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The Gibraltar Corridor: Watergate of the Messinian Salinity Crisis

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ABSTRACT

The existence and evolution of a Messinian salt giant in the Mediterranean Sea has caused much debate in the marine science community. Especially the suggestion that the Mediterranean was a deep desiccated basin during the Messinian Salinity Crisis (MSC, 5.97–5.33 Ma), triggered by a temporal disconnection from the global ocean, made it a well-known crisis beyond the scientific boundaries. Approximately ~50 years after this provocative statement, it remained unknown which Mediterranean–Atlantic seaway delivered the 5–6% of the global ocean's salt into the Mediterranean basin. Here, we review the changes in Mediterranean-Atlantic connectivity throughout the late Miocene in order to locate, date and quantify the missing Messinian gateway that provided the salt water inflow during the MSC. We conclude that all the known pre-MSC gateways through southern Spain and northern Morocco were closed, leaving the "Gibraltar Corridor" at its Messinian configuration as the sole candidate. We consider the possibility of longer and narrower straits existing at depth below the present Gibraltar region, and using strait dynamic theory we calculate its dimensions during the Messinian based on the salinity changes in the Mediterranean. A marine Messinian gateway through the Gibraltar Corridor is in agreement with growing evidence that Atlantic waters reached the Mediterranean Sea during all three stages of the MSC.

1. Prologue

The initial picture of a deep-desiccated Mediterranean filled with km-thick evaporites (Fig. 1) developed from the scientific results of the Deep Sea Drilling Project (DSDP) Leg 13 in deep Mediterranean basins (Hsü et al., 1973a, 1973b). The Mediterranean-wide extent of the Messinian evaporites (gypsum and halite) was further established from seismic profiles, deep-sea cores and land-based sections (see Roveri et al., 2014a for a review). This re-fueled the older concept of a "Messinian salinity crisis" (MSC) (Selli, 1954, 1960), which is considered as one of the most dramatic paleoceanographic crises in Earth's history (e.g., Ruggieri, 1967; Ryan, 2009). The widespread canyon incisions of the rivers draining into the Mediterranean indicated a MSC water level of ~1500 m below global sea-level (Chumakov, 1973; Ryan, 1978, 2008; Clauzon, 1982). Consequently, the "desiccated-deep basin" model of the MSC has been used as an argument for temporal disconnections of the Mediterranean from the Atlantic (Hsü et al., 1973a). It was realized from the beginning that intermittent input of Atlantic water to the Mediterranean was necessary to explain the huge amount of halite in the deep basins and it was estimated that eight or ten marine invasions could have been sufficient to account for all the salts (Hsü et al., 1973a, 1973b). Spectacular though this model is, the exact location of the marine Messinian gateway(s) remained enigmatic over the years.

During the last decade, evidence is accumulating that the Messinian sequences in the Mediterranean require regular sea-level and at least one continuously open Atlantic connection to provide the salts for repeated events of gypsum and halite deposition (Krijgsman and Meijer, 2008; Lugli et al., 2010; Simon and Meijer, 2015). A complex network of marine gateways through Morocco and Spain (the Betic and Rifian Corridors; Fig. 2) is thought to have progressively closed during the latest Miocene (Flecker et al., 2015). Well before the MSC, the Mediterranean Sea already underwent significant environmental changes. Step-wise increases in stress tolerant benthic foraminiferal faunas at ~7.2 Ma and ~6.8 Ma indicate early evidence for a more restricted basin setting (Kouwenhoven et al., 2003, 2006). With the onset of the Primary Lower Gypsum (PLG, 5.97–5.6 Ma: Roveri et al., 2014a) during MSC Stage 1, the Mediterranean salinity was potentially above 130 g/

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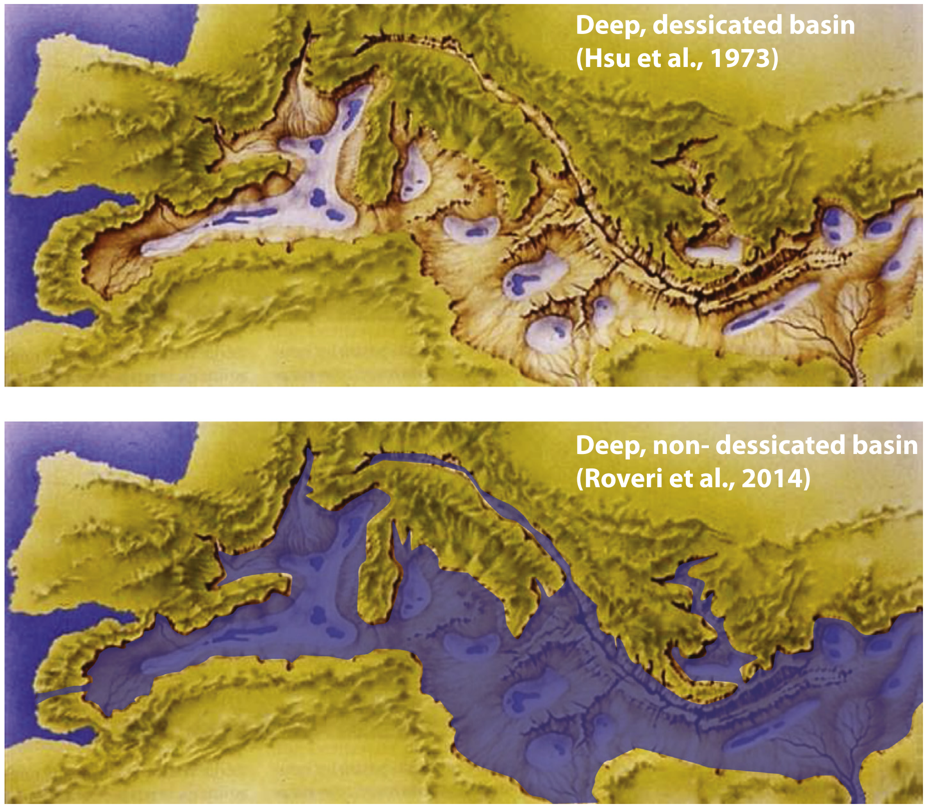

