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The Desiccation and Catastrophic Refilling of the Mediterranean: 50 Years of Facts, Hypotheses, and Myths Around the Messinian Salinity Crisis

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Abstract

According to some authors, the Messinian salinity crisis was ended by a giant waterfall or megaflood 5.33 million years ago, when the Atlantic Ocean reconnected in a catastrophic way with the desiccated Mediterranean, creating the Strait of Gibraltar. An erosional surface deeply cutting upper Miocene or older rocks and sealed by lower Pliocene sediments is the geological feature that inspired this fascinating hypothesis. The hypothesis, which recalls several ancient myths, is well established in the scientific community and often considered to be a fact. However, several studies are suggesting that the Atlantic–Mediterranean connection through the Strait of Gibraltar was probably active before and during the entire Messinian salinity crisis. This allows us to consider the possibility that long-lived, more gradual physical processes were responsible for the evolution of the strait, opening the idea of a nondesiccated Mediterranean Sea.

1. INTRODUCTION

1.1. The Messinian Salinity Crisis: 50 Years of Controversies

The great paleoenvironmental changes that affected the Mediterranean Basin and surrounding areas at the end of the Miocene are known in the scientific literature as the Messinian salinity crisis (MSC) (Selli 1954, Ruggieri 1967, Hsü 1972, Hsü et al. 1973). The attempts to understand the nature and causes of the paleoceanographic processes that transformed a large and deep semienclosed sea into a giant salt pan and then a brackish lake resulted in several contrasting hypotheses that are still fueling a hot scientific debate (Roveri et al. 2014a, Mascle & Mascle 2019, Ryan 2023).

It is commonly accepted that during the late Miocene (late Tortonian–early Messinian), the freshwater budget of the Mediterranean became negative when a combination of geodynamic and climatic factors led to a progressive, stepwise restriction of its connections with the Atlantic Ocean (Kouwenhoven et al. 2003), an idea that is also supported by the detachment of $^{87}Sr/^{86}Sr$ values from the global ocean field (Flecker et al. 2002). Afterward, the MSC started at 5.97 Ma (Manzi et al. 2013) with the deposition of the first sulfate evaporites and ended at 5.33 Ma (Krijgsman et al. 1999, Van Couvering et al. 2000) with the return to normal marine conditions at the base of the Zanclean. What really happened during the 640 ka of the crisis itself is still debated and not fully understood.

The Messinian deposits show a well-developed lithological cyclicity within periodicities in the Milankovitch frequency bands and testify to the high sensitivity of the semienclosed Mediterranean Basin to regional, astronomically driven climate oscillations, particularly in the precession range (Krijgsman et al. 1999, Hilgen et al. 2007). This cyclical pattern is one of the main elements of a chronostratigraphic model largely accepted by the scientific community (CIESM 2008, Roveri et al. 2014a) (**Figure 1**) that subdivides the MSC into three evolutionary stages. Each stage is characterized by important changes in the hydrological conditions of the Mediterranean that were recorded by distinct evaporitic suites and very different ranges of $^{87}Sr/^{86}Sr$ values, especially between stages 1–2 and stage 3 (Flecker et al. 2002; Roveri et al. 2014a,b; Andreetto et al. 2021) (**Figure 2**).

The first stage (5.97–5.60 Ma) is characterized by the widespread deposition of bottom-grown selenite gypsum of the Primary Lower Gypsum unit (Roveri et al. 2008b, Lugli et al. 2010). Some authors contend that evaporite deposition during this stage was limited to shallow and silled marginal basins (Lugli et al. 2010, Roveri et al. 2014c) and that only organic-rich shales (the foraminifera-barren interval; Manzi et al. 2018, 2021) (**Figure 1**) accumulated in deep-water settings. Others believe that evaporite precipitation (gypsum or even halite) started in deep settings in this stage as well (Ochoa et al. 2015; Meilijson et al. 2018, 2019). The second stage (5.60–5.54 Ma) represents the peak of the crisis, with the deposition of a large volume of evaporites (mainly halite and cumulate and clastic, resedimented gypsum) in the deepest basins, belonging to the Resedimented Lower Gypsum unit (Roveri et al. 2008b), which largely corresponds to the Mobile Unit defined through seismic data in the offshore areas (Lofi et al. 2011) (**Figure 1**). The third stage (5.54–5.33 Ma) is characterized by a complete change of the Mediterranean hydrology from hypersaline to brackish-water environments (Lago Mare; Gignoux 1936, Ruggieri 1967, Orszag-Sperber 2006) populated by nonmarine mollusks, ostracods, and dinoflagellate cyst assemblages of supposed Paratethyan origin (similar to the present-day Caspian Sea and Black Sea). During this stage, the evaporite deposition was dominated by a limited volume of gypsum (the Upper Gypsum unit), which was restricted to the southern and eastern marginal basins (Sicily, Crete, and Cyprus) and showed much lower $^{87}Sr/^{86}Sr$ values (**Figure 2**).

The most celebrated model of the crisis, the desiccation hypothesis (Hsü 1972, Hsü et al. 1973), implies that the Mediterranean underwent an evaporative sea-level drop of at least 1,500 m,

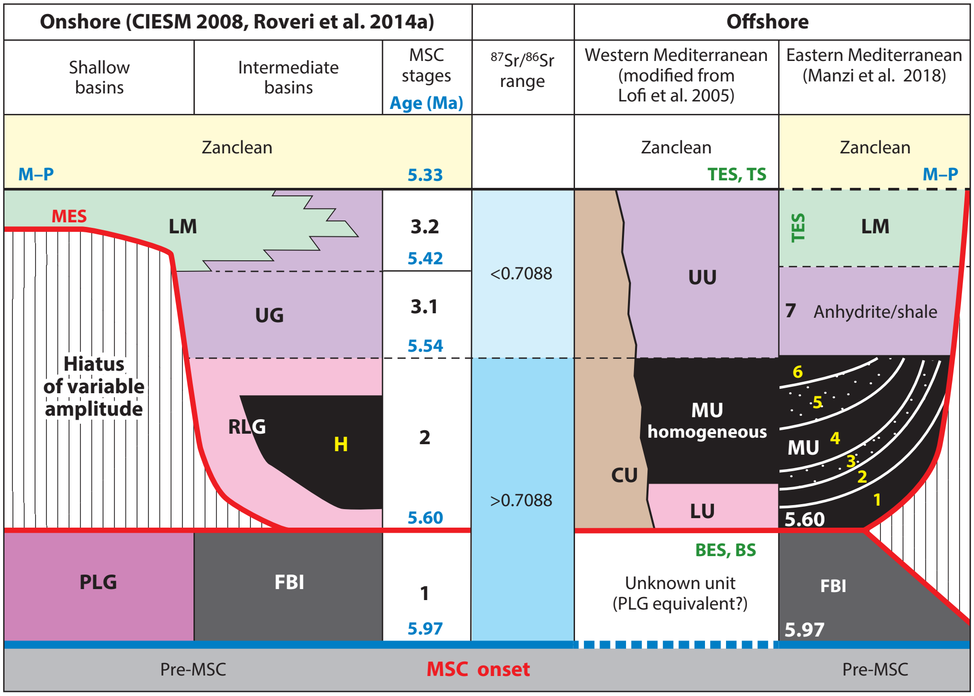


Figure 1

Three-stage chronostratigraphic scheme for the MSC with the main stratigraphic units and their bounding surfaces, which characterize each evolutionary stage of the crisis onshore (*left*) and offshore (*right*). Geological units: FBI, foraminifera-barren interval; H, halite; LM, Lago Mare; PLG, Primary Lower Gypsum; RLG, Resedimented Lower Gypsum; UG, Upper Gypsum. Seismic units: CU, Chaotic Unit; LU, Lower Unit; MU, Mobile Unit; UU, Upper Unit. Surfaces: BES, bottom erosional surface; BS, bottom surface; MES, Messinian erosional surface; M–P, Miocene–Pliocene boundary; MSC onset, onset of the Messinian salinity crisis; pre-MSC, pre–Messinian salinity crisis; TES, top erosional surface; TS, top surface. Additional abbreviation: MSC, Messinian salinity crisis. Figure adapted with permission from Roveri et al. (2019).

leading to its almost complete desiccation either during or at the end of stage 2 and during stage 3 of the crisis (Clauzon et al. 1996; Lofi et al. 2005; Rouchy & Caruso 2006; Ryan 2008, 2009; Garcia-Castellanos et al. 2009, 2020; Urgeles et al. 2011; Bache et al. 2012; Madof et al. 2019). This model imposed itself as the paradigm of the MSC because at that time it was the only one able to explain in a logical way the three main (supposed) lines of evidence: (*a*) the occurrence of shallow-water to subaerial evaporites in the deep basins, (*b*) the widespread fully subaerial erosion of the Mediterranean slopes, and (*c*) the catastrophic flood of Atlantic water at the base of the Zanclean, which returned the Mediterranean Sea to the open and deep marine conditions that existed before the crisis. The sea-level drop of the Mediterranean would have caused the capture of Paratethyan freshwaters, leading to the formation of several disconnected brackish water bodies during the final phase of the crisis (the Lago Mare of stage 3) just before the sudden return to fully marine conditions.

