Zoubi, 2007; Götze et al., 2007). Potential data were also employed in the investigations of the spatial distribution of salt diapirism and also in the identification of underground salt structures in the entire Dead Sea basin (Neev and Hall, 1979; Al-Zoubi and ten Brink, 2001; Choi et al., 2011). Moreover, data were used in the identification of sinkhole development and for the estimation of the dissolution karst and the detection of caves in salt formations along the Dead Sea coast (El-Isa et al., 1995; Closson et al., 2005; Rybakov et al., 2001, 2005; Eppelbaum et al., 2008; Shirman and Rybakov, 2009; Ezersky et al., 2010, 2013). On the other hand, gravity and magnetic investigations were important for delineating sedimentary basin geometry during the early stage of petroleum exploration as an indication of potential hydrocarbon bearing structural anomalies (Rybakov et al., 1995b, 2000, 2009; Hassouneh, 2003; Eppelbaum and Katz, 2011).

The literature review of the previous gravity and magnetic works, conducted throughout the years in the transform region, showed that most of them have integrated the interpretations of both potential fields, at the local and regional level, onshore and offshore. The gravity and magnetic investigations are distributed on three main sectors of the Jordan DST zone, which represents the main structural segments of the transform fault including the Gulf of Aqaba segment followed by Wadi Araba, in the south, the Dead Sea in the middle, and the Jordan valley in the north (Figure 1b). This paper reviews these earlier potential field studies, available for the Jordan DST zone, and considers the regional and local geological, structural and tectonic development of the study area and their interrelationships. Interested geoscientists may find this information useful for their future work, especially concerning the Dead Sea Transform region.

2. Regional geological setting

The development of the DST went through folding, faulting, rifting, uplifting, offset, and volcanic activity on a regional scale, where the Precambrian basement outcrop is on the surface in the southwest but is deeply buried in the northeast beneath the Dead Sea basin sediments. The Precambrian basement was shaped by the late Proterozoic Pan African orogeny (Figure 2). Afterward, the region became a stable platform on which sediments of continental and of shallow water marine origin were deposited during several periods from the Cambrian to the Early Cenozoic. Rifting was the main tectonic event in this period, shaping the Mediterranean continental margin in the Early Mesozoic (Garfunkel, 1988, and references therein). Mild folding and faulting expressing compression started from Pre-Jurassic to Oligocene-Miocene by forming the Syrian arc fold system, which extends from southern Syria to northern Sinai creating an S-shaped fold belt that is crossed by the transform fault, and followed by forming the Erythrean fault system, which consists of E-W and NW-SE trending faults (Garfunkel, 1981).

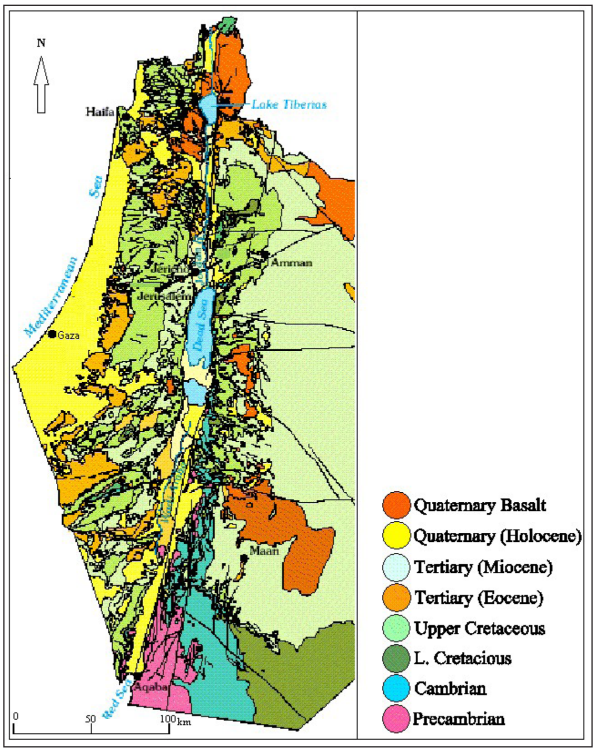

Figure 2. Geological map of the study area (USGS open report, overview of Middle East water resources, 1998).

During the Middle Cenozoic, a deformational phase resulted in the creation of N- and NNE-trending strike–slip faults forming the DST (Figure 1b). Some of these faults are arranged en-echelon, resulting in the creation of rhomb-shaped, pull-apart basins (Freund et al., 1970; Garfunkel, 1981; Aydin and Nur, 1982; Garfunkel and Ben-Avraham, 2001; Ben-Avraham et al., 2008).

The multi-stage volcanic activities and magma intrusion resulted in widespread igneous rocks along the continental transform margin. The impact of the fault systems on the volcanic activity show the relation between the spatial distribution of the igneous rocks and tectonic changes of the DST (Mimran, 1972; Sass, 1980; Gvirtzman and Sreinnitz, 1983; Dvorkin and Kohn, 1989; Garfunkel, 1989; Segev and Rybakov, 2010; Ibrahim et al., 2014; Griffin et al., 2018). Geological field observations, enhanced by geophysical evidence, show that there are matchable numerous markers between the geologies of areas facing each other across the DST which indicates a left-lateral movement of c. 107 km (Quennell, 1958, 1959, 1984; Girdler, 1990).

3. Gravity and magnetic surveys in the Jordan Dead Sea Transform zone

3.1 Gravity surveys

Significant gravity data were collected in the Dead Sea Transform region, mainly by the Natural Resources Authority (NRA) in Jordan and the Geophysical Institute (GII), at different scales in time and space. In total, approximately 100,000 gravity stations (Figure 3), covering the DST region and its eastern and western plateaus, were homogenised (Hassouneh, 2003; Götze et al., 2007, 2010b; Rosenthal et al., 2015). They are fairly and uniformly spaced with a station spacing ranging between 0.5 and 2 km; gravity points' distribution in the study area is shown in Figs. 3a and b. Bouguer gravity values were compiled according to standard procedures, using the 1967 Geodetic Reference System and the standard density of 2670 kg/m. Sea level was taken as the reference datum and the terrain corrections were calculated up to Hayford zone O2 (167 km), using a digital terrain model with a 25 m grid. The overall accuracy of the station complete Bouguer anomaly values are estimated to be 0.1 to 0.8 mGal.

