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# Discovery of vast fluvial deposits provides evidence for drawdown during the late Miocene Messinian salinity crisis

Andrew S. Madof<sup>1</sup>, Claudia Bertoni<sup>2</sup>, and Johanna Lofi<sup>3</sup>

<sup>1</sup>Chevron Energy Technology Company, Houston, Texas 77002-7308, USA

<sup>2</sup>Department of Earth Sciences, University of Oxford, Oxford OX1 3AN, UK

<sup>3</sup>Géosciences Montpellier, CNRS, Université de Montpellier, Montpellier 34095, France

## ABSTRACT

The late Miocene Messinian salinity crisis (MSC) was a significant oceanographic event that caused widespread evaporitic accumulation throughout the Mediterranean Basin. Although multiple hypotheses exist regarding the origin of evaporitic and post-evaporitic deposits, researchers remain divided on the magnitude of base-level fall, and on whether these accumulations record deep-water or non-marine conditions. Here, we introduce a previously unknown, upper Messinian fluvial deposit comparable in size to the late Miocene Nile River fluvial valley fill and show that near-complete desiccation of the eastern Mediterranean was responsible for its development. The basin-wide accumulation, which is located offshore Cyprus, Syria, Lebanon, and Israel, lies directly atop deep-basin evaporites and related erosional surfaces, and is one of the largest known riverine deposits associated with the terminal MSC. From marked onshore incision and basinward thinning trends, the source of the accumulation is presumed to be a formerly unidentified drainage basin in southern Turkey and western Syria; the deposit extends >500 km into the western Levant Basin, where its depositional sink is marked by six well-developed backstepping lobes. Based on the deposit's seismic stratigraphy and morphology, which provide clear evidence of subaerial exposure, we question current hypotheses proposing a deep-water origin for late Messinian accumulations. We also draw specific attention to the development of extensive circum-Mediterranean non-marine conditions prior to Zanclean marine transgression, and to the previously overlooked role of fluvial systems in diluting hypersaline lakes in evaporitic basins.

## INTRODUCTION

The Messinian salinity crisis (MSC) was a major late Miocene oceanographic event that led to the emplacement of  $>1 \times 10^6$  km<sup>3</sup> of evaporites in the Mediterranean Basin (Ryan, 1973) in <640 k.y. (i.e., between 5.97 and 5.33 Ma; Manzi et al., 2013). Although multiple hypotheses were initially proposed to explain the origin of the evaporitic and post-evaporitic deposits, a shallow-water deep-basin model was generally accepted (Hsü et al., 1973). While some workers have refined this model, others have re-adopted an earlier and alternative hypothesis for the MSC: a deep-water deep-basin model (i.e., small-magnitude base-level fall; see Roveri et al., 2014). Proponents of this idea envisage these evaporites as deep marine, suggest that late Messinian post-evaporitic accumulations are subaqueous

in origin (Gvirtzman et al., 2017), and conclude that subaerial exposure had little to no bearing on the MSC.

Although proprietary data (i.e., those acquired during offshore hydrocarbon exploration) can be used to test hypotheses related to the MSC, accessibility issues regularly preclude further investigation. This is particularly true in the eastern Mediterranean, where questions regarding the crisis largely remain unanswered. To address this issue, we present previously unpublished two- and three-dimensional (2-D and 3-D) seismic data from the Levant Basin, test hypotheses related to origin of latest Messinian deposits, and evaluate the claim that during the MSC, “the eastern Mediterranean became evaporated to near dryness” (Wallmann et al., 1997, p. 31).

## NAHR MENASHE DEPOSIT

Interpretation of 2-D and 3-D seismic data (see Methods in the GSA Data Repository<sup>1</sup>) from offshore Cyprus, Syria, Lebanon, and Israel has led to the recognition of a formerly unidentified basin-scale accumulation. This deposit, herein termed Nahr Menashe (Fig. 1), has an areal extent approximately equal to that of the Messinian Nile River (Eonile) fluvial valley fill (Abu Madi Formation) and a volume of >4150 km<sup>3</sup> (calculated from 2-D seismic data in two-way traveltime [TWTT] and using an interval velocity of 2925 m/s). From its position and morphology, as well as interpreted age and depositional environment, we show that the Nahr Menashe is one of the largest riverine accumulations associated with the terminal MSC, and that it deposited in a subaerially exposed, actively deforming Levant Basin.

