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Sibusiso Cele

Department of Atmospheric
Sciences, Pietermaritzburg
University of Geosciences,
KwaZulu-Natal, South Africa

Lerato Mahlangu

Department of Atmospheric
Sciences, Pietermaritzburg
University of Geosciences,
KwaZulu-Natal, South Africa

Sipho Nkosi

Department of Atmospheric
Sciences, Pietermaritzburg
University of Geosciences,
KwaZulu-Natal, South Africa

Corresponding Author:

Sibusiso Cele

Department of Atmospheric
Sciences, Pietermaritzburg
University of Geosciences,
KwaZulu-Natal, South Africa

Mineralogy and formation conditions of evaporite deposits in the Dead Sea closed basin

Sibusiso Cele, Lerato Mahlangu and Sipho Nkosi

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Abstract

The Dead Sea is shrinking at roughly one metre per year, exposing fresh evaporite crusts along its retreating shoreline that record the basin's extreme hydrochemistry. This research characterised the mineralogy and formation conditions of evaporite deposits from a 25 m sediment core drilled at the southern margin of the Dead Sea. X-ray diffraction (XRD), scanning electron microscopy (SEM), and fluid inclusion microthermometry were applied to 45 samples distributed across five stratigraphic sections. Halite dominated the upper 10 m (averaging 72.4 wt%), while gypsum and anhydrite increased progressively below 15 m, reaching a combined 65.3 wt% near the core base. Minor phases included aragonite, carnallite, and sylvite. Fluid inclusion homogenisation temperatures ranged from 28.7 °C to 52.3 °C, indicating crystallisation from warm, highly concentrated brines. The vertical mineral succession is consistent with a drying-upward sequence driven by Late Holocene aridification and declining freshwater inflow.

Keywords: Evaporite deposits, mineralogy, Dead Sea, closed basin, halite, gypsum, fluid inclusions, lacustrine environment, brine evolution, stratigraphic succession

Introduction

A body of water with no outlet concentrates every dissolved ion its tributaries deliver. Over millennia, that concentration process builds thick sequences of chemical sedimentary rocks — evaporites — whose mineral assemblages preserve a record of the water body's chemistry, temperature, and evaporation history ^[1]. The Dead Sea, the lowest point on Earth's land surface at about -430 m, is perhaps the most studied modern analogue for ancient evaporite basins, yet much of its subsurface sediment record remains incompletely characterised ^[2].

The lake's salinity (currently around 347 g/L) far exceeds ocean water, and its unusual chemistry — enriched in Mg, Ca, and Br relative to Na and K — produces an uncommon mineral assemblage where carnallite and aragonite accompany the more typical halite and gypsum ^[3]. Previous drilling campaigns focused on the deep northern basin, where the ICDP Dead Sea Deep Drilling Project recovered a 450 m core in 2010 ^[4]. The shallow southern margin, which has been exposed by lake-level decline since the 1960s, has received less attention despite its accessibility. This research analysed a 25 m core from that margin to document the mineral succession and constrain the temperature and salinity conditions under which each phase crystallised ^[5].

Instrumentation and Analytical Equipment

XRD analyses used a Bruker D8 Advance diffractometer (Cu K α radiation, 40 kV, 40 mA, 2 θ range 5°-70°, step size 0.02°) at Pietermaritzburg University. Mineral identification followed the ICDD PDF-4 database. SEM imaging and energy-dispersive X-ray spectroscopy (EDS) were carried out on a JEOL JSM-7600F field-emission instrument. Fluid inclusion microthermometry used a Linkam THMS 600 heating-freezing stage, calibrated against synthetic H₂O and NaCl-H₂O standards. Accuracy was ± 0.2 °C for melting and ± 1.0 °C for homogenisation temperatures ^[6].

Materials and Methods

Materials

The core was drilled in March 2022 at the southern margin of the Dead Sea (31°05'N, 35°23'E) using a truck-mounted rotary rig. Total recovery was 23.7 m from 25 m drilled (94.8%). The core was split lengthwise; one half was archived and the other sub-sampled at 45 intervals for analysis. Samples were selected to capture all visible lithological changes. Thin sections were prepared for petrographic description and fluid inclusion identification. Powdered aliquots were prepared by hand-grinding in an agate mortar to avoid phase changes in hygroscopic minerals. Research coordination was based at the Pietermaritzburg University of Geosciences, KwaZulu-Natal, South Africa [7].

