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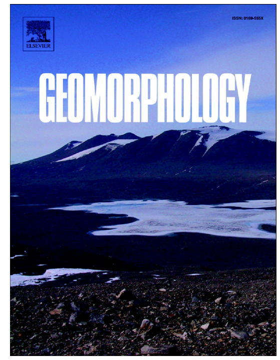

Out of sight, out of mind. Submarine springs in the Dead Sea — An underappreciated phenomenon

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Out of sight, out of mind. Submarine springs in the Dead Sea - an underappreciated phenomenon

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Abstract

The drastic drop in Dead Sea lake levels during the last few decades has caused the formation of over 6000 dangerous sinkholes along its coasts. Concurrently, retreating shorelines have led to the exposure of an under-explored phenomenon – submarine spring systems. Once exposed on land, these features are labeled as the more familiar geological hazard – i.e. sinkholes, with no distinction between the two. While visually they may seem similar, the underlying formation mechanism is different, as may well be their hazard potential. This study utilizes high-resolution seismic reflection data collected in 1984 when lake levels were some 35 m higher, together with multibeam bathymetric data from 2014, visual observations and water chemistry data from a verified spring system in order to assess the underlying formation mechanisms of these features, their stability and morphology. Results show that the springs are relatively stable and long-lived systems. They "deserve" to be separated from the sinkholes and studied as a distinct phenomenon. The springs discharge into the lake a significant amount of freshwater from the adjacent aquifers and are therefore, a largely underestimated part of its hydrological budget and the connected fresh groundwater resources. The acceptance of submarine springs as a distinct

geological phenomenon and their consideration as a major groundwater outlet into the lake will lead to more realistic groundwater resource models of the Judea and Samaria Eastern Mountain aquifer than exist today. This is extremely important given the increase aridification of the area and the increased demand for freshwater resources.

1. Introduction

The Dead Sea basin is a tectonically active 150 km long and 15–17 km wide terminal pull-apart basin located along the southern Jordan-Dead Sea rift valley that separates the Arabian plate from the Sinai sub-plate (Fig. 1). It comprises two tectonic sub-basins of which the southern one is covered by industrial evaporation ponds belonging to the Dead Sea Works Ltd. and the Arab Potash Company. These ponds are frequently filled with brine, which is pumped from the northern basin. The northern basin hosts the shrinking natural lake, known as the Dead Sea and is the lowest place on earth (435 meters below mean sea level). The Dead Sea is the hypersaline remnant of a series of ancient lakes that have existed in the area since the Neogene (e.g. Stein, 2001 and references therein). Though lake levels varied remarkably over the millennia, they have been dropping during the last few decades with an unprecedented rate of over 1 meter per year, leading to an annual decrease in volume of 700×10^6 m^3 (Gavrieli et al., 2006). This is the joint effect of climate change and anthropogenic intervention. The latter is a combination of (i) diverting water from the main sources of the Dead Sea, the Jordan River and the lake's direct tributaries, (ii) overdraft from surrounding freshwater aquifers (e.g. Salameh and El Nasser 1999), and (iii) net subtraction of brine from the northern lake to supply the salt and potash industries (e.g. Al-Weshah, 2000).

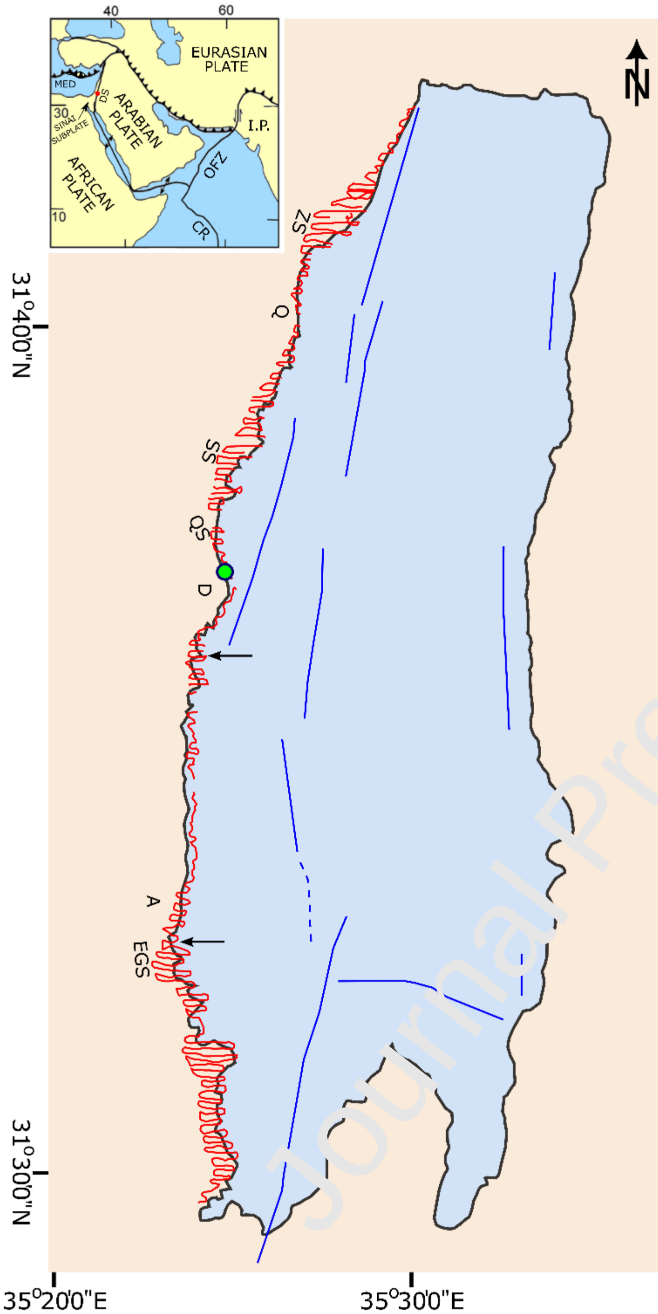

Figure 1. The northern Dead Sea basin showing the location of the November 1984 high-resolution 3.5 kHz seismic survey along the western margin (red lines), the study area (green circle), location of the profiles shown in Figure 4a (bottom arrow) and 4b (top arrow). Blue lines within the lake represent the location of the shallow, presumably active

faults mapped by Niemi and Ben-Avraham (1997). ZS – Zukim springs; Q- Qane springs; SS – Samar springs; D – Darga alluvial fan; A – Arugot stream; EGS – Ein Gedi springs. Inset – generalized tectonic map of the area. A red dot marks the approximate location of the Dead Sea basin.

One of the most wide-spread and hazardous results of dropping lake levels and subsequent shoreline retreat, is the formation of over 6000 sinkholes, which has accelerated dramatically during the last ca. 20 years (e.g. Yechieli et al., 2006; Abelson et al., 2017; Abelson 2021 and references therein). They appear predominantly along the western shore of the lake and to a certain extent, along its southeastern and northeastern shores (Al-Halbouni et al., 2017). These features have caused the destruction of infrastructure, such as roads, and have led to the loss of livelihood due to closure of local businesses. From a more hydrogeological perspective, dropping lake levels cause falling groundwater tables in the surrounding aquifers, which are crucial for water supply in this arid area (Yechieli, 2006). The combined effect of groundwater overdraft and dropping base level accelerates the problem (McCulloch, 2006). Groundwater from these aquifers discharge through springs along the lake shore, and as a less known phenomenon through underwater springs (Ionescu et al. 2012; Siebert et al. 2014a; Häusler et al., 2014; Munwes et al., 2019). Springs with strong discharge rates are fed by open pipes (Siebert et al., 2014b) and produce deep funnels. When lake level retreats, the funnels eventually become exposed on land mimicking the shape of sinkholes. However, their underlying formation mechanism is different, as is surely their hazard potential. Thus, there is some confusion between the two phenomena, with sinkholes being the result of cavity collapse due to salt dissolution (e.g. Yechieli and Wood, 2002), and springs – a hydrogeological feature, which releases water from the subsurface through dissolution or via tectonic pathways (e.g. Mallast et al., 2011; Ionescu et al., 2012). In principle, both phenomena result from flowing groundwater. In a hypersaline environment like the Dead Sea sediments, such passing freshwater always causes dissolution of evaporitic minerals leading to increased mineralization of the water. However, while on- or offshore spring appear solely as a result of zones of higher hydraulic conductivity, (e.g. cracks; faults) and can even discharge saturated brines that cannot dissolve halite, sinkholes require both freshwater undersaturated in respect to evaporitic minerals (e.g. halite) and massive layers of such dissolvable evaporites. Though sinkholes and springs occur along both shores of the Dead Sea, the following discussion focusses on the western part of the lake.

