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Mass wasting records the first stages of the Messinian Salinity Crisis in the eastern Mediterranean

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ABSTRACT

The geological processes that occurred during the deposition of the Mediterranean salt giant are poorly constrained, limiting our understanding of the earliest phase of the Messinian Salinity Crisis (MSC). Using three-dimensional seismic reflection data from the northern Levant Basin in the eastern Mediterranean Sea, we investigated a previously unrecognized deposit at the base of the Messinian halite that we interpret as an extensive mass-transport complex (MTC). While MTCs have been described within stratigraphically equivalent deposits in the western Mediterranean Sea, this is the first such MTC documented at the base of the halite in the eastern Mediterranean. The spatial distribution and seismic facies of the MTC suggest a slope failure origin, likely in response to multiple processes including tectonic activity and sea-level fall. Our study indicates that margin instability was diffuse across the entire Mediterranean during the early stages of Messinian halite deposition, with implications for the chronology of erosional events and sediment transport to the deep basin.

INTRODUCTION

The Messinian Salinity Crisis (MSC; 5.97–5.33 Ma) was a period of extreme variation in the level of the Mediterranean Sea (CIESM, 2008; Roveri et al., 2014b, 2014c). According to some, sea-level drawdown led to the deposition of a thick, halite-dominated evaporite layer (i.e., the Messinian salt) and the initiation of basin-wide erosional processes (e.g., Lofi et al., 2011; Roveri et al., 2014a). Mass-transport complexes (MTCs) have been recognized within MSC deposits across the Mediterranean Sea and are linked with a major sea-level drop and tectonic activity along the basin margins (e.g., Cameselle and Urgeles, 2017; Gorini et al., 2015). Pre-halite MTCs have been described in the western Mediterranean Sea (Gargani et al., 2014), and late- or post-halite MTCs have been documented around the basin (e.g., complex/chaotic units [CUs]; Gorini et al., 2015). While erosional canyons and clastic depositional systems have been recognized at the base of the halite in the eastern Mediterranean (Bertoni and Cartwright, 2007; Feng et al., 2017), MTCs within the pre- and early halite have not yet been observed in this basin. As such, the occurrence and magnitude of erosional processes and the mode of sediment transfer to the eastern Mediterranean deep basin during the early stages of the MSC remain uncertain.

We use three-dimensional (3-D) seismic reflection data from the Levant Basin (eastern Mediterranean Sea) to identify a previously unrecognized large MTC occurring at the base of the Messinian salt (Fig. 1). By demonstrating the occurrence of MTCs within early halite units in this region, and investigating their origin, distribution, stratigraphic setting, and inferred ages, we provide a better understanding of the processes occurring across the Mediterranean Sea during the early phases of the MSC. Furthermore, since the postdepositional flow of salt-dominated successions (i.e., salt tectonics) typically destroys the stratigraphic record of the earliest stages of salt deposition, these insights are also valuable to our understanding of other salt giants globally. The Messinian salt is thus unique because its young age means it has yet to experience intense salt deformation, and so it potentially preserves the record of this key phase of salt giant development.

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GEOLOGICAL SETTING

The MSC began in the Late Miocene due to the gradual isolation of the Mediterranean Sea from the Atlantic Ocean (Hsü et al., 1973). Restricted water circulation led to the relatively rapid (~0.64 Myr) deposition of the kilometer-thick, layered Messinian salt (CIESM, 2008). According to established models, the Messinian salt consists of various seismic units (U1 to U7 and ME1 to ME4) and MSC stages in the deep Levant Basin (Fig. 1C). Here, the Messinian salt is dominated by halite (i.e., Main Halite), with interbeds of argillaceous diatomite (Meilijson et al., 2019). Well data show that the diatomite contains open-marine planktonic taxa, confirming that the Main Halite was deposited in deep water (Roveri et al., 2014c). There are two contrasting models for the timing of Main Halite deposition in the eastern Mediterranean: during stage 2 (ca. 5.6 Ma), preceded by a clay-rich foraminifera-barren interval deposited during stage 1 (Manzi et al., 2018), or directly at the onset of the MSC during stage 1 (ca. 5.97 Ma) (Lofi et al., 2011; Meilijson et al., 2018, 2019).

