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The Messinian Salinity Crisis: Past and future of a great challenge for marine sciences

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A B S T R A C T

Forty years after the image of the Mediterranean transformed into a giant salty lake was first conceived, the fascinating history of the Messinian Salinity Crisis (MSC) still arouses great interest across a large and diverse scientific community. Early outcrop studies which identified severe palaeoenvironmental changes affecting the circum-Mediterranean at the end of the Miocene, were followed by investigations of the marine geology during the 1950s to 1970s. These were fundamental to understanding the true scale and importance of the Messinian event. Now, after a long period of debate over several entrenched but largely untested hypotheses, a unifying stratigraphic framework of MSC events has been constructed. This scenario is derived mainly from onshore data and observations, but incorporates different perspectives for the offshore and provides hypotheses that can be tested by drilling the deep Mediterranean basins.

The MSC was an ecological crisis, induced by a powerful combination of geodynamic and climatic drivers, which had a great impact on the subsequent geological history of the Mediterranean area, and on the salinity of the global oceans. These changed the Mediterranean's connections with both the Atlantic Ocean and the freshwater Paratethyan basins, causing high-amplitude fluctuations in the hydrology of the Mediterranean. The MSC developed in three main stages, each of them characterized by different palaeoenvironmental conditions. During the first stage, evaporites precipitated in shallow sub-basins; the MSC peaked in the second stage, when evaporite precipitation shifted to the deepest depocentres; and the third stage was characterized by large-scale environmental fluctuations in a Mediterranean transformed into a brackish water lake.

The very high-resolution timescale available for some Late Miocene intervals in the Mediterranean makes it possible to consider environmental variability on extremely short time scales including, in some places, annual changes. Despite this, fundamental questions remain, some of which could be answered through new cores from the deepest Mediterranean basins. Improvements in seismic imaging and drilling techniques over the last few decades make it possible to plan to core the entire basinal Messinian succession for the first time. The resulting data would allow us to decipher the causes of this extreme environmental change and its global-scale consequences.

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1. Introduction. The Messinian Salinity Crisis: an enduring challenge for land-based and offshore researchers

Unraveling the history of the environmental modifications experienced by the Mediterranean region at the end of the Miocene is an intellectual challenge that has fascinated a large community of earth and life scientists for almost 50 years. As with the other saline giants that developed episodically during the Earth's history (Hsü, 1972; Warren, 2010), the causes of, and mechanisms by which more than a million cubic kilometers of salt accumulated on the Mediterranean sea-floor over a brief period of less than 700 ka are difficult to understand. In part this is because of the absence of modern evaporitic systems comparable in terms of both size and mineralogy. However, what is commonly known as the Messinian Salinity Crisis (MSC), i.e. the transformation of a small ocean into a giant evaporitic pool and then into a brackish-water lake, is unique amongst the saline giants, because it occurred relatively recently, in a basin that has not subsequently undergone significant modifications. Consequently, the majority of the MSC's sedimentary record is still preserved below the present-day Mediterranean seafloor (Fig. 1). Marine scientists, and amongst them marine geologists, therefore have a key role in exploring and elucidating this extraordinary event and extracting its general implications for the formation of saline giants.

The concept of a Messinian salinity crisis (Selli, 1954) was first formulated from onshore studies, which demonstrated the widespread, coeval development of hyper- and hyposaline environments all around the Mediterranean at the end of the Miocene (Ogniben, 1957; Selli, 1960; Ruggieri, 1967). However, the true scale and importance of the Messinian environmental changes in the Mediterranean was fully realized only after pioneering marine geology studies carried out during the late 50s to early 70s (Bourcart et al., 1958; Bourcart, 1959a,b; Alinat and Cousteau, 1962; Bourcart, 1962; Hersey, 1965; Alinat et al., 1966; Glangeaud et al., 1966; Cornet, 1968; Mauffret, 1969, 1970; Montadert et al., 1970; Auzende et al., 1971; Ryan et al., 1971; Biscaye et al., 1972; Mauffret et al., 1972; Bellaiche and Recq, 1973; Bellaiche et al., 1974). These studies identified in the western Mediterranean diapiric structures rooted in an offshore salt layer up to 2 km thick, an erosional surface on basin margins, and a deep basin trilogy of seismic units (Fig. 1) topped by a series of strong reflectors (the "M" reflectors) that were soon correlated with the onshore evaporitic units. The 1970 Deep Sea Drilling Project (DSDP) Leg 13 (Hsü, 1972, 1973; Hsü et al., 1973a,b), drilled in the Mediterranean, recovered cores from the top of the evaporite unit for the first time in the deep basins (Fig. 1). This confirmed the early hypothesis about the age and nature of the MSC and generated an explosion of interest and publicity. Partly as a result of this, the MSC burst on to the pages of *Marine Geology*, becoming one of the most common topics of papers published by the journal, with 153 articles citing the phrase *Messinian Salinity Crisis* from 1972 to present.