1.1 Sinkholes

A sinkhole is defined as a circular-to-subcircular surface depression or collapse structure resulting from the formation of small subterranean cavities, usually karstic, connected to dissolution of the underlying rock (e.g. Williams 2003; Waltham et al. 2005; Gutiérrez et al., 2008). The present study focusses on the western shore of the Dead Sea, where sinkholes can be found in a narrow <1 km wide, east-west trending strip that extends along the entire coast (Yechieli et al., 2016). The rate of sinkhole formation has been correlated to lowering lake levels (Shalev et al., 2006; Yechieli et al., 2006), which leads to an eastward progradation of the fresh-saline-interface (FSI). This allows fresh groundwater to interact with a buried (20-70 m) salt layer that was formed ca. 10,000 years ago. This layer is presently being leached by the approaching groundwater, which is under-saturated with respect to halite, gypsum and aragonite (e.g. Yechieli and Wood, 2002, Wust-Bloch and Joswig, 2006). This results in the formation of subsurface cavities, which eventually collapse, as confirmed by analog models (Oz et al., 2016).

Two main hypotheses exist regarding the spatial distribution of sinkholes along the shores of the Dead Sea (Kottmeier et al., 2016). Ezersky et al. (2013) suggested that sinkholes develop along the edge of the subsurface salt layer where the approaching fresh groundwater dissolves it. The edges of such deposits reflect ancient shorelines, which may or may not be fault controlled. Alternatively, Abelson et al. (2003) and Closson et al. (2005) proposed that since some sinkhole belts develop with similar strike directions as the major fault system in the Dead Sea, their alignment reflects hidden neotectonic faults that act as preferential flow paths and direct the groundwater.

1.2 Springs

Numerous studies have been conducted on the perennial onshore terrestrial springs along the Dead Sea such as Einot Zuqim (Ein Feshkha), Qane, Samar, and Ein Gedi (e.g., Mazor, 1997; Laronne Ben-Itzhak and Gvirtzman, 2005; Gräbe et al., 2013; Avrahamov et al., 2018; Levy et al., 2020). It has been suggested that the springs represent the discharge of water from the Upper Cretaceous Judea Group Aquifer, of which the Dead Sea corresponds to its eastern border. According to Burg et al. (2016), the rapid drop in lake level has caused the location of these springs to shift over time. Despite this, the aquifer remains hydrologically connected to the Dead Sea through the permeable alluvial fans of the major rivers (Levy et al., 2020) and through the permeable strata and cracks within newly exposed shorelines and lakebed (Ionescu et al., 2012). Simultaneously, thermal springs occur in Qedem, discharging hot brines from deep buried aquifers of probably Lower Cretaceous age (Gavrieli et al., 2001).

The presence of submarine springs has been studied, mainly in terms of their contribution to the Dead Sea water budget (e.g. Stiller and Chung, 1984; Yechieli and Gat, 1997) resulting in a modelling-based contribution of 20.6 x 10^6 m^3 per year or about 25% of the total (on- and offshore) spring discharge (Laronne Ben-Itzhak and Gvirtzman, 2005). Lensky et al. (2005) estimated the contribution of the underwater springs to be a maximum of 60 x 10^6 m^3 per year, which equals 12.6%-22.6% of the total annual inflow of water from all sources (the Jordan River, springs, precipitation and floods) into the Dead Sea between the drought years of 1996-2001. According to Siebert et al. (2014b), the quantity of submarine discharge into the Dead Sea is comparable to that of the onshore springs. In addition, Munwes et al. (2019) suggest that standard methods for estimating the discharge from submarine springs lead to an underestimation of the actual flow. Thus, these dimensions show that the underwater spring systems are a major contributor to the water budget of the lake and represent an important outflow from the freshwater aquifers. With few directly observed outliers, on- and offshore springs are usually located relatively close to the shoreline. However, they significantly differ in temperature (21-45 °C) and salinity (TDS: 1-250 g/l).

Indirect evidence for underwater hydrothermal activity (i.e. active spring systems) within the lake was proposed by Ben-Avraham and Ballard (1984) based on near-lake floor temperature anomalies. Niemi and Ben-Avraham (1997) suggested the presence of fluid or gas in the sediments of the Dead Sea and recognized hydrothermal activity features based on acoustic blanking of the signal (e.g. Judd and Hovland 1992; Hart and Hamilton 1993) observed on high-resolution 3.5 kHz seismic reflection profiles collected in July 1984. They suggested that these springs were located along active tectonic faults within the lake that act as conduits and facilitate fluid flow from deep below.

Underwater springs were mapped by surface thermal imaging on both the eastern (e.g. Akawwi et al., 2008) and western sides of the lake (e.g. Mallast et al., 2013a), which accumulate to 37 distinct (on- and offshore) seep clusters around the entire Dead Sea coast (Mallast et al. 2013b). Solely applying thermal imaging, makes it difficult to distinguish individual underwater springs and hence to locate springs on the lake floor or to provide information on their morphology (e.g. diameter, water depth, shaft depth, etc.).

The most comprehensive study of the active underwater springs was carried out by Ionescu et al (2012) who collected measurements by SCUBA diving directly to these features (Fig. 2a). While their focus was on water chemistry and the microbial communities that populate these springs, they did observe distinct systems and morphologies. In terms of water chemistry, the authors point to two types of spring systems. In the first, water from the Judea Group Aquifer flows through well-developed open cracks thus limited the contact with surrounding sediments. In contrast, in the second type of system, the water flows through small fissures and tight cracks through the sediment, leading to a more mineral-enriched discharge. They also point to distinct differences in the structure of underwater springs. According to their direct visual observations, which have been confirmed by subsequent diving campaigns conducted by Siebert and colleagues between 2014 and 2020, some springs formed deep and steep walled shafts (as deep as 20 m) that extended from water depths of 10 m to as deep as 30 m and possibly beyond. Several shafts seemed to be connected. Other springs were located at the bottom of steep walls descending directly from the water surface and were covered by cobble. Large water seeps without clear boundaries were also found, at depths greater than 15 m.

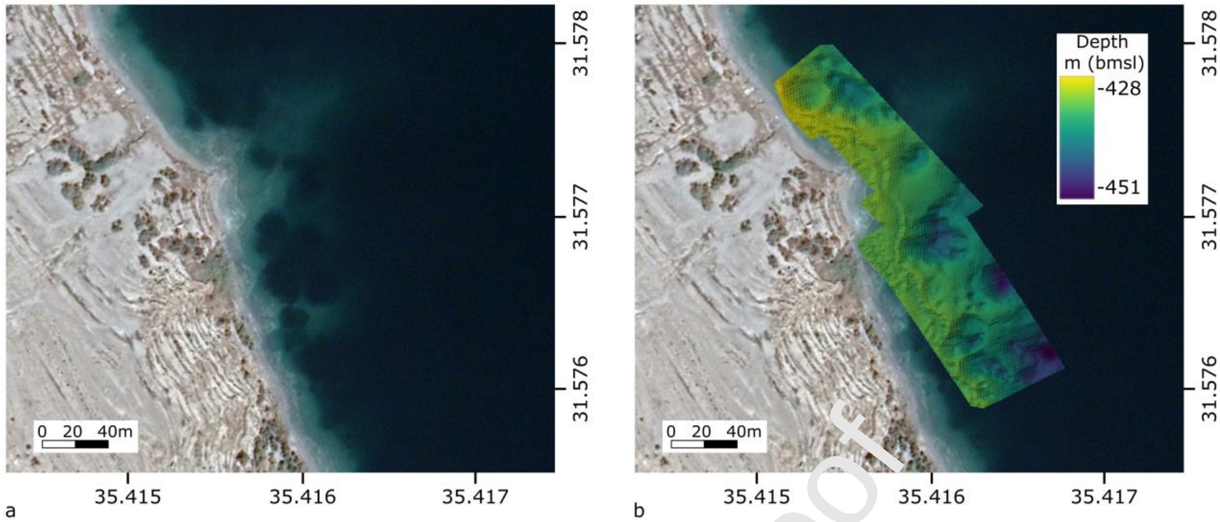

Figure 2. The study area located along the northern Darga alluvial fan. (a) Google earth image from September 2019. Notice black circular forms in the shallow water near the shore. These are the springs that were verified by SCUBA divers in 2010 and 2011. (b) Results of the Sonobot bathymetric survey. Depths are in meters below mean sea level (m bmsl).

