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^{10}Be dating of Neogene halite

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Abstract

Direct radioactive dating of ancient halite formations is difficult because this mineral typically lacks conventionally datable material. We describe an attempt to date Neogene halite using the cosmogenic isotope ^{10}Be ($T_{1/2} = 1.39$ Ma). We dated marine-derived salt deposits from the Sedom and Amora (The Hebrew forms of Sodom and Gomorrah) Formations, Dead Sea basin, Israel. To verify whether Be is incorporated into marine halite we measured the stable isotope ^{9}Be, ^{7}Be (the short lived "cosmogenic brother" of ^{10}Be having $T_{1/2} = 53.3$ d), and ^{10}Be in evaporation pans of sea-salt production plants. The data suggest that seawater beryllium is incorporated into the halite with a halite–brine distribution coefficient, (K_D) of about unity. A ^{10}Be/^{9}Be decay curve constructed for Sedom Formation halite yielded an age that lies in the range of ~2–6 Ma. The ^{10}Be decay curve constructed for Sedom Formation halite yielded an age that lies in the range of 3–5 Ma. This age is consistent with previous estimates of the Sedom Formation age. Furthermore, this age lies in the same range of ^{10}Be *in situ* ages obtained on the lacustrine Erq El Ahmer Formation located in the northern Jordan Valley. This may imply that during the Mid Pliocene the Sedom Lagoon, the water-body that deposited the Sedom Formation, might have been already disconnected from the open sea.

1. INTRODUCTION

Dating ancient halites is important for reconstructing geological histories of hypersaline water bodies (e.g., lagoons, and lakes) and for paleoclimate studies (Phillips et al., 1983). To date, Neogene halite deposits have not been dated directly because they usually lack biostratigraphic markers or igneous material (for K/Ar dating) and are typically poor in Rb (for Rb/Sr dating). In this study we tested the feasibility of applying meteoric ^{10}Be ($T_{1/2} = 1.39$ Ma) as a dating tool for Neogene halite deposits.

Our study focuses on the Sedom Formation that was deposited in the Sedom lagoon, a marine lagoon that filled the tectonic depression of the Dead Sea basin sometime during the Neogene (Zak, 1967; Starinsky, 1974; Steinitz and Bartov, 1991; Stein et al., 2000). The Sedom Formation comprises halite beds that are several kilometers thick (Zak, 1967). A reliable age estimate of the Sedom Formation is crucial for understanding the tectonics, climate, and hydrology of the Dead Sea Rift (DSR) and its vicinity, e.g., the relation of the Sedom lagoon to the Messinian event in the Mediterranean and the timing of the uplift of the Judean Mountains. In this work we applied the decay of meteoric ^{10}Be to date the Sedom Formation halites. Our approach may be feasible for dating other salt deposits that were formed in evaporated marine waters (Warren, 2010). To our knowledge, this study presents the first measurements of ^{10}Be in marine halites and brines.

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1.1. Meteoric ^{10}Be as potential chronometer of Neogene halite

The cosmogenic isotope ^{10}Be is produced mainly in the upper atmosphere by cosmic ray (CR) induced spallation reactions (Lal and Peters, 1967). Its production rate is dependent on the CR flux penetrating into the atmosphere, which is modulated by variations in solar activity (via the heliomagnetic field) and the geomagnetic field. After production, ^{10}Be is attached to aerosols and removed from the atmosphere after a mean residence time of 1–2 years (McHargue and Damon, 1991). Due to its short atmospheric residence time and long half-life, ^{10}Be may serve as a dating tool for Neogene evaporites. This is important because during the late Neogene extensive thick evaporitic sequences such as the Sedom Formation were deposited in the Mediterranean and their ages are not well constrained. The application of ^{10}Be as a chronometer of halite deposits requires an assessment of the following issues: (1) Is the source of ^{10}Be in halite ^{10}Be that is adsorbed on dust particles that were trapped in the precipitating halite or is it dissolved ^{10}Be that co-precipitated with the halite? (2) What is the initial ^{10}Be value in the halite to be used in a ^{10}Be age model? (3) What is the distribution coefficient of beryllium between halite and brine?

We addressed these issues by measuring beryllium isotopes (^{9}Be, ^{10}Be and ^{7}Be) in modern halites precipitated in the evaporation pans of two solar salt plants of the Israel Salt Company located near the cities of Eilat, Red Sea (Fig. 1, Supplementary Fig. 1A) and Atlit, Mediterranean Sea (Fig. 1, Supplementary Fig. 1B). In these simulated lagoon systems, seawater is pumped into a series of flow-through evaporation pans (Supplementary Fig. 1) where evaporite minerals precipitate in the sequence aragonite-gypsum-halite. The brines are discarded when their density reaches $\sim$1.26 g cm^{-3} at which point more than 80% of their potential halite content has precipitated. The halite deposition rate within the saltpans is $\sim$1 m y^{-1}.

