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Sinkholes hazard around the evaporation ponds
Dead Sea southern basin

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Abstract

This report was prepared according to the request of the Dead Sea Preservation Governmental Company (DSPGC), in purpose to review and to present an evaluation of the sinkholes hazard around the evaporation ponds at the southern basin of the Dead Sea. Here we review results from a multi-disciplinary research conducted by the Geological Survey of Israel (GSI), with assistance of the Geophysical Institute of Israel (GII). Observations were obtained by geological mapping, aerial photographs, drilling, groundwater geochemistry, seismic refraction and reflection, and satellite radar interferometry. The suggested model for the formation of the Dead Sea sinkholes is based on the following observations: (1) presence of a thick salt layer (or layers) at depths between 20 and 50 m (depth of layer top), sandwiched between aquiclude layers of clay and silt, (2) identification of cavities within the salt layer in sinkhole sites, (3) presence of water undersaturated with respect to halite in aquifers confined beneath the salt layer, (4) the composition of the groundwater in the salt layer which indicates salt dissolution, and (5) formation of sinkholes along and above buried faults. These observations combine to suggest that the primary cause of sinkhole formation is dissolution of the salt layer by undersaturated groundwater. The interface between the Dead Sea brine and this groundwater migrated eastward due to the Dead Sea decline. Undersaturated water accessed the salt layer via faults that cut through the soft aquiclude layers. The water level at the evaporation ponds has ceased to decline since the early 1970s. Consequently, the sinkholes formation rate along the ponds coastline is significantly lower than the northern basin of the Dead Sea: in the southern basin the rate of sinkhole formation is ~3 sinkholes/year, whereas at the northern basin the formation rate is 200-380 sinkholes/year since 2003. The sinkholes activity in the southern basin is concentrated in five sites, where the most active site is at Neve Zohar with appearance of 28 sinkholes since the early 1980s. According to these findings we have produced potential maps for sinkholes formation which were recently updated by incorporating results from new boreholes. The zonation of the potential levels is based mainly on the distribution of the salt layer obtained from boreholes with auxiliary seismic refraction. At places where the western boundary of the salt layer is ambiguous, we used the elevation distribution of sinkhole sites along the evaporation ponds coastline to determine the potential area for sinkhole formation. In this report we describe in details the criteria for the potential levels and present new potential maps. Finally, we recommend the required operations for the refinement of the potential maps and monitoring in existing boreholes the variations in groundwater regimes.

Introduction

The Dead Sea Preservation Governmental Company (DSPGC) requested the GSI to review the state of sinkholes evolution along the coastline of the evaporation ponds of the Dead Sea Works Ltd. (DSW) in the southern basin of the Dead Sea. We were further requested to suggest other operations in order to refine the contours depicted in the maps of potential levels for sinkholes collapse along the coastline of the Dead Sea. Potential maps were first published in 2004 (Abelson et al., 2004) after a five-year interdisciplinary research conducted by the GSI with the assistance of the Geophysical Institute (Yechieli et al., 2004). Since then the GSI maintains follow-up surveys of sinkhole collapses by scanning aerial photographs along the coastline of the Dead Sea from the northern edge of Mt. Sedom to the northern Dead Sea coast near the inlet of the Jordan River (Abelson et al., 2002, 2003, 2005, 2007). The present report presents a short description of the evolution of the Dead Sea sinkholes and their formation mechanism. We also present a more up-to-date potential map which was refined in recent years by the GSI and/or by the DSW, incorporating new data from boreholes. We also recommend more operations to improve the present potential map along the coastline of the evaporation ponds.

Dead Sea (DS) sinkholes – General background

Collapse-sinkholes started to appear along the Dead Sea (DS) coast in Israel and Jordan in the early 1980s. Sinkhole development has significantly accelerated since 2000 with abrupt occurrence of hundreds of sinkholes. This regional-scale collapse is attributed to the rapid decline of the Dead Sea level (~1 m/y) (Arkin, 1993; Arkin and Gilat, 2000; Taqeiddin et al., 2000; Wachs et al., 2000). The decline of the Dead Sea, which exceeds ~30 m since the early 1930s, reflects human activities such as interception of freshwater supply from the Jordan River and the maintenance of large evaporation ponds by the Dead Sea mineral industries in Jordan and Israel.

According to recent examination of aerial photographs (Abelson et al., 2009, a Geological Survey technical report in preparation) a total of more than 2500 sinkholes appeared along the DS west coast. These sinkholes are clustered in ~50 sinkhole sites along a narrow coastal strip, ~60 km long and 20–1000 m wide, which stretches from the water line westward (Figs. 1 and 3). Each sinkhole site comprises between one and >500 sinkholes. In recent years the growth rate of the number of sinkholes has increased significantly: since 2003 it stands on 200-380 sinkholes per year (Fig. 2). Consequently, more than 80% of the 2500 DS sinkholes occurred since 2000.

The sinkholes tend to develop along lineaments (Raz, 2000; Abelson et al., 2003; Fig. 3), which can be traced up to ~2 km. The orientations of the sinkhole lineaments are strikingly similar to the orientation of the faults forming the DS rift. These two observations imply that the sinkhole formation is related to tectonic faults buried in the rift sediments (Abelson et al., 2003). This notion was strongly supported by seismic reflection and by the absence of spatial relationships between the sinkhole lineaments and surface features such as coast steps, shape of alluvial fans, etc.

The sinkholes are observed in two main sedimentary environments along the Dead Sea western coast, mud-flats and alluvial fans. The alluvial fans are made of coarse gravel alternating with fine-grained sediments (silt and clay), whereas the mud flats are mainly fine-grained sediments. The sinkholes in the alluvial fans tend to be much deeper, where single sinkholes sometimes reach a depth of 20 m (Fig. 2C). In the wet mud plains, the sinkholes are shallower and wider than the sinkholes in the alluvial fans.

Formation mechanism of the Dead Sea sinkholes – Dissolution of 10 kyrs old salt layer

Previous studies have shown that the primary cause for collapse sinkholes around the globe is the formation of cavities by dissolution within layers of soluble rocks (e.g., Martinez et al., 1998; Galloway et al., 1999; Neal and Johnson, 2002). At some stage, overlying layers fail to bridge the growing cavities and collapse structures may reach the surface, forming a sinkhole. In order to assess whether the Dead Sea sinkholes formed by a similar process we have searched for layers of soluble rock in the upper section of the sedimentary fill of the Dead Sea rift, and investigated groundwater chemistry for potential dissolution. The subsurface setting was explored by seismic refraction, boreholes, and sampling of groundwater from the boreholes. The following sub-sections review the key observations obtained by this exploration.

Shallow salt layer buried within the Dead Sea fill: findings from boreholes and seismic refraction

Seismic refraction profiles were conducted along most of the Dead Sea coast by the Geophysical Institute of Israel. These data, and 20 boreholes in the vicinity of seven sinkhole sites, indicate that a salt layer, several-meter-thick, is embedded within the upper part of the sedimentary section along the Dead Sea coast. A typical profile of seismic refraction in the Dead Sea region displays three layers with P-wave velocities of 600-800 m/s, 2000-2300 m/s, and 2900-3600 m/s for the upper to lower layers, respectively. The upper two layers consist of uncemented or unconsolidated alluvial and fluvial sediments. The lower layer, where observed, is the salt layer. This stratigraphy was verified by boreholes in several sites (e.g., Hever-south, Ze'elim, En-Gedi, Shalem, En Bokek, Neve Zohar; Fig. 4), where a solid salt layer was penetrated at depths predicted by the seismic refraction. For example, the borehole Hever-2 at the Hever-south site penetrated an 11 m-thick salt layer at a depth of 24 m, as predicted by the refraction profile (Yechieli et al., 2004). The age of the salt layer was found to be ~10,000 years (Yechieli et al., 1993). The salt layer shows a broad range of P-wave velocities, between 2900-3600 m/s, perhaps due to the occurrence of both solid and "crumbly" salt. Accordingly, we have used seismic refraction profiles cautiously to identify the extension of the salt layer.