Questions remain as to whether or not the occurrence of these springs is erratic or follows certain geological or hydrological principles. This study examines a verified spring system located offshore the Darga alluvial fan, at the interface between the land and the lake (Fig. 2). High-resolution, 3.5 kHz seismic reflection data collected in 1984 when lake levels were ca 30 m higher was examined for this purpose. The aim is to examine and characterize the lesser-studied underwater spring systems and their possible connection to active tectonics along the western shore of the Dead Sea. To date, the spatial distribution of submarine springs is not known, nor is how they change and develop with lowering lake levels. Questions remain as to whether these are a new phenomenon resulting from dropping lake levels (and hydrostatic pressure) below a certain threshold or have they existed in the past but have never been observed because the higher Dead Sea water column in the past kept them concealed?

2. Methods

During November 1984, 145 km of high-resolution 3.5 kHz seismic reflection data were collected along the western shore of the Dead Sea in shallow water. Lines were mostly oriented perpendicular to coast. Data were collected in water depths from 1-50 m at the time of collection (see Fig. 1). Their lengths varied from 250 m to 3 km, with a spacing of 250 m between lines. Analog data were acquired using an Ocean Research Equipment (O.R.E.) sub-bottom profiler operating at a maximum output power of 10 kW and at a frequency of 3.5 kHz and recorded using an EPC 19-inch dry paper graphic recorder with a 0.25-second sweep. Penetration was on the order of 10-40 msec (~9-35 m) with a vertical resolution of a few tens of centimeters. Navigation was obtained from a Motorola Miniranger system, which provided ship-to-shore range measurements of position every 2.5 seconds (Niemi and Ben-Avraham, 1997). Locations were plotted onboard, on a scale of 1:25,000. A Raython DSS-6000, 1000 kHz digital echo sounder was used to periodically calibrate depths to an accuracy of ±5 cm. For the purpose of this study data were examined over an area that contains verified spring systems, that are now either in shallow water or exposed onland and classifies as sinkholes. The paper printouts were scanned, converted to SEGY format and assigned the coordinates according to the coordinate printouts recorded at the time of the survey, using the SeisPrho software package (Gasperini and Stanghellini, 2009). Data were then loaded into dGB Earth Sciences OpendTect open-source seismic interpretation package. It should be noted that this process reduces the resolution of the original, printed data. However, for this study both the (original) analog and digital sections were examined.

To map the bathymetry offshore the Darga sedimentary fan, in an area with a series of diver-confirmed springs, an EvoLogics (Germany) Sonobot was deployed in 2014 over an area approximately 170 m (E-W) by 230 m (N-S). This autonomous jet-powered bathymetric sounder was equipped with an Imaginex 837B "Delta T" 120 kHz 120° x 2.5° multibeam sonar and two dual-mode 340/680 kHz side-scan sonar units used to survey the area. The multibeam sonar was adopted to the density and temperature-dependent sound velocity in the Dead Sea in order to return reliable depth-related data. An average velocity of sound for the Dead Sea of 1819 m/s (Beaudoin et al., 2011) was applied to convert the data to depth.

3. Results

3.1 Calculations:

3.1.1 Water level drop in seismic units – milli seconds (msec) two-way travel time (TWT)

The amount of lake level drop between the survey in 1984 and the date of observations, was calculated in TWT in order to evaluate what parts of the seismic data examined are still underwater and what sections are exposed on modern satellite images. The highest resolution Google Earth image available from the Darga area at the time this study was conducted was from 3.9.2019. Lake levels in meters were provided by Israel Water Authority (https://www.gov.il/BlobFolder/reports/dead_sea_report/he/deadsea_deadsea_deadsea-from1976.pdf Last accessed Jan 31st, 2023) and the closest measurement (lake level) date to relevant parameter (survey or Google Earth image) chosen.

Level November 1st 1984 (survey): -402.96 m msl.

Level September 1st 2019 (Google Earth image 3.9.2019 – Fig. 3): -434.03 m msl.

ΔLevel$_{(1984\text{-}2019)}$: 31.07 m

Speed of sound in Dead Sea brine:

Measured in 1974 (Neev and Hall, 1979) - 1770.6 m/s

Measured in 2006 (Beaudoin et al., 2011) – between 1798-1840 m/s. Average 1819 m/s

Using these two values, acoustic velocity in 1984 was calculated as a simple average and found to be 1785.725 m/s. This value was then used to convert time to depth on the seismic cross sections (Fig. 3) as well as to calculate the drop in lake level (1984-2019) from meters to msec:

Drop in lake levels in t(sec) = 31.07/1,785.725 = 0.0174 sec

Drop in lake levels in TWT = 0.0174×2 = 0.0348 sec = 34.8 msec

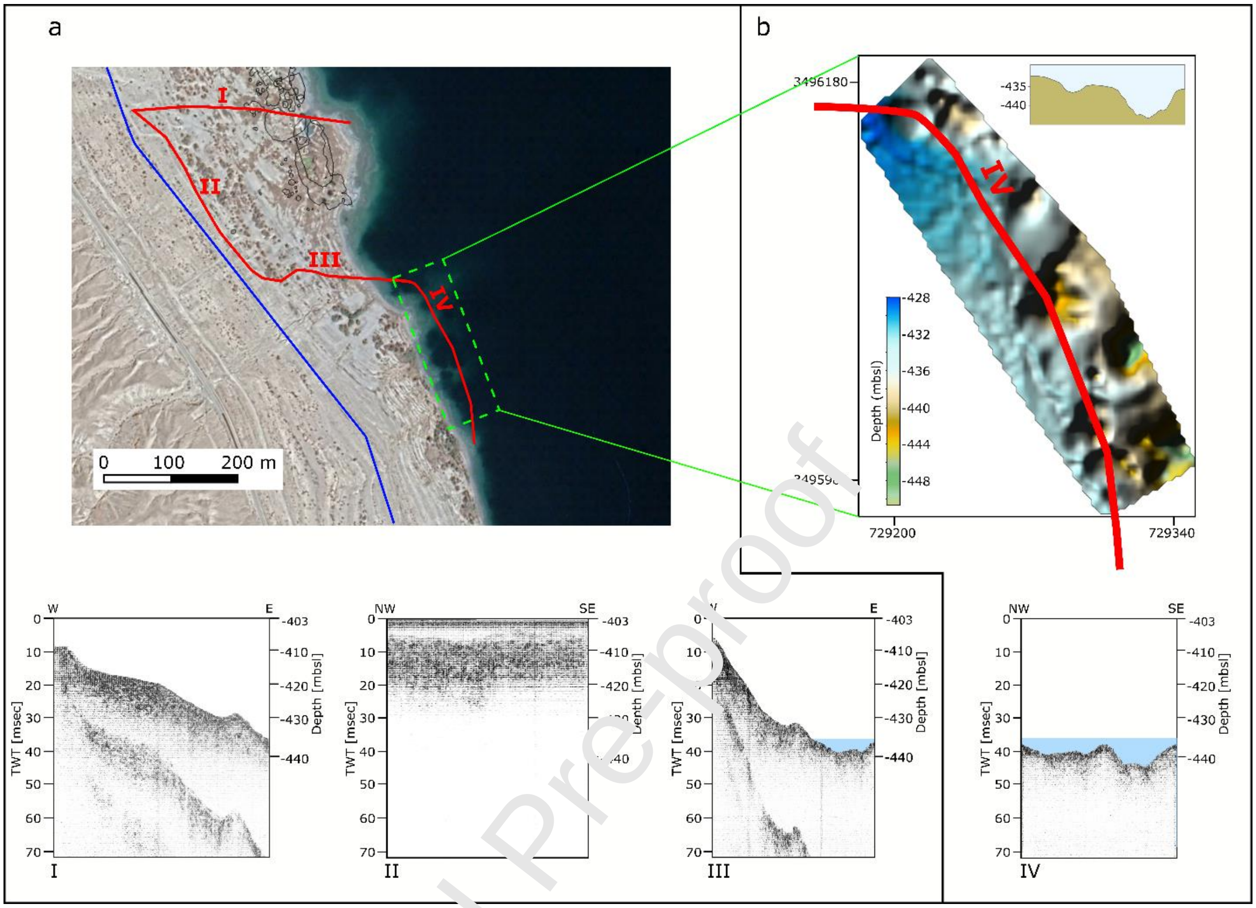

Figure 3. High-resolution 3.5 kHz seismic reflection data collected in 1984 in the vicinity of and across the Darga spring system examined by Ionescu et al. (2012). Left axis is two-way travel time in milliseconds. Right axis is depth below mean sea level in meters (a) Top – Satellite image from 9.3.2019 showing the location of profiles I-IV, which are presented at the bottom. See Figure 1 for general location. Green rectangle marks the limits of (b) Top – bathymetry over the Darga springs collected in 2014 by the Sonobot system showing the approximate location of profile IV. Inset – topography of line IV from the Sonobot data. Bottom – 3.5 kHz profile IV. Blue shading marks the height of the Dead Sea in September 2019 at the time the Satellite image was taken.

3.1.1 Hydrostatic pressure

Hydrostatic pressure was calculated in order to estimate how much pressure was removed from the seafloor between the 1984 survey and 2019.

$$P=\rho g d$$

Where P = hydrostatic pressure at a water depth of d given a water density of ρ.

For the Dead Sea, removal of 31.07 m of water between 1984 and 2019, assuming a constant density of 1240 kg/m^3 (Lensky et al., 2005) is equivalent to the removal of:

$$P=1240(kg/m^3) \times 9.8(m/s^2) \times 31.07(m) = 377{,}562.64\ kg/ms^2 = 377{,}562.64\ Pascal$$

$$= 377{,}562.64\ N/m^2 = 3.7262 atm$$

Where 1 N/m^2 = 9.86923e^{-6} atm.

3.2 Seismic data

Figure 3 presents the analysis of the 1984 3.5 kHz high-resolution seismic reflection data over the Darga spring system. Four profiles cover the 750 m long shoreline. The northern section (profile I) crosses a sinkhole field, which was defined by the Geological Survey of Israel (GSI), while the profile IV crosses the exact springs examined by Ionescu et al. (2012), which is still under shallow water. Both areas were underwater during the 1984 survey and water depths ranged from ca 5-40 m. As can be seen, the lake floor is undulating, exhibiting 2-5 m deep pits (Fig. 3b). The seismic data across the entire region is acoustically blanked, with a suggestion of gas/fluid escape features. In fact, profile II is totally blanked and has the appearance of gas cloud escape along its entire length. In terms of seismic amplitudes and nature of reflections, there is no clear difference between the northern and southern areas.

Seismic data from the (GSI-defined) sinkhole field that lies onshore, some 15 km to the south of the Darga springs (Fig. 4a) shows a similar series of depressions in the lake floor of 1984. Data are blanked under these depressions and there seems to be plumes visible in the water column, at the western edge of the profile. Examination of the lake-floor multiple indicates that the bottom in this area should be flat and slightly sloping upwards towards the west (land) and not dome shaped as it seems to appear on the cross-section. To the east, outside the defined sinkhole field, data become coherent with seismic reflectors becoming clearly visible in the subsurface.

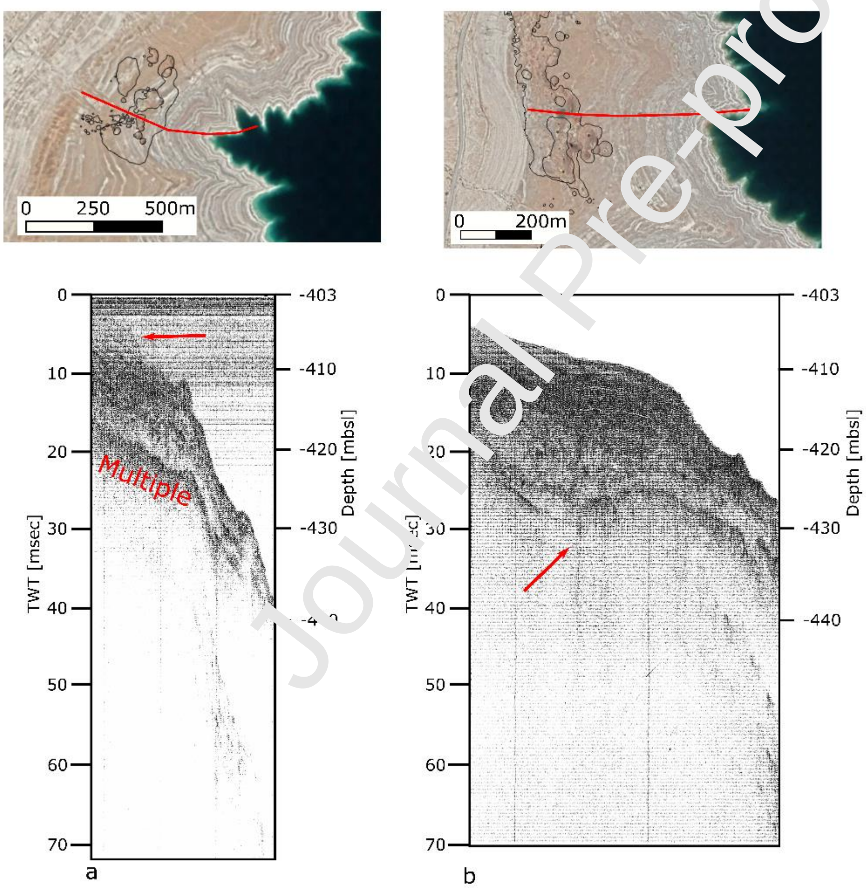

Figure 4. High-resolution 3.5 kHz seismic reflection data collected in 1984. Left axis is two-way travel time in milliseconds. Right axis is depth in meters below sea level. Top images – location (red lines) on Google Earth image from 12.4.2020. Black polygons

mark pockmarks defined by the GSI (https://egozi.gsi.gov.il/WebApps/hazards/sinkholes_subsidence/ Last Accessed Jan. 30th, 2023). See Figure 1 for general locations. (a) Line 93.5 from near Ein Geddi showing the lake floor multiple and its overall trend. Red arrow might point to a deviation from this trend on the lake floor and could possibly indicate gas/fluid escaping into the water column. (b) Line 105.75, which crosses a small water-filled depression marked as a sinkhole just to the south of the study area. Red arrow points to a vertical lineament that cuts through the sediments. Note how the seismic reflections bend towards this feature on both of its sides. In addition, they are clear and not blanked indicating that they are not gas/fluid bearing. The expression of this lineament on the lake floor is a very small depression.

3.3 Sonobot

Results of the Sonobot bathymetric mapping verified the location of springs offshore the Darga alluvial fan. Seepages (i.e. active spring systems), reported by SCUBA divers, were seen mainly at the lowermost parts of deep submarine funnels. The funnels are indicated in blue colors in Figure 2.

