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Salinity stratification of the Mediterranean Sea during the Messinian crisis: A first model analysis

Dirk Simon *, Paul Th. Meijer

Department of Earth Sciences, Utrecht University, The Netherlands

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ABSTRACT

In the late Miocene, a thick and complex sequence of evaporites was deposited in the Mediterranean Sea during an interruption of normal marine sedimentation known as the Messinian Salinity Crisis. Because the related deposits are mostly hidden from scrutiny in the deep basin, correlation between onshore and offshore sediments is difficult, hampering the development of a comprehensive stratigraphic model. Since the various facies correspond to different salinities of the basin waters, it would help to have physics-based understanding of the spatial distribution of salt concentration. Here, we focus on modelling salinity as a function of depth, i.e., on the stratification of the water column. A box model is set up that includes a simple representation of a haline overturning circulation and of mixing. It is forced by Atlantic exchange and evaporative loss and is used to systematically explore the degree of stratification that results under a wide range of combinations of parameter values. The model demonstrates counterintuitive behaviour close to the saturation of halite. For parameter values that may well be realistic for the Messinian, we show that a significantly stratified Mediterranean water column can be established. In this case, Atlantic connectivity is limited but may be closer to modern magnitudes than previously thought. In addition, a slowing of Mediterranean overturning and a larger deep-water formation region (both in comparison to the present day) are required. Under these conditions, we would expect a longer duration of halite deposition than currently considered in the MSC stratigraphic consensus model.

1. Introduction

The Mediterranean sedimentary record hosts a kilometre-thick salt giant, deposited during the Messinian Salinity Crisis (MSC, Roveri et al., 2014a, and references therein). The occurrence of evaporites indicates that, overall, basin salinity must have been high. Several different evaporitic lithologies are found in outcrops and are interpreted from seismic profiles. Considerable attention has been paid to establishing the stratigraphy of the MSC, both vertically and laterally (e.g., Ochoa et al., 2015; Lugli et al., 2010; Lofi et al., 2011). A stratigraphic consensus model has been proposed (Fig. 1, summarized by Roveri et al., 2014a), which subdivides the MSC into three evolutionary stages, the first two of which are relevant to this study. Stage 1 is, in marginal basins, dominated by cycles of primary selenitic gypsum alternating with marls. The main halite body is thought to be deposited in the deep basin in stage 2 (in association with cumulate and clastic gypsum). This consensus interpretation notwithstanding, much is still uncertain for the simple reason that most of the deposits are hidden from scrutiny below the present sea (e.g., Roveri et al., 2016). It is therefore difficult to establish a definitive correlation between marginal sequences studied in the field and the deep record as seen in seismics. While the halite mined on Sicily is commonly considered an exposed representative of the deep-basin record (the only, in fact), this is also uncertain. In the consensus model (Roveri et al., 2014a) the halite basin of Sicily is considered an intermediate-depth basin.

Given that the different evaporitic facies correspond to different salinities of the waters from which they precipitated (e.g., Warren, 2016), it would help to have insight from physics as to which spatial distribution of salinity is most likely at any one point in time. Is it possible that the shallow waters of the marginal basins reside at gypsum saturation while, at the same time, the deeper waters reach levels high enough for halite precipitation? Or, are there reasons to expect the basin to be always well mixed? In the latter case, primary selenitic gypsum in marginal basins and halite in the deep basin are not expected to be lateral equivalents and the physics would support the consensus model (Fig. 1).

In the literature one almost exclusively finds qualitative ideas about the spatial distribution of salinity during the MSC. An early

* Corresponding author.
E-mail address: d.simon@uu.nl (D. Simon).

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example (Sonnenfeld and Finetti, 1985) suggests various precipitation cycles in which gypsum forms in the shallow parts of the basin and halite at greater depth. More recently this configuration was envisaged by de Lange and Krijgsman (2010), who present a chemical mechanism that allows for synchronous deposition of gypsum at the surface and dolomite at depth and take stratification to be more stable due to the presence of deep brines. Roveri et al. (2014b) numerically simulate the notion that cascading explains the Messinian erosional surface and forms deep supersaturated brines. Also Yoshimura et al. (2016) propose that the deep basin is density stratified and that halite-oversaturated brines transport salt from the margins to depth. While Meijer (2006) and Topper and Meijer (2013) investigated the effect that an imposed stratification has on their model results for the MSC, they did not study how and whether stratification arises in the first place.

The purpose of this paper is to gain quantitative, physics-based, understanding of the factors that controlled the vertical distribution of salinity in the Messinian brine basin. For this we use a simple box model. Although general circulation models (e.g., Topper and Meijer, 2015) certainly provide insight about stratification, their long computation time and the extreme ocean salinity during the MSC preclude their use for our purposes. These limitations do not affect box models and these have proven to be valuable tools for testing the sensitivity of Mediterranean parameters to external forcing. In this first study of this kind we explore a box model that includes a deep-water formation region feeding a basin-wide circulation, which can be thought of as a simple representation of a haline overturning circulation. In addition, exchange with the Atlantic, evaporative surface forcing and mixing within the basin are taken into consideration. The model calculates surface and deep Mediterranean salinity through time, which provides a crude quantitative measure for the degree of stratification. A systematic model analysis allows us to identify under which range of parameters the basin is mixed and when, in contrast, it is stratified. Our findings will be discussed in terms of their potential implications for the stratigraphical relationships within the Messinian sedimentary record. What makes the analysis timely is that industry data of the Levant basin have become available (e.g., Feng et al., 2016) and that the scientific community is working towards drilling the deep Messinian record (e.g., MEDSALT initiative, https://medsalt.eu).