The association between sinkhole occurrence and the subsurface salt layer was corroborated by boreholes in seven sinkhole sites, Darga, Shalem, En-Gedi, Mazor, Hever-south, En-Bokek, Neve-Zohar (Fig. 1). At all these sites, a salt layer was penetrated at the vicinity of the sinkholes, supporting a dissolution-collapse origin for the Dead Sea sinkholes (Fig. 4). In addition, a salt layer has *not* been found in boreholes north of the Einot Zukim reservation, an area where sinkholes are absent (Fig. 1).

The depth of the top of the salt layer ranges between 20 and 50 m, and in some locations the thickness of the salt layer exceeds 20 m. We do not yet know whether there is a single salt layer or multiple layers from several stratigraphic units. For this purpose more dating of salt layer in several sites is required.

Cavities within the salt layer

In two of the seven sinkhole sites examined by boreholes, cavities were encountered in the salt layer (Abelson et al., 2006). At the Hever-south site, one borehole (Hever-1) penetrated an 11 m thick salt layer. A second borehole (Hever 3) drilled 40 m south of Hever-1 encountered a cavity at 23-29 m depth, at the same stratigraphic level as the salt layer found in Hever-1. At the Shalem site (Mineral Beach, Fig. 1) the salt layer was penetrated at a depth of 19 m and a cavity was found at its base, over a depth range between 28 to 31 m. A water-proof camera inserted into the cavity through the borehole indicated that the cavity wall is made of coarse-crystal salt (Fig. 5b). The diameter of the cavity is larger than the 1.5 m maximum spread of caliper arms. The cavities found in the salt layers support the inference that salt dissolution causes the formation of the Dead Sea sinkholes.

Hydrology and groundwater chemistry

Alternating fine-grained (clay and silt) and gravel layers occur in the upper sedimentary section along the Dead Sea coast, forming several sub-aquifers. In some locations (e.g. En Gedi area), the groundwater head in the lower sub-aquifer is higher than in the upper sub-aquifer (Yechieli et al., 2004, 2006), indicating upward flow potential. The groundwater in the lower sub-aquifer beneath the salt layer is much less saline (Cl=15 g/l, 78 g/l in various boreholes in En Gedi area; Fig. 3) than the Dead Sea brine (Cl=210 g/l) (Yechieli et al., 2004, 2006). Calculations indicate that whereas the Dead Sea brine is saturated with respect to halite, the dilute groundwater is far below saturation and therefore has the potential to dissolve salt. Furthermore, geochemical evidence proves that dissolution of salt does occur. This is best exhibited by the high Na/Cl ratio of groundwater (0.6) from within the cavity in the salt layer in Mineral-2 borehole, compared to the Dead Sea brine (0.25) (Yechieli et al., 2006). The increased Na/Cl ratio reflects dissolution of the salt layer by groundwater consisting of mixed Dead Sea type brine and more diluted groundwater. In Mineral Beach, the source of the fresher groundwater is thermal brine seepage from deep strata. In En Gedi and most other sites the dilute groundwater is derived from the regional freshwater aquifer recharged in the mountains to the west (Yechieli et al., 2001). The active groundwater flow, which drains to the declining Dead Sea, maintains a continuous flux of undersaturated water through the salt layer, thereby enhancing ongoing dissolution.

Sinkhole lineaments along cryptic, likely active, young faults

Almost all sinkhole clusters display a clear linear shape. Comparison between the trends of the sinkhole lineaments, the exposed faults, and the zigzagging rift wall segments shows a striking similarity (Fig. 6). All features show a predominantly bimodal distribution with NE and NW principal directions (Fig. 6b). No relationship is found between sinkhole lineaments and other surface features such as ancient or current DS shorelines, or alluvial fans. These observations suggest that sinkhole formation is controlled by faults concealed within the rift fill.

To confirm this linkage between buried faults and sinkhole lines we conducted 10 profiles of seismic reflection across and along sinkhole lines in six different sites. In the examined sites the sinkhole lineaments were found to overlie prominent discontinuities. For instance, profiles across the sinkhole lines in the Neve Zohar and Hever-south sites (Figs. 6 and 7) display clear discontinuities interrupting the reflectors beneath the sinkhole lines that offset young sediments several thousands of years old.

The observed linkage between tectonic faults and sinkholes implies genetic relationships, where beside the presence of salt layer, the formation of sinkholes is strongly affected by presence of a prominent tectonic fault. Several-meter-thick aquiclude layers above and below the salt layer (as indicated in several boreholes [Yechieli et al., 2006; Abelson et al., 2006]) may restrict access of the sub-saturated water to the salt layer. The buried tectonic faults may then serve as conduits for the sub-saturated water to percolate to the salt layer through the aquiclude layers, to dissolve the salt layer and promote the development of sinkholes along lineaments parallel to the faults (Abelson et al., 2003). The ascent of sub-saturated water is possible due to overpressure in the confined aquifers below the salt and clayey layers, which was found to be higher than the upper phreatic aquifer in the boreholes along the DS coast (Yechieli et al., 2006).

Sinkhole sites around the evaporation ponds – Dead Sea southern basin

There are five defined sinkhole sites at the Israeli side around the evaporation ponds within the southern basin of the Dead Sea. These sites are (Fig. 1): Mor at the southwestern side of the Lintch strait, Ye'elim adjacent to Mor site at the north-easternmost side of the evaporation ponds, En Bokek, and Neve Zohar. Beside these sinkhole sites we are aware of more sinkhole-collapses at the area of the DSW, but we do not know the exact details such as their dates, locations, and dimensions. In addition, in February and July 2004 two sinkholes collapsed on road 90 opposite to the southern part of Mt. Sdom and in its vicinity.

It is noteworthy that an additional, unusual sinkhole site was found by the areal photographs on the pond coastline, east of the edge of Mt. Sdom, namely the Hemar site (Fig. 1). It seems that the sinkholes of the Hemar site are not the usual sinkholes found along the Dead Sea coast. These sinkholes are probably formed by dissolution of surface salt layer rather than a collapse into a pre-existing cavity, however, this site demands more examination.

If the primary trigger for sinkholes formation is the DS level decline, the ensuing question is how sinkholes form along the coastline of the evaporation ponds, where the water level has not been declining since the early 1970s. The site of Yeelim and Mor located at the Lintch strait are probably subjected to the hydrological regime of the northern basin (Yechieli et al., 2006, 2007). Therefore, this question is restricted to En Bokek, Neve Zohar, and Road 90 sinkholes.