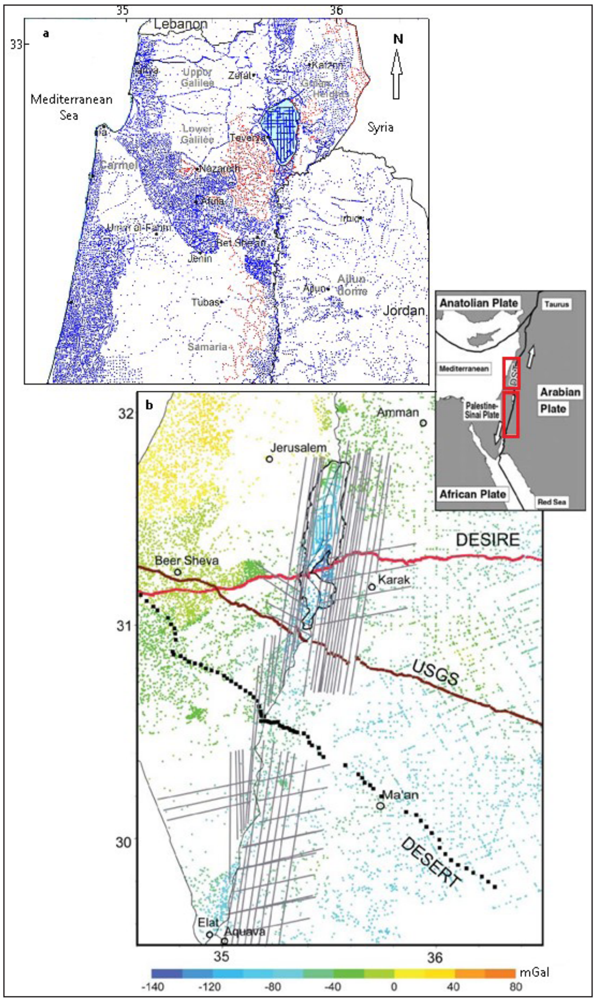

Figure 3. a. Coverage of gravity stations in the northern part of the Jordan DST zone. Red dots indicate new stations collected from 2009 to 2013 (Rosenthal et al., 2015); blue dots are previous gravity stations compiled from different sources (Ben-Avraham et al., 1996; Rybakov et al., 1997; ten Brink et al., 1999; Rybakov and Al-Zoubi, 2005). **b.** Map showing survey flight lines (grey) and the locations of terrestrial points (green, yellow, and light blue) of gravity data in the central and southern parts of the Jordan DST zone in the study area. The flights (Götze et al., 2010b) cover gaps in terrestrial gravity data (ten Brink et al., 1993; Hassouneh, 2003; Götze et al., 2007), mainly on the eastern side of the Dead Sea basin. The blue lines represent gravity profiles at the surface of the Dead Sea. Three wide-angle and refraction seismic profiles are shown: Dead Sea Integrated Research (DESIRE), line in red (Mechie et al., 2009); Dead Sea Rift Transect (DESERT), stippled line (Weber et al., 2009); and the U.S. Geological Survey (USGS) profile (ten Brink et al., 2006).

The data include regional land-based gravity point measurements (Rybakov et al., 1997; ten Brink et al., 1999; Hassouneh, 2003; Rybakov and Al-Zoubi; 2005; Rosenthal et al., 2015). Further gravity data collection has been conducted onshore at the Sea of Galilee (Ben-Avraham et al., 1996) and the Dead Sea (ten Brink et al., 1993). Other local gravity surveys were carried out in the Jericho area (El-Kelani, 2007), and in Wadi Araba (Götze et al., 2007). To provide a complete picture of the gravity field in the Dead Sea region, a high- resolution aerogravity campaign was conducted to cover gaps in terrestrial gravity data coverage, mainly on the Jordanian side (Götze et al., 2010b).

3.2 Magnetic surveys

For an integrated analysis of poetical fields and a better understanding of the geological settings in the DST region, magnetic surveys were conducted in the transform region and its shoulders. In the fall of 1979, a total of 54,185 km of aeromagnetic data were flown by Phoenix Corporation contracted by the NRA of Jordan. In total, 378,622 aeromagnetic stations have been measured to produce the total field aeromagnetic anomaly map of Jordan, which covered central parts of the transform fault zone and its eastern plateau (Phoenix Corp., 1980). Doppler navigation was employed in addition to visual navigation through the use of topographic map flight strips, airborne magnetometer (Geometrics Model G803) proton precession magnetometer with sensor mounted in a tail stinger. The magnetometer resolution was 0.5 gammas with a sampling interval of 1.0 second. Depending on the topography, the flight heights varied between 1.5-2.0 km above sea level; flight-line spacing of these surveys was in the range of 1-2 km (Hassouneh, 2003).

Aeromagnetic surveys had been also carried out in the western central parts of the DST zone and its plateau (Domzalski, 1967; Folkman, 1970; Folkman and Yuval, 1976; Rybakov et al., 1999b; ten Brink et al., 2007). A High Resolution, low altitude Aeromagnetic (HRAM) survey was carried out in 2003 in southern Wadi Araba (Al-Zoubi et al., 2004). Additionally, local scale magnetic ground surveys were carried out in specific geological areas to reliably estimate the depth and geometry of the causative magnetic bodies, and to identify their composition (Ben-Avraham et al., 1980; Ginzburg and Ben-Avraham, 1986; Frieslander and Ben-Avraham, 1989; Segev et al., 1999; Shirman, 2000; Khesin et al., 2005; Rybakov et al., 2009; Schattner et al., 2019). In 1998, the digital set of aeromagnetic data for the two divisions of the Jordan DST zone were compiled from several published surveys (Hassouneh, 2003). However, as mentioned before, the aeromagnetic data measurements over Jordan were collected at different elevations. The data, therefore, were numerically up-warded to a constant elevation of 2 km in order to avoid problems in the interpretation.