Subsequent research pointed out that (*a*) no unquestionable subaerial exposure features occur in the deep basins, where only fully subaqueous evaporites were deposited (Hardie & Lowenstein 2004; Lugli et al. 2013, 2015; Roveri et al. 2014b,c; Christeleit et al. 2015), and (*b*) the strong erosion of Mediterranean slopes, with deeply incised canyons usually interpreted as fluvial valleys

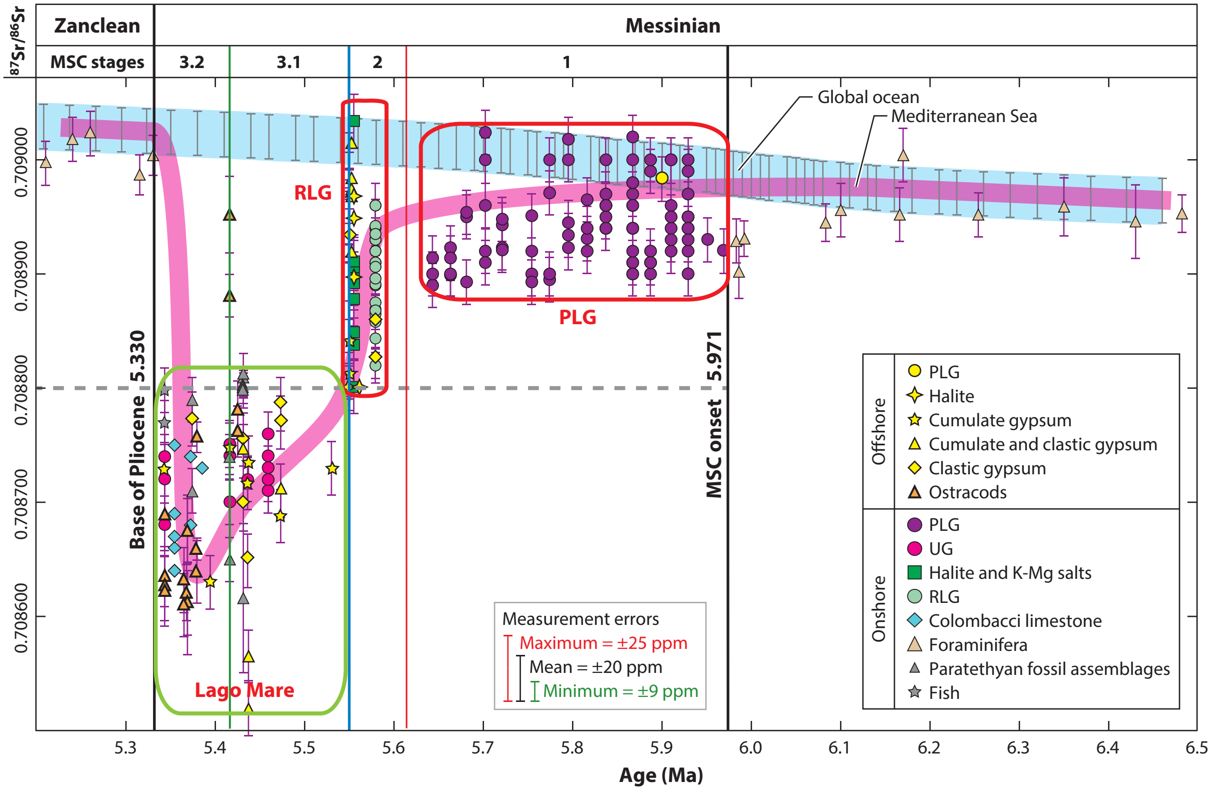


Figure 2

^{87}Sr/^{86}Sr curve of the Mediterranean during the late Messinian–early Pliocene, showing the progressive detachment (toward lower values) from the global ocean curve. Note the range of isotope values of stage 3 (Lago Mare), which is well separated from previous MSC stages. Geological units: PLG, Primary Lower Gypsum; RLG, Resedimented Lower Gypsum; UG, Upper Gypsum. Additional abbreviation: MSC, Messinian salinity crisis. Figure adapted with permission from Roveri et al. (2014a).

(Ryan & Cita 1978, Clauzon et al. 2005, Kartveit et al. 2019, Madof et al. 2019), may be explained in large part by a wide variety of subaqueous processes, such as submarine slides, gravity flows, and cascading of hypersaline dense waters (Lugli et al. 2013; Roveri et al. 2014c, 2016; Moneron & Gvirtzman 2022). Therefore, the desiccation paradigm now essentially relies on the evidence of a catastrophic refill of the Mediterranean at the end of the MSC. This requires that the Atlantic connections were closed at the end of the crisis, which in turn implies that the Strait of Gibraltar area was largely subaerially exposed during the latest Messinian and that the Mediterranean base level was significantly lower than the global ocean.

How much lower? The catastrophic flood models indicate a Mediterranean base level 1,200–1,500 m below the Atlantic Ocean (Lofi et al. 2005, Garcia-Castellanos & Villaseñor 2011, Urgeles et al. 2011). However, recent research on stage 3 of the MSC (the Lago Mare phase) supports the idea that the Mediterranean was a single large water body (Roveri et al. 2014b, Stoica et al. 2016, Andreetto et al. 2021, Moneron & Gvirtzman 2022), as evidenced by homogeneous strontium isotope values (from both fossils and evaporites) and paleontological data (Paratethyan assemblages). It follows that the Mediterranean level should have been higher than the level of all the internal sills but not necessarily equal to the level of the Atlantic Ocean (e.g., a few hundred meters lower). Recent studies have calculated a maximum sea-level drop of 800 m (Cartwright & Jackson 2008, Amadori et al. 2018) or 600 m (Gvirtzman et al. 2022), although large uncertainties exist in the definition of the Messinian paleo-shoreline (Lugli et al. 2013). These considerations suggest that our understanding of the end of the MSC depends largely on a reconstruction of the history of the Atlantic–Mediterranean gateway.

1.2. The Catastrophic Versus Gradual End of the Messinian Salinity Crisis

Some MSC scenarios share impressive similarities with the greatest myths of human history, which are shared by many cultures: the Pillars of Hercules, the tragic fate of Atlantis, Noah's flood, the transformation of Lot's wife into a pillar of salt, and the Red Sea crossing, with its parting of the waters and subsequent flood. In fact, the desiccation hypothesis (Hsü et al. 1973) implies the closure of the Mediterranean–Atlantic connections at Gibraltar (the Pillars of Hercules, Atlantis, and the Red Sea crossing); the consequent evaporation, desiccation, and transformation of the whole Mediterranean into a giant salt pan (Lot's wife); the subsequent development of brackish conditions (Lago Mare); and, finally, the catastrophic restoration of the ocean connections, causing giant waterfalls or cataracts at Gibraltar and at internal sills (Noah's flood and the Red Sea crossing).

It may not be a coincidence that one member of the group that first formulated the desiccation hypothesis was among the proponents of the idea linking Noah's flood to the possible catastrophic refill of the Black Sea after the late Quaternary glaciation (Ryan et al. 1997, Ryan & Pitman 1998). Moreover, the debate around the MSC has resurrected the old controversy between catastrophism and gradualism of geological events that characterized the birth of geology as a science (Garcia-Castellanos et al. 2020).

As a matter of fact, catastrophic natural events are obviously much more exciting and interesting than normal ones, not only from a scientific point of view, but also for their ability to capture the attention of a broader audience of nonexperts. In our case, a good example of how large an impact these catastrophic events may have on society is provided by a stamp series celebrating the history of the Gibraltar isthmus that includes, as a historical fact, a 3,000-m-high waterfall that would have occurred 5 million years ago.