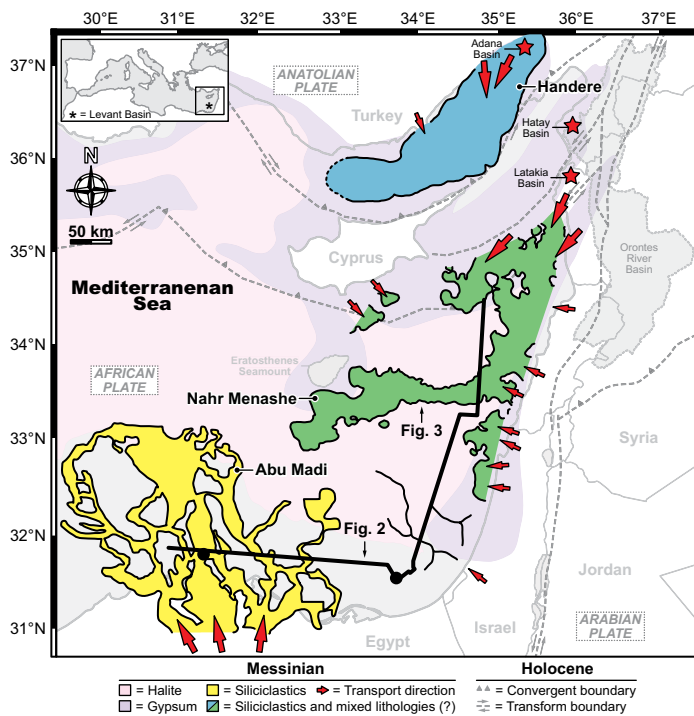
## Position and Morphology

The Nahr Menashe is situated directly atop deep-basin Messinian evaporites (Fig. 2A), with its lower and upper boundaries (intermediate erosional surface [IES] and top erosional surface [TES]; see Lofi, 2018) forming conformable to unconformable contacts with surrounding units. When traced toward the southwest, the top of the Nahr Menashe is coincident with the upper boundary of the Abu Madi Formation, offshore Egypt (Fig. 2B); to the northeast, the surface shallows (Fig. 2C) and deepens (Fig. 2D). The Nahr Menashe reaches a maximum thickness of 300 ms (TWTT) in areas offshore of northwestern Lebanon and western Syria and thins to the southwest (Figs. DR1A–DR1F and DR2A–DR2F in the Data Repository).

In the Levant Basin, the Nahr Menashe consists of a major axial accumulation flanked by smaller transverse deposits (Fig. 3A). The trunk-like axial accumulation extends >500 km in a northeast-southwest to east-west direction and is >20–50 km in width; the deposit terminates at six

<sup>1</sup>GSA Data Repository item 2019062, methods involving 2-D and 3-D seismic interpretation as well as generating isochrons and spectral decompositions, is available online at <http://www.geosociety.org/datarepository/2019/>, or on request from [editing@geosociety.org](mailto:editing@geosociety.org).

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**Figure 1.** Map of eastern Mediterranean showing major Messinian accumulations and main Holocene tectonic elements. Previously unidentified deposit (Nahr Menashe, green) covers approximately same surface area as accumulations filling paleo-Nile River (Eonile) fluvial valleys (Abu Madi Formation, yellow). See Figure 2 for line drawing of regional seismic line intersecting two wells, and Figure 3 for isochron. Abu Madi polygon modified from Abdel Aal et al. (2000) and Loncke et al. (2006); evaporite polygons modified from Rouchy and Caruso (2006); and structural elements and Handere Formation polygons from Walsh-Kennedy et al. (2014) and Radeff et al. (2017).

well-developed backstepping lobes south of the Eratosthenes Seamount. Where 3-D seismic data are available (Fig. 3B; Figs. DR3A–DR3D and DR4A–DR4D), the Nahr Menashe is highly variable and is interpreted to consist of valley fill, channel belts, and lobes. Based on its longitudinal expression, the Nahr Menashe displays more thickness variation in inboard locations associated with channelized accumulations than in outboard settings corresponding to lobes (Fig. 3C).