4. Discussion

High-resolution 3.5 KHz seismic reflection data collected in 1984 in shallow water along the western shore of the Dead Sea revealed a vast number of depressions on the lake floor. Examination of this data over an area of verified underwater springs (the Darga spring system), allows for the characterization of such features in the dataset. The presence of acoustic blanking on seismic data (Figs. 3 and 4) is a telltale sign of gas/fluid escape (e.g. Lazar et al., 2019 and references therein). However, since active fluid outflow has been documented from springs and seeps (Ionescu et al., 2012), blanking in the seismic data is henceforth interpreted as fluid escape. Evidence for such blanking appears across the data from the Darga springs, leading to the conclusion that these were actively seeping in 1984. The hydrostatic pressure at the time would have been almost 4 atm more than today, indicating that these features did not form due to the removal of this pressure as a result of lowering lake levels but have been there at least for a number of decades. It can cautiously be concluded therefore, that these are relatively stable features.

As can be seen from Figs. 1, 3 and 4, the spacing between the 1984 survey lines (250 m) is too large in relation to the actual spatial distribution of a verified spring system to be able to fully characterize it. To obtain a better image of the submarine springs, lake floor topography was examined across the Darga spring system 30 years after the seismic survey (Fig. 3b) through the collection of high-resolution bathymetric data. The combined seismic and bathymetric dataset indicates that the depths and morphology of the springs have remained more-or-less the same during the 30 years that passed between the two surveys (1984-2014). In addition, they can be found in exactly the same location (i.e., they have not migrated with lowering lake levels). While Levy et al. (2020) suggested that lake levels fluctuations lead to the migration of terrestrial springs and to a change in spring discharge volumes (with some springs drying up and new ones emerging), results presented here seem to indicate that the submarine springs, at least in the Darga area, belong to a more stable system that could be connected to a deep-seated process.

Data show that some features defined today as on land sinkholes, exhibit seismic characteristics that are similar to those of the verified submarine springs. Line 93.5 (Fig. 4a) crosses a defined sinkhole field in its western part. However, examination of the seismic data clearly shows signs of blanking in this area. The dome-shaped “lake floor” resembles a plume of escaping from the depression located at the eastern side of the profile pointing to active fluid escape. This raises the possibility that these were indeed underwater springs in 1984. However, a comprehensive analysis of all the 1984 seismic survey in comparison to the sinkhole/spring definition is beyond the scope of this study,

One of the most investigated and monitored sites for sinkhole development in the Dead Sea is Shalem/Mineral Beach (Fig. 4b; e.g. Abelson et al., 2006; 2018). Interestingly enough, the seismic data show an unblanked, fault-related shallow depression underwater in 1984 that corresponds today to a small, water-filled sinkhole on land. Tectonics has been suggested in the past as the controller of sinkholes at Mineral Beach (e.g. Ezersky et al., 2017). From the data presented here it would seem that there is a linear feature that is "feeding" this depression, a pipe or chimney similar to what is found in many marine-related pockmarks (e.g., Lazar et al. 2016 and references therein). Seismic reflectors dip towards this pipe from both the west and the east and there may be indications for small offsets, although the quality of the data is too poor to say for certain. The depression on the lake floor is minor. This could be an example of a large water seep without clear boundaries observed by Ionescu et al. (2012) or of a different type of feature, which is more in keeping with classic seafloor pockmarks where fluid flows through a conduit (such as a fault) and is expelled on the seafloor (e.g. Hovland et al., 2002; Schramm et al., 2021).

The relation between sinkholes and springs in the Dead Sea should be assessed in relation to other such similar systems. Sinkholes formed by evaporite dissolution are often found along with saline/brackish/fresh water spring systems (e.g. Ege, 1984). These can be found in Texas (Gustavson et al., 1982), New Mexico (Land, 2003), the Canyonlands section of the Colorado Plateau (sinkholes: Gutiérrez, 2004; springs: Crossey et al., 2009), Sichuan Basin China (sinkholes: Wang et al., 2010; springs: Guo et al., 2019), Ebro Valley Spain (Acero et al., 2015) and northeastern Italy (Calligaris et al., 2020). As with the Dead Sea, these features are often attributed to the presence of tectonic faults. However, in all of these cases mentioned above, the setting is terrestrial and not lacustrine although sinkholes themselves are often considered lakes (e.g. the Bottomless Lakes in New Mexico - Martinez et al., 1998; Land, 2003; the sinkhole lakes of southern Turkey - Pisanty et al., 2020; the Blackwood sinkhole in the Bahamas - Tamalavage et al., 2020). In Lake Seminole, southeastern US, both submarine sinkholes and submarine springs have been reported as separate and distinct features (Torek et al., 2005), yet neither are related to drops in lake levels, as in the Dead Sea (e.g. Abelson et al., 2017; Abelson, 2021 and references therein). In other places, such as Sirino Lake in Italy (e.g. Giampaolo et. al, 2016), Dry Lake Valley Arizona and Lake Peigneur Louisiana (Martinez et al., 1998), the formation of sinkholes can lead to the draining of water from an existing lake.

The Dead Sea seems to be a different case. It is not a karst or sinkhole lake, nor is it currently being drained by the >6000 sinkholes that have appeared along its western and eastern shores during the last few decades. The accepted mechanism for sinkhole formation around the lake is the dissolution of a subsurface salt layer by fresher groundwater from the nearby aquifers that is migrating lakewards as a result of the dropping water levels. As lake levels drop, the edge of the sinkhole belt also migrates lakewards, with new sinkholes forming a few meters to 10s of meters behind the new shoreline. This has been well documented for the eastern side of the lake (e.g. Watson et al., 2019) and implied for the western side (Yechieli et al., 2006; Abelson et al, 2017). This lakeward migration cannot explain the presence of **older** sinkholes within the lake itself since they would have had to "jump" over the area, which is currently under deformation. The Darga "sinkholes" do not appear to develop on the backshore as lake levels drop but seem to become exposed at the water's edge, thus implying that this mechanism does not adequately describe the formation of the underwater features, as also pointed out by Charrach (2019). Results of the current study also show that at least some of these features have been in place for decades, thus their formation seems to be unrelated to the drop in lake levels. Therefore, it can be concluded, that these features are indeed submarine springs and not groundwater-discharging sinkholes that formed underwater similar to Lake Huron (where limestone dissolution by groundwater led to its seepage from a collapse feature - Coleman, 2002; Biddanda et al., 2006) or Sawa Lake in Iraq whose deepest part contains a sinkhole that is discharging water into the lake and maintaining it (Merkel et al., 2021).

An alternative mechanism for sinkhole formation in the Dead Sea was proposed by Charrach (2019) - that of dissolution of faulted halite sediments by artesian water, which leads to the collapse of the overlying sediment. This would then be more in line with Abelson et al. (2003) and Closson et al. (2005) who suggest that hidden, active faults acting as conduits for groundwater flow are responsible for the spatial distribution of sinkholes on land. However, according to the models of Oz et al. (2020), while the faults offset the buried halite layer, the mechanism that actually forms the sinkhole is still related to the lakeward migration of the FSI, which dissolves the offset halite. The flow of freshwater along the faults themselves plays a minor role in the formation process. In contrast, the underwater spring systems need open channels to overcome the FSI (Strey, 2014), maintain activity, shape, size and depth. Their formation mechanism thus may be the result of groundwater flow through active tectonic faults without the need for dissolution and collapse. Ben Avraham and Ballard (1987) and Niemi and Ben Avraham (1997) did in fact suggest that submarine springs were located along active tectonic faults within the lake and they act as conduits and facilitate fluid flow from deep below, although they did not map the location of the springs in detail. The verified underwater spring system examined in the present study and by Ionescu et al. (2012), offshore the Darga alluvial fan, is located near (but not on) tectonic faults both on land (Eyal et al., 2002) and in the lake (Fig. 1; e.g. Niemi and Ben-Avraham, 1997; Lazar et al., 2006). However, the current active fault map for the Dead Sea (Niemi and Ben Avraham, 1997) shows that the Darga system lies some 2.5 km to the west of the nearest active fault, thus stressing the lack of knowledge on nearshore and terrestrial faults.