Since 2004 less than 20 sinkholes appeared along the coast of the evaporation ponds of the southern basin, i.e. ~3 sinkholes per year. Beside the two sinkholes along Road 90 near

Mt. Sdom, all sinkholes appeared in the site of Neve Zohar (Eli Raz, Tamar R.C., follow-up reports of sinkhole collapses). This means that seepage of undersaturated groundwater occurs around the alluvial fan of W. Zohar. We have previously suggested two plausible explanations for the sinkhole formation in this area (Yechieli et al., 2004): 1. A result of earlier dissolution triggered due the sea level decline prior the early 1970s. 2. A possible connection between the deeper sub-aquifers and the DS north basin. At this stage, we do not have sufficient data to confirm/contradict the latter notion. Nevertheless, the occurrence of sinkholes around the evaporation ponds is two-orders of magnitude lower than the northern basin where the water level keeps declining rapidly. This fact confirms the Dead Sea shrinkage as the primary control on the DS sinkholes.

Potential levels for sinkholes formation

The observations presented in the previous sections point out that the formation of the Dead Sea sinkholes is caused by dissolution of a salt layer about 10 kyr old (Yechieli et al., 2006; Shalev et al., 2006). The dissolution is by groundwater that is undersaturated with respect to halite that flows from the west towards the Dead Sea. This flow is triggered by the shrinkage of the Dead Sea, which in turn causes the retreat of the hypersaline groundwater eastward, thereby inducing the eastward flow of the less saline, undersaturated groundwater (Yechieli et al., 2006). For this reason, recognition of the extension of the salt is crucial for the delineation of potential levels of the sinkholes hazard (Abelson et al., 2004). The potential levels depicted on the enclosed maps (Figs. 9-12) are as follows:

Potential zone 1 – Zones of sinkhole sites (yellow in maps), including buffer areas around the sinkhole clusters/sites (black dots).

Potential zone 2 – Zones of high potential for sinkhole appearance (red in maps), comprising the major conditions for sinkhole formation, namely, (i) the presence of a salt layer in the sub-surface, (ii) decline in the level of the Dead Sea and the associated groundwater. In the southern basin, where the decline of the DS level is absent, this zone encircles the "*potential zone 1*", i.e., the sinkhole sites of Neve Zohar and En Bokek (Figs. 9, 11-12).

Potential zone 3 – Low potential zones in which the possibility of sinkhole formation is low but cannot be ruled out (green in maps). These include areas where the probability of finding a salt layer in the subsurface is very low but still exists.

As mentioned above the primary trigger for sinkhole formation is the shrinkage of the Dead Sea. This notion is strongly supported by the fact that in the northern basin of the Dead Sea, where there is a constant level decline, the growth rate in sinkholes number is 200-380 sinkholes/year in the recent 5 years (Fig. 2) (Abelson et al., 2007, 2009-a report in preparation). On the other hand, in the southern basin there is no water level decline since the early 1970s, the rate of sinkhole formation is only several sinkholes per year concentrated mainly in Neve Zohar site. This means that the cessation of the water level decline has moderated significantly the formation of sinkholes. Thus, the coastline of the southern basin is classified as a low probability zone (green in Fig. 1), despite the presence of a sub-surface salt layer. The western boundary of the salt layer is unknown along most of the ponds coastline. Exceptions are the areas of Neve Zohar and Yeelim sinkhole sites, where arrays of several boreholes enable to depict the western boundary of the salt layer (Figs. 10 and 12). At the regions where the western boundary is unknown we depicted the boundary of the green province along the topographic contour of -390 m. Across the alluvial fans the green boundary was along -380 m contour (Fig. 11). The use of these topographic contours as boundaries of the green province were inferred from the elevation distribution of the sinkhole sites (Fig. 8). However, in order to refine this boundary in most areas along the coastline of the ponds, additional boreholes are required.

Recommendations for future work

The western boundary of potential areas for sinkhole collapses should be refined by boreholes, in order to verify or to reject the presence of a salt layer. This point information should be backed up by seismic refraction in order to obtain a better regional distribution of the salt layer. Most of the area along the ponds coastline requires such a refinement. The exceptions, as mentioned above, are the areas of Yeelim fan and Neve Zohar, where several boreholes enabled some of this refinement (Figs. 10 and 12). Still, more boreholes are required also in these sites to remove uncertainties.

Beside the presence of salt layer, a crucial condition for the formation of new sinkholes is the presence of groundwater sub-saturated with respect to halite. Furthermore, groundwater with a chemical signature of salt dissolution (Na/Cl> 0.4) increase the probability of sinkhole collapses even where sub-saturated groundwater is not found. Therefore, a routine sampling of groundwater from existing boreholes is needed. Consequently, we suggest that electrical conductivity profiles and general chemical analyses of water samples should be monitored twice a year in selected boreholes. In addition, all pumping data should be documented. We also suggest that monitoring of water levels in existing boreholes (~50 boreholes) will take place four times a year. Continuous level measurements with automatic transducers and data loggers should be installed in ten representative boreholes.

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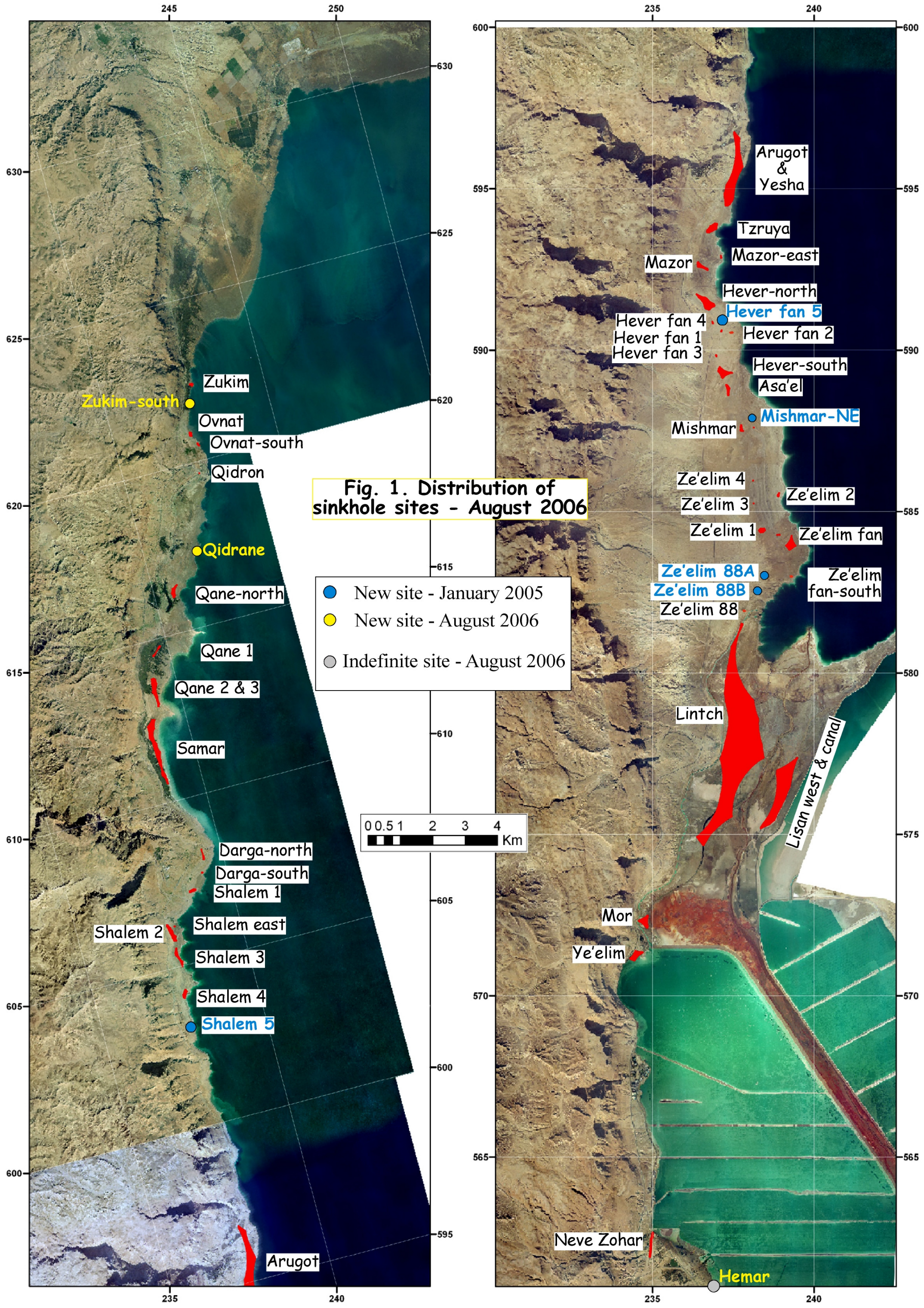

