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Research paper

Tectonic and sedimentary conditions necessary for the deposition of the Messinian evaporite successions in the eastern Mediterranean: A simple 2D model

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ABSTRACT

The existing literature shows that the only saline water source for the eastern Mediterranean during the Messinian was the Atlantic Ocean and that the Sicily sill created a physical barrier between the eastern and western Mediterranean, higher than the physical barrier at the Gibraltar sill between the western Mediterranean and the Atlantic Ocean. The presence of distinctive Messinian subunits in the eastern Mediterranean similar to those observed in the western Mediterranean, suggests the existence of a similar set of depositional processes across the entire Mediterranean during the Messinian Salinity Crisis. The above statements impose two critical conditions: the eastern Mediterranean massive salt deposits must be older than their counterparts in the western Mediterranean, and the Sicily Gateway must have remained within a "goldilocks" zone during the deposition of the massive eastern Mediterranean evaporites (predominantly halite), while the sea level in the western Mediterranean would remain at the level of the Sicily sill. A simple 2-D model is developed which satisfies these conditions. The model suggests that the eastern and western basin margins experienced a nearly synchronized gypsum deposition associated with the initial drawdown of the Mediterranean level, followed by re-sedimentation in the deep basins of the terrigenous and early evaporite deposits as the drawdown intensified. The synchroneity of evaporite deposition across the eastern and western basins broke down as the Sicily Gateway became largely subaerial during a period when the Calabrian Arc area experienced uplift associated with slab break-off: the Sicily sill must have remained within a "goldilocks" zone to allow the right amount of saline water inflow into the eastern Mediterranean so that evaporites (massive halite) could be deposited. During this time, the sea level in the western Mediterranean was at the breach-level of the Sicily sill, and still open to Atlantic water influx, thus no evaporite deposition took place there. The model suggests that further restriction of the inflow occurred across the Gibraltar region which became largely subaerial associated with the uplift of the Gibraltar Arc caused again by lithospheric slab break-off. Similar to the Sicily Gateway, the Gibraltar Gateway also remained within the "goldilocks" zone to allow the right amount of saline water inflow into the western Mediterranean so that massive halite could be deposited. The re-opening of the Gibraltar Gateway re-flooded the western Mediterranean first, then the eastern Mediterranean allowing the deposition of a mixed evaporite-siliciclastic unit, followed by the transgressive sediments with distinctive brackish water *Lago Mare* fauna.

1. Introduction

The Messinian Salinity Crisis refers to a series of events that occurred between ~5.97 and 5.33 Ma, which resulted in the reduction/cessation of water inflow from the Atlantic Ocean into the Mediterranean Sea, creating widespread evaporite precipitation across the Mediterranean basins (Fig. 1; Montadert et al., 1978; Garfunkel and Almagor, 1987; Gorini et al., 1993, 2015; Gradmann et al., 2005; Rouchy and Caruso, 2006; Roveri et al., 2008a,b,c, 2014a,b,c). During the Messinian the base-level of the Mediterranean Sea dropped considerably below its present level. In the western Mediterranean, a ~1500 m deep river valley incision occurred and propagated at least ~300 km inland from the coast. Karst systems that were formed in association with the Messinian canyons of the Ardèche and Rhône rivers suggesting that the base level dropped to −1500 m (Loget et al., 2006; Mocochain et al., 2006; Urgeles et al., 2010). In the eastern Mediterranean several erosional surfaces are observed in seismic profiles along the Egyptian margin at a depth between −2500 and −3000 m (Gargani and Rigollet, 2007). These authors argued that the Pliocene–Quaternary subsidence ranges between 750 and 1000 m, thus, the