4. Features of the gravity and magnetic anomaly fields

The continuous updating of gravity and magnetic data in the DST region produced different versions of the Bouguer and magnetic anomaly maps, followed by several studies, over several years, dealing with the qualitative interpretation of the gravity and magnetic anomaly fields of the region (Woodside and Bowin, 1970; Folkman and Yuval, 1976; Folkman and Bein, 1978; Ginzburg and Makris, 1979; Folkman, 1981; Kovach and Ben-Avraham, 1986; Hassouneh, 2003; El-Kelani, 2006, 2007; Götze et al., 2007; Rybakov et al., 2011; Schattner et al., 2019). Qualitative interpretations were conducted in order to reveal the characteristic features of the objects under investigation, their spatial location, and preliminary geological identification. To enhance the various frequency components of the magnetic and gravity fields, a variety of filtering techniques were employed. Gravity first and second derivatives for the residual Bouguer were calculated in order to highlight fault patterns bounding the Dead Sea basin and Lake Tabeires (ten Brink et al., 1993; Segev and Rybakov, 2011). Horizontal gradient analysis of the gravity field was applied for the definition of discrete border of causative bodies at depth in order to study the deep structure of the Carmel fault zone (Achmon and Ben-Avraham, 1997). An isostatic regional gravity field of the southern transform region has been calculated, enhanced by curvature analysis of the local features in the isostatic residual gravity field, which are caused by near-surface density inhomogeneities (Hassouneh, 2003; Tašárová et al., 2006; Götze et al., 2007). A wavelength filtering technique was used to separate the regional-residual gravity anomalies north of the Dead Sea basin. The residual field revealed a complex pattern of anomalies, variously shaped and extended, showing a correlation with geological structures associated with the Dead Sea origin (El-Kelani, 2007). To remove the distortion caused by the low latitude, the total magnetic intensity map of the entire transform region was processed using a reduction-to-pole (RTP) technique (Rybakov et al., 2011; Segev and Rybakov, 2011; Schattner et al., 2019), which made the map represent the geology of the study region more directly.

In regional rifting areas, the qualitative analysis of gravity and magnetic anomalies provide the initial information about basin type, geometry, crustal structure, basement depth, and mostly the regional anomalies which correlate with the major geologic features at the surface. This study adopted the most newly-compiled gravity and magnetic anomaly maps (Figs. 4 and 5), and reviewed the regional scale qualitative interpretation of the potential fields in the transform region based mainly upon previous publications.

4.1 Description of the gravity anomaly fields

The detailed Bouguer anomaly map (Figure 4) shows values ranging from +70 mGal at the Mediterranean coastline to less than -130 mGal at the southern end of the Dead Sea. It is characterized by the presence of different anomalies that differ in their amplitudes, sizes, shapes, and trends. These anomalies are caused by a combination of various sources that are located at different depths. Major gravity features, having a regional extent, are most probably associated with the crustal type. Increasing Bouguer values can be observed on the map, towards the Mediterranean, attributed to crustal thinning beneath the coastal plain (Ginzburg and Makris, 1979) that is associated with a change from continental to oceanic crust, and caused by lateral lithological variations within the upper crust material beneath the northwestern part of the transform fault (Folkman and Bein, 1978; El-Kelani, 2007). The gravity low observed from the south to the north reflects the deepening of Precambrian basement beneath a thick accumulation of low density sedimentary rocks of Tertiary age (Folkman, 1981). Within the rift zone, a series of Bouguer minima along the transform fault, with the lowest values at the southern end of the Dead Sea, represents major depressions that correspond to pull-apart basins filled with sediments (Figure 1a), that include the Gulf of Aqaba in the south, the Dead Sea, Lake Tiberias (also called Sea of Galillee or Kinneret), and the Hula basin in a successive order (Ginzburg and Makris, 1979; Folkman, 1981; Kashai and Crocker, 1987; ten Brink et al., 1993; Rybakov et al., 2003; ten Brink et al., 2007). Negative Bouguer gravity on the southeastern plateau reaches a minimum value of -80 mGal which coincides with El-Jafr depression. There is a relatively large-scale local positive Bouguer anomaly over the eastern Dead Sea high lands, with a maximum value of -20 mGal along an axial of NW-SE trend, where its general trend follows an inferred zone of intrusion along the Karak-Wadi El-Fayha fault system (El-Kelani, 2006; Götze et al., 2007).

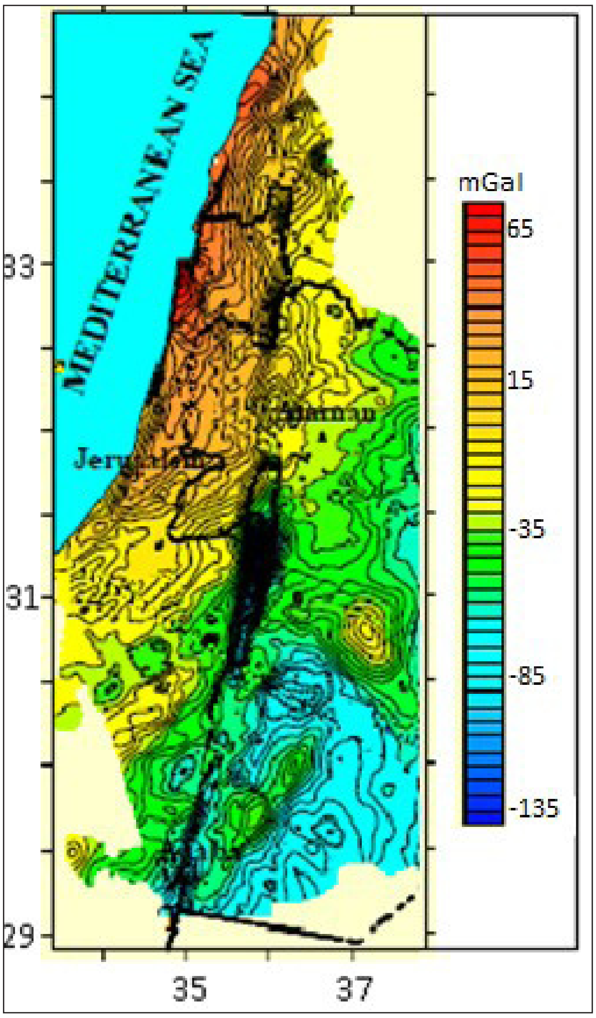

Figure 4. Bouguer anomaly map of the Jordan Dead Sea transform region, contoured at 5 mGal intervals (modified after Hassouneh, 2003).

The two opposite-facing plateaus are marked by a steep gravity gradient along the eastern and the western escarpments of the Dead Sea basin, with the lowest values at the southern end. This indicates a considerable increase of sedimentary thickness beneath the basin (Ginzburg and Makris, 1979; Folkman, 1981; ten Brink et al., 1993; Batayneh et al., 1995; Hassouneh, 2003; El-Kelani, 2006). The gradual decreasing of the Bouguer anomaly along the axis of the basin from both the northern and southern ends suggests that the basin sags toward the center, and is not bounded by faults at its narrow ends (ten Brink et al., 1993). The positive gravity value, observed in the northern Dead Sea basin and referred to as the Ajlun dome anticline structure, could have resulted from the high density of Precambrian carbonates (Hassouneh, 2003). However, prior interpretations attributed this positive anomaly to changes of the depth of the Moho discontinuity with a relatively small elevation (Hofstetter et al., 2000).

