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The circulation of the Dead Sea brine in the regional aquifer

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ABSTRACT

Ca-chloride brines have circulated between the lakes and the adjacent aquifers throughout the history of the Dead Sea lacustrine-hydrology system. The Ein-Qedem (EQ) hydrothermal saline springs system discharging at the western shores of the modern Dead Sea is the modern manifestation of this essential and continuous process. The EQ springs comprise the most significant source of Ca-chloride brine that currently discharges into the lake. The chemical composition of EQ brine has remained virtually uniform during the past ca. 40 yr, indicating that the brine represents a large groundwater reservoir. The EQ brine evolved from ancient Ca-chloride brine that occupied the tectonic depression of the Dead Sea Basin during the Quaternary. During this period, the composition of lake's brine was affected by mixing with freshwater and formation of primary minerals. Based on chronological and geochemical data, we argue that the EQ brine comprises the epilimnetic solution of last glacial Lake Lisan that penetrated and circulated through the adjacent Judea Group aquifer. ^{14}C and ^{81}Kr dating indicates recharge ages spanning the time interval of ∼40–20 ka, coinciding with the period when the lake reached its highest stand (of $\sim 200 \pm 30$ m below msl, at ∼31–17.4 ka) and maintained a stable layered (stratified) configuration for a period of several ten thousand years. The presented evidence suggests that the circulation of the Ca-chloride brine involves penetration into the aquifer during high stands (EQ brine recharge) and its discharge back into the lake during the modern low stands (∼400 to 430 m below msl). Accordingly, the mechanism of brine circulation between the lake and the marginal aquifers is related to the long-term hydro-climate history of the Dead Sea basin and its vicinity.

1. Introduction

1.1. General

Saline terminal lakes develop in arid and semi-arid regions worldwide where a negative balance exists between precipitation and evaporation (Yechieli and Wood, 2002 and references therein). Hydrologic systems around such hypersaline lakes are sensitive to climate changes (Tyler et al., 2006) and thus can be used for reconstruction of past climates and hydrological regimes (Teller and Last, 1990; Torgersen et al., 1986). Brines filling hypersaline lakes can be circulated by density-driven force and free convection cells from the lake into the adjacent aquifer (Bentley et al., 2016; Duffy and Al-Hassan, 1988; Fan et al., 1997). The circulation of the brines within the aquifers is associated with processes such as mixing and water–rock interaction that can modify the composition and salinity of the circulating brine and the lake's waters (e.g., Stein et al., 2000). The brine circulation between the lake and the aquifer is impacted by the regional hydro-climate regime. Thus, understanding the circulation processes and the mechanism that operates them is instrumental in establishing the hydro-climate history of a studied region.

The Ein-Qedem (EQ) hydrothermal saline springs system (Fig. 1), which discharges along the western shores of the northern basin of the Dead Sea, constitutes the major brine inflow to the lake today. The main springs of this system, Ein Shalem and Ein Qedem, are located between Mineral Spa and Ein Gedi Spa (Fig. 1B) with some diluted appearances as far north as Einot Zuqim (Gavrieli et al., 2001). The circulation of the EQ brine in the

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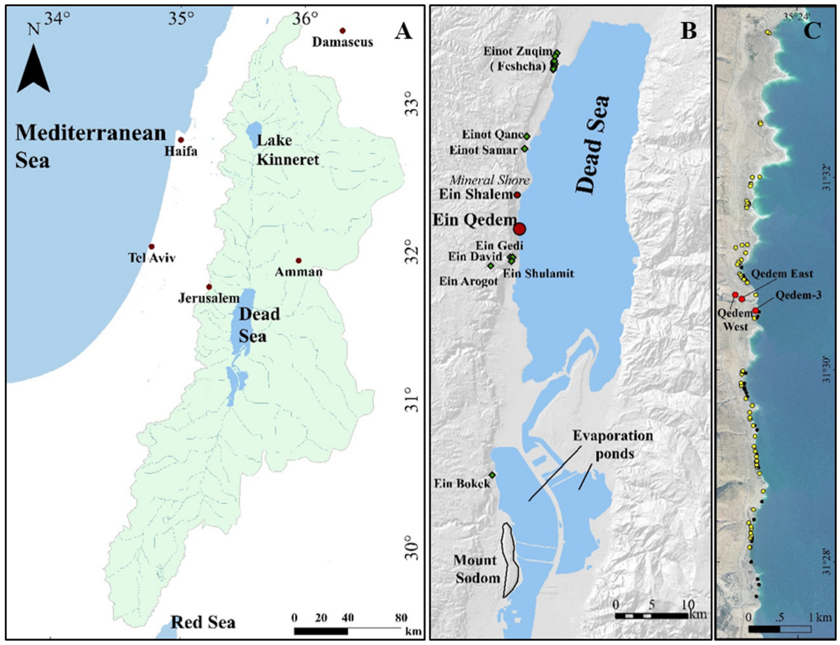