Fig. 1. Map of the wider Mediterranean region. Two extreme MSC scenarios are shown; top panel: a 1500 m sea-level drop; bottom panel: deposition with normal sea-level. Modified after "The First Eden: The Mediterranean World and Man" by David Attenborough (1987).

kg, indicating an even further constriction of the Mediterranean-Atlantic gateway(s). Numerical models have shown that at least one Mediterranean-Atlantic gateway must have persisted to explain the chemical (strontium) composition (Topper et al., 2011) and the Mediterranean-wide evolution of the PLG (Lugli et al., 2010; Simon et al., 2017). This may similar hold true for the Upper Gypsum/Lago-mare Stage 3 (Carnevale et al., 2006; Grunert et al., 2016; Vasiliev et al., 2017), which lasted from 5.55 Ma until 5.33 Ma (Roveri et al., 2014a). In between, the thick halite layer (up to 3 km) was deposited in < 50–60 kyr during the most extreme Stage 2, which stored up to 6% of the global ocean salt in the Mediterranean basin (Ryan, 2009). Due to the lack of a deep Messinian record, several contradicting models have been proposed. Two extreme scenarios are: (a) ~1500 m sea-level drop (Hsü et al., 1973a; Clauzon et al., 1996; Lofi et al., 2005; Bache et al., 2012, Fig. 1a) and (b) deposition from dense brines under normal sea-level (Manzi et al., 2005; Roveri et al., 2014b; Fig. 1b). Both scenarios agree, however, that a marine connection with the Atlantic must have been present, at least during the first two MSC stages.

The Betic and/or Rifian Corridors are commonly envisaged as the late Miocene Atlantic connections supplying sea water into the Mediterranean until its complete isolation (Martín et al., 2001; Krijgsman, 2002; Flecker et al., 2015). Antecedent to the crisis, the Strait of Gibraltar is believed to be closed and it breached only at the Mio-Pliocene boundary (5.33 Ma) by a combination of tectonic and river-erosion processes (Loget et al., 2005; Loget and Van Den Driessche, 2006; Garcia-Castellanos and Villaseñor, 2011). The opening is thought to have originated a catastrophic flood that refilled a deep, desiccated Mediterranean at the end of the MSC (Blanc, 2002; Garcia-Castellanos et al., 2009; Micallef et al., 2018).

In this paper, we synthesize and integrate newly acquired field data on each of these late Miocene gateways, obtained within the scope of the European Union Initial Training Network *MEDGATE*. This network had the objective to investigate the Atlantic–Mediterranean connectivity throughout the late Miocene in order to locate, date and quantify the missing Messinian gateway. We conclude that all gateways through southern Spain and northern Morocco reflect an uplift trend starting as early as the late Tortonian and show no evidence for a marine MSC connection to the Atlantic (Capella et al., 2017b, 2018; Tulbure et al., 2017; Van den Berg et al., 2018; Van der Schee et al., 2018). We thus corroborate the alternative hypothesis of a Messinian connection through the Gibraltar region and present a computational reconstruction on how the dimensions of this "Gibraltar Corridor" may have evolved throughout the Messinian.

2. Quest for the missing Messinian gateway

During the Tortonian (~11.6 to 7.2 Ma), several marine gateways through southern Spain, northern Morocco and potentially Gibraltar, connected the Mediterranean Sea with the Atlantic Ocean (Fig. 2). Most of the gateway sediments that are now exposed on land have been intensively studied, but the timing of corridor closure is still subject to significant uncertainty (Benson et al., 1991; Martín and Braga, 1994; Krijgsman et al., 1999a; Martín et al., 2001; van Assen et al., 2006; Achalhi et al., 2016; Capella et al., 2017a). It is very difficult to pinpoint the exact location or timing of closure from field data alone, because the area which first blocks the marine connection is, by default, the area that experiences the strongest uplift and erosion and the sedimentary succession preserved is therefore often incomplete (e.g., Tulbure et al., 2017). In case an erosional surface is observed, the youngest marine sediments below the unconformity are always older than the final closure age (e.g., Hüsing et al., 2010). When a gradual marine to continental transition is present it is in principle possible to date the last marine sediments. In these cases, however, biostratigraphic dating with planktonic foraminifera is hampered by the absence of deep marine marker species. A combination of magnetostratigraphy and small mammal biostratighraphy can be applied to continental deposits, but