4.2 *Description of the magnetic anomaly fields*

As shown in Figure 5, the magnetic anomalies in the DST region are characterized by diverse amplitudes, shapes, and wavelengths. Their values ranging from -500 to 500 nT, superimposed on the geological map, show the relationship between the deep basement features, which cause magnetic anomalies, and the shallow structures shown on the geological map.

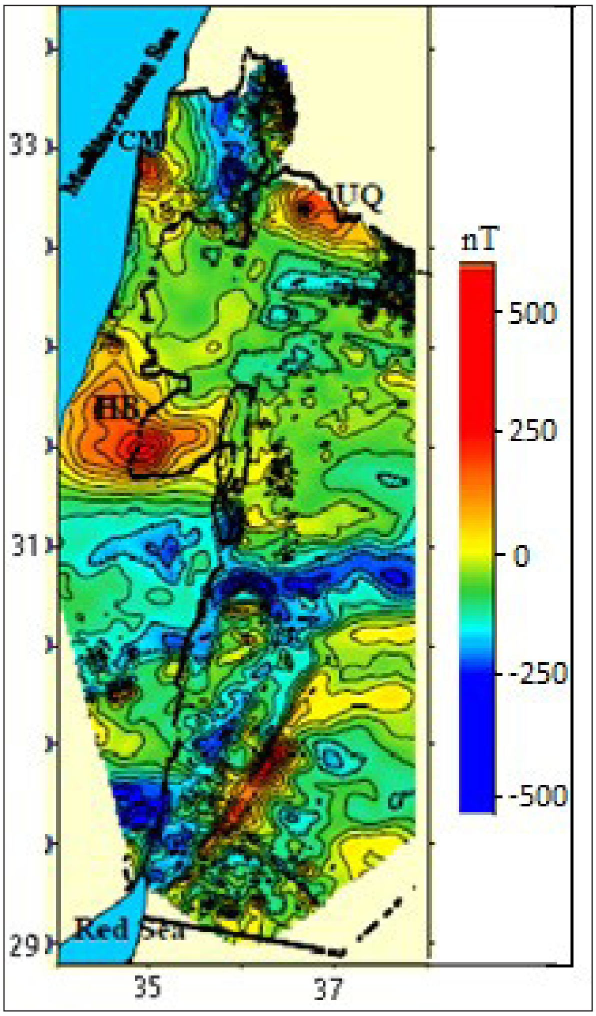

Figure 5. Aeromagnetic anomaly map of the Jordan Dead Sea Transform region, contoured at 50 nT intervals (modified after Hassouneh, 2003).

The total field aeromagnetic anomaly map is dominated by high frequency signals associated with the basalt flows north, northeast, east, and southeast of the Dead Sea basin that produce a strongly contrasting pattern of short wavelength, high frequency anomalies of low amplitude related to highly magnetic mafic rocks. The high-frequency signals are associated with surficial sources; whereas, the long-wavelength, lower-frequency signal anomalies reflect the deep basement features. In the south, a comparison of the geological and magnetic maps (Figures. 2 and 5) shows that the magnetic anomalies are directly correlative with the outcropping Precambrian crystalline rocks. Comparing the Hebron magnetic anomaly (HB) in the western plateau, with Um Qeis anomaly (UQ) in the eastern plateau (Figure 5), which are of a similar structure (Rybakov et al., 1999b; Khesin et al., 2005), correspond to the 105-107 km left-lateral movement along the DST fault (Hassouneh, 2003). This result is in agreement with the earlier magnetic investigations (Hatcher et al., 1981) which attributed the poor correlation in the magnetic anomalies facing each other across the DST fault, despite the short distance separating the two data sets, to something quite drastic geologically which has occurred in the intervening region.

On the other hand, the Hebron anomaly was suggested to be associated with a change in the composition and depth of the deep-seated basement rock (Domzalski, 1967, 1986; Folkman, 1976), or by a magmatic body related to Early Mesozoic intrusion that appears to penetrate the Triassic sedimentary strata at a depth of few kilometres (Rybakov et al., 1995a, 2011). Furthermore, the large contrast between the Hebron anomaly with the long wavelength and high amplitude and the anomaly of the very low amplitude immediately to the south, both being of a roughly east-west strike, was explained to indicate that a pre-Late Jurassic crustal boundary is present here; it was believed that this boundary could represent one between Tethyan and Arabian-African crust (Folkman and Bein, 1978).

The Carmel (CM) positive magnetic anomaly (Figure 5), corresponding to the Mount Carmel structure, was initially thought to be caused by a highly elevated crystalline basement (Ben-Avraham and Hall, 1977), or by the existence of a buried shield of Jurassic volcanoes beneath Mount Carmel (Gvirtzman et al., 1990). However, more recent studies suggested that it is high only in relation to the deep basin filled with considerable thickness of sediments in the surrounding areas, where the average densities of the Jurassic and Cretaceous volcanics, in the Mount Carmel region, are generally lower than those of the background sedimentary rocks (Rybakov et al., 2000; Segev and Rybakov, 2011), and the anomaly does not correspond to high-density magmatic rocks or the crystalline basement uplift (Rybakov et al., 2011).

5. Integrated interpretation of the gravity and magnetic anomalies

In addition to the comprehensive qualitative interpretations of the gravity and magnetic anomalies in the DST region, integrated quantitative interpretations of the two potential fields provided information about the density and magnetization models in the study area which allowed for a better delineation of the geologic structures and gave more reliable and accurate estimation of the depth, size, and composition of causative bodies. Previous quantitative interpretations of the gravity and magnetic data in the study area can be divided into two groups: large-scale, and small-scale interpretation.

5.1 *Data interpretation at large-scale*

The large-scale quantitative interpretation in the DST region is comprised of the studies that modelled the gravity and magnetic anomalies as being caused by structures of lithospheric and crustal scale (Ben-Avraham and Hall, 1977; Folkman and Bein, 1978; Ginzburg and Makris, 1979; Folkman, 1981; Ginzburg and Ben-Avraham, 1986; Frieslander and Ben-Avraham, 1989; ten Brink et al., 1990, 1993; Ben-Avraham et al., 1996; Hofstetter et al., 2000; Rybakov et al., 2000; Batayneh and Al-Zoubi, 2001; Al-Zoubi and Ben-Avraham, 2002; Hassouneh, 2003; Rybakov and Segev, 2004; El-Kelani, 2006; Ben-Avraham and Schubert, 2006; Götze et al., 2007; Segev and Rybakov, 2011).