The abrupt end of the MSC has always been associated with the idea of a geologically instantaneous refill of an almost desiccated Mediterranean by oceanic waters (re)entering through one or more marine seaways between southern Spain and northern Morocco. The apparently instantaneous and synchronous transition from brackish (Lago Mare) to open marine deposits observed at the Messinian–Zanclean boundary (i.e., at 5.33 Ma; Van Couvering et al. 2000) across the whole Mediterranean led to the commonly accepted idea of an MSC ended by a geological event of giant magnitude that caused the failure of the Gibraltar sill.

Different models have been proposed for the modality and timing of such a catastrophic event, including (*a*) the capture of Atlantic water by retrogressive erosion of a river draining into the Alboran Basin (Hsü et al. 1973, Blanc 2002, Loget & Van Den Driessche 2006) and (*b*) the spillover of Atlantic water into the Mediterranean through Gibraltar causing a catastrophic flood [the Zanclean megaflood (Garcia-Castellanos et al. 2009, 2020; Garcia-Castellanos & Villaseñor 2011) or terminal Messinian flood (van Dijk et al. 2023)]. Alternative, less catastrophic scenarios have been proposed by both supporters and opponents of the MSC desiccation model. These scenarios imply either (*a*) a more gradual, two-step reflooding of the desiccated Mediterranean, with an initial slow rise of some 500 m and then a second, much faster 600–900-m refill, both pre-dating the Zanclean base (Bache et al. 2012), or (*b*) a Mediterranean base level slightly lower than the Atlantic that progressively rose during stage 3 due to local freshwater input and a mechanism of water pumping from the Paratethys (Marzocchi et al. 2016); a similar mechanism would have been activated when the Mediterranean water reached the Gibraltar sill, allowing the reconnection with the Atlantic.

The interest in the reconstruction of Messinian events is also due to the important consequences that the formation of salt giants during the Earth's history may have had for the regional and global climate, due to the fundamental role played by exchanges between oceans and semienclosed basins in the general ocean circulation pattern (see Flecker et al. 2015) and possibly in the global long-term carbon cycle (see Krijgsman et al. 2024). In this article, we critically review these models and discuss new observations supporting a noncatastrophic scenario for the end of the MSC.

2. LATE MIOCENE ATLANTIC–MEDITERRANEAN GATEWAYS

The location of the seaway(s) connecting the Atlantic Ocean and the Mediterranean Sea during the late Miocene is an open problem due to the intense tectonic deformation that throughout the Neogene affected the area between southern Spain and Morocco, which corresponds to the collisional boundary between the Eurasian (Iberian) and African plates (Comas et al. 1999; Duggen et al. 2003, 2004) (**Figure 3**). It was a well-established idea that the water exchanges with

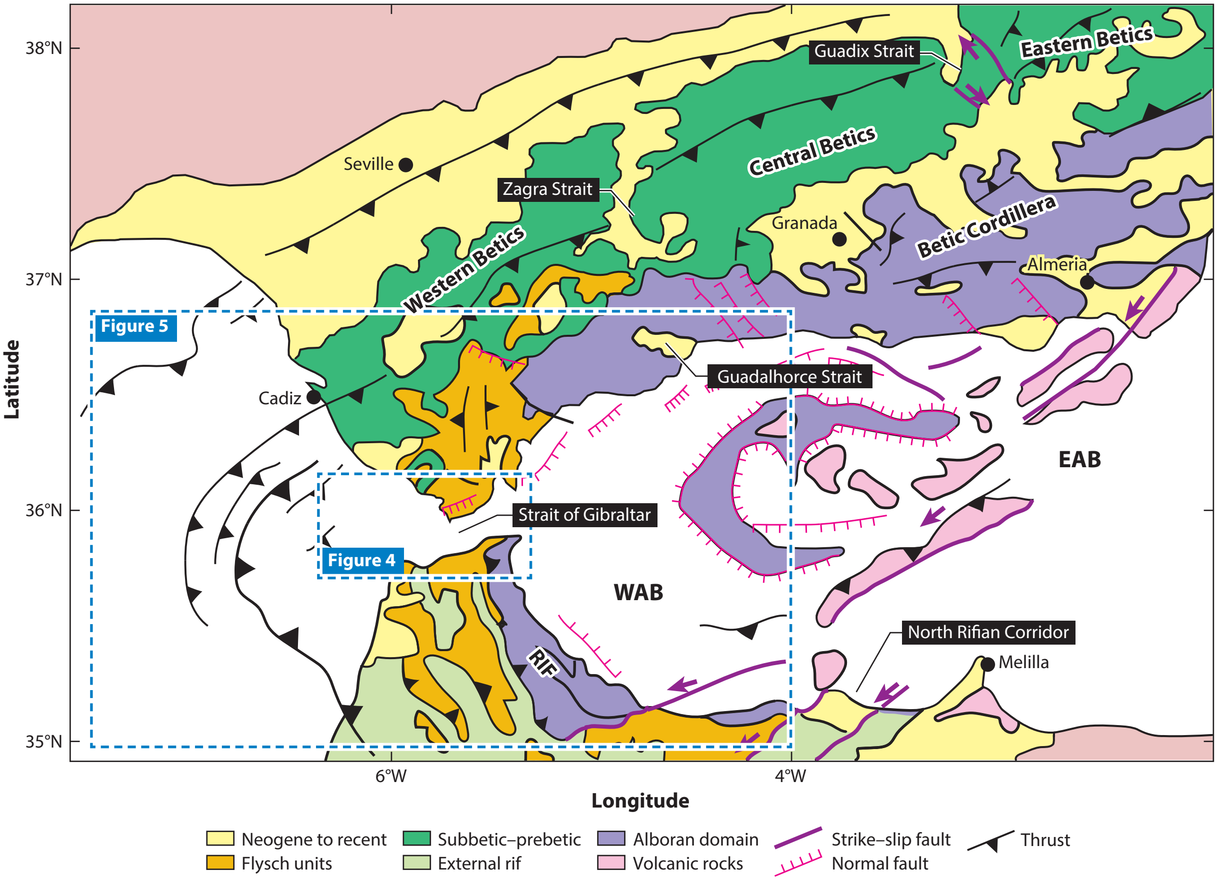


Figure 3

Geological map of the Gibraltar Arc area with the approximate locations of the main marine corridors connecting the Atlantic Ocean and the Mediterranean Sea before (the Rifian, Guadalhorce, Zagra, and Guadix Straits) and during (the Strait of Gibraltar) the Messinian salinity crisis. Abbreviations: EAB, East Alboran Basin; WAB, West Alboran Basin. Figure adapted with permission from Jiménez-Bonilla et al. (2016).

the Atlantic from the Neogene to the late Miocene occurred through a complex seaway consisting of the Betic Corridor to the north and the Rifian Corridor to the south (**Figure 3**), both of which include several minor straits. In particular, the Betic Corridor includes the Guadalhorce, Zagra, and Guadix Straits (Martín et al. 2001, 2009, 2014) (**Figure 3**), and the Rifian Corridor is split into a northern and southern strait (Capella et al. 2017). Their progressive closure due to the ongoing compressive deformation and uplift of the Gibraltar Arc during the Tortonian–early Messinian (Benson et al. 1991, Martín et al. 2001, Betzler et al. 2006, Achalhi et al. 2016, Capella et al. 2017) resulted in the reduction and/or interruption of water exchanges and the development of a negative hydrological budget of the Mediterranean. This led, according to the most accepted model, to the MSC and desiccation.

We now know from recent studies that these two corridors closed at the latest during the early Messinian—the Betic Corridor at approximately 7.1 Ma, and the Rifian Corridor at approximately 6.8 Ma (Capella et al. 2018, Krijgsman et al. 2018). This caused a progressive restriction of exchanges with the Atlantic, leading to a slight detachment of ^{87}Sr/^{86}Sr values from the global ocean values just before the crisis onset at 5.97 Ma (Flecker et al. 2002). However, the deposition of gypsum with a marine geochemical signature—albeit with a significant continental water input (Lugli et al. 2007, 2010; Roveri et al. 2014c; Reghizzi et al. 2018) (**Figure 2**)—and the huge volume of halite that accumulated in the deep basins during the crisis point to a continuous supply of ocean water at least throughout the first and second evolutionary stages (CIESM 2008, Roveri et al. 2014a) (**Figure 1**).

This makes the present-day Strait of Gibraltar the only possible candidate for such an ocean connection during the MSC, with a two-way connection during stage 1 and a unidirectional flow toward the Mediterranean during stages 2 and 3 (Krijgsman et al. 2018). Booth-Rea et al. (2018) proposed an alternative hypothesis envisaging that the main sill between the Mediterranean and the Atlantic was located in the volcanic arc of the East Alboran Basin (**Figure 3**). An intense, Tortonian–Messinian volcanic activity would have caused the formation of an archipelago, allowing faunal exchanges between Africa and Iberia and modulating the Atlantic–Mediterranean water connections before and during the MSC. This scenario, which implies permanent oceanic conditions in the West Alboran Basin throughout the MSC (**Figure 3**) and rules out the Zanclean flood hypothesis at the Strait of Gibraltar, has been recently questioned by Heida et al. (2024) on the basis of geophysical data and paleotopographic reconstructions.