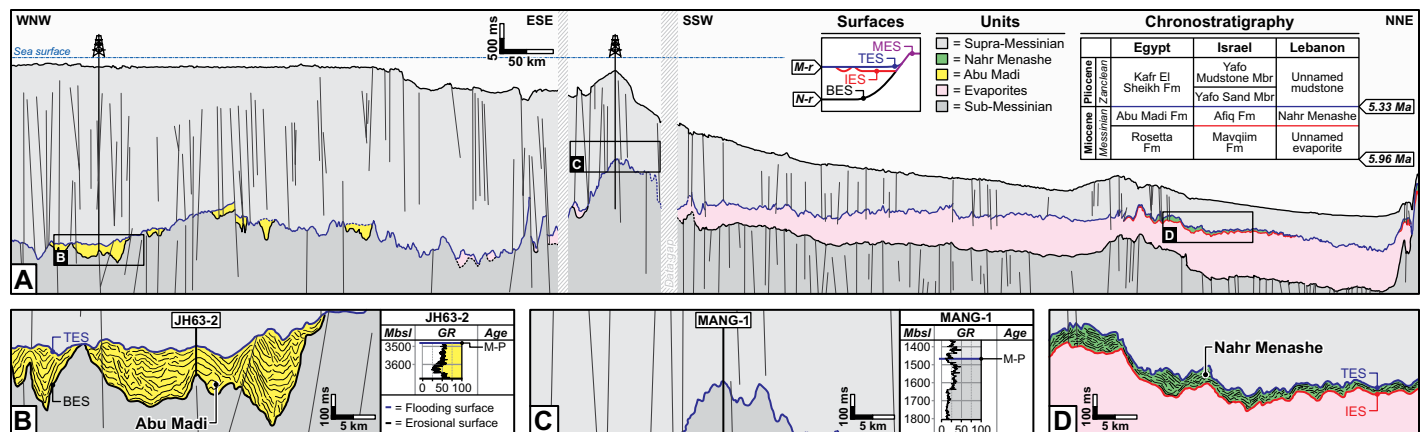
## Age and Depositional Environment

From its supra-evaporitic position and its relationship with the Abu Madi, the Nahr Menashe is interpreted to be late Messinian in age (stage 3 of Roveri et al., 2014). This interpretation, which suggests that the deposit developed during the terminal MSC between 5.55 and 5.33 Ma, is consistent with that of other late Messinian-aged non-marine accumulations in the eastern Mediterranean, namely: the Eosahabi deposit, offshore Libya (Bowman, 2012); the Abu Madi, offshore Egypt (Leila et al., in press); and the Handere Formation, offshore Turkey (Radeff et al., 2017). Assuming an astronomically induced climatic origin (see Krijgsman et al., 1999), we tentatively propose that each of the six lobes of the Nahr Menashe may have accumulated over a single precession cycle (i.e., 21.7 k.y.), and that the deposit developed in ~130 k.y.

Based on its seismic stratigraphy and morphology, the Nahr Menashe is interpreted to be a fluvial accumulation (Fig. DR5) sourced from southern Turkey and western Syria and is presumed to consist of poorly sorted siliciclastics and mixed lithologies (i.e., marls). A fluvial (as opposed to deep-water) interpretation is supported by the paucity of large-scale erosional and aggradational confinement underlying the main axial deposit, the significant lateral variability in overbank accumulations, the existence of smaller-scale lateral accretion and tributary channel fill, and the late-stage topographic inversion (Fig. DR6), which is most commonly associated with subaerial settings (see Pain and Ollier, 1995). A riverine interpretation is further validated by the occurrence of numerous late Messinian fluvial deposits in the eastern Mediterranean and the presence of onshore MSC fluvial valleys situated directly inboard of the Nahr Menashe (i.e., in the Hatay Basin [Turkey] and Latakia Basin [Syria]; see Mocochain et al., 2015). Although the Nahr Menashe can be interpreted as submarine in origin, the accumulation lacks diagnostic deep-water features (i.e., slope-valley and channel-levee deposits [see Fig. DR7], homogenous overbank accumulations, and shingled [turbidite] reflection geometries).

