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Quantitative Assessment of In-situ Salt Karstification Using Shear Wave Velocity, Dead Sea

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ABSTRACT

The Dead Sea (DS) coastal areas have been dramatically affected by sinkhole formation since around 1990. Such sinkholes along both Israeli and Jordanian shores are linked to karst cavities that form through slow salt dissolution. A quantitative estimate of such in-situ salt karstification would be an important indicator of sinkhole hazard. One of the indications of salt karstification is its increased hydraulic conductivity, caused by the development of dissolution cavities forming conducting channels within the salt layer. We measured the hydraulic conductivity (K) versus shear-wave velocity (Vs) of DS salt in situ for estimating the actual salt karstification in areas of sinkhole development. These parameters were measured with the Magnetic Resonance Sounding (MRS) and Multichannel Analysis of Surface Waves (MASW) methods, respectively. Understanding of the field relationships was augmented by similar inter-relations obtained in the laboratory on samples of DS salt. In-situ salt velocities Vs vary from 750 m/s to over 1650 m/s, while hydraulic conductivity (K) in the same zones varies between about 10^{-4} m/s to slightly over 10^{-8} m/s. Both field and laboratory K and Vs values fit the exponential function $\ln(K) = -0.0045 * V_s - 5.416$ with a determination coefficient (R^2) of 0.88. A classification based on Vs and K was generated for salt conditions and the corresponding degrees of sinkhole hazard, which was verified in the Mineral Beach sinkhole development area. The mapping of sinkhole sites shows that they form within highly conductive zones with $K \geq 5.5 * 10^{-5}$. It is suggested that this methodology, with some modification, can be used for evaluating the conductive properties of karstified rock and associated sinkhole hazards.

1. Introduction

The Dead Sea (DS) coastal areas of Israel and Jordan have been dramatically affected by sinkhole formation since around 1990 (Fig. 1). This development continues today, with an obvious potential for further collapse beneath roads, dwellings and in the potash works. Most researchers accept that such sinkholes near the shorelines are caused by salt dissolution (karstification) by under-saturated groundwater (Frumkin and Raz, 2001; Abelson et al. 2006; Yechieli et al., 2006; Legchenko et al. 2008a). Our hypothesis proposes that sinkholes form along a dissolution front over the edge of a buried salt layer (western edge in Israel and eastern edge in Jordan). This hypothesis is based on seismic refraction surveys carried out mainly along the western DS shore (Ezersky, 2006; Ezersky et al., 2010) and in Ghor Al-Haditha (El-Isa et al., 1995; Abueladas and Al-Zoubi, 2004).

Following the dissolution front salt edge concept, we have suggested a general model of the salt layer deposited around the DS. This model (Fig. 2) suggests that there is a 10–30 m-thick buried salt belt around much of the DS shore, controlling the sinkhole hazard (Legchenko et al., 2008b; Ezersky and Frumkin, 2013). All known cases of collapses and accidents including the alarming catastrophe at pond 18 in Jordan (Closson, 2005) have occurred within this salt belt. The model presented in Fig. 2 enables us to conclude that: (1) the dissolution front follows an ancient shoreline which existed at the stage of salt unit deposition (10.2–10.8 ka) – modern sinkholes are formed along this dissolution front; and (2) the buried salt layer extends from the modern Dead Sea shoreline landward, towards the dissolution front, permitting its investigation from the surface.

The working hypothesis is that circulating groundwater dissolves salt, causing a gradual increase of salt porosity and permeability. This increase, connected with the evolution of pore space during salt dissolution, was suggested by Bernabé et al. (2003). Shalev et al. (2006) applied this mechanism to DS salt dissolution, demonstrating that porosity and permeability are important factors in both salt dissolution and sinkhole development.

In our previous works, a geophysical methodology was proposed for sinkhole-hazard evaluation based on (1) salt-edge delineation by seismic refraction, and (2) the spatial distribution of bulk resistivities (ρ_x) and shear-wave velocities in salt (Vs). The mapping of ρ_x is based on