Thus, considering the Strait of Gibraltar hypothesis to be the most likely scenario, what remains undetermined is whether the strait was already open during the Late Miocene, together with the Betic and Rifian Corridors, thus forming a composite seaway with multiple corridors and seaways. Given that the Strait of Gibraltar is a long-lived feature, its morphological features may not necessarily have resulted from a single catastrophic event; rather, they may have come from a long and much more complex history related to alternative scenarios that imply that the strait had a fully marine origin.

3. THE STRAIT OF GIBRALTAR: PRESENT-DAY MORPHOLOGY AND PROCESSES

3.1. The Morphology of the Strait of Gibraltar

The modern Strait of Gibraltar is an almost rectilinear, east–west-trending depression approximately 60 km long and 14 km wide that developed above the Gibraltar Arc. This area is now characterized by a highly complex morphology (**Figure 4**) consisting of a north–south-oriented sill (the Camarinal Sill, which has a minimum depth of 284 m) that acts as a hydrological boundary between the western (Atlantic) sector and the eastern (Mediterranean) sector, and a

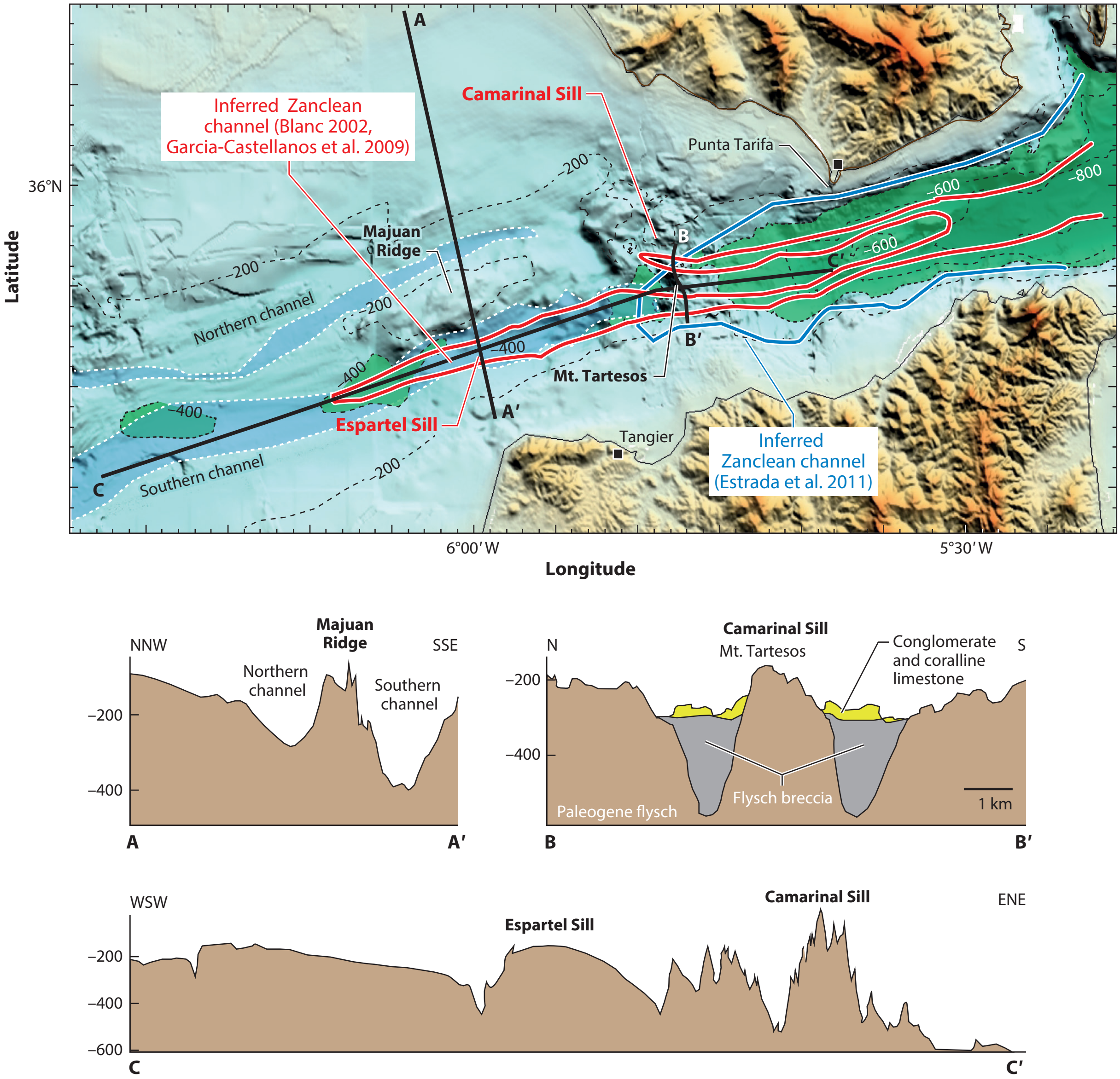


Figure 4

Morphology of the present-day Strait of Gibraltar area shown in a plan view and along cross sections perpendicular (A–A′) and parallel (C–C′) to the strait axis. Red and blue lines show the location of the inferred Zanclean channel; green indicates the main topographic lows (depth >400 m), which are interpreted as possible remnants of the Zanclean channel(s) shown in cross section B–B′. Mapping was performed using the PLOTMAP package (Ligi & Bortoluzzi 1989), with light from the northwest, using datum WGS84 and a Mercator projection at 37°N. Cross sections A–A′ and C–C′ adapted with permission from Blanc (2002); cross section B–B′ adapted with permission from Krijgsman et al. (2018).

second, deeper sill (the Espartel Sill, which has a minimum depth of 350 m) to the west of the Camarinal Sill. The Camarinal Sill is located to the west of the narrower section of the strait (Punta Tarifa; **Figure 4**) and separates the Atlantic from the Mediterranean sector of the Strait of Gibraltar.

In the Atlantic sector, the present-day morphology is characterized by two relatively deep channels separated by the Majuan Ridge (see **Figure 4**), a morphostructural high whose top is less than 100 m deep. The two channels (referred to as the northern and southern channels; **Figure 4**) gradually deepen to the southwest and then turn to the northwest, following the Iberian slope in the Cadiz Basin area. Several small deeps separated by morphostructural highs and not fully connected further complicate the morphology of the gateway area (see the depressions highlighted in green in **Figure 4**).

The Mediterranean sector of the strait is characterized by a much steeper gradient. The deep, rectilinear depression of this sector represents the western termination of the Alboran Basin, an area with a highly complex morphology due to several structural elements (faults, mud diapirs, and volcanic bodies) of different ages.

3.2. Hydrological Processes of the Strait of Gibraltar

At present, the Strait of Gibraltar is characterized by a two-way water circulation pattern (**Figure 5**). The less salty surface Atlantic water flows eastward at the surface into the Mediterranean; the denser, more saline Mediterranean water, known as Mediterranean outflow water (MOW), flows along the bottom of the Strait of Gibraltar, spills over the Camarinal Sill, and moves downslope, splitting into several branches along the Cadiz Basin and Moroccan slopes (**Figure 5**). This circulation pattern is driven by the negative hydrological budget of the Mediterranean Basin due to its substantial evaporation and is further complicated by a tidal component whose effects are amplified by the Strait of Gibraltar. Both currents may reach velocities greater than 2 m/s, able to produce sea-bottom erosion in the northern and southern channels to the west of the Camarinal Sill and/or to rework sediments to form large-scale bedforms imaged by geophysical tools along the shelf as well as in deeper settings (Hernández-Molina et al. 2014). The high energy associated with the MOW is shown by the large contourite systems that form along the Cadiz Basin slope at depths of 300–800 m before the deceleration due to the mixing with Atlantic waters (Hernández-Molina et al. 2016).