The initial ^{10}Be value (the ^{10}Be concentration at time of deposition in units of atoms g^{-1}) was validated by measuring ^{10}Be in halite deposited from the modern Dead Sea and in a $\sim$400 ky old halite (independently estimated age by Torfstein et al., 2009) from the late Pleistocene Amora Formation (Fig. 1B; Supplementary Fig. 8). Finally, ^{10}Be was measured in the Sedom Formation halite and its age was estimated using the age model we developed. Sharma and Middleton (1989) demonstrated that ^{10}Be could be present in ancient salt deposits due to *in situ* radiogenic production. In this study we assumed that this source is negligible and does not affect the age model. In future research this assumption will be validated by measuring ^{10}Be in very old (>10 Ma) halites and by measuring the U, Th, Li, and B content of the Sedom salt members discussed in this study. In addition, we attempted to examine the influence of the evaporation degree on the ^{10}Be concentration using the Br/Cl concentration ratio as a proxy for the former (Valyashko, 1956).

1.2. Geological background

The Sedom Formation, exposed at the Mount Sedom salt diapir (inset of Fig. 1A) and sampled via several deep-drilling holes, comprises a thick sedimentary sequence (up to 2000 m) of salts (mostly halites), marls and clastic material that are divided into five stratigraphic Members: Karbolet salt and shale, Lot salt, Benot Lot shale, Me'arat Sedom salt, and Hof shale and salt (Fig. 1B; Zak, 1967). This sedimentary sequence was deposited in the Sedom lagoon which extended from the Mediterranean Sea to the Dead Sea Rift valley some time in the late Neogene (Zak, 1967; Stein et al., 2000). The evaporite sequence was interpreted to have a marine origin (Zak, 1967; Stein et al., 2000) due to following characteristics: (1) The evaporite sequence comprises gypsum in the northern Jordan Valley and halites, gypsum, and dolomites in the southern Dead Sea Basin; (2) The salt deposits are thousands of meters thick; and have marine chemical and isotope compositions (e.g., the Br/Cl ratio and the δ^{34}S values). The Sedom lagoon brine interacted with the surrounding limestone country rocks, evolved to a Ca-chloride brine (Starinsky, 1974) and formed epigenetic dolomite bodies in the basin walls (Starinsky, 1974; Stein et al., 2000; Gavrieli and Stein, 2006; Katz and Starinsky, 2009). After the disconnection of the Sedom Lagoon from the open sea, possibly in the late Pliocene-early Pleistocene time, the Dead Sea Basin was occupied by a series of hypersaline terminal lakes containing a mixture of ancient Sedom Ca-chloride brine and freshwater from the basin watershed. This sequence of lakes (Amora, Samra, Lisan and the Dead Sea) occasionally precipitated halite, mainly when their water level dropped below 400 m below mean sea-level or when the Ca-chloride brine refluxed from their margins, i.e., when the brine that formed during the Sedom lagoon period flowed back from the aquifers into the lakes (Stein, 2001).

Based on general stratigraphic considerations, the age of the Sedom Formation was estimated between late Pliocene (Zak, 1967; Torfstein et al., 2009) up to late Miocene (Steinitz and Bartov, 1991).

2. SAMPLING AND METHODS

2.1. Halite sampling

Modern halite was sampled from saltpans located near the cities of Eilat and Atlit, Israel (Fig. 1; Supplementary Fig. 1). Three saltpans in the Eilat evaporation system and three saltpans in the Atlit evaporation system were sampled as follows: In each of the six saltpans, the top crust of the halite bed, i.e., the halite slush was scraped off together with the interstitial brine by the use of a tray (Supplementary Fig. 2). The scraped salt slush was put in a 20 L bucket. Subsequently, the interstitial brine was decanted through a Teflon tube that was connected to the bottom part of the bucket (termed here "Method A"; Supplementary Fig. 3). After decantation, analysis continued as described in Section 2.2 without washing or filtering the salt slush. In addition to the salt slush, a 20 L brine sample was taken from each of these saltpans and the salt at the top of the salt column was scraped and collected for analysis (termed here "Method B"). A 40 × 40 × 50 cm (length × width × depth) salt-box (salt slush) was dug out from the bottom of one of the Eilat saltpans and cut to