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The Dead Sea Sinkhole Hazards – New Findings based on the Multidisciplinary Geophysical Study

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1. **Introduction.** Numerous sinkholes have appeared in alluvial fans and other unconsolidated sediments along the coastlines of the Dead Sea (DS) in Israel and Jordan. There are two principal competitive geological models explaining sinkhole development: (a) the piping model and (b) the salt dissolution model. The latter is accepted today as being the main mechanism of sinkhole formation. The salt dissolution model requires the simultaneous existence of three factors: (1) a salt layer within the uppermost subsurface, (2) unsaturated groundwater in the vicinity of the salt layer, and (3) fractures or faults capable of conducting the unsaturated water into the salt layer and removing of the brine from the dissolved cavity. In the framework of NATO Science for Peace Project SfP 981128 a multidisciplinary geophysical study has been performed out. Scientifically, the goal of the study is *to develop an integrated approach for prediction of natural hazards caused by the development of sinkholes in the Dead Sea region of Israel and Jordan through the joint application of hydrogeological and geophysical studies* (Ezersky et al., 2005). Typically for this region extremely saline Dead Sea water causes a very low electrical resistivity of the subsurface. Resistivity abruptly drops from 50-300 $\Omega m$for the upper 10 - 20 m of the subsurface to less than 1 Ωm below the resistive layer (Kafri et al, 1997).

2. **Methods**. A new approach using geophysical methods for sinkhole hazards assessment at the Dead Sea coastal areas in Israel and Jordan consists of the following procedures: (a) Salt mapping in the subsurface using the seismic refrac-

tion method; (b) Transient Electromagnetic (TEM) and Magnetic Resonance Sounding (MRS) techniques for the study of hydrogeological conditions. Field studies using the StrataView 48-channel seismograph (Geometrics, Canada), Numis^{plus} (IRIS Instruments, France) and TEM FAST 48HPC system (AEMR, Netherlands) were performed in the Ein Gedi, Nahal Hever South and Newe Zohar sites in Israel and in the Ghor Al-Haditha site in Jordan.

3. **Results**. **a)** The Seismic Refraction technique based on the General Reciprocal Method (GRM) has revealed that the salt outer edge (that is western in Israel and Eastern in Jordan) is a major indicator of the sinkhole hazard. Interpretation of the seismic refraction data acquired in the 11 sites of the western DS coastal area (Israel) testifies that sinkholes are as a rule formed along the salt edge some west in Israel and east in Jordan. The compressional wave seismic velocity Vp = 2900 – 3000 m/s is accepted as the lower limit of the salt velocity. Thus, unit with velocity more than 2900 m/s was identified as salt, whereas section with Vp $<$ 2750m/s was considered as water saturated either loose or consolidated alluvium (Ezersky, 2006, Ezersky et al., 2007a). **b)** The MRS method allows characterizing aquifers and delineating water filled karst caverns in the low resistive environment (Legchenko et al., 2006, Legchenko et al., 2007a). MRS monitoring was carried out in the sinkhole site. MRS results obtained between November 2005 (first survey) and March 2007 (second survey) reliably revealed that after sinkhole collapse karst voids are filled with unconsolidated rocks worsening the soil hydraulic conductivity in vicinity of the salt edge (Legchenko et al., 2007b). Development of new karst voids after sinkhole appearance was not observed. **c)** TEM FAST results show slight alternations of the bulk resistivity during some years of study. Soil resistivity in the salt vicinity does note extent 1 Ωm testifying that pores are filled with the Dead Sea brine. The resistivity increase is associated rather with lithological changes in the subsurface after sinkhole collapse than with the water salinity changes (Ezersky et al., 2007b).

4. **Conclusions**. Results of our geophysical study allow concluding that sinkholes develop along the salt edge where consolidate salt material is corrupted by karst caverns. Refill of the karstic cave by the collapsing material worsens the hydraulic conductivity of soil and slows down the salt dissolution. It is likely that karstic caverns are a result of continuous salt dissolution during a few thousands years and not a rapid dissolution during a few tens of years as is suggested by actually accepted model of sinkholes formation.

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