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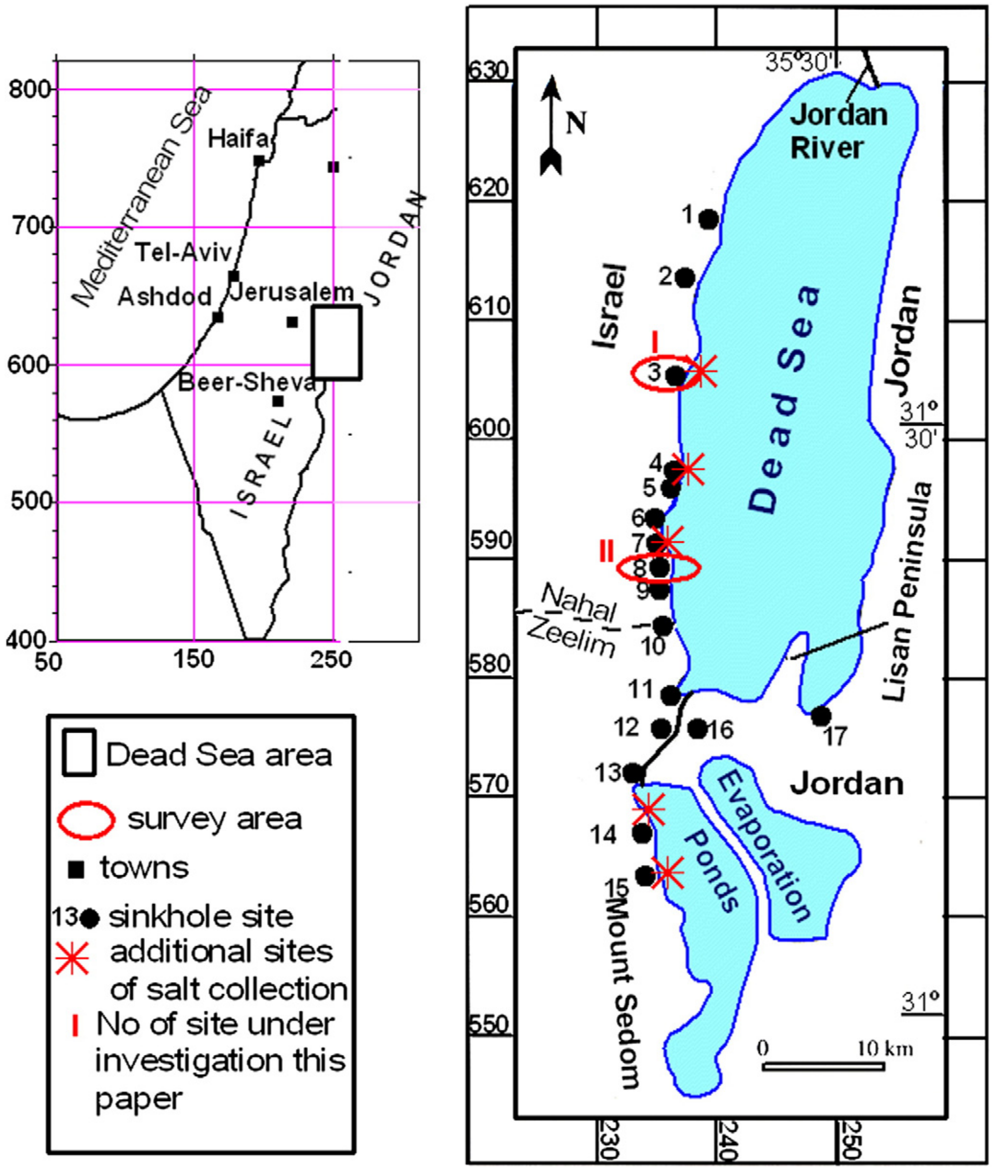

Fig. 1. Sinkhole sites along Dead Sea shore: 1 Palms, 2 Samar Spring, 3 Mineral Beach, 4 Ein Gedi and Nahal Arugot, 5 Yesha, 6 Zeruya, 7 Nahal Hever North, 8 Nahal Hever South, 9 Asa'el, 10 Nahal Ze'elim, 11 Masada, 12 Rahaf, 13 Mor, 14 Ein Boqeq, 15 Newe Zohar, 16 Lisan Peninsula, 17 Ghor Al-Haditha. Sites under investigation are shown. Boreholes for salt-sample collection are located in sites 3 and 14. Sites of additional sample collection are shown by stars.

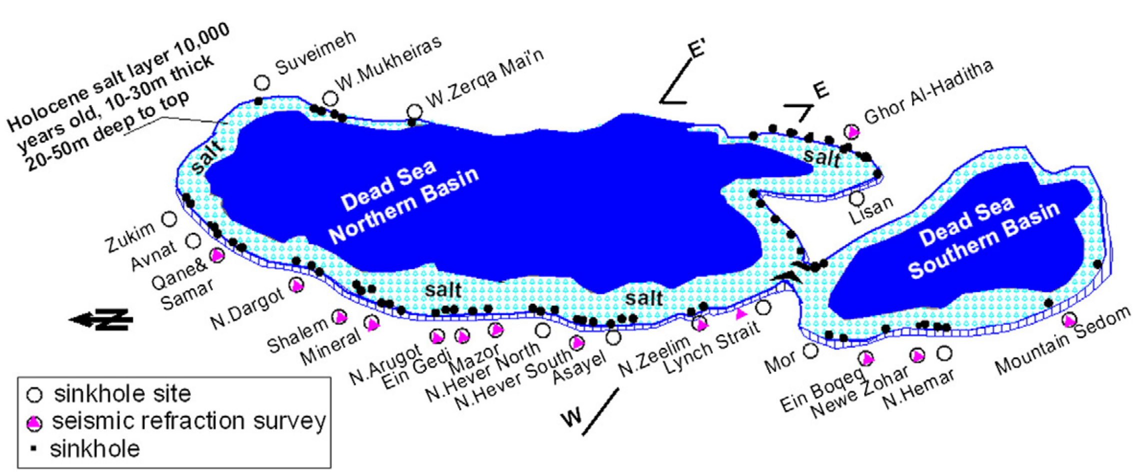

Fig. 2. Hypothetic salt distribution around the Dead Sea at the elevation of −415 to −445 m where the salt layer was formed in the latest Pleistocene (Ezersky et al., 2013b, permission of Springer, Ezersky and Frumkin, 2013, permission of Elsevier).