Figure 1. Distribution of sinkhole sites along the Dead Sea coast, updated from aerial photographs from August 2006 (Abelson et al., 2007).

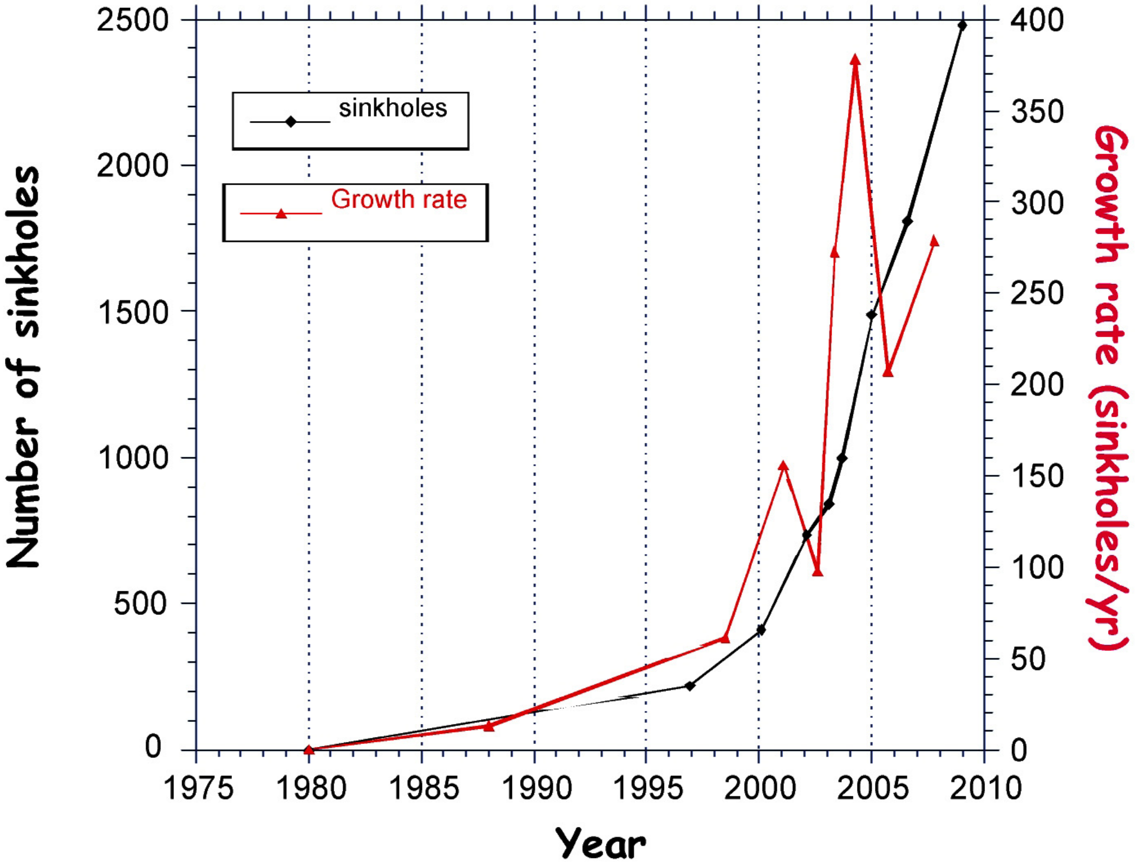

Figure 2. Growth rate (red line) and cumulative number of the sinkholes (black line) along the Dead Sea shorelines (updated to December 2008).

