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Deep confined karst detection, analysis and paleo-hydrology reconstruction at a basin-wide scale using new geophysical interpretation of borehole logs

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SUMMARY

Deep karst voids can be identified by a new method of geophysical interpretation of commonly used borehole logs in deeply confined carbonate aquifers. We show that deep, buried karst voids can be characterized by combining this geophysical interpretation together with geological and hydrological data, and with known speleological constraints. We demonstrate how this characterization can reveal past hydrological regimes and allow mapping of karst distribution on a basin-wide scale.

A combined analysis of geophysical, geological, hydrological, and speleological data in the confined Yarkon–Taninim aquifer, Israel, led us to reconstruct past groundwater levels at different relief and sea levels, with the karst voids as a marker for long-term flow close to the water table. Paleo-canyons along the Mediterranean Sea shoreline strongly affected the region's paleo-hydrology, by serving as major outlets of the aquifer during most of the Cenozoic. We conclude that intensive karstification was promoted by flow periods of longer duration and/or higher flux and flow velocities close to the aquifer's past and present outlets. In addition, we suggest that karst voids found under shallow confinement were developed by renewed aggressivity due to hypogene water rising in cross-formational flow becoming mixed with fresh lateral water flow from the east.

1. Introduction

Subsurface karst features have often been used to reconstruct the paleo-hydrology and landscape development of uplifting (or geomorphically down-cutting) regions, in which caves are readily accessible above the water table (Farrant et al., 1995; Ford et al., 1993; Frumkin, 1996; Granger et al., 2001; Haeuselmann et al., 2007; Hill et al., 2008; Polyak et al., 2008; Stock et al., 2004). In subsiding regions, however, most karst features are well below the water table, and often deeply buried by sediments, so that they are mostly inaccessible. Understanding the constraints on karst voids development (speleogenesis) in such zones is important for water supply management as well as for paleo-hydrologic reconstruction. The scarcity of available data on karstic features below the water table offers little support and leads to debate on speleogenesis processes (Dreybrodt and Gabrovsek, 2003; Ford, 1971; Glennie, 1954; Klimchouk, 2009; Palmer and Palmer, 1989). Canyon dynamics such as those that followed the Messinian Crisis, have intensively affected karstification in the western Mediterranean (e.g. Mocochain et al., 2009). Here we attempt a paleo-hydrological reconstruction in the eastern Mediterranean, which reveals the association between paleo-canyons and karstification in deeply buried karst along the coast of Israel.

Detection of deep karst features in a confined basin is not an easy task since most karst investigations correspond to a single cavern or system, often under modern vadose conditions (Palmer, 2007). Karst voids can be detected mainly in the unsaturated zone of an aquifer or under shallow phreatic or confined zones by speleological exploration, boreholes, and surface geophysics. Speleological exploration is limited to caverns with an opening to the surface, while the depth of penetration in surface geophysics (such as seismic refraction, electrical resistivity, electromagnetic (EM), ground penetrating radar (GPR) and microgravity) is limited to some few tens of meters. Deeper investigations of karst voids, usually within the saturated zone of an aquifer, rely on borehole geophysics. Borehole image logs and caliper logs (continuous record of borehole diameter versus depth) are insufficient (Paillet, 1998, 2001), but high-resolution logging equipment such as heat-pulse and electromagnetic flowmeters (Hess, 1986; Molz et al., 1994) can record hydraulic properties, including karst and fractures.

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In this study, we use a new geophysical interpretation combining four borehole logs from wells scattered throughout the confined Yarkon–Taninim aquifer, Israel (Laskow, 2008). This interpretation is based on the straightforward logging tool that indicates borehole irregularities (caliper log), complemented by additional borehole logs. The caliper log can indicate weaker intervals along a borehole (local increase of borehole diameter in hard rocks indicates fracturing with possible enlargement by dissolution), but those intervals can also indicate collapses and washouts caused by drilling. In order to verify that the weaker intervals indicate solely karst voids, we incorporated three additional, commonly used borehole logging methods: Resistivity, gamma-ray and acoustic. These data logs have been commonly collected during past decades at both water wells and oil wells throughout the world, and thus a vast database exists that can now be investigated further to characterize karst regions.

Once the log data were analyzed and karst voids were detected throughout the aquifer basin (see Section 3.1), the karstic character of the aquifer was identified and verified. In order to overcome the difficulties in characterizing an aquifer from geographically scattered boreholes we combined the existing geological and hydrological data with established speleological processes. First, we estimated the historic hydrological regimes of the aquifer and in doing so considered temporally changing factors, such as: lithology (including permeability, thickness and spatial distribution of each lithological unit); tectonic and structural constraints (affecting the hydrological head and outlet, unsaturated and saturated areas, sedimentation thereafter, and stratal dip).

Examining the scenarios for karst development under different hydrological regimes is a crucial step in categorizing the karst voids found using geophysical methods (Ford and Williams, 2007). A majority of common caves display different "levels" in their major conduits that have been created in response to changes in the elevation of springs and associated water tables (Ford, 1999). A close association of large and relatively common karst voids with the water table is observed also in hypogenic, hydrothermal, and isolated caves (Dublyansky, 2000; DuChene and Hill, 2000; Frumkin and Fischhendler, 2005; Hose et al., 2000; Klimchouk, 2009). Within the lateral flow zones of karst aquifers, voids are particularly abundant close to discharge areas, with a wider distribution along carbonate coastlines (e.g. Mylroie and Mylroie, 2007). These observations imply base-level controls on speleogenesis, that can be used as a proxy for paleo-hydrological reconstruction.