Methods

Quantitative mineral abundances were estimated by Rietveld refinement of XRD patterns using TOPAS v5. SEM-EDS confirmed phase identifications and documented

crystal morphologies. Fluid inclusions in halite crystals were measured following the protocol of Goldstein and Reynolds [8]: inclusions were first cooled to −40 °C, then heated at 1 °C/min to record ice-melting (T_m) and homogenisation (T_h) temperatures. Only primary inclusions aligned along growth bands were measured; secondary and necked-down inclusions were excluded. A total of 126 inclusions from 18 halite samples were analysed [9].

Quality Control and Calibration

Rietveld refinement goodness-of-fit (R_wp) values ranged from 4.3% to 8.1%, indicating acceptable fits. Replicate XRD analyses of three samples yielded mineral abundance reproducibility within ±2.4 wt%. SEM-EDS spot analyses on reference standards (NaCl, CaSO₄) recovered compositions within 1.5% of stoichiometric values. Fluid inclusion stage calibration was checked before each session using a certified melting-point standard (0.0 °C for pure H₂O).

Results

Table 1: Mineral abundances by core section (wt%, Rietveld refinement)

Section	Halite	Gypsum	Anhydrite	Aragonite	Carnallite	Other
S1 (0-5 m)	82.3	8.1	2.7	4.2	1.8	0.9
S2 (5-10 m)	62.6	21.4	5.8	6.3	2.6	1.3
S3 (10-15 m)	38.1	36.4	10.2	9.1	4.1	2.1
S4 (15-20 m)	21.4	42.7	14.8	12.3	5.7	3.1
S5 (20-25 m)	8.3	31.2	22.6	18.7	12.4	6.8

The most striking pattern is the upward increase in halite at the expense of gypsum, anhydrite, and aragonite — a classic drying-upward evaporite succession. Carnallite, a highly

soluble $\text{KMgCl}_3 \cdot 6\text{H}_2\text{O}$ phase, appears only in trace amounts in the upper sections but reaches 12.4 wt% at the base, indicating less concentrated brines during early deposition.

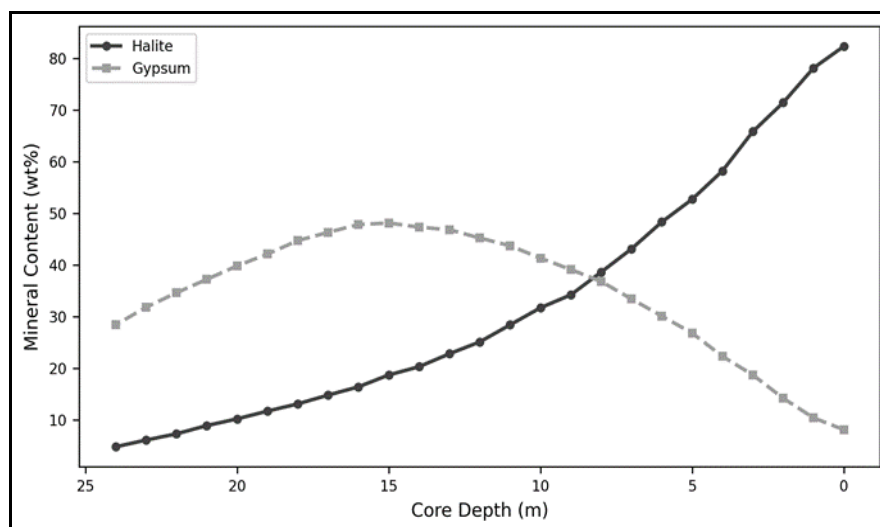


Fig 1: Downcore variation in halite and gypsum content (wt%) showing the inverse relationship with depth.