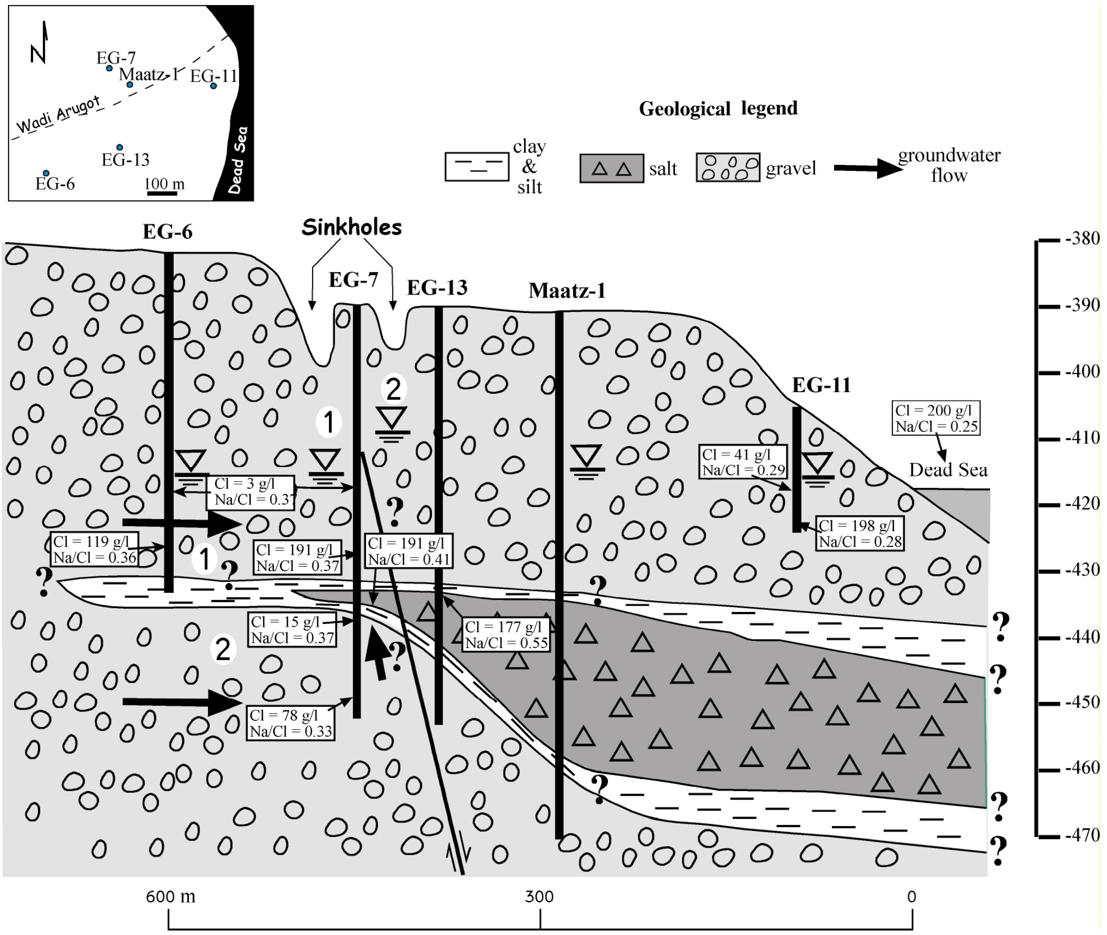

Figure 3. A schematic hydro-geological section across the elongated cluster of sinkholes in En-Gedi plantations (Yechieli et al., 2006). The water chemistry in borehole EG-13 exhibits a clear signal for salt dissolution (Na/Cl=0.55). Relatively low saline water was found within the lower sub-aquifer in EG-7, (Cl=15-78 g/l, as compared to the Dead Sea brine, Cl=220 g/l). This water is confined beneath the salt layer, showing a hydraulic head 5 m higher than the phreatic water level. As in many other sinkhole sites, the lineament over which the sinkholes develop here is found close to the margins of the salt layer.

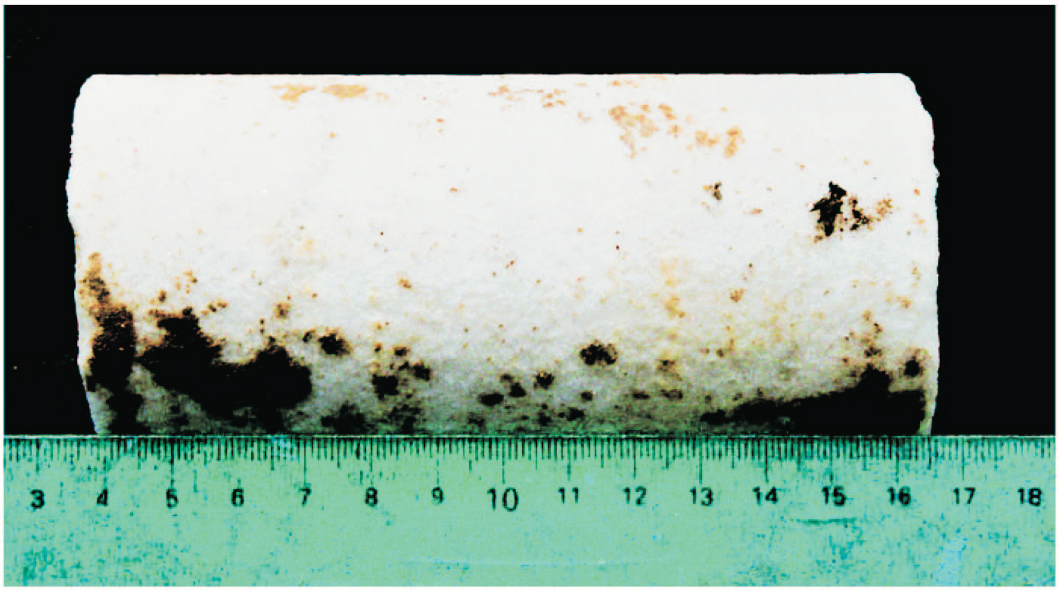

Figure 4. A salt core from the En Bokek-1 borehole.

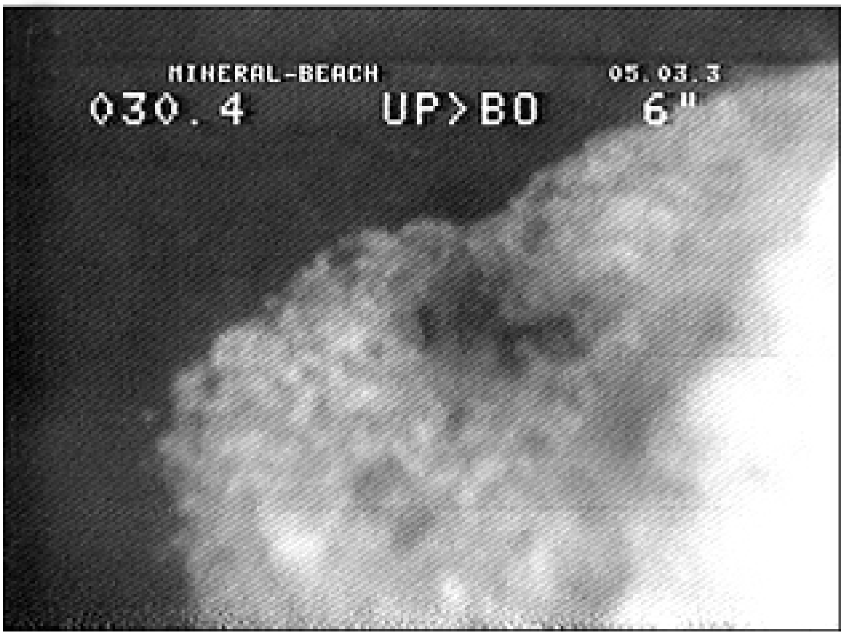

Figure 5. A photograph from the cavity found in the borehole Mineral-2 at the Shalem site (Fig. 1). Note the coarse salt crystals in the cavity wall.