The MOW derives from at least five Mediterranean water masses, four of which are well defined in the Alboran Basin (Millot 2009, Ercilla et al. 2016) (**Figure 5**): the shallower Levantine intermediate water and western intermediate water, the deeper western Mediterranean deep water, and the shelf water, which forms where the western Mediterranean deep water mixes with the surface Atlantic water along the Moroccan margin. The fifth water mass, the Tyrrhenian deep water, is not well distinguished from the Levantine intermediate water and western Mediterranean deep water in this area (Ercilla et al. 2016). These water masses flow to the west and are accelerated by morphological restrictions in the Alboran Basin and (obviously) in the Strait of Gibraltar. Recent works have highlighted the role of bottom currents related by the movement of these water masses in shaping both the southern Moroccan slope and the northern Spanish slope throughout the Plio-Quaternary (Juan et al. 2020). Erosive moats and channels and contourite drifts are common in the Alboran Basin, testifying to the strong activity of the bottom currents and their complex interplay with gravity flows originating on the basin margins as well as with the morphostructural elements of the area.

In the Strait of Gibraltar, the current regime is even stronger due to the vertical and lateral confinement, and several oceanographic studies (Armi & Farmer 1988, Sanchez-Garrido et al. 2008, Sannino et al. 2015, Garcia-Lafuente et al. 2018, Roustan et al. 2023) have attempted to better define the strait's hydrological dynamics. The water exchange in the strait is strongly influenced by tidal cycles (Candela et al. 1990). Experimental data and in situ observations have shown that, due to the interplay between topography and tides, the MOW flow may become supercritical in

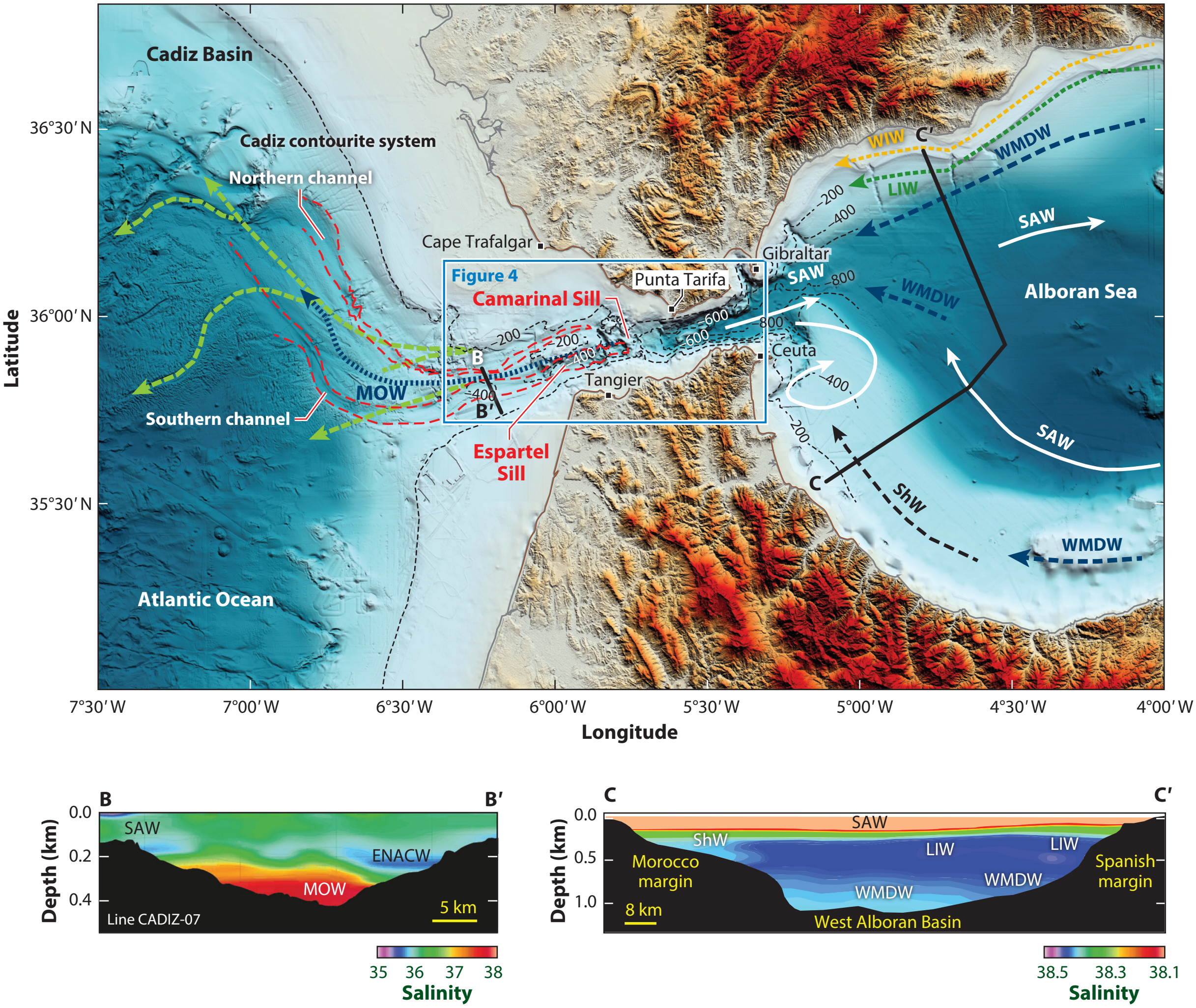


Figure 5

Bathymetric map of the Gibraltar area, eastern Atlantic Ocean, and western Alboran Basin, showing the circulation pattern of Atlantic and Mediterranean surface and deep waters in a plan view and along hydrographic sections at the exit of the Strait of Gibraltar (A–A′) and in the Alboran Sea (B–B′). Abbreviations: ENACW, eastern North Atlantic central water; LIW, Levantine intermediate water; MOW, Mediterranean outflow water; SAW, surface Atlantic water; ShW, shelf water; WIW, western intermediate water; WMDW, western Mediterranean deep water. Mapping was performed using the PLOTMAP package (Ligi & Bortoluzzi 1989), with light from the northwest, using datum WGS84 and a Mercator projection at 37°N. Hydrographic section A–A′ adapted with permission from Hernández-Molina et al. (2014, 2016); hydrographic section B–B′ adapted with permission from Ercilla et al. (2016).

the Camarinal Sill area, with the formation of hydraulic jumps especially to the west of the sill (Armi & Farmer 1988). Accordingly, the topographic lows in this area have been suggested to be long-lived erosional features produced by the hydraulic jumps (Garcia-Lafuente et al. 2018).

Despite such a strongly dynamic setting that has been well described by oceanographers, the present-day morphology of the strait is interpreted by many geologists and paleoceanographers as being essentially related to the event(s) that ended the MSC (Blanc 2002, Garcia-Castellanos et al. 2009, Estrada et al. 2011, Ercilla et al. 2016), which also rules out a purely tectonic origin of the

Gibraltar depression. Of course, erosional and depositional events during the Plio-Quaternary have somewhat modified the Messinian morphology of the strait, but in these scenarios, the Zanclean flood is considered the main erosional event that left an indelible mark.

According to Ercilla et al. (2016), a single erosional Zanclean channel developed eastward of the Camarinal Sill; Blanc (2002) and Garcia-Castellanos et al. (2009) suggested a double incision with canyon heads located much more to the west, which is still shown by the two deeps to the south of the Majuan Ridge, in the Espartel Sill area (**Figure 4**). These hypotheses are based mainly on (*a*) the recognition of two parallel channels in the Camarinal Sill area (**Figure 5**), which are deeply incised in the rock substratum of the area (consisting of Paleogene turbidites) and filled with a breccia made of Paleogene flysch elements attributed to the Plio-Quaternary (Esteras et al. 2000, Garcia-Castellanos et al. 2009, Krijgsman et al. 2018), and (*b*) a deeply incised channel with terraced flanks in the western Alboran Basin (e.g., the Zanclean channel of Garcia-Castellanos et al. 2009 and Estrada et al. 2011), which is cut into folded Miocene deposits and sealed by less deformed Pliocene sediments. In both cases, no concrete data exist for dating the deposits (Esteras et al. 2000, Krijgsman et al. 2018); therefore, the age of the channel incision cannot be accurately defined, and it is not possible to determine whether it had a submarine or subaerial origin. Interestingly, the two paleochannels of the Camarinal Sill are roughly superposed on the present-day northern and southern channels, the two erosional features carved by the MOW.

Evidence of normal faults along the Strait of Gibraltar has been pointed out by other authors, suggesting that the origin of its complex morphology is due to the interplay between extensional tectonics and erosional processes. In this scenario, the Camarinal Sill would be a north–south-oriented structural high of the west-verging Betic–Rif arc, which was uplifted during the Miocene and subsequently dissected by east–west-trending normal faults (Luján et al. 2011) during the phase of extensional collapse phase of the arc. An alternative model relates the end of the MSC to the strong subsidence caused by the rollback and steepening of the Gibraltar lithospheric slab (Govers 2009).