Additional studies (e.g. Ionescu et al., 2012; Siebert et al., 2014a) have postulated that submarine springs must be connected to a high-pressure flow system, which is able to penetrate the FSI along the Dead Sea, probably along tectonic faults and cracks. Fractures in the sediment would force variable rates of flow depending on width of the fractures, thus possibly leading to the different chemical compositions found in the underwater springs over a short distance. Despite this, the springs identified by Ben Avraham and Ballard (1987) and Niemi and Ben Avraham (1997) were located in relatively deep water; the shallowest being at 0.32 seconds (two-way travel time) or roughly some 280 m below the surface of the lake in July 1984. Therefore, it would seem that there is another system of springs located in deeper waters. Similar to seafloor pockmarks, they may be expulsion features and not collapse ones. Thus, springs, as opposed to sinkholes, do not form as a result of sudden collapse, but are pre-existing features that become exposed (rather than formed) on land due to dropping lake levels. In conclusion, while they may look similar, sinkholes and springs are two different phenomena.

The aim of this study was to characterize and point to the presence of submarine springs as a long-lived stable feature that exists alongside the formation of sinkholes in the Dead Sea. Our results show a large number of submarine springs that have existed over time and which still discharge an important amount of freshwater from the adjacent aquifers into the lake. It is hence a largely underestimated part of the hydrological budget of the lake and the connected fresh groundwater resources. As such, it is worthy of its own study and should not be studied together with other morphologically similar features such as sinkholes. The acceptance of submarine springs as a distinct geological phenomenon and their consideration as a remarkable groundwater outlet into the lake will lead to more realistic groundwater resource models of the Judea and Samaria Eastern Mountain aquifer than exist today.

Aside from its great historical, cultural and geographical significance, the Dead Sea is also one of the region's most important tourist resources. While not a high-densely populated area, the Dead Sea alone receives around 46% of the 3.6 million foreign tourists that come to Israel annually and is a major tourist attraction for locals as well. The Jordanian side also receives close to 1.5 million tourists a year. To date, great efforts and resources are being dedicated to understanding, mapping and trying to predict sinkhole formation and associated hazards. On the other hand, no efforts have been made to distinguish these features from the underwater spring systems, which hardly anything is known about. Once exposed on land, they are counted as sinkholes (e.g. https://egozi.gsi.gov.il/WebApps/hazards/sinkholes_subsidence/ Last Accessed Jan. 30th, 2023), thus skewing the hazard potential for the area. This inflates the number of true sinkholes making it more difficult to understand their patterns of occurrence as well as the ability to predict new formation. While sinkholes are a crucial and important element in the Dead Sea hazard assessment, these studies portray only a partial picture, with a large gap, that of the underwater springs, missing from the story. Since lake levels in the Dead Sea are dropping at an accelerated pace, this can be used as a case study for other lacustrine environments in the world that are suffering the same fate (i.e. underwater springs and lowering lake levels), but at a much slower pace such as Great Salt Lake and Utah Lake (e.g. Baskin, 1998) or the Salton Sea (Svensen et al., 2007).

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Bibliography

1. Abelson, M. 2021. Hydrological and geological controls on the evolution of the Dead Sea sinkholes, p. 273-298, In: U. Kafri and Y. Yechieli [eds.], The many facets of Israel's hydrogeology. Springer Hydrogeology. Springer, Cham.
2. Abelson, M., G. Baer, V. Shtivelman, D. Wachs, E. Raz, O. Crouvi, I. Kurzon, and Y. Yechieli. 2003. Collapse-sinkholes and radar interferometry reveal neotectonics concealed within the Dead Sea basin. Geophys. Res. Lett. 30: 1545.
3. Abelson, M., Y. Yechiel, O. Crouvi, G. Baer, D. Wachs, A. Bein, and V. Shtivelman. 2006. Evolution of the Dead Sea sinkholes, p. 241-253. In: Y. Enzel, A. Agnon, and M. Stein [eds.], New frontiers in Dead Sea paleoenvironmental research. Geological Society of America Special Paper 401.
4. Abelson, M., Y. Yechieli, G. Baer, G. Lapid, N. Behar, R. Calvo, and M. Rosensaft. 2017. Natural versus human control on subsurface salt dissolution and development of thousands of sinkholes along the Dead Sea coast: J. Geophys. Res. 122: 1262–1277.
5. Abelson, M., T. Aksinenko, I. Kurzon, V. Pinsky, G. Baer, R. Nof, and Y. Yechieli. 2018. Nanoseismicity forecasts sinkhole collapse in the Dead Sea coast years in advance. Geology 46: 83–86.
6. Acero, P., L.F. Auqué, J.P. Galve, F. Gutiérrez, D. Carbonel, M.J. Gimeno, Y. Yechieli, M.P. Asta, and J.B. Gómez. 2015. Evaluation of geochemical and hydrogeological processes by geochemical modeling in an area affected by evaporite karstification. J. Hydrol. 529: 1874-1889.

7. Akawwi, E., A. Al-Zouabi, M. Kakish, F. Koehn, and M. Sauter. 2008. Using thermal infrared imagery (TIR) for illustrating the submarine groundwater discharge into the eastern shoreline of the Dead Sea-Jordan. Am. J. Environ. Sci. 4: 693-700.

8. Al-Halbouni, D., E.P. Holohan, L. Saberi, H. Alrshdan, A. Sawarieh, D. Closson, T.R. Walter, and T. Dahm. 2017. Sinkholes, subsidence and subrosion on the eastern shore of the Dead Sea as revealed by a close-range photogrammetric survey. Geomorphology 285: 305-324.

9. Al-Weshah, R. 2000. The water balance of the Dead Sea: an integrated approach. Hydrol.14: 145-154.

10. Avrahamov, N., Y. Yechieli, R. Purtschert, Y. Levy, J. Sultenfuß, V. Vergnaud, and A. Burg. 2018. Characterization of a carbonate karstic aquifer flow system using multiple radioactive noble gases (3 H- 3 He, 85 Kr, 39 Ar) and C as environmental tracers. Geochim. Cosmochim. Acta. 242: 213–232.

11. Beaudoin, J., A. Sade, B. Schulze, and J. Hall. 2011. Dead Sea multi-beam echo sounder survey. Hydro Int. 15: 21-23.

12. Ben-Avraham, Z., and R.D. Ballard. 1984. Near bottom temperature anomalies in the Dead Sea. Earth Planet. Sci. Lett. 71: 356–360.

13. Biddanda, B.A., D.F. Coleman, T.H. Johengen, S.A. Ruberg, G.A. Meadows, H.W. Van Sumeren, R.R. Rediske, and S.T. Kendall. 2006. Exploration of a submerged sinkhole ecosystem in Lake Huron. Ecosystems. 9: 828–842.

14. Burg, A., Y. Yechieli, and U. Galili, 2016. Response of a coastal hydrogeological system to a rapid decline in sea level; the case of Zuqim springs - The largest discharge area along the Dead Sea coast. J. Hydrol. 536: 222–235.

15. Calligaris, C., L. Zini, S. Nisio, and S. Piano. 2020. Sinkholes in the Friuli Venezia Giulia region focus on the evaporates, p. 73-90. In: M. De Maio and A. Tiwari [eds], Applied Geology. Springer, Cham.

16. Charrach, J. 2019. Investigations into the Holocene geology of the Dead Sea basin. Carbonates Evaporites. 34: 1415–1442.

17. Closson, D., N.A. Karaki, Y. Klinger, and M.J. Hussein. 2005. Subsidence and sinkhole hazard assessment in the southern Dead Sea area, Jordan. Pure Appl. Geophys. 162: 221–248.

18. Coleman, D.F. 2002. Underwater archaeology in Thunder Bay National Marine Sanctuary, Lake Huron - Preliminary results from a shipwreck mapping survey. Mar. Technol. Soc. J. 36: 33-44.

19. Crossey, L.J., K.E. Karlstrom, A.E. Springer, D. Newell, D.R. Hilton, and T. Fischer. 2009. Degassing of mantle-derived CO2 and He from springs in the southern Colorado Plateau region—Neotectonic connections and implications for groundwater systems. Geol. Soc. Am. Bull. 121: 1034–1053.