The transition between the Main Halite and the overlying clastic-rich facies records an initial stage of sea-level fall in the Levantine Basin (Meilijson et al., 2018). This may have caused dense, hypersaline shelf waters to cascade down and erode into the deep basin margin

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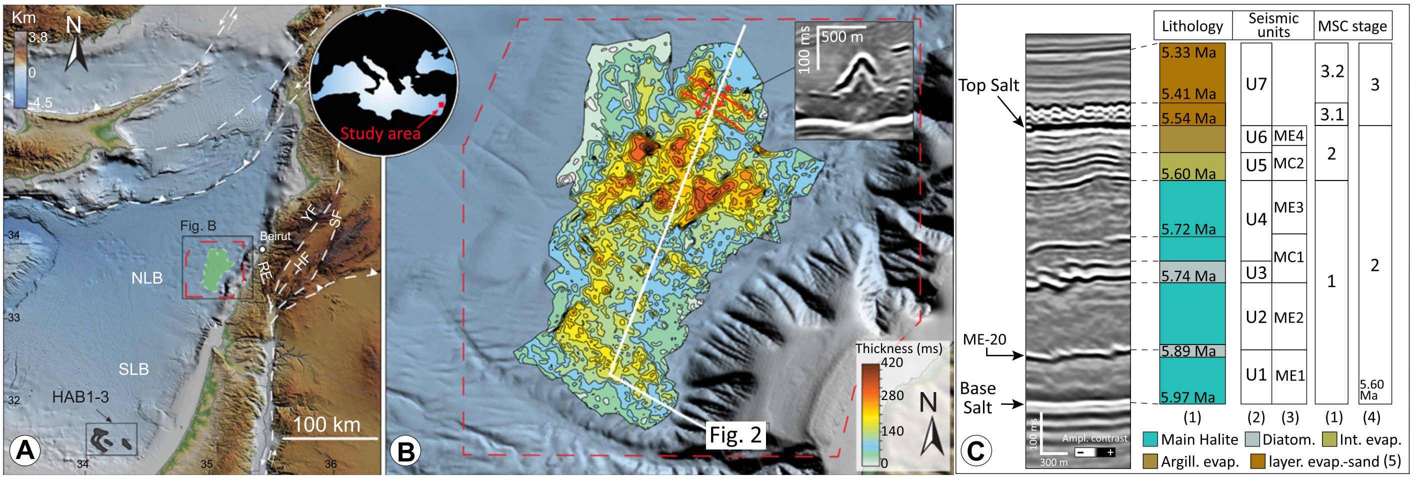

Figure 1. (A) Map of eastern Mediterranean showing mass-transport complex (MTC) interpreted in this study. Bathymetry is from General Bathymetric Chart of the Oceans (GEBCO) and European Marine Observation and Data Network (EDMOnet) databases. NLB—North Levant Basin; SLB—South Levant Basin; RF—Roum fault; HF—Hasbaya fault; YF—Yammouneh fault; SF—Serghaya fault. HAB1–3 lobes are from Bertoni and Cartwright (2007). (B) Extent of three-dimensional (3-D) seismic survey (dashed red) and isopach map of MTC; inset shows a fold marked by solid red lines in main panel. (C) Stratigraphic column in study area with main Messinian salinity crisis (MSC) subdivisions in literature. References: 1—Meilijson et al. (2019); 2—Gvirtzman et al. (2013); 3—Feng et al. (2017); 4—CIESM (2008); 5—Kabir et al. (2022). ME-20 horizon is from Bertoni and Cartwright (2007). Int./Argill. evap.—interbedded/argillaceous evaporites.

(e.g., Roveri et al., 2014c). Enhanced clastic input in the eastern Mediterranean resulted in the deposition of interbedded evaporites and argillaceous evaporites (Fig. 1C), capped by the Nahr Menashe unit (Kabir et al., 2022; Madof et al., 2019). A rapid sea-level rise at ca. 5.33 Ma reestablished fully marine conditions, marking the end of the MSC (Garcia-Castellanos et al., 2009; Micallef et al., 2018).