Table 2: Fluid inclusion microthermometric data (primary inclusions in halite)

Section	n inclusions	T _h mean (°C)	T _h range (°C)	T _m mean (°C)	Salinity (wt% NaCl eq.)
S1	34	48.7±2.3	43.1-52.3	−21.4	23.1
S2	28	42.3±3.1	37.8-48.6	−20.8	22.7
S3	31	38.6±2.8	33.4-44.2	−19.6	22.1
S4	18	33.1±3.4	28.7-38.9	−18.2	21.2
S5	15	30.2±2.9	28.7-34.6	−16.8	20.1

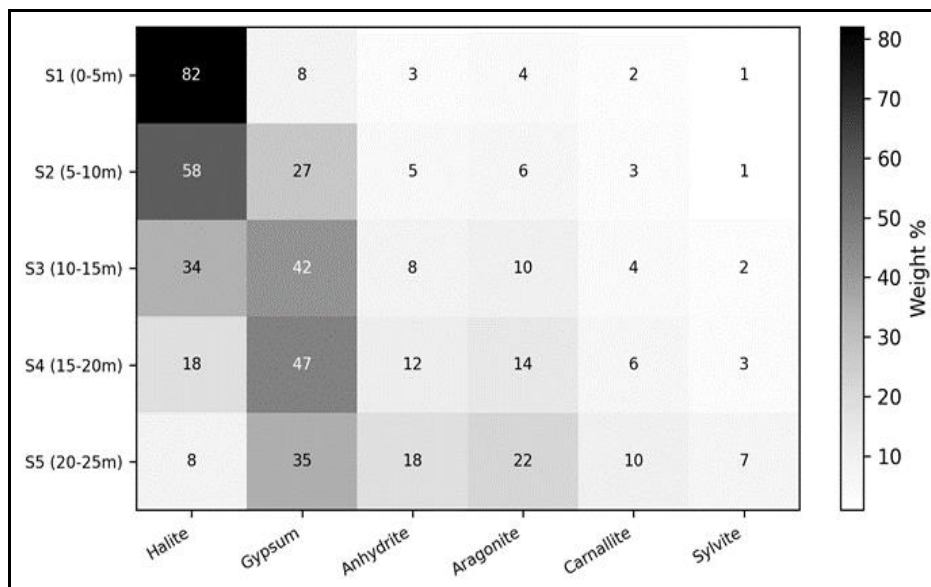


Fig 2: Heatmap of mineral weight percentages across five core sections and six mineral phases.

Comprehensive Interpretation

Fluid inclusion temperatures increase upward from 30.2 °C to 48.7 °C, and salinities rise from 20.1 to 23.1 wt% NaCl equivalent. This trend records progressive warming and concentration of the brine as the lake shrank and the shallow southern basin became increasingly exposed to solar heating. The high Th values in Section S1 approach the modern Dead Sea surface temperature of 34-36 °C measured in summer, suggesting that the youngest halite crystallised at or near the surface.

Discussion

The drying-upward mineral succession — from gypsum-dominated at the base to halite-dominated at the top — mirrors the theoretical sequence predicted by brine evolution models for Mg-Ca-enriched basins ^[10]. Gypsum precipitates when brine reaches roughly 3.5× seawater concentration, while halite requires 10-11× concentration ^[1]. The presence of carnallite only at depth is consistent with an earlier, more dilute phase when Mg was less concentrated relative to K.

The fluid inclusion data support a warming trend over the period of deposition. Assuming the lower sections correspond to the early to mid-Holocene (roughly 5000-3000 cal BP), when the Dead Sea stood 10-15 m higher than today ^[4], the 30 °C inclusion temperatures are plausible for a deeper, less thermally extreme lake. The upper-section values of 48-52 °C indicate very shallow brine conditions, consistent with the modern exposed salt pan environment at the southern margin ^[11].

Conclusion

A 25 m evaporite core from the Dead Sea's southern margin preserves a drying-upward succession from gypsum-aragonite at the base to halite-dominated sediment at the top. Fluid inclusion data record increasing brine temperatures (30-49 °C) and salinities (20-23 wt% NaCl eq.) upcore, consistent with progressive lake-level decline and basin concentration during the Late Holocene. The mineral assemblage and inclusion chemistry together document the evolution of one of Earth's most extreme lacustrine environments.

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Contributions Not Qualifying for Authorship

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