The first stages of gravity and magnetic 2-D modelling introduced initial results on the lithospheric structure beneath the western side of the DST and the central part of the Dead Sea rift (Folkman and Bien, 1978; Ginzburg and Makris, 1979; Folkman, 1981). The computed models were constrained by preliminary seismic information and the available borehole data.

The modelling results showed considerable thinning of the crust in the west along the Dead Sea- Mediterranean cross section, accompanied by lateral variations in the lithology of the upper crust, where mafic composition of the rock type increases from east to west (Folkman and Bien, 1978; Folkman, 1981). The E-W lateral lithological changes in the crustal rocks, associated with significant variations in stratigraphic thickness, have been interpreted to be caused by a transition between the Arabia-African continent and the Tethyan crust (Folkman and Bien, 1978).

On the other hand, the central portions of the transform zone were interpreted to be filled by young low-density sediments reaching about 7.5 km in depth beneath the Dead Sea basin (Folkman, 1981). Density distribution and magnetic susceptibility were also computed in the crust and upper mantle from the Gulf of Aqaba in the south towards the Mediterranean Sea in the north (Ginzburg and Makris, 1979; Folkman, 1981). The results indicated a slight thickening of the crystalized crust towards the north with an increase in the thickness of the low-density sediments. Whereas, the southern portion of the transform fault was modelled to be underlain by a low-density wedge in the upper mantle (Ginzburg and Makris, 1979; Folkman, 1981). The low-density wedge was explained to be connected with the presence of high temperature, low density upper mantle that is related to the invasion of upper mantle material into the crust beneath the southern part of the transform fault (Ginzburg and Makris, 1979), which may form an extension of the geodynamically active Read Sea rift system.

Later crustal and upper mantle models of the northern Jordan DST fault, using potential field data, were computed for both sides of the Dead Sea rift (ten Brink et al., 1990; Hofstetter et al., 2000). The transition in crustal structure across the transform fault was modelled based on gravity data with a combination of teleseismic P-wave inversion and refraction seismic investigations. The geometry of the transition showed more gradual transition in Moho depth with an abrupt transition across the transform fault where a 4-5 km offset in the depth to Moho was required to be modelled (ten Brink et al., 1990). The thickness of the crust under the western side of DST fault reaches about 24 km at the Mediterranean shore; whereas, the crust on the eastern side of the transform is about 30 km thick, and is fairly constant in thickness (ten Brink et al., 1990) with an abrupt change in crustal thickness across the Dead Sea rift (ten Brink et al., 1990; Hofstetter et al., 2000). This abrupt change was explained to be caused by the 107 km left-lateral movement along the DST fault (ten Brink et al., 1990). A comparison between the two crustal and upper mantle models under the DST fault computed by ten Brink et al. (1990) and Hofstetter et al. (2000) is shown in Figure 6.

In addition, the depth to the top of the crystalline basement has been mapped and modelled for the medium valley of the Dead Sea rift and the surrounded shoulders using magnetic and gravity data (El-Isa and Kharabsheh, 1983; Rybakov and Segev, 2004; Al-Zoubi and Ben-Avraham, 2002; Segev et al., 2006). The results of the potential field data interpretation after reviewing the available information on the study area (deep boreholes and seismic profiles) showed that the depth to the basement is variable; within the rift it is always greater than 5 km, and generally increases toward the Dead Sea and Tiberias basins at about 8-10 km depth (El-Isa and Kharabsheh, 1983; ten Brink et al., 1990; Hofstetter et al., 2000; Al-Zoubi and Ben-Avraham, 2002; El-Kelani, 2006; Götze et al., 2007). The basement in the eastern and western flanks of the rift deepens gradually northward from 3 to 7 km, while the top of the crystalline basement becomes shallow to about 1 km southward, where the Precambrian complex rocks can be seen on the surface (Al-Zoubi and Ben-Avraham, 2002; Rybakov and Segev, 2004; Segev et al., 2006).

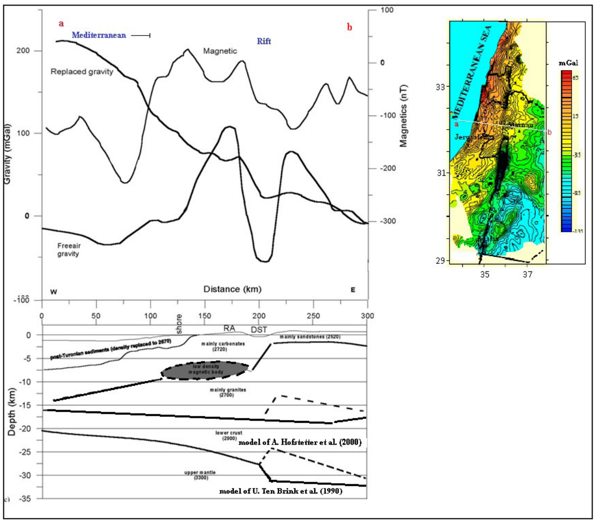

Figure 6. 2-D crustal model of the northern Jordan DST fault. Solid lines indicate the earlier gravity model of ten Brink et al. (1990), while dashed lines represent the modification made by Hofstetter et al., (2000) based on best gravity and magnetic data and teleseismic velocity anomalies.

Moreover, the string of young sedimentary basins, separating the two sides of the rift (Ginzburg and Makris, 1979, Folkman, 1981; Kashai and Crocker, 1987; ten Brink et al., 1993; Rybakov et al., 2003; ten Brink et al., 2007), has a basement step that reaches about 5 km which represents a displacement for the largest vertical faults along the DST fault zone (Hofstetter et al., 2000; Tašárová et al., 2006).