20. Ege, J.R. 1984. Formation of solution-subsidence sinkholes above salt beds. U.S. Geological Survey Circular 897.

21. Eyal, Y., I. Bruner, G. Cadan, Y. Enzel, and E. Landa. 2002. High-resolution seismic study of the Nahal Darga fan-delta, Dead Sea, Israel, with the aim to relate the surface and subsurface tectonic structures. EGU Stephan Mueller Special Publication Series 2: 21–33.

22. Ezersky, M.G., L.V. Eppelbaum, A. Al-Zoubi, S. Keydar, A. Abueladas, E. Akkawi, and B. Medvedev. 2013. Geophysical prediction and following development sinkholes in two Dead Sea areas, Israel and Jordan. Environ. Earth Sci. 70: 1463–1478.

23. Ezersky, M.G., A. Legchenko, L. Eppelbaum, A. Al-Zoubi. 2017. Overview of the geophysical studies in the Dead Sea coastal area related to evaporite karst and recent sinkhole development. International Int. J. Speleol. 46 :277–302.

24. Gasperini, L., and G. Stanghellini. 2009. SEISPRHO: An interactive computer program for processing and interpretation of high-resolution seismic reflection profiles. Comput. Geosci. 35: 1497-1507.

25. Gavrieli, I., Y. Yechieli, L. Halicz, B. Spiro, A. Bein, and D. Efron. 2001: The sulfur system in anoxic subsurface brines and its implication in brine evolutionary pathways: the Ca-chloride brines in the Dead Sea area. EPSL. 186: 199-213.

26. Gavrieli, I., N.G. Lensky Y. Dvorkin, V. Lyakhovsky, and I. Gertman. 2006. A Multi-component chemistry-based model for the Dead Sea: Modifications to the 1D Princeton Oceanographic Model. Ministry of National Infrastructures, Geological Survey of Israel Report GSI/24/2006, 62 p.

27. Giampaolo, V., L. Capozzoli, S. Grimaldi, and E. Rizzo. 2016. Sinkhole risk assessment by ERT: The case study of Sirino Lake (Basilicata, Italy). Geomorphology. 253: 1-9.

28. Gräbe, A., T. Rödiger, K. Rink, T. Fischer, F. Sun, W. Wang, C. Siebert, and O. Kolditz. 2013. Numerical analysis of the groundwater regime in the western Dead Sea escarpment, Israel + West Bank. Environ. Earth Sci. 69: 571–585.

29. Guo, J., X. Zhou, Y. Zhang, M. Ta, and Y. Wang. 2019. Occurrence and hydrochemical characteristics of saline and salty springs in the Sichuan Basin of China, Geofluids. 2019: 8671973.

30. Gustavson, T.C., W.W. Smpkins, A. Alhades, and A. Hoadley. 1982. Evaporite dissolution and development of karst features on the rolling plains of the Texas panhandle. Earth. Surf. Process. Landf. 7: 545–563.

31. Gutiérrez, F. 2004. Origin of the salt valleys in the Canyonlands section of the Colorado Plateau: Evaporite-dissolution collapse versus tectonic subsidence. Geomorphology. 57: 423-435.

32. Gutiérrez, F., A.H. Cooper, and K.S. Johnson. 2008. Identification, prediction and mitigation of sinkhole hazards in evaporite karst areas. Environ. Geol. 53: 1007-1022.

33. Hart, B.S., and T.S. Hamilton. 1993. High resolution acoustic mapping of shallow gas in unconsolidated sediments beneath the strait of Georgia, British Columbia. Geo-Mar. Lett. 13: 49–55.

34. Häusler, S., M. Weber, C. Siebert, M. Holtappels, B.E. Noriega-Ortega, D. De Beer, and D. Ionescu. 2014. Sulfate reduction and sulfide oxidation in extremely steep salinity gradients formed by freshwater springs emerging into the Dead Sea. FEMS Microbiol. Ecol. 90: 956– 969.

35. Hovland, M., J.V. Gardner, and A.G. Judd. 2002. The significance of pockmarks to understanding fluid flow processes and geohazards. Geofluids. 2: 127-136.

36. Ionescu, D., C. Siebert, L. Polerecky, Y.Y. Munwes, C. Lott, S. Häusler, M. Bižić-Ionescu, C. Quast, J. Peplies, F.O. Glöckner, A. Ramette, T. Rödiger, T. Dittmar, A. Oren, S. Geyer, H-J. Stärk, M. Sauter, T. Licha, J.B. Laronne, and D. de Beer. 2012.

Microbial and chemical characterization of underwater fresh water springs in the Dead Sea. PLoS ONE 7(6): e38319.

37. Judd, A.G., and M. Hovland. 1992. The evidence of shallow gas in marine sediments. Cont. Shelf Res. 12:1081–1095.

38. Kottmeier, C., A. Agnon, D. Al-Halbouni, P. Alpert, U. Corsmeier, T. Dahm, A. Eshel, S. Geyer, M. Haas, E. Holohan, N. Kalthoff, P. Kishcha, C. Krawczyk, J. Lati, J.B. Laronne, F. Lott, U. Mallast, R. Merz, J. Metzger, A. Mohsen, E. Morin, M. Nied, T. Rödiger, E. Salameh, A. Sawarieh, B. Shannak, C. Siebert, and M. Weber. 2016. New perspectives on interdisciplinary earth science at the Dead Sea: The DESERVE project. Sci. Total Environ. 544: 1045-1058.

39. Land, L.A. 2003. Evaporite karst and regional ground-water circulation in the lower Pecos Valley of southeastern New Mexico, p. 227-232. In K.S. Johnson and J.T. Neal [eds.], Evaporite karst and engineering/environmental problems in the United States: Oklahoma Geological Survey Circular 109.

40. Laronne Ben-Itzhak, L., and H. Gvirtzman. 2005. Groundwater flow along and across structural folding: An example from the Judean Desert, Israel. J. Hydrol. 312: 51–69.

41. Lazar, M., Z. Ben Avraham and U. Schattner. 2006. Formation of sequential basin along a strike slip fault – geophysical observations from the Dead Sea basin. Tectonophysics. 421: 53-69.

42. Lazar, M., G. Lang, and U. Schattner, 2016. Coincidence or not? Interconnected gas/fluid migration and ocean-atmosphere oscillations in the Levant Basin. Geo-Mar. Lett. 36: 293–306.

43. Lazar, M., L. Gasperini, A. Polonia, M. Lupi, and A. Mazzini. 2019. Constraints on gas release from shallow lake sediments – a case study from the Sea of Galilee Geo-Mar. Lett. 39: 377-390.

44. Lensky, N.G., Y. Dvorkin, V. Lyakhovsky, I. Gertman, and I. Gavrieli. 2005. Water, salt, and energy balances of the Dead Sea. Water Resour. Res. 41 W12418.

45. Levy, Y., A. Burg, Y. Yechieli, and H. Gvirtzman. 2020. Displacement of springs and changes in groundwater flow regime due to the extreme drop in adjacent lake levels: The Dead Sea rift. J. Hydrol. 587: 124928.

46. Mallast, U., R. Gloaguen, S. Geyer, T. Rodiger, and C. Siebert. 2011. Derivation of groundwater flow-paths based on semi-automatic extraction of lineaments from remote sensing data. Hydrol. Earth. Syst. Sci. 15: 2665–2678.

47. Mallast, U., F. Schwonke, R. Gloaguen, S. Geyer, M. Sauter, and C. Siebert. 2013a. Airborne thermal data identifies groundwater discharge at the north-western coast of the Dead Sea. Remote Sens. 5: 6361-6381.

48. Mallast, U., C. Siebert, B. Wagner, M. Sauter, R. Gloaguen, S. Geyer, and R. Merz. 2013b. Localisation and temporal variability of groundwater discharge into the Dead Sea using thermal satellite data. Environ. Earth Sci. 69: 587–603.

49. Martinez, J.D., K.S. Johnson, and J.T. Neal. 1998. Sinkholes in evaporite rocks: surface subsidence can develop within a matter of days when highly soluble rocks dissolve because of either natural or human causes. Am. Sci. 86: 38-51.