4. THE OPENING OF THE STRAIT OF GIBRALTAR: THE CATASTROPHIC HYPOTHESES

As discussed above, two main mechanisms have been proposed for the formation of the Strait of Gibraltar: (*a*) subaerial retrogressive erosion of a river draining into the Alboran Sea that led to the capture of Atlantic water and (*b*) a megaflood that originated when the pressure of oceanic water coupled with a phase of subsidence of the Gibraltar sill caused its failure and the development of a catastrophic flow into the Mediterranean. Both models imply that a sill emerged at Gibraltar during the final stage of the MSC that then underwent an abrupt failure, causing the almost instantaneous refill of a desiccated Mediterranean.

These models hold that, during the Messinian, the sill was to the west of the present-day Camarinal Sill, and that all of the modern depressions are remnants of an original valley or an east-dipping erosional surface cut by either a river or a megaflood of marine waters. The modern configuration would then be the result of the continuous subsidence since the Pliocene and sediment deposition controlled by an interplay between marine currents and sediment input from the continents.

The Messinian and pre-Messinian morphology of the strait is entirely unknown. Seismic profiles show deep incisions in the Camarinal Sill area and to the east, in the western Alboran Basin, that, according to the poor available data, were cut during an unspecified moment between a time interval spanning from the (late?) Tortonian to the early Pliocene, not recorded by sediment deposition. No data are available from the Atlantic side, which hampers the reconstruction of late

Miocene morphology. Krijgsman et al. (2018) pointed out the lack of arguments that can rule out an older Messinian age for the observed erosional features but did not offer a clear alternative hypothesis for their formation.

Given the impossibility of reconstructing a clear history of erosional and depositional events in the shallower and narrower sector of the Strait of Gibraltar, one possible way to understand when and how the gate opened is to look for indirect evidence of Atlantic–Mediterranean exchange along the Spanish Atlantic margin (Cadiz Basin) and in the Alboran Basin. Hernández-Molina et al. (2016) looked for evidence of MOW activity in the sedimentary record of the Cadiz Basin area, and their borehole and seismic data show that, during the Messinian, the Cadiz Basin was characterized by deposition of hemipelagic sediments, thus indicating absent or extremely weak bottom currents. The base of MOW-related contourite deposits occurs around the Miocene–Pliocene boundary, a date also confirmed by the transition from an oxygen-deficient to a well-oxygenated sea bottom observed through the study of benthic foraminifera assemblages (van der Schee et al. 2016).

On the Mediterranean side, chaotic, coarse-grained deposits, made of basement and volcanic clasts, have been recovered by the Deep Sea Drilling Project (site 976B), the Ocean Drilling Program (site 121), and industrial well cores crossing the Miocene–Pliocene boundary in the western Alboran Basin (Bulian et al. 2021). These deposits, which originally provided evidence for subaerial exposure during the desiccation of the Mediterranean, are associated with a deep erosional surface at the Miocene–Pliocene boundary. The chaotic deposit is now considered to be more likely placed during the third stage of the MSC, but a possible link to the Zanclean megaflood has not been ruled out (Bulian et al. 2021). These data have obviously strengthened the idea of a catastrophic opening of the Strait of Gibraltar at the base of the Zanclean, independent of the modalities and causes.

The same authors of the megaflood hypothesis suggested that the competition between uplift of the Gibraltar sill and erosion by marine water flowing toward the Mediterranean (Garcia-Castellanos & Villaseñor 2011) could explain the high-frequency cyclicity of MSC stage 1 sulfate evaporites, usually related to precessional-driven climate changes (Krijgsman et al. 1999, Lugli et al. 2010). This model implies that the Gibraltar Corridor could have already been open during the MSC, at least during stage 1; therefore, erosion may have occurred well before the Zanclean, thus contradicting the megaflood hypothesis. It can be argued that erosion could have been negligible during the MSC and/or that the Strait of Gibraltar area was uplifted after stage 1 and thus that the main erosional event indeed occurred at the base of the Zanclean, but no independent data exist to support such a hypothesis.

In a recent review, Garcia-Castellanos et al. (2020) did not discuss the important issue of the possible history of the Strait of Gibraltar during the crisis and gave significant emphasis to the search for the sedimentary record of the megaflood. Such a catastrophic event is obviously expected to produce a large volume of clastic sediments that should have accumulated as the megaflood began to decelerate. Unfortunately, no evidence for such clastic deposits associated with the erosional surface has been found. An exception is a seismic unit bounded by sharp and erosional bottom and top surfaces recognized in the western Alboran Basin and interpreted as a coarse-grained giant bar that would have formed in a shadow area produced by a volcanic structure that acted as an obstacle to the flow. The interpretation of the origin of this body is not straightforward. Its position is not in a flat area behind the obstacle but on the steep flank of one of the channels cut around the volcanic edifice. It seems unlikely that such a morphological setting could have produced a significant deceleration of the megaflood.

The other claimed evidence is the chaotic seismic unit observed along the Malta Escarpment at its northern end, close to the Noto Canyon (Micallef et al. 2018). This elongated body, which lies below the Pliocene and above a unit interpreted as consisting of halite, has been related to a megaflood produced when the Mediterranean base level reached this area, which would have been the sill connecting the deep western and eastern basins. Its attribution to the Upper Gypsum unit (the uppermost Messinian unit in offshore areas), which would be logical for a unit sandwiched between halite below and the lower Pliocene deposits above, has been ruled out because the calculated seismic velocity of 2.6 km/s would be too low with respect to that expected for an evaporitic unit. However, the Upper Gypsum unit, in both deep and shallow settings, is made up of an alternation of shales and gypsum; thus, its interval velocity would be much lower than that expected for a unit consisting entirely of gypsum. In the Tyrrhenian Basin, the Upper Gypsum unit recovered by Ocean Drilling Program borehole 654 is made up of an alternation of thin gypsum beds and thicker shale intervals (Kastens et al. 1987, Roveri et al. 2014b). The velocity that can be calculated for the corresponding seismic unit is indeed approximately 2.6 km/s.

Further evidence for a strong flow flushing southern Sicily would have been found in the Hyblean plateau, where limestone breccia deposits have been interpreted as a Zanclean chaotic unit produced by the megaflood (Micallef et al. 2018). However, our examination revealed that the clasts forming the breccia consist of Pliocene Trubi calcareous limestones—as also reported in the official geological map of Italy (Serv. Geol. Ital. 1972) and by Carbone et al. (1987)—that were deposited and lithified after the megaflood. Consequently, an attribution of this unit to the Zanclean flood conflicts with the principles of stratigraphy.

Van Dijk et al. (2023) recently reinterpreted a sandstone unit at the top of the Messinian succession in the Eraclea Minoa section (the Arenazzolo Formation, southern Sicily) as consisting of shallow-water contourites. These deposits would record the activation of bottom currents at the end of the MSC along the Sicily sill, which separated the western from the eastern Mediterranean Basin. This scenario suggests a close genetic link of the bottom currents with the Zanclean megaflood and its propagation across the Mediterranean. However, the Eraclea Minoa section is the official Global Stratigraphic Section and Point of the Zanclean stage (i.e., the Miocene–Pliocene boundary; Van Couvering et al. 2000), which is placed at the base of the Trubi Formation, immediately above the Arenazzolo sandstones. Therefore, van Dijk et al. (2023) argued that the Mediterranean catastrophic refilling would have occurred slightly before what is usually thought—slightly before the end of the Messinian rather than at the base of the Zanclean—and suggested that this event be referred to as the "Terminal Messinian Flood" rather than the Zanclean flood. The proposed scenario may cause some confusion in an already complex issue; we believe that an alternative interpretation of these deposits is possible (see Section 5.2.4).

5. DISCUSSION: THE NEED FOR A CHANGE OF PARADIGM

5.1. An Alternative Hypothesis for the Opening of the Strait of Gibraltar

As previously mentioned, a Strait of Gibraltar that was already open before the Zanclean base has been suggested by several aspects of the geological evolution of the area (Flecker et al. 2015, Krijgsman et al. 2018) as well as by geochemical and paleontological data from the Alboran and Cadiz Basins (Bulian et al. 2021, 2022, 2023). The latter are particularly significant because they document the possible influence of the MOW along the Iberian Atlantic margin and the influence of Atlantic water in the Alboran Basin during the whole Messinian, when we know that the Betic and Rifian Corridors were closed. This allows us to explore the history of the Atlantic–Mediterranean water exchanges before, during, and after the MSC in a completely new way.