DATA AND METHODS

We interpreted 2650 km^2 of 3-D time-migrated seismic reflection data in the northern Levant Basin (Fig. 1B). The intra-halite Messinian stratigraphy has been drilled but never sampled in the northern Levant Basin, thus preventing exact lithological and age calibrations. We correlated stratigraphic units preserved onshore in Lebanon with those proven by well data from the southern Levant Basin (Fig. 1C; Gvirtzman et al., 2013; Hawie et al., 2013; Meilijson et al., 2019) to infer the lithological characteristics and ages of the analyzed sedimentary sequence. See Supplemental Material[1] for more details on our data set and methods.

SEISMIC EXPRESSION AND SOURCE OF THE INTRA-MSC MTC

In the northern Levant Basin, the lower Main Halite hosts a distinct seismic-stratigraphic unit. The unit lies at the base of the continental slope and extends 40 km N-S and 26 km E-W. The basal surface of the unit is defined by a high-amplitude, negative (white) reflection that truncates underlying reflections and is thus considered to be erosional (Fig. 2). Notably, this surface correlates with the base of the Messinian salt (base salt; Figs. 2 and 3A), except on the west and north margins of the unit, where it ramps up to be stratigraphically equivalent to the ME-20 horizon (Figs. 2 and 3C), dated at ca. 5.89 Ma (Meilijson et al., 2019). A high-amplitude negative reflection also marks the top of the unit, which is irregular and characterized by relief associated with prominent NW-trending folds (Figs. 1B and 3F). The average fold amplitude is ∼100 ms, only involves the topmost portion of the unit, and occasionally shows well-preserved internal stratification. The top surface is typically onlapped or draped by seismic units U2 and U3 (Figs. 2, 3D, and 3F). The seismic expression of this top surface (i.e., a negative impedance contrast) suggests the unit is composed of lithologies with a substantially slower seismic velocity than the overlying, high-velocity Main Halite (see Supplemental Material). This interpretation is supported by the velocity push-down of the basal reflection beneath areas where the overlying unit is thicker (vertical white arrows in Fig. 2). The unit is defined internally by low-amplitude, hummocky to chaotic reflections, with occasional

[1]Supplemental Material. Information on the seismic data, MTC thickness and volume calculations, and uninterpreted seismic data. Please visit https://doi.org/10.1130/GEOL.S.22687978 to access the supplemental material, and contact editing@geosociety.org with any questions.

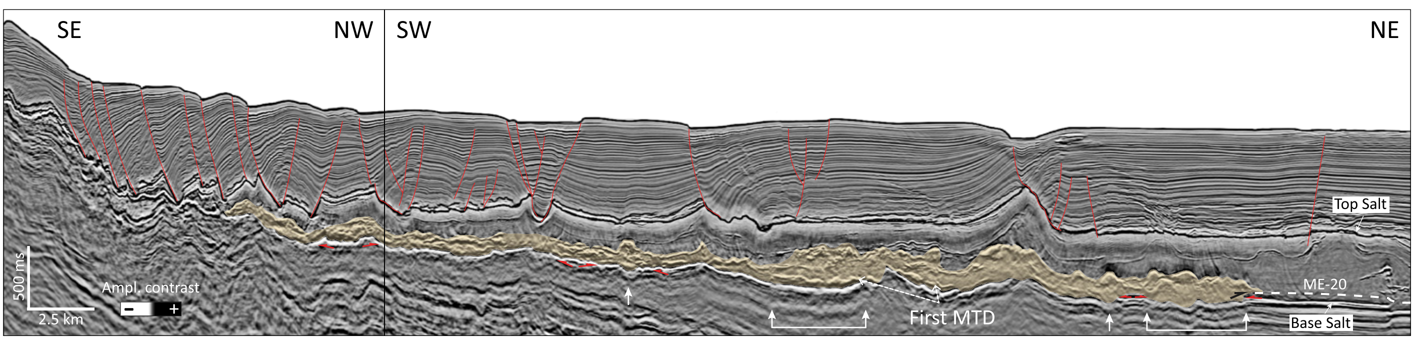

Figure 2. Mass-transport complex (MTC) in northern Levant Basin. Seismic section is parallel to inferred direction of movement of main MTC (yellow shading). Solid white arrows indicate seismic pushdown. Red faults are late to post-Messinian and are related to salt gliding toward basin. Red arrows mark erosional contacts at base of MTC. Black arrow marks ramp of MTC onto ME-20 reflection. MTD—mass-transport deposit.