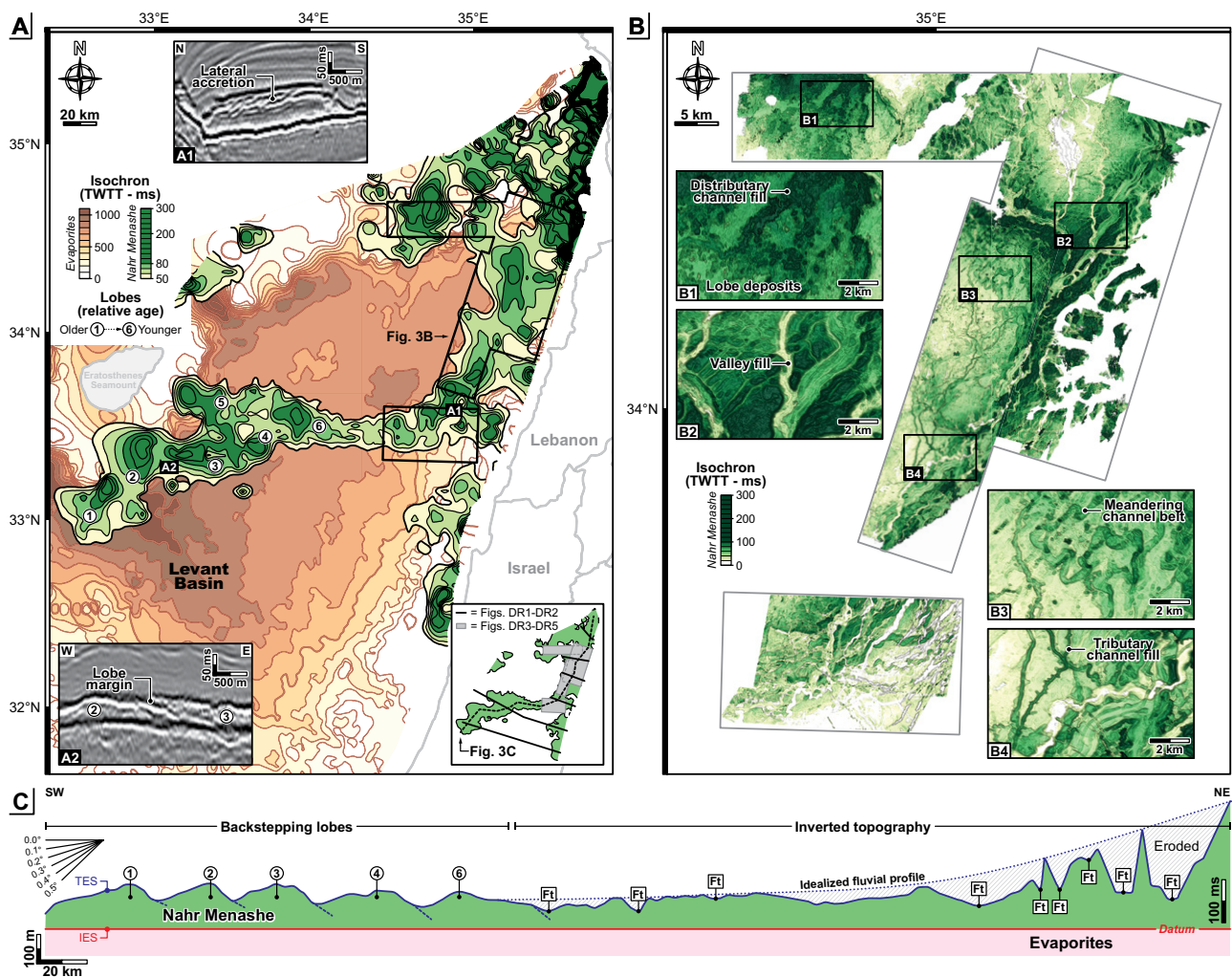
## Paleogeography and Deformation

While available data indicate that the updip portion of the Nahr Menashe represents riverine accumulation, the interpretation of its downdip terminus is less clear. As such, we propose two scenarios to explain the paleogeography of the lobate deposits: a dryland setting and a lacustrine environment. In the former (Fig. 4A, left), lobate accumulations develop in ephemeral lakes; systems are desiccated to near or complete dryness during times of evaporation. In the latter (Fig. 4B, left), deposition occurs in persistent lakes; minor lake-level fluctuations occur during increased evaporation,