The main obvious implication is that the water exchanges between the Atlantic and the Mediterranean in all the stages of the MSC were modulated by changes in the cross section of the Strait of Gibraltar, which in turn were due to an interplay between the ongoing tectonic processes in the area and climate-driven sea-level changes. In such a scenario, the different Mediterranean hydrological conditions related to the variation of its freshwater budget throughout the MSC may have resulted in a complex history of water circulation through the strait and consequently of its erosional and depositional processes.

We know that at least during MSC stage 1, and possibly also during stage 2, a remarkable volume of Atlantic water must have entered the Mediterranean Basin to account for the deposition of the huge amount of evaporites (gypsum and halite) present there. If this is true, then it is plausible that the erosional and depositional processes along the Strait of Gibraltar may have been dominated by the variable regime of marine currents flowing along it, which in turn depends on the water exchanges between the Atlantic and the Mediterranean and, ultimately, on the freshwater budget of the latter. Paradoxically, these processes could have been even stronger given a Mediterranean sea level that was lower by hundreds or thousands of meters.

The possible uplift of the Strait of Gibraltar area during the crisis and the concurrent global sea-level falls during glacials TG12 and TG14 (up to >110 m; Suc et al. 2023) could have further reduced the cross-sectional area of the strait, thus increasing the velocity and hence the erosional power of the currents flowing along it. Moreover, the complex topography of the strait and of the western Alboran Basin, resulting from volcanic edifices, mud diapirs, and tectonic structures, may have further confined and accelerated the currents flowing inside and outside the strait, resulting in locally enhanced erosional processes.

Depositional and erosional subaqueous processes of seaways and straits have been extensively described and analyzed in recent works (Longhitano 2018, Dalrymple 2022, Rossi et al. 2022) that clearly documented the effects of current confinement in these settings, especially those characterized by tidal action. Many examples in the literature (e.g., the late Quaternary history of the Messina Strait) describe the impact of tectonic activity and sea-level changes on the evolution of seaways and straits and could provide many points of comparison for the history of the Strait of Gibraltar.

Based on these considerations, we suggest that fully marine normal processes might have concurred to produce the erosional features observed in seismic profiles and separating the upper Miocene deposits from the Zanclean ones. These erosional features may have been produced since the Rifian and Betic Corridors closed at approximately 7.0 Ma and were then continuously reworked and further incised during the different stages of the crisis.

It is possible that the Strait of Gibraltar was completely closed during stage 3 and reopened at the Zanclean base; in this case, the observed erosional surface could be a polygenic one, including a final phase characterized by the activation of the catastrophic processes suggested by the supporters of the Zanclean flood. However, the amplitude of such a catastrophic final event could have been much smaller than is usually thought if the largest part of the inferred erosion occurred before and during the crisis.

The Messinian successions of the Mediterranean margins, slopes, and deep basins are characterized by several erosional surfaces that merge upslope into a single surface known as the Messinian erosional surface (Roveri et al. 2014a) or margin erosional surface (Lofi et al. 2011). This and other erosional surfaces are commonly related by the desiccation hypothesis to subaerial processes during the drawdown of the Mediterranean at the peak of the crisis. Alternative explanations for its origin include a large variety of mainly subaqueous processes (cascading of dense hypersaline waters, gravity flows, slumps, etc.; Roveri et al. 2014c). In any case, the Messinian erosional surface is sealed by uppermost Messinian or lower Pliocene deposits, thus linking its origin to Messinian events.

In the Strait of Gibraltar area, as well as in the Alboran Basin (i.e., the Alboran Channel), Messinian deposits are absent, and a deeply incised erosional surface separates the upper Miocene and older deposits from the Plio-Quaternary ones (Garcia-Castellanos et al. 2009, Estrada et al. 2011). This is one of the arguments supporting the idea of a Messinian erosional surface origin as it relates to a sudden catastrophic event at the end of the crisis. However, reliable stratigraphic data are missing, making it impossible to constrain the age of the erosional event(s). Moreover, the models invoking the single catastrophic event do not consider that submarine canyons or deep-water valleys normally form through multiple phases of incision and enlargement, while deposition may continue in the adjoining slopes outside the main valley axis, leading to complex morphologies commonly characterized by terraced flanks. The evolution of such systems could result in a puzzling stratigraphy because these erosional surfaces may develop diachronously over a time interval corresponding to a large part of the inferred stratigraphic gap. As a matter of fact, the origin from a single-event hypothesis is essentially based on the undemonstrated idea that the Strait of Gibraltar did not exist before the end of the crisis.

The growing evidence of a much older age for the Strait of Gibraltar allows us to consider the possibility that the observed erosional features are the result of a polyphase history related to the structural evolution coupled with the complex paleoceanographic processes characterizing the water exchanges between the Atlantic and the Mediterranean. Based on these considerations, we favor the idea that the erosional surface of the Strait of Gibraltar and related areas may be older than the Messinian erosional surface and mainly originated from fully subaqueous processes.

5.2. A New View of Atlantic–Mediterranean Connections Through the Strait of Gibraltar

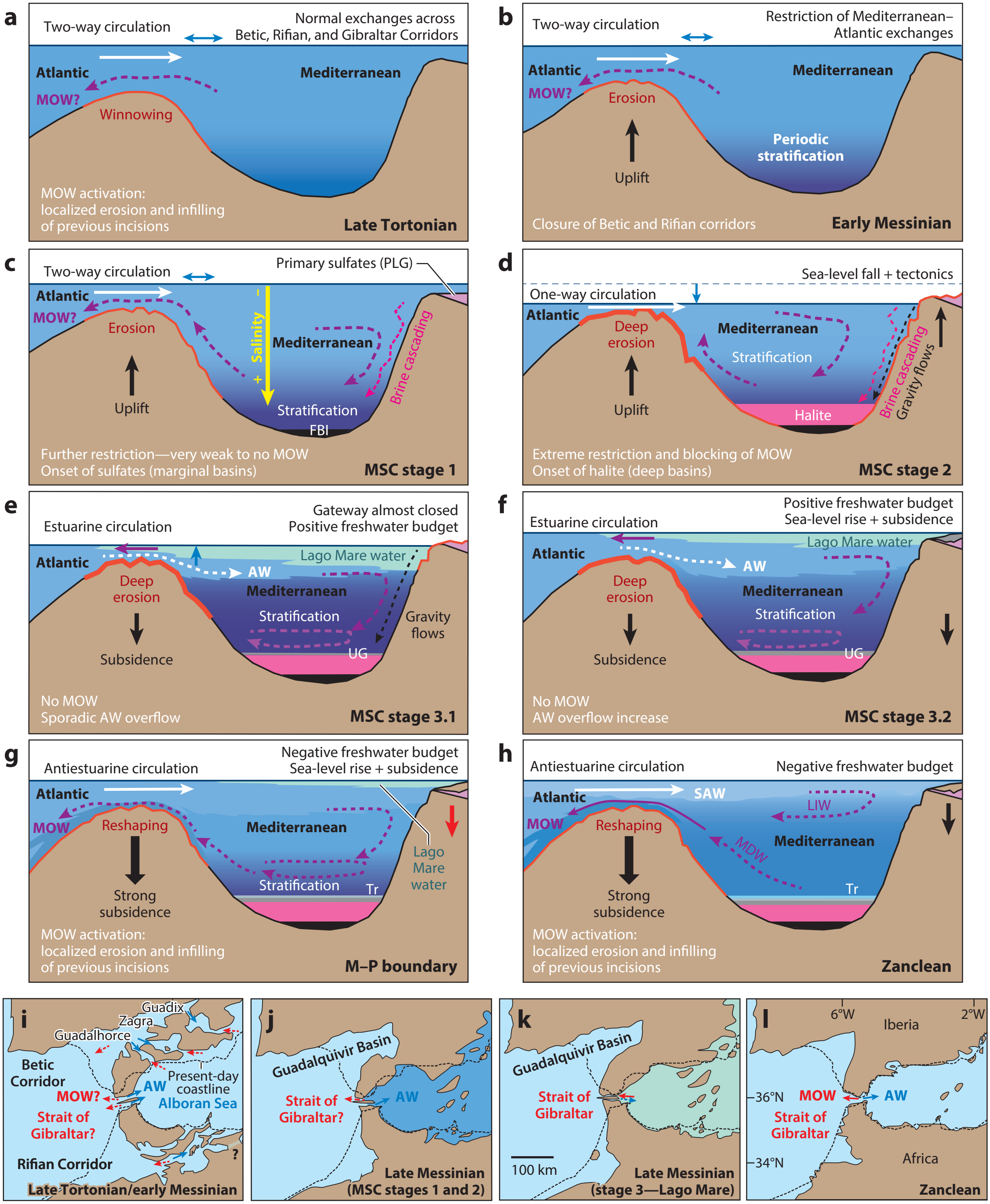
A Strait of Gibraltar that was always open provides a fundamental key for a revision of the history of Atlantic–Mediterranean connections and hence of the MSC.