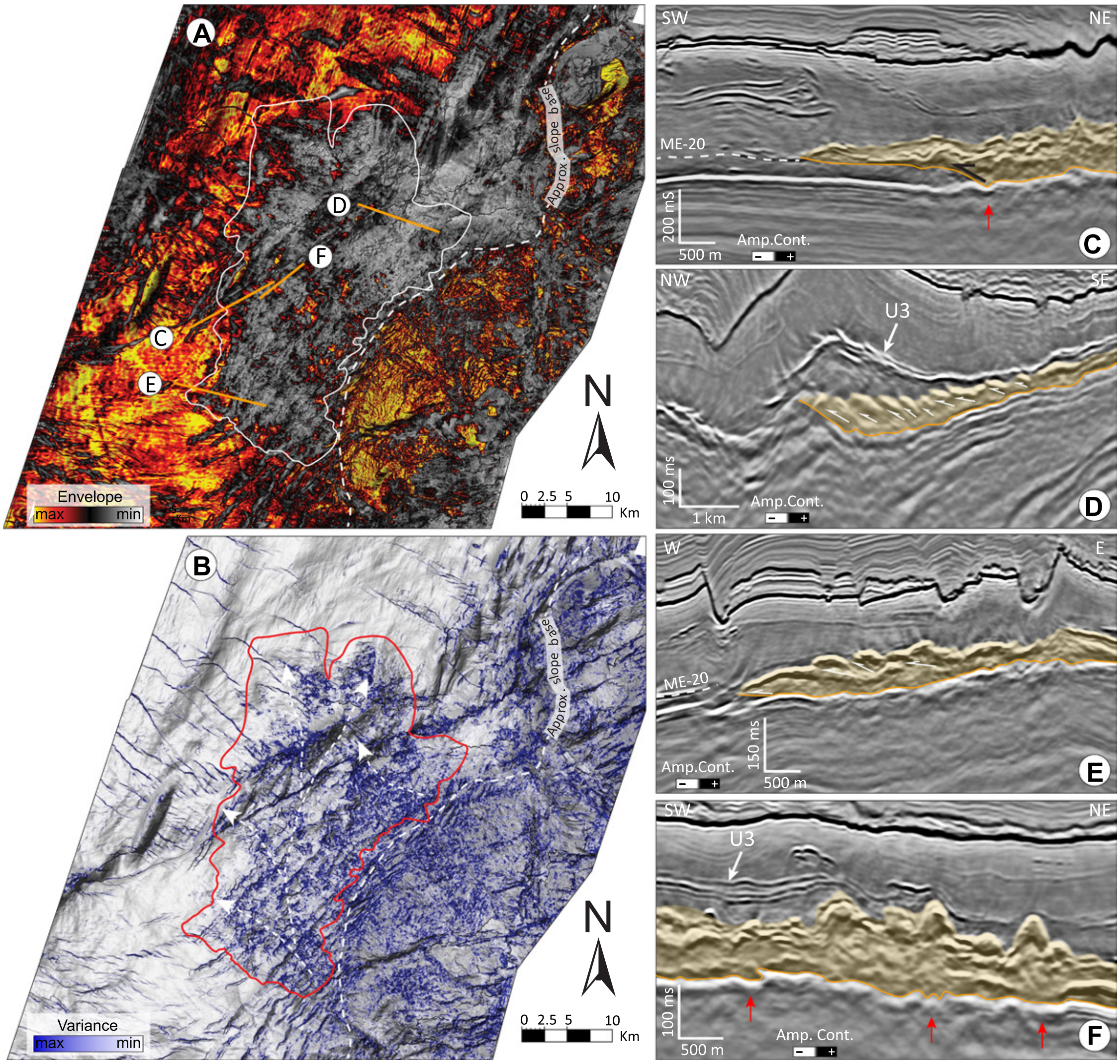

Figure 3. Details of mass-transport complex (MTC). (A–B) Envelope (A) and variance (B) attributes calculated on base salt surface show rugose topography. Note smoothness on west and north sides where MTC ramps onto ME-20 horizon. White dashed line—approximate location of base slope. White (A) and red (B) lines—maximum extent of MTC. In B, dashed white arrows are inferred direction of movement. (C–E) MTC toe thrusting and ramping on preexisting units. (F) Particular of folding at MTC top. Arrows: red—erosion at basal surface; white—internal thrusts; black—ramps onto ME-20.