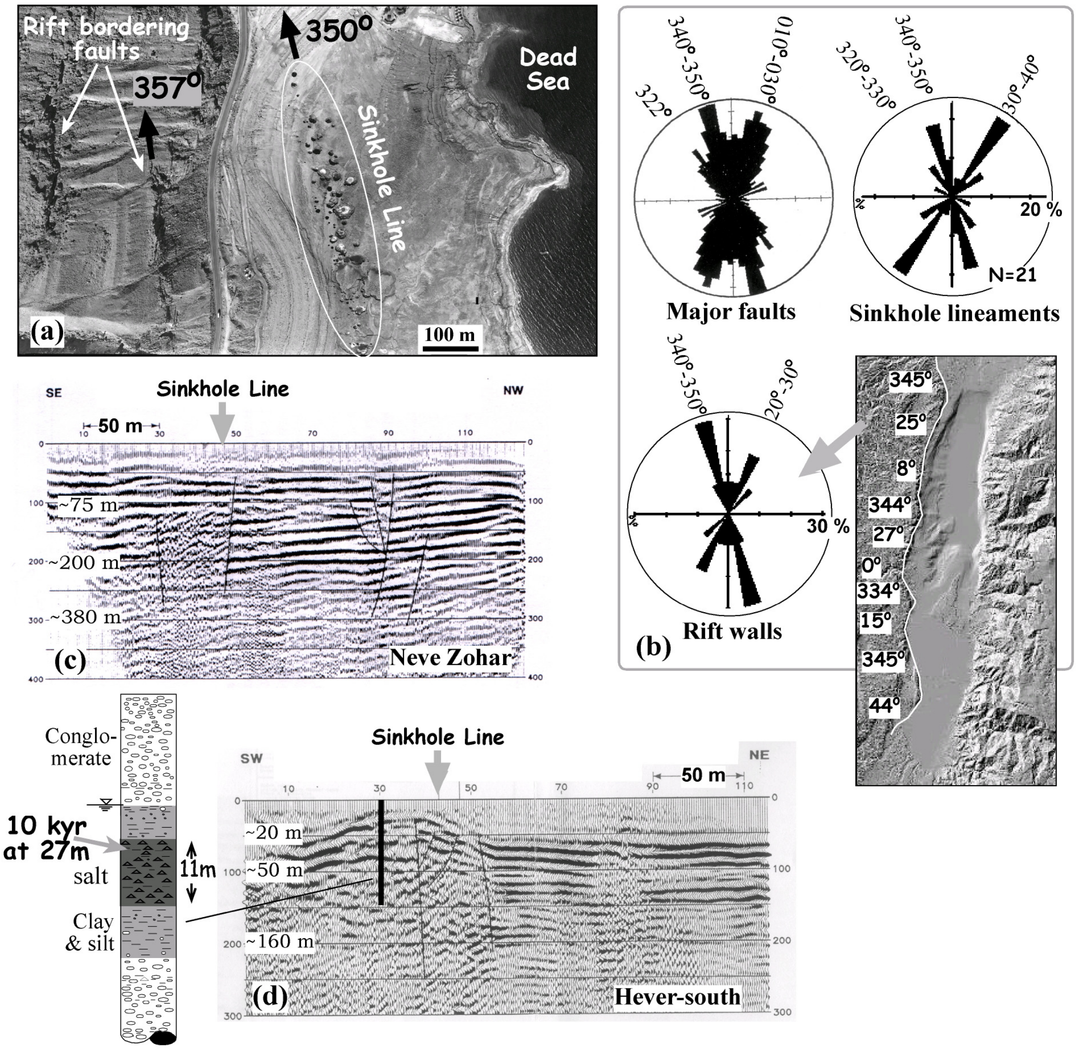

Figure 6. Sinkhole lineaments and buried faults (after Abelson et al., 2003). (a) A rectified air photograph from 1999 showing the sinkhole site of Hamme Shalem (Fig. 1). The sinkholes are aligned sub-parallel to the local rift-margin faults. (b) Area weighted, rose-diagrams of strikes of major faults on the western margin of the DS rift [Sagy et al., 2002] (cumulative length 322 km), sinkhole lines, and strikes of the western rift wall segments displayed on a digital shaded-relief map [Hall, 1994]. Note the similar bimodal distribution of the various populations, implying a tectonic control on the sinkhole lines. (c) and (d) Seismic reflection profiles across the Neve Zohar and Hever-south sites, respectively (see Fig. 1 for location) showing prominent discontinuities beneath the sinkhole lines. In Neve Zohar, a sequence of disturbed layers is bounded by two discontinuities interpreted as faults. The northwesterly discontinuity is beneath the sinkhole line. A seismic reflection profile parallel to the sinkhole line at this site shows no discontinuity, suggesting that the buried discontinuities/faults are parallel to the sinkhole line. The lithology in an 80 m deep borehole at Hever-south site is presented in (d); ^{14}C dating from a 27m-deep clay horizon within the salt layer indicates an age of ~10,000 years, suggesting that the observed offsets shallower than 20 m are younger than 7500 years.

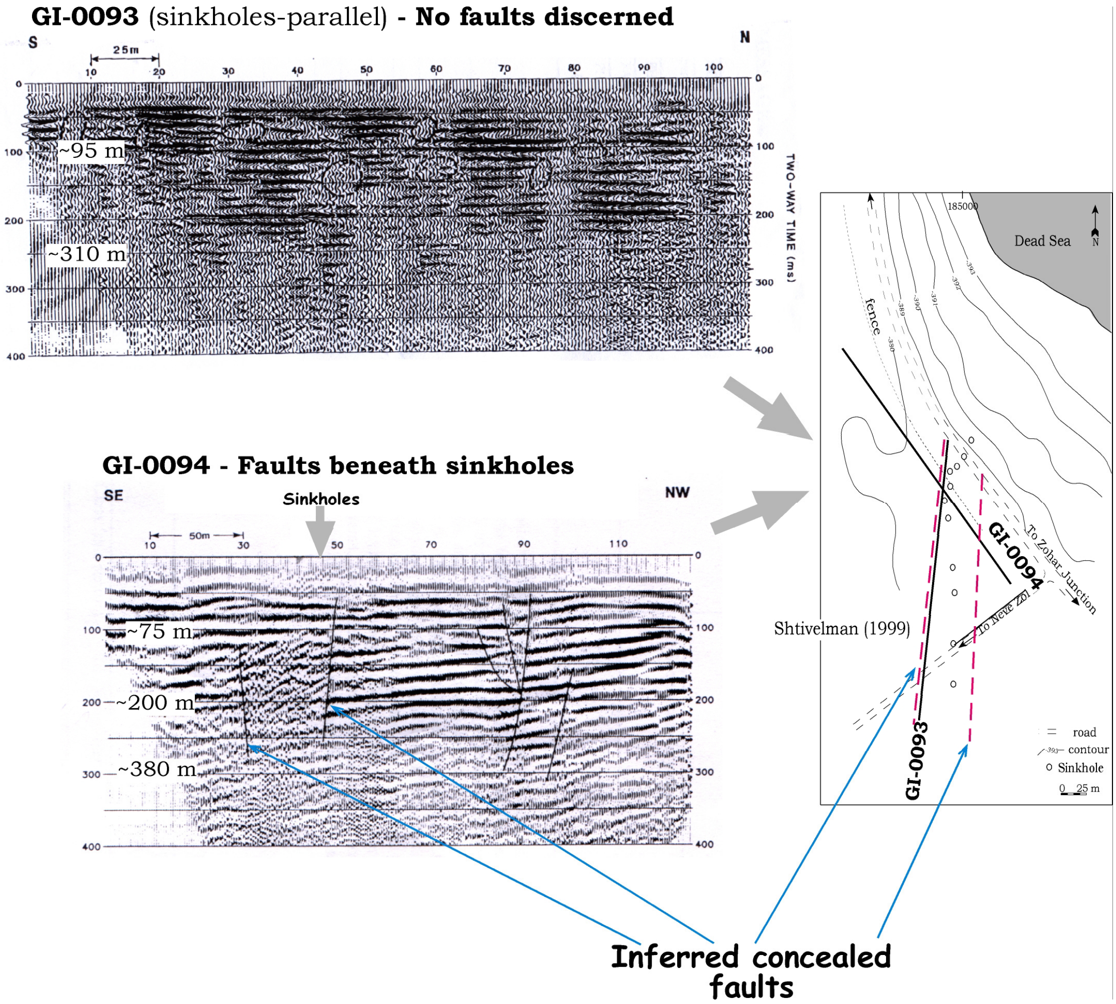

Figure 7. Two seismic reflection profiles provide the fault structure beneath the sinkhole lineament of Neve Zohar. GI-0094 profile reveals a graben beneath the sinkhole line, whereas GI-0093 indicates no sign of faulting. Therefore, the latter is probably parallel to the fault strike. This assumption is in agreement with parallelism between the fault strike and the sinkhole lineament.