Fig. 1. Location maps: (A) the Dead Sea Basin watershed (modified from Greenbaum et al., 2006); (B) The Dead Sea lake and major water sources on its west coast (background DEM map from Hall, 1996); (C) The Ein Qedem system, springs locations along the Dead Sea shore (Israel Hydrology Service surveys: yellow dots from 2009, black dots from 2015; red dots are the boreholes; background Dead Sea shore Orthophoto January 2011). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

lake-groundwater aquifer system illustrates a fundamental process in the geochemical–limnological history of the water bodies in the late Neogene–Quaternary Dead Sea Basin. Tracing the circulation history of the brine is crucial for evaluating the paleo-hydro-climate conditions in the lakes' watershed that in turn reflect global climate conditions and their impact on the eastern Mediterranean-Levant (e.g. Stein, 2014 and references therein). Moreover, the circulation of the EQ brine may serve as an example for other environments of brines surface-groundwater circulation elsewhere.

Here, we evaluate the time of brine penetration into the Dead Sea regional adjacent aquifers and correlate it with the period of the Lake Lisan high stand when it developed a layered configuration. We further discuss the geochemical properties and isotope values (^{14}C and ^{81}Kr) of the EQ brine and apply these data, together with the reported geochemical composition of the hypolimnetic (deep) brine of Lake Lisan (Levy et al., 2018, 2017) to constrain the circulation of the brine between the adjacent regional aquifer and the lake.

1.2. Geological and hydrological setting

The modern Dead Sea comprises a hypersaline terminal lake that evolved from a sequence of late Quaternary lakes that occupied the tectonic depression of the Dead Sea Basin (e.g., Neev and Emery, 1967; Stein, 2014, 2001). The lake is located in the hot and arid area of the Judean Mountain's "rain shadow desert", with an air temperature of 32–39 °C and 20–23 °C during summer and winter, respectively (Israel Meteorological Service), and an average annual precipitation less than 100 mm. The lake level has been declining continuously since the 1960s, and has recently experienced a very rapid drop rate of more than 1 $m\,y^{-1}$, reaching 432.4 m below msl in January 2018 (Israel Water Authority). The steep decline is a result of the increased exploitation of freshwater in the watershed, and water loss in the evaporation ponds of the Israeli and Jordanian potash industries in the lake's southern basin. The lake volume for January 2018 level was ca. 120 km^3 (according to the hypsometric curve of Hall, 1996; see Eq. (11) in Zilberman et al., 2017). The modern Dead Sea evaporation rate, based on energy and mass balances, is 1.05–1.30 $m\,y^{-1}$ (Lensky et al., 2005; Stanhill, 1994; Yechieli et al., 1998).

1.2.1. The history of the Dead Sea Ca-chloride brine

The Dead Sea is a Ca-chloride brine, which is defined as a solution having equivalent ratios of $Na^+/Cl^- < 1$ and $Ca^{2+}/(SO_4^{2-} + HCO_3^-) > 1$, meaning that it has an excess of chloride over sodium and calcium over dissolved gypsum and $CaCO_3$ (defined by Starinsky, 1974; see also Katz and Starinsky, 2009). The Ca-chloride brine evolved from evaporated seawater that intruded the early Dead Sea Rift Valley during the late Neogene (∼5–3 Ma, Belmaker et al., 2013), forming the "Sedom Lagoon" (Zak, 1967). The evaporated seawaters percolated into the Judea aquifer and were modified there by water–rock interaction processes (mainly dolomitization) to a Ca-chloride brine (Stein et al., 2002, 2000). During the existence of the Sedom Lagoon, its hypersaline groundwater body recirculated through the aquifer and, upon returning back to the lagoon, mixed there with "freshly" evaporated seawater, keeping on the deposition of vast amounts of halite sequences, i.e., the Sedom Formation (Stein et al., 2000; Zak, 1967). After the disconnection of the lagoon from the open sea (∼3 Ma, Torfstein et al., 2009) the Dead Sea Basin was occupied by a series of hypersaline terminal lakes that drew their salts mainly from the huge hypersaline groundwater reservoir (Katz and Starinsky, 2009). These lake sequences had highly variable chemical compositions and fluctuating water levels, reflecting the mixing between the Ca-chloride brines and freshwaters (Stein, 2001). The latest (Holocene) expression of these Ca-chloride brines is the modern Dead Sea brine and the solutions of saline (and hot) springs discharging along the central part of its western shores (Gavrieli et al., 2001; Gavrieli and Stein, 2006; Mazor et al., 1969; Yechieli et al., 1996). The discharge of Ca-chloride saline springs probably played a significant role throughout the geological history of the lake (Katz and Starinsky, 2009; Stein et al., 1997; Torfstein et al., 2008).