laterally continuous, higher-amplitude reflections. Locally, thrust faults occur within the unit in marginal areas, detaching downward on its basal surface (Figs. 3D and 3E). The top of these thrusts resembles a folded and thrusted ME-20 reflection. The unit is up to 420 ms two-way traveltime thick, covering an area of ~704 km^2 (Fig. 1) and defining a volume of 369–410 km^3 (see Supplemental Material).

Based on the chaotic seismic facies characteristics, the slightly mounded, lobate geometry, the erosive nature of the basal surfaces, and the style and distribution of the internal deformation, we interpret the sedimentary unit as an MTC (e.g., Bull et al., 2009). The MTC is elongated normal to slope strike, and the internal folds trend normal to the elongation direction (Fig. 1B). Based on the general geometry of the MTC, we suggest that its source flow originated from the collapse of the slope and flowed northward, involving contraction in distal areas (Fig. 3B). Extensive erosion of the upper slope and shelf during the MSC, which likely removed the entire Cenozoic succession (e.g., Ghalayini et al., 2018), means we cannot define the MTC headscarp and precise source area. The MTC location and its seismic character suggest that it consists of reworked clastics, which crop out along the slope and are observed onshore on the northern Lebanese coast, where they comprise stacked conglomerate sheets with interbedded carbonates (facies FA6 of Hawie et al., 2014). The erosional base of the MTC suggests these clastics are likely mixed with early MSC deposits eroded during emplacement, including clay-rich foraminifera-barren shales, if present in this location, and the Main Halite of seismic unit U1.

AGE OF THE MTC

Well-to-seismic ties offshore Israel (Feng et al., 2017; Meilijson et al., 2019) combined with excellent imaging of the intra-halite seismic stratigraphy allowed us to correlate and date seismic horizons across the Levant Basin. The stratigraphic position of the MTC at the base of the Main Halite indicates that slope failure began at or soon after the start of salt deposition. According to the two main models for the onset of Main Halite deposition in the Levant Basin (for simplicity, the Manzi and Meilijson models), MTC was emplaced either ca. 5.6 Ma (stage 2, Manzi) or ca. 5.97 Ma (stage 1, Meilijson). We can refine this age estimate by using the constraints of intra-halite markers presented in Meilijson et al. (2019) (note that Manzi et al. [2018] did not provide them). The basal surface erodes down from the ME-20 horizon, suggesting that most of the MTC was emplaced ca. 5.89 Ma. The topmost part of seismic unit U2 onlaps the MTC upper surface (e.g., Fig. 2), indicating the deposit is older than 5.74 Ma. The dating of the intra-halite markers thus constrains the MTC emplacement between ca. 5.97 and 5.74 Ma, a period of ~230 k.y. (according to the Meilijson model).

POSSIBLE TRIGGERS

The stratigraphic position of the MTC links its emplacement to events that occurred during the earliest Main Halite deposition. According to different models, the stage of Main Halite deposition was associated with the occurrence of a sea-level drop of variable amplitude, intense tectonic activity, and erosion along the basin margins (Ryan, 2009). All these processes, alone or in combination, may have contributed to MTC triggering and emplacement.