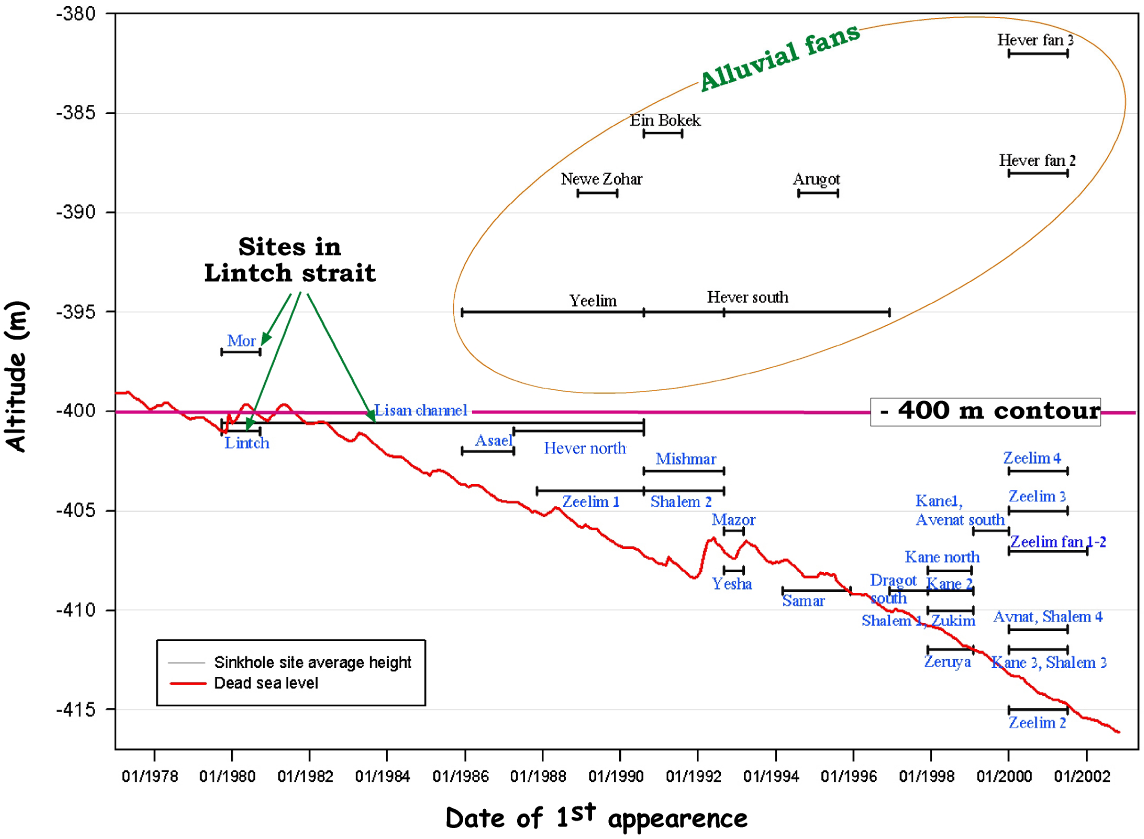

Figure 8. History of the decline of the Dead Sea level (red line) and altitude of sinkhole sites (horizontal bars). Appearance of sinkhole sites began in 1980 when the Dead Sea level was at ~400 m below sea level. The bars describe error in time of first appearance of sinkhole sites. Most sinkhole sites are found below -400 m, while accompanying the Dead Sea decline, except for those in the alluvial fans.

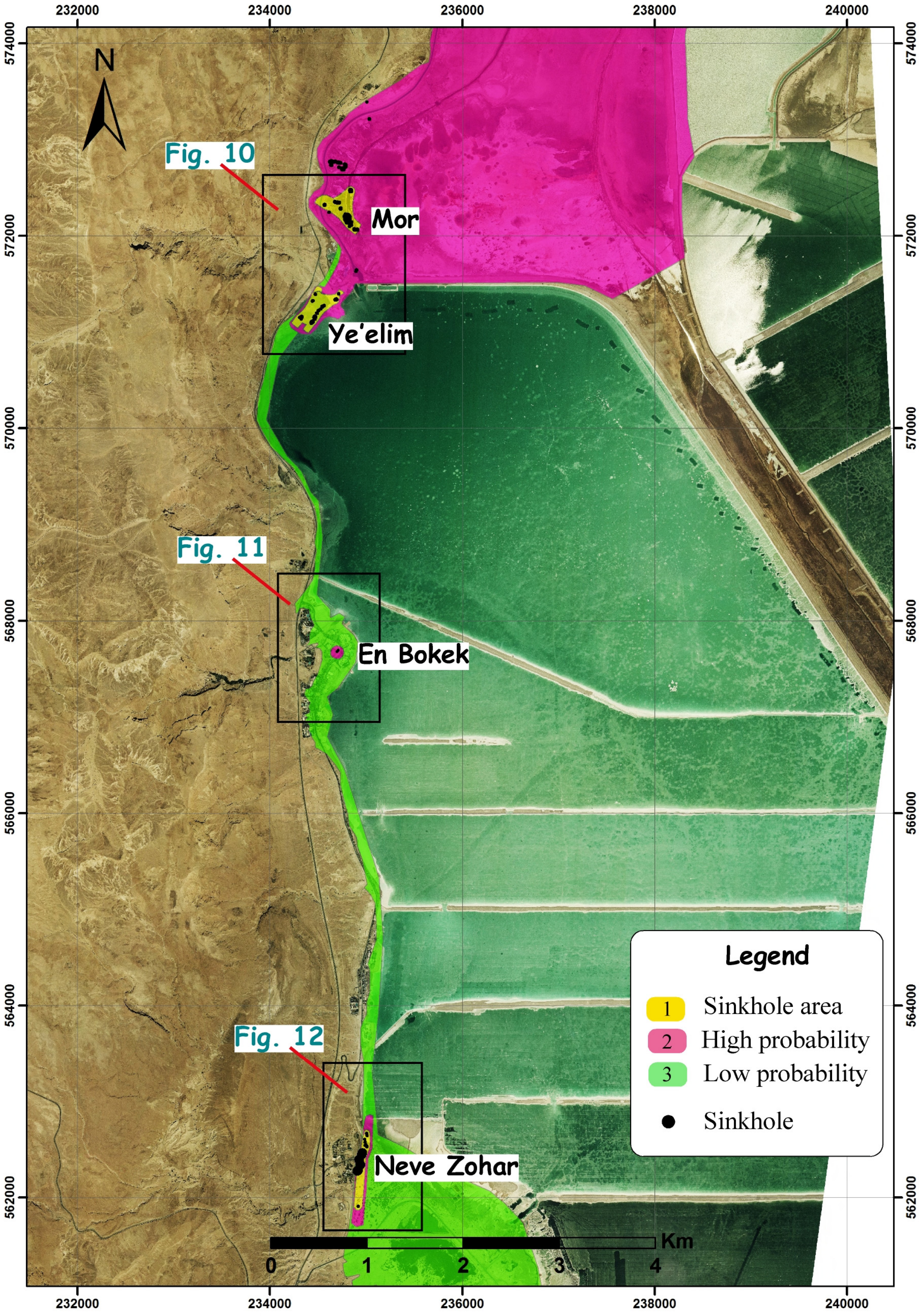

Figure 9. An updated map of potential levels for sinkhole collapses along the coastline of the evaporation ponds. The locations of more detailed maps, Figs. 10-12, for individual sites are marked.

