Quaternary Science Reviews 231 (2020) 106111

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Reply to Charrach (2019) comment on “Mount Sedom salt diapir - Source for sulfate replenishment and gypsum supersaturation in the last glacial Dead Sea (Lake Lisan)” by Levy et al. (2019)

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A R T I C L E I N F O

Article history:
Received 24 November 2019
Accepted 26 November 2019
Available online 3 January 2020

A B S T R A C T

The main comment by Charrach (2019) on the Levy et al. (2019) paper is that the Sedom salt diapir could not have been a source for sulfate to Lake Lisan (last glacial Dead Sea), arguing that the dissolution of the salt diapir started following the onset of the Holocene Dead Sea. We refute the comment for the following reasons: (1) The nature of the unconformity between the salt diapir and the overlying sediments indicates that it emerged from the surface prior to the last glacial and was submerged in Lake Lisan; (2) The formation of a ~40 m thick layer of dissolution residue (caprock) sitting on an almost flat dissolution unconformity surface (salt mirror) suggests that 600 m-to-800 m thick layer of Sedom Fm. was dissolved under phreatic settings. During most of the Holocene, the diapir has been subjected to vadose type dissolution which formed karst cutting through the caprock, salt mirror and rock-salt below; (3) Based on the Charrach (2019) hypothesis, estimated diapir uplift rates during the early Holocene would have required to be an order of magnitude higher than the measured and calculated rates for the present and Holocene, respectively, provided by other studies; (4) Na/Ca ratios from primary aragonite in the Lisan Fm. found at the vicinity of Mt. Sedom, as well as Na/Cl ratios, saturation state of halite and isotopic composition of chloride in the pore fluids from the deep Dead Sea Deep Drilling Project (DSDDP) core 5017-1-A, suggests significant dissolution of halite from Mt. Sedom into Lake Lisan. In addition to halite, dissolution of the next abundant evaporite mineral, anhydrite, resulted in mobilization of sulfate to the lake.

1. Introduction

The exposed part of the Sedom salt diapir at the southwestern part of the Dead Sea, known as Mt. Sedom, is about 2 km wide (E-W) and 10 km long (N–S). The lower part of the Sedom outcrop, the Sedom Fm., are tilted and sub-vertical sequences of rock-salt (mostly NaCl), anhydrite ($CaSO_4$), units of clastic material and carbonate rock. The upliftig diapir is estimated to have breached the surface by ca. 100 ka (Weinberger et al., 2006). Above the Sedom evaporites is a caprock comprising insoluble residue which remained *in situ* following rock-salt dissolution, and is predominantly of anhydrite and clastic material composition of an average thickness of ~40 m. A near horizontal plane, termed the ‘salt mirror’, separates the caprock and the undissolved salts below (see arrow in Fig. 1a). Based on the morphology of the caprock, Zak and Bentor (1968) estimated that it represents the dissolution of a 600-to-800 m thick salt section under phreatic conditions.

2. Dissolution of the Sedom evaporite section and formation of the caprock

Charrach (2019) writes that following the lake level drop

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https://doi.org/10.1016/j.quascirev.2019.106111
0277-3791/

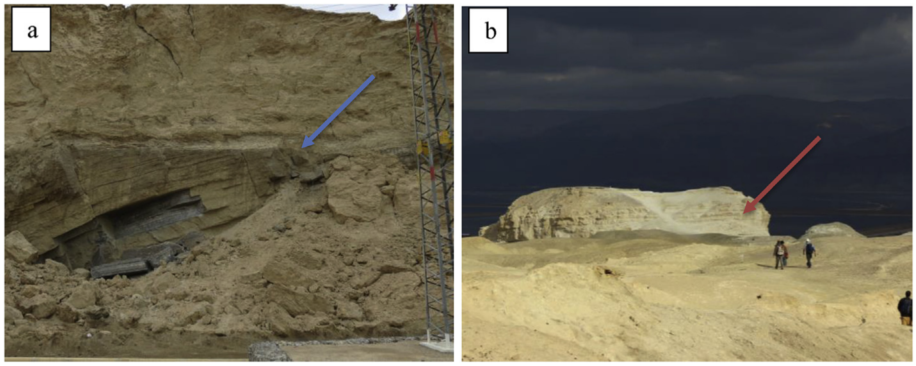

Fig. 1. Photos of Mt. Sedom. (a) Tilted Sedom Fm. evaporites below a near horizontal salt mirror (blue arrow) and overlying caprock; (b) Relict of part of the Lisan Fm. (red arrow), the 'White Hill', found on Mt. Sedom resting on an erosional and structural unconformity and caprock. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

corresponding to the end of the last glacial and Younger Dryas "the Dead Sea was at a low point enabling drainage of saturated brines from Mt. Sdom and accelerating the formation of the caprock" and that "the caprock has to be younger than the Lisan Formation". Below we show that this statement disagrees with the available geological, geophysical, and geochemical evidence.