On the other hand, gravity and magnetic 2-D modelling was conducted to reveal the geometry of the large sedimentary basins within the DST fault zone, and to compute the thickness of the basin fills, and identify their types (Frieslander and Ben-Avraham, 1989; Ben-Avraham et al., 1996; ten Brink et al., 1993; Batayneh et al., 1995; Rybakov et al., 2003; Ben-Avraham and Schubert, 2006). The analysis and modelling of gravity data for the Dead Sea basin, being the largest one, showed that the basin has two main depth levels. The northern one has a sedimentary fill of about 6 km; whereas, the southern Dead Sea basin is unusually deep, and the thickness of sediments is about 14 km (ten Brink et al., 1993; Batayneh et al., 1995; Ben-Avraham and Schubert, 2006). The density distribution of the basin sediments was also assigned by depth in the range of 2150-2620 kg/m^3, which represent light sediments (mainly evaporates), of Quaternary deposits, at the top, to Mesozoic-Palaeozoic sediments, of carbonate and sandstone rocks at the bottom. The analysis and modelling of gravity data revealed that the geometry of the Dead Sea basin is 132 km long, 17-18 km wide, and the basin becomes narrower and shallower towards the northern and southern ends. The 2-D gravity model of the second largest basin, Tiberias Lake in the northern Jordan DST fault zone, divided the basin into two distinct units (Ben-Avraham et al., 1996). The southern half represents the deepest half of about 14 km in depth; northwards, the basin becomes wider (the width varies between 8-18 km) and the thickness reaches 12 km. The assigned densities lie within the range of the Dead Sea sediments that is between 2150-2250 kg/m^3. In addition, a magnetic study model was performed across the Dead Sea basin in the E-W direction (Frieslander and Ben-Avraham, 1989), where the model showed that the basement rocks under the Dead Sea have the same magnetic characteristics similar to the rocks under the land area to the west. The model study also gave the best fits when the basement rocks east of the basin are modelled as much more elevated than the basement west of the basin with lower magnetic susceptibility. The gravity and magnetic study models of the two main basins (Dead Sea, Tiberias) agreed with a pull-apart structure, as accepted mechanism, but with no existence of diagonal faults at the northern and southern ends of the basin (Frieslander and Ben-Avraham, 1989; ten Brink et al., 1993). However, some earlier results, based on magnetic data, proposed the formation of a rhomb-shaped graben for the Tiberias basin (Ben-Avraham et al., 1980). Moreover, alternative gravity models suggested a “drop down’ basin instead of a pull-apart for the deep part of the southern Dead Sea basin (Ben-Avraham and Schubert, 2006).

Afterwards, a 3-D interpretation of the newly-combined Bouguer anomaly map of the southern Jordan DST fault zone and of the Dead Sea basin (Figure 7) was conducted (Hassouneh, 2003; El-Kelani, 2006; Götze et al., 2007). A regional scale, a high resolution 3-D layered structure-density model was computed. The model was constrained with the more recent seismic results (DESERT, 2004 and references therein) using all of the available geological information and rock density log deep borehole data (Rybakov et al., 1999a). It revealed a possible crustal thickness and density distribution beneath the Jordan DST fault zone (Figure 7).

The model showed that the zone of the maximum crustal thinning (≤30 km) is attained in the western sector at the Mediterranean. The south-eastern plateau shows, by far, the largest crustal thickness in the transform region (38-42 km). The computed results of the thickness and densities of the crust, ranging between 2650-2900 kg/m³, suggested that the DST fault is underlain by continental crust. On the other hand, the modelled deep basins (≥10 km), the relatively large nature of an intrusion, and the asymmetric topography of the Moho, led to the suggestion that a small-scale asthenospheric upwelling might be responsible for the thinning of the crust and subsequent rifting of the DST fault during the left-lateral strike-slip motion at the boundary between African and Arabia Plates (El-Kelani, 2006; Götze et al., 2007).

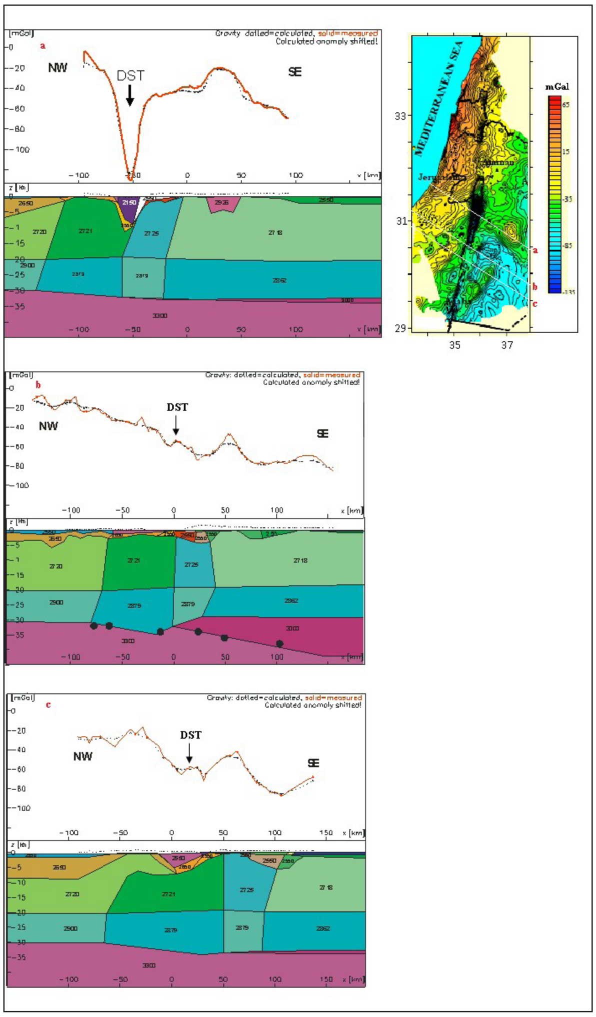

Figure 7. 3-D crustal model of the central and southern Jordan DST fault zone (modified after El-Kelani, 2006; Götze et al., 2007).

5.2 Small-scale data interpretation

Gravity and magnetic data interpretation was also carried out with regard to the investigations that are focused on smaller DST districts. Some detailed investigations studied intrusive bodies within the uppermost crustal layers to a depth of about 5 km (Ben-Avraham and Hall, 1977; Ginzburg and Ben-Avraham, 1986; Segev et al., 1999; ten Brink et al., 1999; Rybakov et al., 2000; Khesin et al., 2005; Eppelbaum et al., 2004, 2007), while other investigations focused on structures and the distribution of salt diapirs in the Dead Sea basin (Neev and Hall, 1979; Al-Zoubi and ten Brink, 2001; Choi et al., 2011). Moreover, meter-scale, highprecision gravimetric and magnetic surveys were utilized to detect caverns and sinkholes along the coast of the Dead Sea (El-Isa et al., 1995; Rybakov et al., 2001, 2005; Closson et al., 2005; Eppelbaum et al., 2008; Ezersky et al., 2010, 2013; Shirman and Rybakov, 2009).