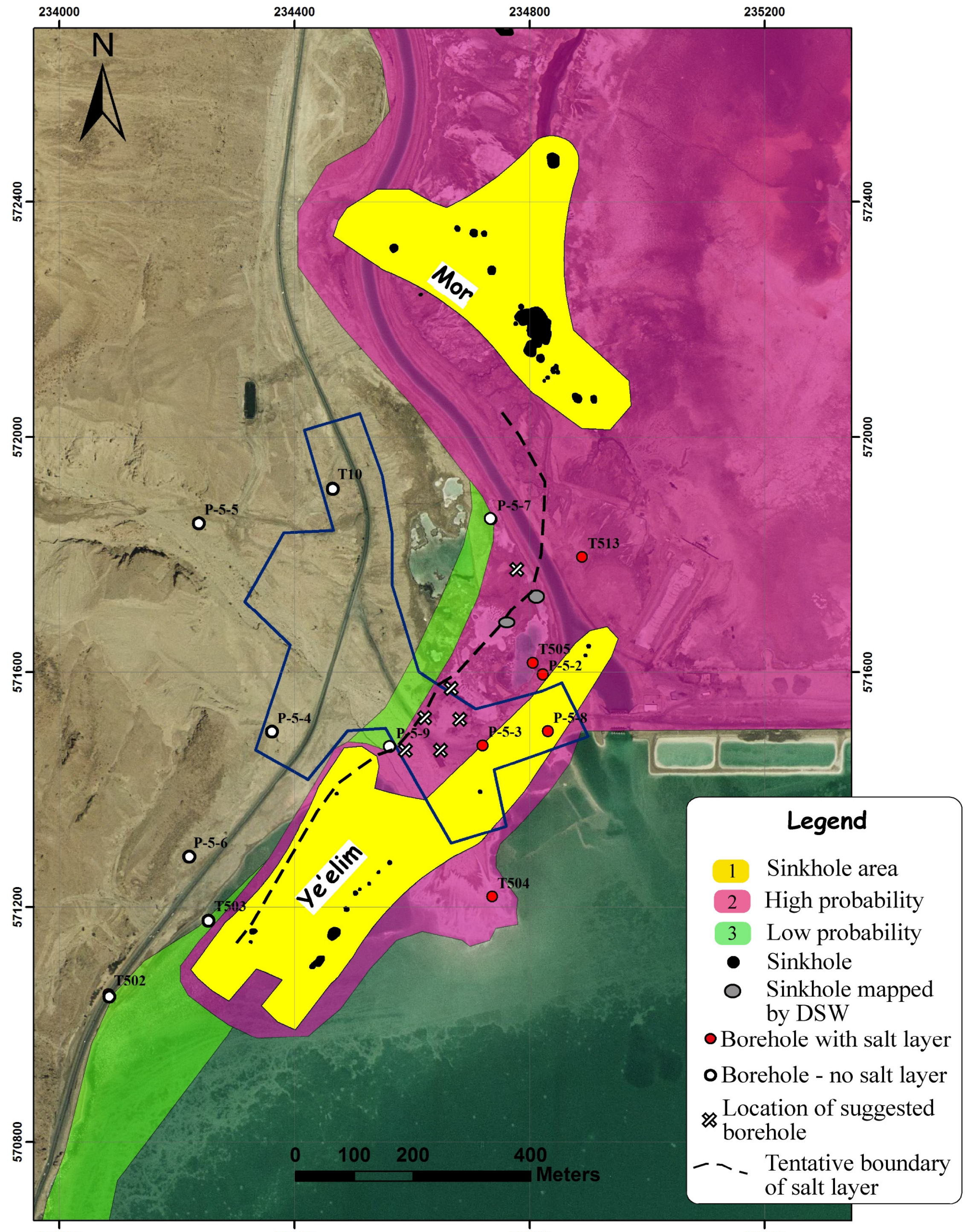

Figure 10. Map of potential levels of sinkholes formation in the area of the northern junction, W. Ye'elim fan.

Figure 11. Map of potential levels of sinkholes formation around En Bokek.

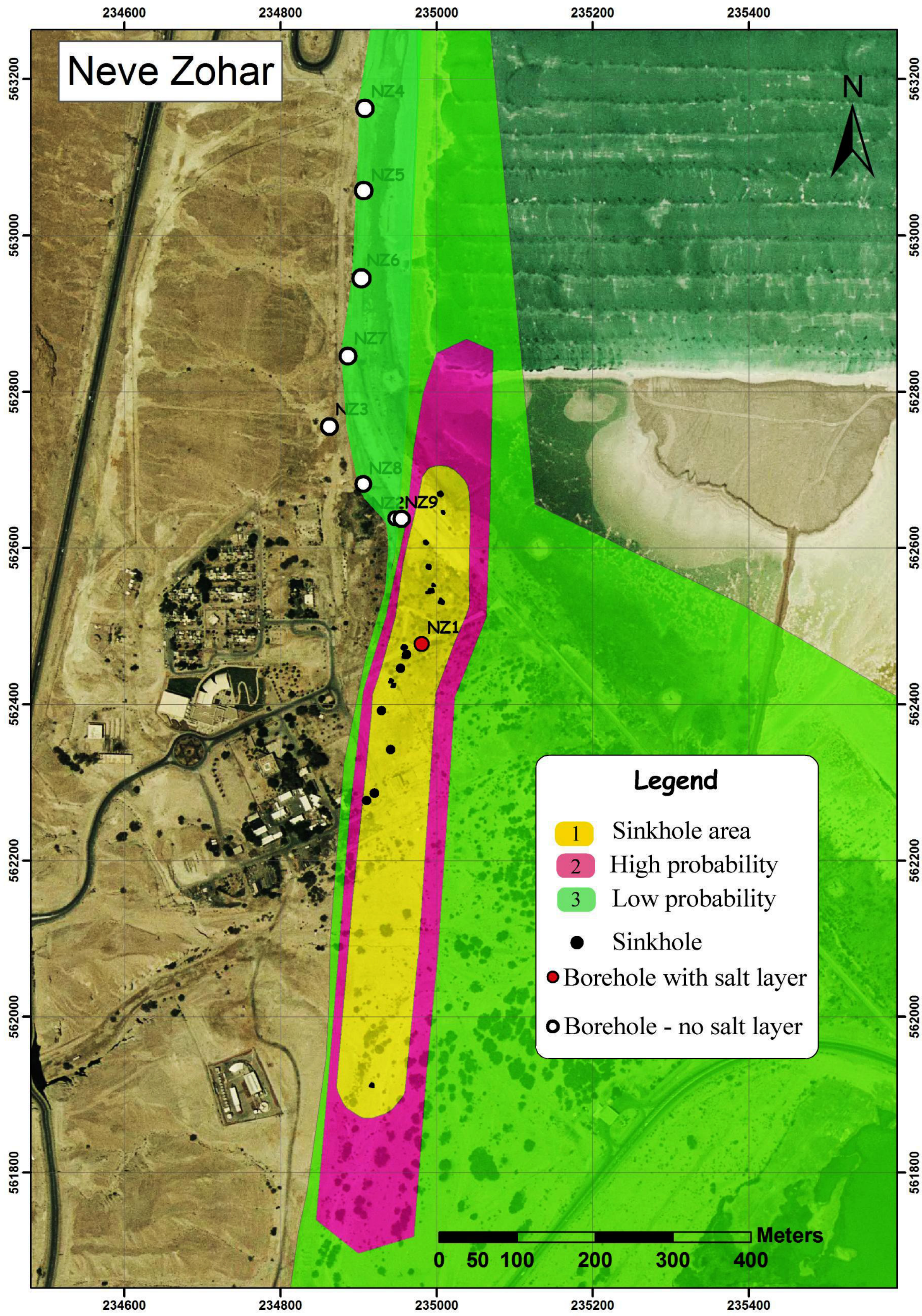

Figure 12. Map of potential levels of sinkholes formation around Neve Zohar.