2. Model description

Consider the following thought experiment: an ocean basin subject to evaporation is represented as a single water column. The evaporation will cause salinity of the surface water to increase. As a result, surface density is enhanced and a gravitational instability is created, which leads to mixing of the water column. As long as evaporation continues, these steps will repeat themselves and the column will be essentially homogeneous at all times. This effect is exemplified by the recent Dead Sea, apart from the fact that here a stable stratification is installed seasonally due to heating (e.g., Sirota et al., 2016). We learn from this thought experiment that, in order to create persistent (i.e., lasting longer than one year) stratification, a single-column representation does not suffice and that lateral variation is crucial.

In this study we use a box model, as show in Fig. 2. In the Mediterranean Sea evaporation exceeds precipitation and river input. We denote net evaporation as e and take it to act uniformly across the basin. Exchange with the Atlantic adds “fresher” water to, and removes saltier water from, the Mediterranean Sea at its western side. Instead of considering the drivers of exchange – Atlantic-Mediterranean density difference and the gateway dimensions (e.g., Simon and Meijer, 2015) – we prescribe a value for the

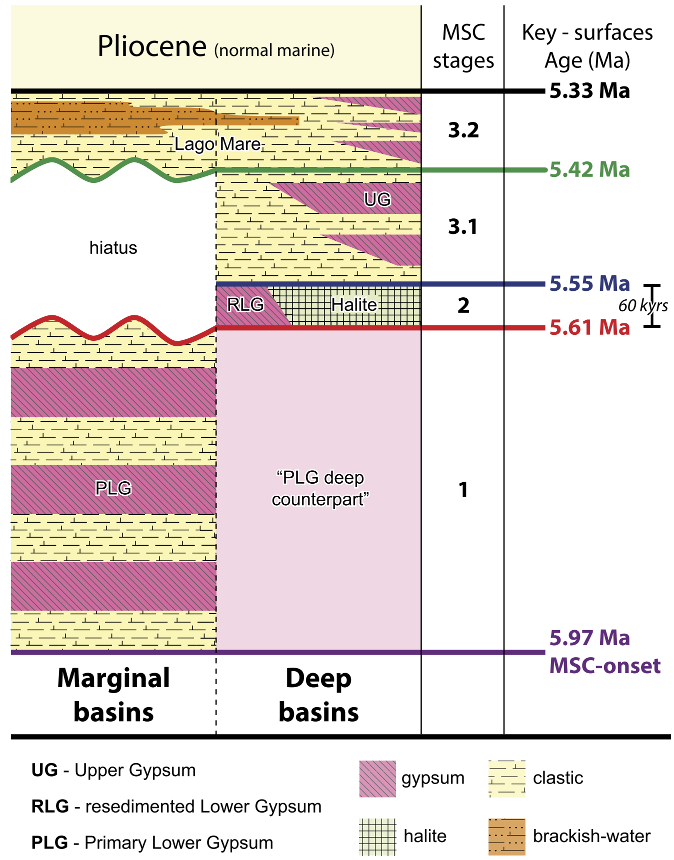

Fig. 1. The MSC stratigraphic consensus model (linear in time), simplified from Roveri et al. (2014a). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

outflow from the Mediterranean (q). Volume conservation then implies the Atlantic inflow equals ($q + e * A$).

Wåhlin and Cenedese (2006) investigate the response of ocean stratification to the inflow of dense water from an adjacent marginal sea by solving the advection–diffusion equation which allows them to obtain a continuous depth variation of water properties. As a first step towards this, we consider the simpler case where the basin is divided into a surface layer (subscript “*Surf*”) and a deep layer (subscript “*Deep*”). Turbulent mixing between the surface and deep box is represented as a diffusive process, following the models for the Mediterranean Sea of Tziperman and Speer (1994) and Matthiesen and Haines (2003). Mixing is controlled by a constant diffusivity κ and a vertical length scale equal to the vertical distance between the middle of the two layers.

In the present-day Mediterranean circulation (e.g., Tsimplis et al., 2006), Atlantic surface water flows towards the east and increases in salinity due to evaporation. In the Levantine basin the water becomes dense enough to sink to intermediate depth, at which level it spreads westwards throughout the basin. On its path to the west, the salt-preconditioned water passes through regions where it is subjected to cold and dry winds (e.g., Schroeder et al., 2012). This leads to further increase in density and forms deep water. Modern deep-water formation occurs at the northern rim of the Mediterranean Sea in shallow, restricted, basins, like the Adriatic Sea or the Aegean Sea, and in open-ocean convection sites (e.g., Gulf of Lions). The dense water produced charges the Mediterranean overturning circulation. In our model the *deep-water formation*-box (*DWF*) represents such a region. The production of deep water (to which we will refer as “convection”) is parametrised as a constant volume flux w. The same volume of water per unit of time is advected upwards outside the DWF. Con-