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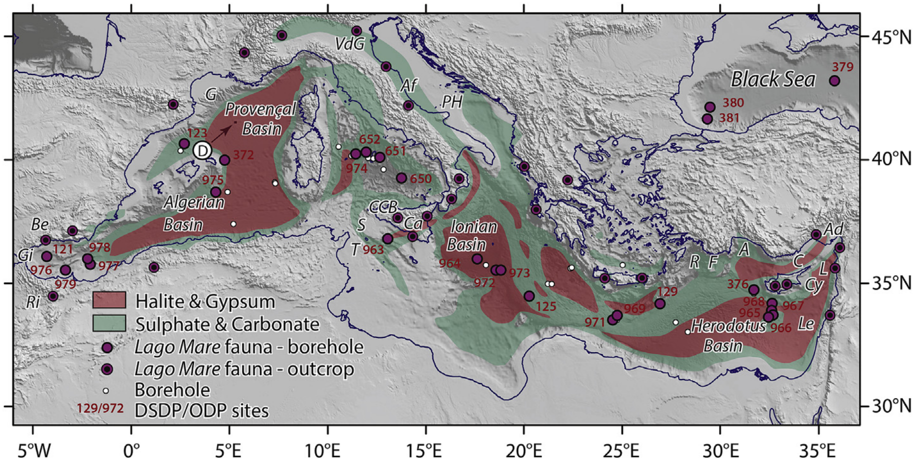

Fig. 1. Present-day distribution of the Messinian evaporites across the Mediterranean (redrawn from Ryan, 2009), and sites where *Lago Mare* fauna has been identified (from Ryan, 2009; Tekin et al., 2010; Bowmann, 2011; Cipollari et al., 2013a; b; Manzi et al., 2014). The morphological basemap of the Mediterranean region is compiled using GeoMapApp (Ryan et al., 2009), and shaded using Caris Base Editor (4.1). Coastline is from the International Bathymetric Charts of the Mediterranean (IOC, 1981). A = Antalya Basin, Ad = Adana Basin, Af = Apennines foredeep, Be = Betic Gateway, C = Cilicia Basin, Ca = Caltanisseta Basin, CCB = Calatafimi, Ciminna and Belice basins, Cy = Cyprus Basin, F = Finike Basin, G = Gulf of Lions, Gi = Strait of Gibraltar, L = Latakia Basin, Le = Levantine Basin, PH = Pelagosa high, R = Rhodes Basin, Ri = Rif Gateway, S = Strait of Sicily, T = Tunisian continental margin, VdG = Vena del Gesso Basin. D in circle = seismic profile illustrated in Fig. 7.

erosional surfaces must have been formed during the Messinian Salinity Crisis at depths of 1500–2250 m below the present-day base level. Successions across the Afiq Canyon in the Levant margin show similar sea-level lowering during the Messinian (Druckman et al., 1995). The Be'eri Gypsum was cored on the shoulder of the Afiq canyon more than 600 m above the Mavqi'im Formation (Druckman et al., 1995). These authors used the $^{87}Sr/^{86}Sr$ values to correlate the evaporites of the Mavqi'im Formation with the Lower Evaporites and the Be'eri Gypsum with the Upper Evaporites, which suggested two high-amplitude sea-level falls (800 m and 660 m) with consequent canyon incision. In a recent paper this interpretation has been questioned by Lugli et al. (2013), who speculated that the profound incision of the Afiq Canyon predates the Messinian Salinity Crisis.

Evaporites of variable thickness and lateral extent were deposited during the Messinian across the entire Mediterranean. For example, up to 3.5 km-thick and 1.5 km-thick evaporite successions were deposited within the deep central basins of the eastern and western Mediterranean, respectively (e.g., Ryan, 2009). However, the deposits associated with the Messinian Salinity Crisis also include variable proportions of terrigenous siliciclastic debris (e.g., Roveri et al., 2014a; b; c; Manzi et al., 2014), which coincided with intense subaerial erosion of the basin margins and subsequent deposition of these siliciclastic materials in the deep central basins (Hsü et al., 1978; Ryan and Cita, 1978; Barber, 1981; Savoye and Piper, 1991; Druckman et al., 1995; Lofi et al., 2005; Ryan, 2009; Bache et al., 2009).