Model studies of the gravity and magnetic anomalies, corresponding to the Mount Carmel structure, suggested that they are caused by basic intrusive igneous bodies, ≥4km, associated with elevated crystalline basement (Ben-Avraham and Hall, 1977). While, thereafter, the idea of being related to magmatic roots of volcanics at shallow depths between 3-5 km was adopted (Rybakov et al., 2000), suggesting that average densities of the volcanics are lower than those of the background sedimentary rocks.

Also, the results of the magnetic interpretation showed that a model incorporates a gabbroic intrusion at 2-4 km within the light sediments of Tiberias basin overlaid by a basaltic layer (Ginzburg and Ben-Avraham, 1986; Eppelbaum et al., 2004, 2007).

On the other hand, magnetic characteristics were studied for a complex of metamorphosed carbonate rocks in the Hatrurium Basin, west of the Dead Sea, which is situated at the Hebron aeromagnetic anomaly (Figure 5). Magnetic measurements were used to study the Hatrurium formation, where shallow small bodies of variable magnetic susceptibility were found with marked heterogeneity and anisotropy reflecting the high-grade of metamorphism (Khesin et al., 2005). Furthermore, magnetic and gravity data were applied to investigate the Precambrian basement north of Aqaba (Segev et al., 1999). The interpretation of the potential data enabled the characterizing of the tectono-magmatic setting of the crystalline basement, where the results showed common intrusive relationships between dissimilar intrusive bodies, while the dense basic and intermediate magmatic bodies have different magnetic properties.

Among the upper crustal-scale interpretation as well, 2-D and 3-D density models, using gravity data, were constructed to present information on the underground structures associated with the generation of salt domes and diapirs in the Dead Sea basin (Al-Zoubi and ten Brink, 2001; Choi et al., 2011). 2-D gravity models constrained seismic reflection data, and a magnetic map was computed to delineate the extent and depth of two salt diapirs under Lisan Peninsula and Sedom area (Al-Zoubi and ten Brink, 2001). The Lisan diapir reaches a maximum depth of about 7 km, and extends further to the south, whereas the Sedom diapir south of the Lisan is no deeper than 5.5-6 km (Figure 8a). Moreover, 3-D density modelling led to the identification of three salt structures found beneath the Sedom area, the Lisan Peninsula, and the northern basin of the Dead Sea (Choi et al., 2011). The 3-D density models were based on a new compilation of Bouguer gravity data stemming from airborne, shipborne, and terrestrial data, and the most recent seismic investigation (Weber et al., 2009). 3-D gravity modelling enabled a detailed resolution of the upper crustal structures from the southern to the northern subbasin below the saline Dead Sea. The results suggest that a salt diaper exists at a top of about 2 km in the northern Dead Sea subbasin with a thickness of about 4 km, which has not been recognized by any other prior geophysical interpretations. However, earlier combined analysis of magnetic and seismic investigations (Neev and Hall, 1979) detected a salt diapir beneath the same location and with a similar geometry.

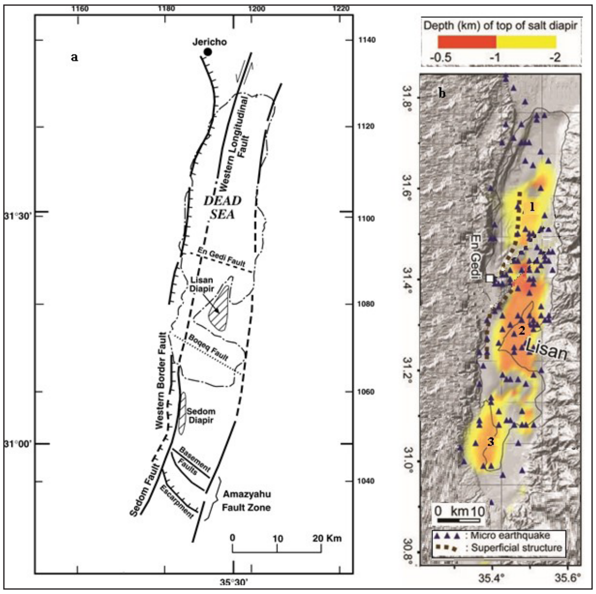

Figure 8. Location maps of the spatial distribution of the inferred salt diapirs modelled by Al-Zoubi and ten Brink (2001) in the Dead Sea basin (left) compared with the modelled salt diapirism (right) by Choi et al., (2011).

The dimensions of the salt diapirs computed by the 3-D models (Figure 8b) are about 10 km by 20 km, with an average thickness of approximately 6 km for the Lisan Peninsula and about 5 km by 10 km, with an average thickness of approximately 4 km for the Sedom salt diapir which are larger than the same ones (Lisan and Sedom) computed by the 2-D modelling. The differences were attributed to the fact that more gravity and constraining data enhanced the 3-D modelling (Choi et al., 2011). Furthermore, the 2-D gravity models assume that the diapiric rise is related to the transtension and subsidence tectonic activity during the formation of the Dead Sea pull-apart basin (Al-Zoubi and ten Brink, 2001) while the 3-D gravity model, referred the shallower micro earthquake activity in the Dead Sea basin to the movement of the salt diapirs (Choi et al., 2011).

Attempts were made, on the other hand, to understand the occurrence and development of sinkholes and other karst features in the Dead Sea coastal area using several geophysical techniques (Ezersky et al., 2017, and references therein). Among these, potential data measurements have been tested and employed to investigate and predict the occurrences of some sinkholes by carrying out, specifically, microgravity and micromagnetic surveys. Microgravity field analysis was implemented on sinkhole hazards along both the western Dead Sea shore (Rybakov et al., 2001; Ezersky et al., 2010, 2013; Eppelbaum et al., 2008), and the eastern coastline (Abou Karaki, 1995; Al-Zoubi et al., 2013), in order to detect caves and determine the sinkhole formation mechanism. This monitoring geophysical technique was chosen to investigate sinkholes based on the existence of sufficient density contrasts regardless of shape or fill material. Residual gravity maps and 3-D microgravity modelling were applied to resolve the sinkhole problem in an attempt to estimate qualitative and quantitative parameters of buried cavities. The microgravity method was tested at different locations along the Dead Sea shorelines to detect buried karst and salt dissolution caverns, and compute their underground spatial distribution (Figure 9). It was tested in the areas of Ein Gedi-Hever (Rybakov et al., 2001), Nahal Hever South (Eppelbaum et al., 2008; Ezersky et al., 2010), Ein Gedi-Arugot (Ezersky et al., 2013), and Ghor Al-Haditha-Lisan Peninsula (Abou Karaki, 1995; Closson et al., 2005; Al-Zoubi et al., 2013). As a feasibility study, the micromagnetic technique was used as well to investigate sinkhole development and to detect caves along the western Dead Sea coast (Rybakov et al., 2005; Shirman and Rybakov, 2009).