50. Mazor, E. 1997. Groundwaters along the western Dead Sea shore, p. 265-276. In: T.M. Niemi, Z. Ben-Avraham J.R. and Gat [eds], The Dead Sea, The lake and its settings. Oxford Monograph on Geology and Geophysics, No 36.

51. McCulloch, C. 2006. DEAD SEA: A future for the Dead Sea Basin: options for a more sustainable water management. INCO International Scientific Cooperation ICA3-CT2002-10019 Joint Synthesis Report.

52. Merkel, B., S. Al-Muqdadi, and T. Pohl. 2021. Investigation of a karst sinkhole in a desert lake in southern Iraq. FOG - Freib. Online Geosci. 58: 85-90.

53. Munwes, Y.Y., S. Geyer, D. Katoshevski, D. Ionescu, T. Licha, C. Lott, J.B. Laronne, and C. Siebert. 2019. Discharge estimation of submarine springs in the Dead Sea based on velocity or density measurements in proximity to the water surface. Hydrol. Process. 34: 455-472.

54. Neev, D., and J.K. Hall. 1979. Geophysical investigations of the Dead Sea. Sediment. Geol. 23: 209-238.

55. Niemi, T.M., and Z. Ben-Avraham. 1997. Active tectonics in the Dead Sea Basin, p. 73-81. In: T.M. Niemi, Z. Ben-Avraham and J.R. Gat [eds], The Dead Sea; The lake and its settings: New York, Oxford University Press, Oxford Monographs on Geology and Geophysics, No. 36.

56. Oz, I., E. Shalev, Y. Yechieli, I. Gavrieli, E. Levanon, and H. Gvirtzman. 2016. Salt dissolution and sinkhole formation: Results of laboratory experiments. J. Geophys. Res. Earth. Surf. 121: 1746– 1762.

57. Pisanty, I., M. Rodríguez-Sánchez, P.T. Orozco, L.A. Granados-Hernández, S. Escobar, and M.C. Mandujano. 2020. Disturbance and the formation and colonization of new habitats in a hydrological system in the Cuatro Ciénegas Basin, p 265–282. In: M. Mandujano, I. Pisanty, and L. Eguiarte [eds], Plant diversity and ecology in the

Chihuahuan Desert. Cuatro Ciénegas Basin: An endangered hyperdiverse oasis. Springer, Cham.

58. Salameh, E., and H. El-Naser. 1999. Does the actual drop in Dead Sea level reflect the development of water sources within its drainage basin? Acta. Hydroch Hydrob. 27:5–11.
59. Schramm, B., C. Berndt, A. Dannowski, C. Böttner, J. Karstens, and J. Elger. 2021. Seismic imaging of an active fluid conduit below Scanner Pockmark, Central North Sea. Mar. Pet. Geol. 133: 105302.
60. Shalev, E., V. Lyakhovsky, and Y. Yechieli. 2006. Salt dissolution and sinkhole formation along the Dead Sea shore. J. Geophys. Res. 111 (B3): B03102.
61. Siebert, C., T. Rödiger, U. Mallast, A. Gräbe, J. Guttman, J.B. Laronne, Y. Storz-Peretz, A. Greenman, E. Salameh, M. Al-Raggad, D. Vachtman, A. Ben Zvi, D. Ionescu, A. Brenner, R. Merz and S. Geyer. 2014a. Challenges to estimate surface- and groundwater flow in arid regions: The Dead Sea catchment. Sci. Total Environ. 485-486: 828–841.
62. Siebert, C., U. Mallast, T. Rödiger, M. Strey, D. Ionescu, S. Häusler, B. Noriega, T. Pohl, and B. Merkel. 2014b. Submarine groundwater discharge at the Dead Sea. 23rd Salt Water Intrusion Meeting, June 16-20, 2014, Husum, Germany pp. 366-370.
63. Stein, M. 2001. The sedimentary and geochemical record of Neogene Quaternary water bodies in the Dead Sea Basin – inferences for the regional paleoclimatic history. J. Paleolimnol. 26: 271–282.
64. Stiller, M., and Y.C. Chung. 1984. Radium in the Dead Sea: A possible tracer for the duration of meromixis. Limnol. Oceanogr. 29: 574–586.
65. Strey, M. 2014. 2-D numerical flow and density modeling in Dead Sea Group sediments (Darga, Israel). FOG - Freib. Online Geosci. 36, 134 pp.

66. Svensen, H., D.A. Karlsen, A. Sturz, K. Backer-Owe, D.A. Banks, and S. Planke. 2007. Processes controlling water and hydrocarbon composition in seeps from the Salton Sea geothermal system, California, USA. Geology. 35 85–88.

67. Tamalavage, A.E., P.J. Hengstum, P. Louchouarn, P.L. Fall, J.P. Donnelly, N.A. Albury, S. Coats, and S.J. Feakins. 2020. Plant wax evidence for precipitation and vegetation change from a coastal sinkhole lake in the Bahamas spanning the last 3000 years. Org. Geochem. 150: 104120.

68. Torak, L.J., D.M. Crilley, and J.A. Painter. 2006. Physical and hydrochemical evidence of lake leakage near Jim Woodruff Lock and Dam and of ground-water inflow to Lake Seminole, and an assessment of karst features in and near the lake, southwestern Georgia and northwestern Florida. U.S. Geological Survey Scientific Investigations Report 2005-5084, 90 p.

69. Yechieli, Y. 2006. Response of the groundwater system to changes in the Dead Sea level, p. 113-126. In: Y. Enzel, A. Agnon, and M. Stein [eds.], New frontiers in Dead Sea paleoenvironmental research. Geol. Soc. Am. Spec.

70. Yechieli, Y., and J. Gat. 1997. Geochemical and hydrological processes in the coastal environment of the Dead Sea, p. 253-264. In: T.M. Niemi, Z. Ben-Avraham and J.R. Gat [eds]. The Dead Sea, The lake and its settings. Oxford Monograph on Geology and Geophysics, No 36.

71. Yechieli, Y., and W.W. Wood. 2002. Hydrogeologic processes in saline systems: Playas, sabkhas, and saline lakes. Earth. Sci. Rev. 58: 343-365.

72. Yechieli, Y., M. Abelson, A. Bein, O. Crouvi, and V. Shtivelman. 2006. Sinkhole "swarms" along the Dead Sea coast: reflection of disturbance of lake and adjacent groundwater systems. Geol. Soc. Am. Bull. 118: 1075-1087.

73. Yechieli, Y., M. Abelson, and G. Baer. 2016. Sinkhole formation and subsidence along the Dead Sea coast, Israel. Hydrogeol. J. 24: 601–612.

74. Waltham, T., F. Bell, and M. Culshaw. 2005. Sinkholes and subsidence. Springer, Chichester, 382 pp.

75. Williams, P. 2003. Dolines, p 304-310. In: J. Gunn [ed] Encyclopedia of caves and karst science. Fitzroy Dearborn, New York,

76. Wang, G., S. Liu, Y. Ma, G. Xu, and X. Cai. 2010. Characteristics of subaerial karstification and late reconstruction in the Dengying Formation, Sichuan basin, southwestern China. J. Earth Sci. 21: 290–302.

77. Watson, R.A., E.P. Holohan, D. Al-Halbouni, L. Saberi, A. Sawarieh, D. Closson, H. Alrshdan, N. Abou Karaki, C. Siebert, T.R. Walter, and T. Dahm. 2019. Sinkholes and uvalas in evaporite karst: spatio-temporal development with links to base-level fall on the eastern shore of the Dead Sea. Solid Earth. 10: 1451–1468.

78. Wust-Bloch, H., and M. Joswig. 2006. Pre-collapse identification of sinkholes in unconsolidated media at Dead Sea area by `nanoseismic monitoring' (graphical jackknife location of weak sources by few, low-SNR records). Geophys. J. Int. 167: 1220-1232.

Highlights

- Hazardous sinkholes develop mainly onshore as a result of dropping Dead Sea levels
- Submarine springs develop independent of lake level due to water flow via conduits
- Morphologically, once exposed on land, submarine springs and sinkholes look similar
- Many springs may be wrongly classified as sinkholes