Several hypotheses are proposed for the timing and duration of evaporite deposition during the Messinian Salinity Crisis across the Mediterranean, including (a) synchronous deposition across the eastern and western Mediterranean basins (e.g., Hsü et al., 1973; Krijgsman et al., 1999, 2002, 2004), (b) hypsometrically diachronous deposition across the shallow water marginal basins and deep basins across the Mediterranean (e.g., Butler et al., 1995; Clauzon et al., 1996; CIESM, 2008) and (c) longitudinally diachronous evaporite deposition (e.g., Blanc, 2000, 2006). Here it is important to note that there is little physical connection between the shallow water marginal basins and the deep Mediterranean basins, or the eastern and western Mediterranean basins, but may be more critically evaporites from the deep basins and many shallow basins have not been sampled at sufficient densities and accurately dated. Therefore, the timing and the environment of evaporites deposition in the Mediterranean deep and many shallow basins (particularly across the eastern Mediterranean) remain uncertain and controversial. The above three hypotheses are briefly explained below:

In the early studies of the Messinian Salinity Crisis, immediately following the first Deep Sea Drilling expedition, the general view was that the onset of evaporite deposition was synchronous across the eastern and western Mediterranean basins (e.g., Hsü et al., 1973). Several subsequent studies further elaborated on the synchroneity of the onset of evaporite deposition across the entire Mediterranean region (e.g., Krijgsman et al., 1999, 2002; 2004; Rouchy and Caruso, 2006). For example, Krijgsman et al. (1999) presented an astronomically calibrated chronology for the Mediterranean Messinian successions tuned to variations in the Earth's orbital parameters to suggest that the onset of the Messinian Salinity Crisis was synchronous across the entire Mediterranean basin, at 5.96 ± 0.02 Ma.

According to the hypsometrically diachronous deposition hypothesis, evaporite deposition initially started across the shallow marginal basins and subsequently migrated progressively into the deeper basins associated with the sustained drawdown and increasing brine concentration (Rouchy, 1982; Clauzon et al., 1996; CIESM, 2008). Data for the hypsometrically diachronous hypothesis come from various locations from the western Mediterranean, such as the fold-thrust belts across Sicilian sub-basins where evaporite deposition in each sub-basin was triggered diachronously with the oldest starting at ~6.88 Ma and the youngest more than 800 kyr later (Butler et al., 1995) and the Betic Cordillera where evaporite precipitation started in the early Messinian in the onshore basins, progressively moving into the western Mediterranean deep basin in the mid-Messinian (Riding et al., 1998).

Finally, Blanc (2000, 2006) also supported the synchronous onset of the evaporites across the entire Mediterranean, but further argued that the deposition of the massive salts (predominantly halite) across the eastern and western Mediterranean basins must have deposited in a longitudinally diachronous fashion. He stated that it appears impossible for the sea water/brines to enter the eastern Mediterranean after the major withdrawal of the western basin below Sicily sill depth, thus the chemical constituents of the deep eastern Mediterranean evaporites must have entered the eastern basin before the basins were separated.

In this paper we present a regional model for the deposition of the eastern Mediterranean evaporites. The paper is based on several critical previously published data, including (a) the notable acoustic similarities in the successions deposited during the Messinian Salinity Crisis across the eastern and western Mediterranean basins, which suggest similarities in the associated depositional processes (Güneş et al., 2018), (b) the presence of only one source for the marine water inflow into the eastern Mediterranean during the Messinian (Bosworth et al., 2005; Gargani et al., 2008; Rohais et al., 2016), and (c) importance of the Sicily Gateway in the deposition of the evaporite successions across the eastern Mediterranean (e.g., Blanc, 2000, 2006).

2. Data acquisition and methods

The principal data used in this paper consist of (a) ~8600 km of multichannel seismic reflection profiles collected in 1991, 1992, and