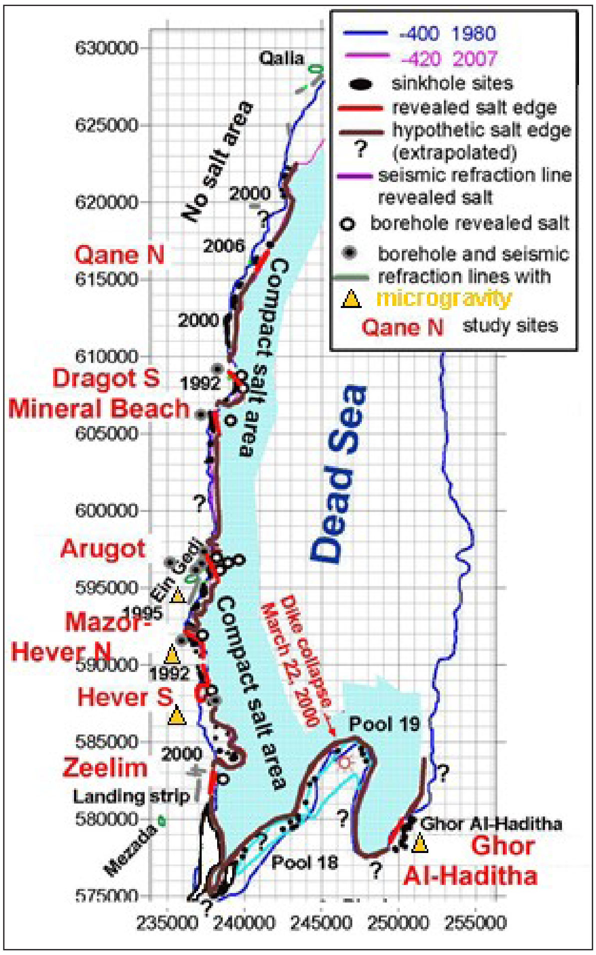

Figure 9. Sinkhole sites studied by means of the microgravity technique (modified after Ezersky et al., 2017).

The micromagnetic study was carried out to test the possibility of delineating weak magnetic anomalies related to shallow voids or caves. The feasibility studies surpassed the expectations, and enabled the delineation of buried fault zones controlling the sinkhole process (Rybakov et al., 2005) and the detection of voids that are reliable precursors of sinkhole development and ground collapse (Rybakov et al., 2005; Shirman and Rybakov, 2009).

6. Conclusions

Gravity and magnetics play a leading role among the reconnaissance geophysical methods. Advances in the collection and the extensive coverage of gravity and magnetic data that exist over the DST region enabled a detailed analysis of the two potential fields on the regional and local scales.

The analysis and interpretation of the gravity and magnetic field data provided a geological picture of the subsurface which allowed for a better understanding of the tectonic evolution in the Jordan DST zone. Major tectonic features such as volcanics, magmatic intrusive bodies, and basin-scale fault trends corresponded with the regional patterns and the abnormal shapes of the gravity and magnetic anomalies over the transform fault zone. Applying a variety of filtering techniques enhanced the qualitative interpretations of the various frequency components of the potential fields; removing the giant regional effect enabled the recognition of shallow depth-causative geological structures. The residual anomalies, on the other hand, showed a correlation with tectonic lineaments, shallow structures and small-scale volcanic intrusions within the uppermost part of the crust inferred from high amplitude of the related anomalies.

The earliest results of the 2-D quantitative interpretation of the combined gravity and magnetic field provided a significant contribution to the investigation of the deep lithospheric structures and led to the identification of Moho offset across the Jordan DST fault zone. Any geophysical interpretation is subject to a fundamental ambiguity involving the effect of a physical property and a volume. In as much as the results obtained from the potential field data were inherently not unique presented by several possible models, their reliability and accuracy were estimated by a comparison with seismic observations and the available drill-hole data. The advanced 3-D density modelling that incorporated results from additional recent geophysical investigations enabled a detailed resolution of the upper crustal structure. Deep basins, vertical offset of basement, relatively large intrusions, and a small asymmetric topography of the Moho were interpreted beneath the Jordan DST fault zone by 3-D density models.

At a shorter scale, the gravity and magnetic data in the DST region were useful for geological interpretations in specific areas. By means of new techniques, microgravity and micromagnetic models proved to be good tools for detecting buried sinkholes and karst cavities along the Dead Sea coast.

The findings of the qualitative and quantitative interpretation of the gravity and magnetic anomaly fields confirmed the contrasting nature of the structures in the eastern and western plateaus of the Jordan DST fault zone. The results correlated with the known geology at the surface, and showed good agreement with the main tectonic elements and geologic structures in the DST region such as the sediment basins, salt diapirs, volcanic activity, magmatic intrusions, thinning of the crust, and the lateral and vertical offset of the basement. The data analysis of the gravity and magnetics at the regional and local scale has been linked to the left-lateral strike-slip movement at the boundary between the Arabian-African plates and to the transition zone marking a major crustal lithological discontinuity from the eastern segment of the northern edge of the continental plate into the oceanic zone at the Mediterranean coastline of a remnant Tethyan crust. Besides, the potential data were utilized, in the transform region, for the qualitative interpretation of regional geology and structural features in sedimentary basins, as one of the first steps in the search for petroleum.

The quantitative integration of varying gravity and magnetic datasets is one of the main challenges of potential field interpretations. These data sets differ in the type of data acquisition, equipments used, and geographical scale, elevation of measurement stations and their spacing, physical limitations in the field, borders, and different datum. These challenges can be tackled through improving the coverage of gravity and the magnetic measurement extent by conducting ground surveys in the DST region and applying the equivalent source technique for the integration of all available data sources, upon their high variability. Conducting new gravity and magnetic surveys in the DST region is also recommended for more local measurements to shed more light on small-scale structures, and to clarify their geological meaning in an attempt to increase the details of information that would represent a decisive step towards minimizing the remaining contentious issues.

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