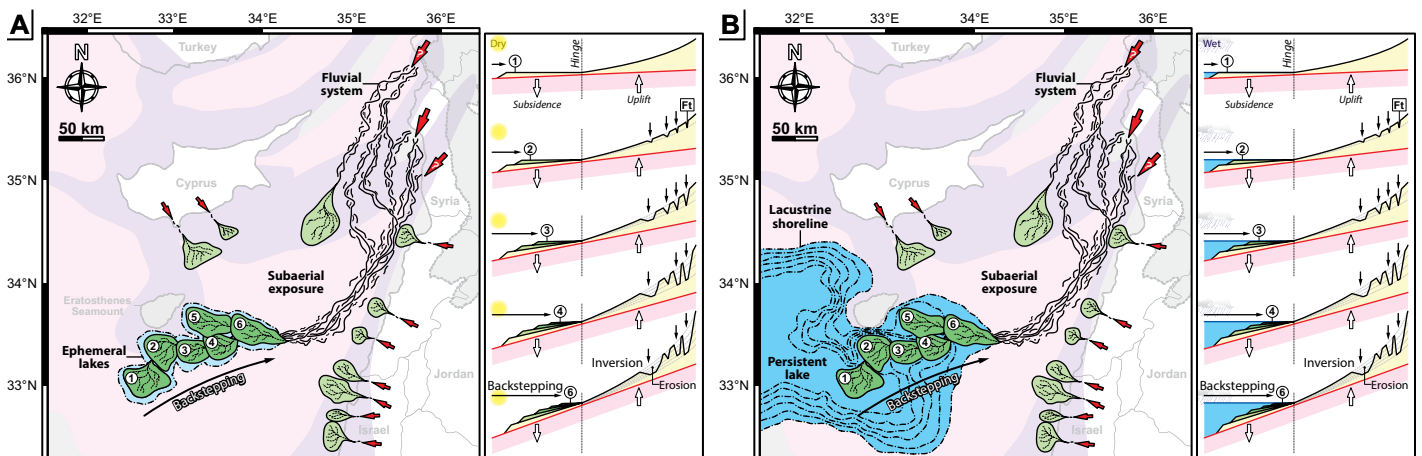


**Figure 2.** A: Line drawing of regional seismic section showing Messinian stratigraphic relationships in southeastern Mediterranean (see Fig. 1 for location). Abbreviations (see Lofi, 2018): MES—margin erosion surface; TES—top erosion surface; IES—intermediate erosion surface; BES—bottom erosion surface; M-r—M reflection; N-r—N reflection; Fm—Formation; and Mbr—Member. Proposed chronostratigraphy for offshore Lebanon is shown at top right. B,C: In areas offshore Egypt (B), fluvial valley fill rests uncomfortably on non-evaporitic accumulations; when traced toward northeast (C), TES separates Miocene (M) from Pliocene (P) deposits. D: In offshore Lebanon, the TES caps the Nahr Menashe deposit. Reflection geometries for the Abu Madi Formation and Nahr Menashe (black lines) shown by lines in B and D. Gamma ray (GR) logs for well JH63-2 are from Sarhan (2015) and for well MANG-1 are from Yousef et al. (2010).





**Figure 3.** Messinian deposits in eastern Mediterranean. **A:** Isochron maps (created from two-dimensional seismic data) showing evaporitic accumulations and overlying Nahr Menashe deposit; latter is thickest at its northeastern edge and thins toward southwest, where it forms six backstepping lobes. Seismic expression of lateral accretion and inter-lobe backstepping are shown in insets A1 and A2. **B:** Isochron map (created from three-dimensional seismic data) showing seismic morphology of updip Nahr Menashe. Highly variable accumulation consists of lobes, channel belts, and valley fill, which are interpreted as fluvial. **C:** Longitudinal profile (470 km in length) along Nahr Menashe. Toward northeast, thickness changes are caused by erosion (i.e., fluvial terraces [Ft] greater than 250 ms [two-way traveltime, TWTT] deep), whereas toward southwest, they are related to depositional topography (i.e., preserved lobes).