2.1. Geological evidence

Sporadic outcrops of the Lisan Fm. are found on Mt. Sedom lying flat on an erosional and structural unconformity at the top of the caprock unit. The aragonite from sequences of primary aragonite-detritus laminae (*aad facies*) at the 'White Hill' exposure of the Lisan Fm. found on Mt. Sedom (Fig. 1b) yield ages between ca. 43 ka to 15.5 ka (Weinberger et al., 2006; Weinberger and Bar-Matthews, 2004). These sediments are elevated by ~100 m in comparison to similar Lisan sediments found regionally, a result of diapir uplift since their accumulation (Weinberger et al., 2007). The appearance of these sediments, and the geochemical evidence provided below, suggest that the diapir was submerged for long periods in Lake Lisan.

During most of the Holocene and until today freshwater runoff formed karst such as caves and chimneys in the caprock and underlying rock-salt of the Sedom Fm. Plant material collected in these caves date back to 7.1 ka, suggesting Mt. Sedom had been elevated to a sub-aerial position and exposed to vadose conditions since that time (Frumkin, 1996). This evidence also indicates that the caprock represents an earlier dissolution event of the diapir, which, as discussed below and in Levy et al. (2019), occurred under Lake Lisan.

2.2. Geophysical evidence

Assuming Charrach's (2019) mechanism for dissolution, the Sedom evaporite section would have been required to uplift to a sub-aerial position during the early Holocene (Item #1 above), at estimated rates of, at least 80 mm/yr to 200 mm/yr (i.e. 600 m to 800 m / 7.4 kyr to 3.9 kyr). This range is an order of magnitude higher than modern uplift rate measurements from interferometric synthetic aperture radar (InSAR) of 5 mm/yr to 11 mm/yr (e.g. Weinberger et al., 2006). The modern InSAR values are corroborated closely by other uplift rate estimations spanning the Holocene based on the relative elevation of the historic Dead Sea water level with the displaced position of the salt mirror and alluvial sediments on the diapir, caves formation, and precise leveling (Weinberger et al., 2006).

2.3. Geochemical evidence

An ongoing increase in Na/Ca ratio in aragonite laminae of the alternating aragonite and detrital facies in the Lisan Fm., in the vicinity of Mt. Sedom, was tied to increasing salinity in Lake Lisan following dissolution of Sedom evaporites (e.g. Katz et al., 1977; Weinberger et al., 2006). Pore-fluids extracted from core 5017-1-A from the deep floor of the Dead Sea show an increase in the Na/Cl ratio and relative enrichment of the ^{37}Cl isotope of chloride during the last glacial period. Together, this evidence suggests dissolution of halite in the lake during the last glacial, with the Sedom Fm. evaporites as the source (Levy et al., 2018).

3. Groundwater from Judea mountains and the Kurnub aquifer as sources for sulfate in Lake Lisan

In our paper (Levy et al., 2019) we made it clear that the Sedom Fm. evaporites were not the sole contributor of sulfate to Lake Lisan and other sources, such as those suggested in key previous studies (i.e. Torfstein et al., 2005), also reached the lake. These fresh to brackish waters may include waters discharging from the Upper Cretaceous Judean Mountains aquifer and the Lower Cretaceous Kurnub aquifer as suggested by Charrach (2019). Quantifying the contribution of sulfate from these sources is problematic as subsurface flow towards the Dead Sea was not measured and estimates based on groundwater modelling (e.g. Siebert et al., 2016), has large uncertainty. Estimates of these inflows during the very different environmental and climatic conditions during the last glacial period are even more challenging, if not impossible. Additionally, the chemical compositions of these waters cannot explain the compositional changes as shown by the pore-fluids (i.e. sodium and chloride enrichment). Our calculations show that dissolution of Sedom diapir evaporites could account for the sodium, chloride, and sulfate enrichment observed in the pore fluids of the deep DSDDP core (Levy et al., 2019).

4. Concluding remarks

The Levy et al. (2018) study tied the dissolution of halite on of the Sedom Fm. with increasing sodium and chloride loads in the deep hypolimnion of Lake Lisan and was the basis for the Levy et al. (2019) study. Mt. Sedom was shown to be an important and previously overlooked source for sulfate, where dissolution of its evaporites can explain the unique pore-fluid compositions recovered from the DSDDP core (i.e. high sulfate concentrations, sulfate stable isotope values, and supersaturation with respect to gypsum).

We would like to thank J. Charrach for bringing to attention two recent papers - Charrach (2018a, 2018b). However, we note that these papers do not alter the outcome of the Levy et al. (2019) study as they do not re-address the formation of the caprock. Furthermore, the new mineralogical observations within the Sedom Fm. evaporites and caprock (i.e. polyhalite) do not constrain the Levy et al. (2019) mass balance calculations which are formulated on the volumetric and bulk sulfate contents in Mt. Sedom provided by Zak (1967) and Raab et al. (2000).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.106111.

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