In our research, we found abundant karst voids at different depths (hundreds of meters below the present groundwater table) and a strong correlation between the spatial distribution of voids and paleo-canyons along Israel's coast line. Following the common occurrence of speleogenetic activity, close to the water table, and evidence from Mediterranean canyons (e.g. Mocochain et al., 2009) we assume strong base-level control on the vertical distribution of karst voids during the gradual rise of sea level and associated river aggragation. This allows us to attempt a reconstruction of the hydrological regime at different sea levels, using the karst voids as markers for stable long-term flow close to the water table (see Section 4.2).

This study shows that deep karst voids can be identified by a new method of geophysical interpretation of common borehole logs. Furthermore, the data can help in understanding paleo-hydrological regimes associated with sea level elevations and river entrenchment.

2. Study area background

Our research area is the confined part of the Yarkon–Taninim aquifer, Israel (Fig. 1). This aquifer is one of the three main fresh water sources in Israel which supply ~40% of drinking water in the country (Gvirtzman, 2002). Many karst systems have been discovered throughout the modern unsaturated zone of the aquifer, some by drillings but most by cave exploration close to the surface (e.g. Frumkin and Fischhendler, 2005; Frumkin et al., 2009). Most of the saturated part of the aquifer is confined by younger formations, that range from several meters in thickness at the foot of the Judea and Samaria mountains up to ~1000 m thick at the Mediterranean shoreline (Fig. 1B).

The aquifer geographical boundaries extend from south of the Carmel mountains in the north to Sinai in the south, and from the Judea and Samaria mountains groundwater divide in the east to the Mediterranean Sea in the west. The western edge of the aquifer is close to the present shoreline, where a karstic shallow water facies (Judea Group) changes laterally to a deep-water chalk facies (Talmei Yafe Fm.) that forms a bordering aquitard under the present Mediterranean Sea. The recharge zone of the aquifer is on the western slopes of the Judea and Samaria mountains, while its natural discharge points are Rosh-Ha'ayin and Taninim springs (Fig. 1). Groundwater flows from the recharge zone mainly westward, and then northward towards the springs. North of the Rosh-Ha'ayin Springs the groundwater flows divide into a southern flow, and a northern flow towards the Taninim Spring. Extensive pumping from the aquifer during recent decades lowered the aquifer groundwater level below the Rosh-Ha'ayin Springs, so today the aquifer's major outlets are water-wells and Taninim Spring.

The Yarkon–Taninim aquifer consists of Cretaceous, mostly carbonate, rocks of the Judea Group. The formations in the Judea Group are divided by their hydraulic properties into three units: upper sub-aquifer (thickness of ~300 m), aquitard (thickness of ~100 m) and lower sub-aquifer (thickness of ~400 m). The Mt. Scopus Group of Senonian–Paleocene age and the Avedat Group of Eocene age, which consist mostly of chalk, overlie the Judea Group. Mt. Scopus Group and Avedat Group along with younger formations confine the Yarkon–Taninim aquifer at the foot of the Judea and Samaria mountains, all the way west to the shoreline (Fig. 1).

In this study, we focus on karst voids indicating past hydrological regimes that the aquifer has experienced. Major events during the Oligocene–Pliocene age changed the aquifer's outlets and associated groundwater flow. During the Oligocene, regional uplift of the mountains began and there was massive erosion while the Tethys Sea regressed (Bar et al., 2008; Frumkin, 1993). According to Neev (1960) and Gvirtzman (1970), deep canyons were formed along the coastline of Israel during the Oligocene, reaching a maximum depth of 2000 m. These canyons exposed part or most of the aquifer's formations.

During the Late Miocene (~6 Ma) the movement of the African plate towards the Euro-Asian plate closed the Straits of Gibraltar and temporarily isolated the Mediterranean Sea from the Atlantic Ocean (Krijgsman et al., 1999). For a period of ~0.6 m.y. (Messinian Salinity Crisis) the Mediterranean Sea dropped to hyper-saline low levels with precipitation of evaporite minerals. According to Flecker and Ellam (2006) this precipitation was a result of a limited Atlantic transgression under a dominant evaporation regime, *contra* the previous desiccation and connected basin hypotheses (Hsü et al., 1973; Cita, 1982; Fabricius and Hieke, 1977). There is a vast range of evidence for the sea level changes occurring in several regression–transgression cycles (Butler et al., 1999; Decima and Wezel, 1973; Hao, 1991; Hsü, 1972; Krijgsman et al., 1999; Clauzon et al., 1996; Flecker and Ellam, 1999), although the causes for the sea level changes are still debated. The bases of the canyons along Israel's coastline are filled with lower Saqiya Group deposits of Oligocene–Miocene age. These deposits reach maximum thicknesses of ~1000 m, so reducing the outcrops of the aquifer formations in the canyons walls during the late Miocene (Fig. 2).