**Figure 4.** Conceptual paleogeographic and deformational models for eastern Mediterranean during late Messinian. Nahr Menashe deposit is interpreted as depositing into either dryland setting or lacustrine environment (A and B, respectively, left). During accumulation, Nahr Menashe was subjected to basinward subsidence and landward uplift, which created backstepping lobes (numbered circles) and inverted topography (A and B, right). Polygons for evaporites are taken from Figure 1; red arrows show sediment-transport direction; and fluvial terraces are marked by Ft.

but do not cause complete lacustrine desiccation. In both models, the Nahr Menashe is interpreted to have developed during a marked increase in fluvial discharge, which was triggered by a wetter climate and/or a significant drainage reorganization in southern Turkey and western Syria.

Along with a climatically and/or tectonically induced increase in discharge, active deformation during the late Miocene can explain the morphologic evolution of the Nahr Menashe (Figs. 4A and 4B, right). The accumulation, which is interpreted to have undergone tilting across a tectonic hinge (i.e., line of zero vertical motion) in the Levant Basin, is presumed to have developed during basinward subsidence and landward uplift. In zones of subsidence, creation of accommodation led to the deposition of successively backstepping lobes; in areas marked by uplift, destruction of accommodation resulted in the exhumation and erosion of preexisting accumulations, which subsequently underwent elevation reversals. This topographic inversion is responsible for the current configuration of the Nahr Menashe, where older and thicker deposits exist at higher elevations than younger and thinner accumulations (Fig. DR6). Our interpretation of active late Miocene deformation in the Levant Basin is supported by the work of Hawie et al. (2013).

## DISCUSSION

The discovery of the Nahr Menashe suggests not only that previously unidentified late Messinian deposits may be present throughout the Mediterranean, but that deep-basin drawdown had occurred in the Levant Basin by the terminal MSC. The latter, which casts serious doubt on current deep-water interpretations, specifically calls into question the mechanism of “dense shelf water cascading” (i.e., hyperpycnal flow) in the formation of Messinian-aged canyons and in the redeposition of eroded sediment (see Roveri et al., 2014). Because we interpret the actively deforming Levant Basin as having been exposed subaerially during the terminal MSC, a late-stage increase in fluvial discharge could have been a major driver in diluting well-developed deep-basin hypersaline lakes. This mechanism, which would have caused a relative lake-level rise resulting in backstepping lobes (i.e., prior to Zanclean marine transgression), supports our lacustrine interpretation for the Nahr Menashe (Fig. 4B). Deposits accumulating in the Sirt Basin, offshore Libya, have also been interpreted as having been controlled by linked climatic-tectonic forcing (Bowman, 2012), thereby suggesting that such mechanisms may have modulated terminal MSC non-marine facies more regionally (i.e., Lago Mare; see Orszag-Sperber, 2006).

## CONCLUSION

Previously unpublished 2-D and 3-D seismic data from the Levant Basin (eastern Mediterranean) reveal a formerly unidentified, late Messinian-aged accumulation. The deposit is positioned directly above deep-basin evaporites, has an extent approximately equal to that of the deposits from the late Miocene Nile River, and extends from southern Turkey and western Syria to south of the Eratosthenes Seamount. The accumulation, which documents a previously unknown transport direction and drainage basin, is interpreted as fluvial and is presumed to have deposited into either a dryland setting or a lacustrine environment. With a volume of >4150 km<sup>3</sup>, the accumulation is one of the largest associated with the terminal MSC and is interpreted to have recorded an abrupt increase in riverine discharge, which would have freshened an actively deforming Levant Basin. Based on marked evidence of subaerial exposure and onshore incision, we question the deep-water deep-basin model for the terminal MSC and suggest that deposits in the eastern Mediterranean hold key insights into one of the greatest desiccation events in Earth history.

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