The relationship between sea-level fall and mass wasting has been widely documented along continental margins (Bryn et al., 2005; Masson et al., 2006; Posamentier and Vail, 1988). Messinian MTCs described elsewhere in the Mediterranean Sea have had their emplacement linked to tectonic deformation and a drop in sea level (CUs; Fig. S2; e.g., Cameselle and Urgeles, 2017; Manzi et al., 2021). However, the CUs postdate or are synchronous with the latest phases of halite precipitation (late stage 2), so it is unlikely they were genetically related to the Levant MTC. In the southern Levant Basin, deep-sea clastic intra-halite lobes (HAB1–3; Fig. 1) have been documented at the same stratigraphic level as the Levant MTC. They have been related to a sea-level fall before or at the start of halite deposition (Bertoni and Cartwright, 2007). The Meilijson and Manzi models agree that high-amplitude sea-level oscillations are unlikely to have occurred during the Main Halite deposition in the Levant Basin. This indicates that the Levant MTC was emplaced in a deep-water setting before a sea-level drop at the end of stage 2 (Ryan, 2009). This difference in timing of emplacement with respect to the sea level suggests that the Levant MTC may not be easily correlative with stratigraphically comparable deposits in both the western and eastern Mediterranean, which have been related to a major sea-level drop (Bertoni and Cartwright, 2007; Gorini et al., 2015). The lack of a major sea-level drop at the time of the Levant MTC emplacement does not exclude the possibility that the MTC (and the HAB1–3 lobes) was temporally associated with a previously unrecognized, small-amplitude sea-level lowering during early Main Halite deposition. A moderate sea-level fall has been defined for stage 1 in the western Mediterranean at Sorbas (~150 m; Clauzon et al., 2015). If future studies prove the age model of Meilijson et al. (2019) correct, and we can relate the Levant MTC to a sea-level fall, then it may indicate that MSC-related sea-level lowering occurred in the eastern Mediterranean earlier than current estimates (for details, see Meilijson et al., 2019).

As in other areas of the Mediterranean Basin, margin erosion and slope instability during the MSC may have had multiple causes, in addition to the frequently cited sea-level lowering. The cascading of dense shelf water down the slope (Roveri et al., 2014c), potentially capable of significant erosion also in deep water, could have enhanced or promoted the destabilization of the slope, contributing to the formation of the Levant MTC. Mass-water movements and sea-level lowering could have also produced gas expansion or destabilized gas hydrates in the shallow subsurface, priming the slope for failure (e.g., Bertoni et al., 2013).

Tectonic processes may have also represented alternative or additional triggers for mass wasting in this structurally complex part of the eastern Mediterranean, as has been observed in other areas of the Mediterranean Basin (e.g., Manzi et al., 2021; Urgeles and Camerlenghi, 2013). During the Messinian, the eastern Mediterranean experienced intense tectonic reorganization due to a structural cycle (NNW-SSE compression) that began just before and continued through the Messinian. This cycle triggered motion on the Levant fracture system, uplifting the eastern margin of the Levant Basin and Mount Lebanon, and was associated with a severe folding event (Butler et al., 1998; Ghalayini et al., 2014). A short pulse of tectonic activity (Homberg et al., 2010) could have coincided with the onset of Main Halite deposition offshore both Lebanon and Israel, triggering MTC emplacement.

However, there are currently insufficient data to determine the relative contributions of sea-level drop and tectonic activity to slope destabilization of the Levant Basin during the MSC. Therefore, the collection of continuous stratigraphic and age records across the base salt and pre-MSC strata, coupled with samples of the MTC deposit, could shed light on the processes active in this area of the Levant Basin during the early MSC.

SIGNIFICANCE FOR THE MSC

We show that the Messinian salt in the Levant Basin hosts a previously unrecognized large MTC emplaced during the early MSC. This MTC suggests the occurrence of a geological process or processes inducing large-scale downslope sediment transfer during the early MSC in the eastern Mediterranean Sea. This observation has three key implications: (1) MSC erosional events started during the initial salt deposition before a significant sea-level drop, and their products were deposited within large MTCs in the deep basin; (2) geological processes triggering slope failure and MTC emplacement were basinwide, with comparable deposits present in the circum-Mediterranean basins; and (3) the nature of equivalent stratigraphic units in the southern Levant Basin offshore Israel, which have been interpreted as deep-sea fans and lobes, may be MTCs.

These findings have significant implications for interpretations in the western Mediterranean, as they suggest that previous assumptions about the primary source of clastic material may need to be reevaluated.

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