The main scientific challenge following that initial drilling has been combining the onshore and offshore records of the MSC into a single, unified scenario. The different approaches, instruments, scale of observations and degree of resolution that characterize the two domains and their rather separate scientific communities, account, in part, for why this has proved so difficult to achieve. Perhaps more important however, is the absence of what could be a common basis for a synthesis, i.e. a complete cored succession from the deep basinal Mediterranean. As a result, the MSC represents an enduring collaborative opportunity for land and marine-based scientists to contribute to, not only a full understanding of what happened in the Mediterranean 6 million years ago, but also to unraveling the complex mechanisms involved in Earth's responses to environmental changes at different temporal and spatial scales. In this respect, the Messinian evaporite record offers a great opportunity for studying the limits of life in the extreme environments of our planet, with important implications for planetary sciences (see Section 5.3). Moreover, Messinian events and deposits are undergoing a renewed interest for the assessment of the petroleum system's potential of the pre-Messinian subsalt successions in several Mediterranean provinces (Pawlewicz, 2004; Belopolsky et al., 2012).

2. Discoveries and controversies

Following the first Messinian colloquium, C.W. Drooger compiled a collection of papers for a book, entitled *Messinian Events in the*

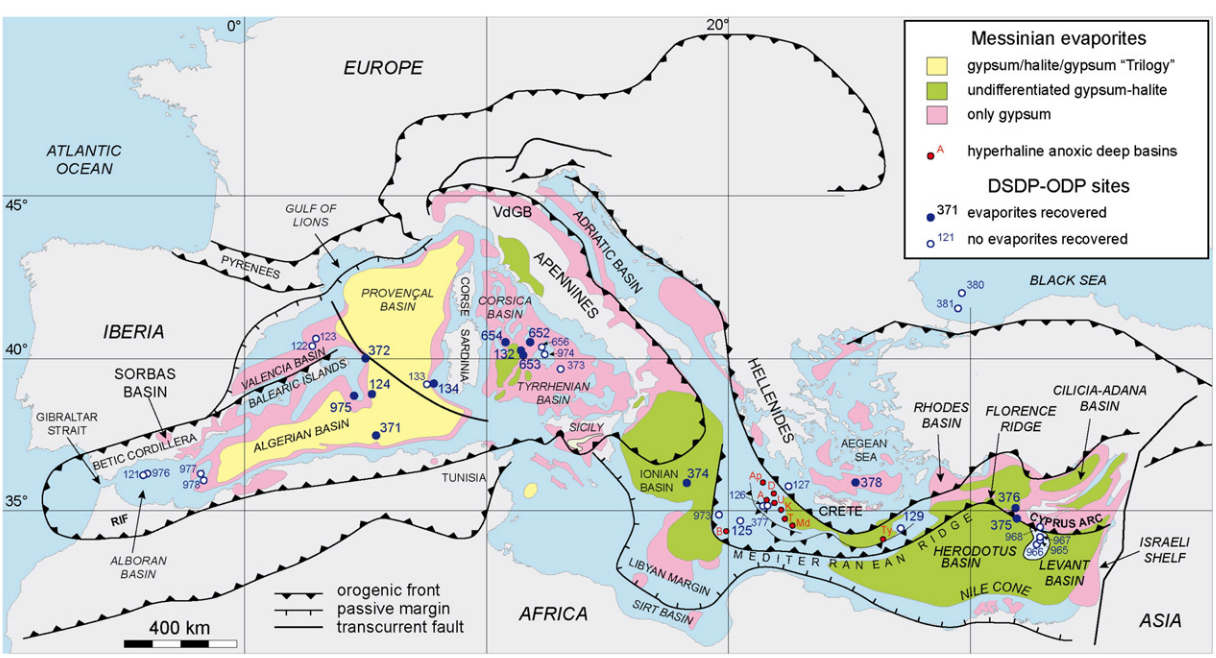

Fig. 1. Distribution of Messinian evaporites and location of the DSDP-ODP boreholes which recovered Messinian deposits. The location of the main hyperhaline anoxic deep basins on top of the Mediterranean Ridge is also shown: Ap, Aphrodite; A, Atlante; B, Bannock; D, Discovery; K, Kryos; M, Medee; T, Thetis; Ty, Tyro; U, Urania.
Modified from Rouchy and Caruso (2006) and Manzi et al. (2012).