5.2.1. Late Tortonian–Early Messinian: 8.00–5.97 Ma.

During this period, the Rifian, Betic, and Gibraltar Corridors were open, forming a complex seaway that allowed two-way exchanges between the Atlantic and the Mediterranean (Martín et al. 2001, 2009, 2014; Flecker et al. 2015; Achalhi et al. 2016; Krijgsman et al. 2018) (**Figure 6*a*,*b*,*i***). There is evidence of strong bottom currents related to the MOW in the Rifian Corridor (Capella et al. 2017). The MOW, which was probably much less powerful than it was during the Plio-Quaternary and not able to produce significant erosional and/or depositional features in the Iberian margin (Hernández-Molina et al. 2016), still played a role in conditioning the hydrology of the Atlantic in the Cadiz Basin, as suggested by geochemical data (Bulian et al. 2021). The Rifian and Betic Corridors were closed at around 7.0 Ma; the Gibraltar Corridor remained active, and—even if this cannot be demonstrated—the currents flowing through it were likely accelerated, resulting in significant erosional processes. In any case, the Mediterranean began to experience a restriction of the circulation, which progressed in a stepwise mode before the onset of the MSC (Kouwenhoven et al. 2003). This evolution is commonly related to the tectonic uplift of the Gibraltar Arc, leading to the progressive reduction of the Strait of Gibraltar cross section (**Figure 6*b***).

5.2.2. Messinian salinity crisis stage 1: 5.97–5.62 Ma.

The restriction of exchanges with the Atlantic led to a salinity increase in the Mediterranean, especially during precessional maxima, causing incipient water column stratification and sea-bottom anoxia (**Figure 6*c*,*j***). In the most commonly held view (Meijer & Krijgsman 2005, Simon & Meijer 2015), the salinity of the whole water mass reached the saturation field for gypsum precipitation. An alternative view is that dense hypersaline waters formed only in silled, shallow-water marginal basins, where the trapping of brines and the consequent concentration processes led to the precipitation during insolation minima of bottom-grown gypsum selenite (the Primary Lower Gypsum unit; Lugli et al. 2010). Conversely, the evaporation in open shelf settings could have promoted the cascading



(Caption appears on following page)

Figure 6 (*Figure appears on preceding page*)

(*a*–*h*) Inferred evolutionary steps of Atlantic–Mediterranean exchanges and Mediterranean hydrology from the late Tortonian to the early Messinian. The Mediterranean Basin is represented in a very simplified way, with the Atlantic gateway (Gibraltar) on the left and a generic basin margin on the right. (*i*–*l*) Maps showing the inferred paleogeographic evolution of the Gibraltar area from the late Tortonian to the early Messinian. Marine currents: AW, Atlantic water; LIW, Levantine intermediate water; MDW, Mediterranean deep water; MOW, Mediterranean outflow water; SAW, surface Atlantic water. Geological units: FBI, foraminifera-barren interval; PLG, Primary Lower Gypsum; UG, Upper Gypsum; Tr, Trubi Formation. Other abbreviations: M–P, Messinian–Pliocene boundary; MSC, Messinian salinity crisis. Panels *i*–*l* adapted with permission from Martín et al. (2014).

of hypersaline dense water that then caused the increase of the salinity in deep basins (Roveri et al. 2014c); in such deep settings with relatively high salinity and anoxic conditions, azoic organic-rich shales (the foraminifera-barren interval) would have been deposited instead of gypsum. In addition, erosion in the Strait of Gibraltar would have likely occurred due to the action of a powerful Atlantic inflow and of a weak, possibly intermittent MOW.

5.2.3. Messinian salinity crisis stage 2: 5.62–5.55 Ma. A further reduction of water exchanges took place in this stage (**Figure 6*d*,*j***) due to a moderate global sea-level fall related to glacials at isotope stages TG12–TG14 (Hilgen et al. 2007, CIESM 2008). It is commonly accepted that in this phase the MOW was locked, causing a further increase of stratification and salinity in the Mediterranean, with halite primary cumulate precipitations and clastic gypsum deposition in deep basins. According to the desiccation hypothesis, the sea-level fall and strong evaporation caused the widespread erosion of Mediterranean margins by subaerial and/or subaqueous processes. In a more conservative scenario, a moderate sea-level fall was associated with a Mediterranean-scale tectonic phase, promoting the dismantling of stage 1 evaporites and their redeposition in a deep setting; evaporite-bearing gravity flow and hypersaline water cascading further produced deep brines. In both scenarios, the erosion processes in the Strait of Gibraltar should have been particularly strong.

5.2.4. Messinian salinity crisis stage 3: 5.55–5.33 Ma. This stage is characterized by a complete change in the hydrology of the Mediterranean from hypersaline to brackish waters (the Lago Mare phase) that is usually related to the complete physical isolation of the Mediterranean from the Atlantic due to the closure and emersion of the Strait of Gibraltar and the input of freshwater from the Paratethys Basin, as suggested by ostracod, mollusk, and dinoflagellate cyst assemblages (**Figure 6*e*,*f*,*k***). This change is commonly considered sharp, but it is worth noting that (*a*) the first occurrence of the Paratethyan assemblages (∼5.47 Ma) is delayed by four precessional cycles after the beginning of stage 3 (5.55 Ma) and (*b*) the largest species diversity of these assemblages is limited to substage 3.2 (5.42–5.33 Ma) (Grossi et al. 2008, Roveri et al. 2008a).

Different scenarios have also been considered for MSC stage 3. The desiccation hypothesis is that after the huge sea-level drop, the Mediterranean was reduced either to several small, isolated lakes at different elevations or to a single water body with a base level much lower than the global ocean. In alternative scenarios, the Mediterranean was a single large, deep basin that was disconnected from the Atlantic and had a base level only slightly lower than the global sea level, fed by Paratethyan waters (Stoica et al. 2016, Andreetto et al. 2021). However, in this stage there is strong evidence of an increase in the meteoric precipitations in the peri-Mediterranean area, as evidenced by the widespread terrigenous deposits and increase in average sedimentation rate (Roveri & Manzi 2006; Omodeo Salé et al. 2012; Roveri et al. 2014b,c). This cannot be explained by the input of Paratethyan water and points instead to a significant increase of discharge from Mediterranean rivers, particularly the North African ones (Griffin 1999) due to the stronger activity of the African summer monsoon (Gladstone et al. 2007, Flecker et al. 2015, Marzocchi et al. 2015). Paleontological data show only shallow-water assemblages, suggesting that deep-water settings were not favorable for life, due to the permanence of brines formed in the previous stage and/or anoxia; in both cases, the water column would have been strongly stratified.

In our opinion, all of these elements may support the hypothesis that the Mediterranean transformed into a giant lake that had a positive freshwater budget and was poorly connected with the ocean, similar to the modern Black Sea, a scenario that has been discussed previously (Roveri et al. 2014c, Flecker et al. 2015). The freshwater budget would likely have been modulated by precession, and thus the Mediterranean would have experienced wetter and dryer conditions during insolation maxima and minima, respectively. However, the relative stability of hydrological and paleoenvironmental conditions indicated by strontium isotope values and fossil assemblages may suggest that, despite minor fluctuations and local exceptions, the freshwater budget could have been positive throughout stage 3.

In other words, the isolation of the Mediterranean from the Atlantic could have been not physical, with the closure of the Strait of Gibraltar due to the uplift of the Gibraltar Arc area, but rather hydrological, with an estuarine circulation (analogous to the Bosporus and the Black Sea). There is no evidence of bottom currents related to the MOW along the Iberian slopes; this obviously indicates a block of deep to intermediate water in the Mediterranean overflow but does not exclude the possibility of a westward surface flow of Mediterranean freshwater rapidly mixing with Atlantic water within the Strait of Gibraltar or immediately outside of it.

In this scenario, the Strait of Gibraltar was open, and erosional processes would persist in this stage, which could help resolve some of the controversies related to the final stage of the MSC. It is commonly recognized that during stage 3, and particularly during substage 3.2 (**Figure *6f*,*k***), the Mediterranean base level had risen, as shown by the progressive onlap of Lago Mare deposits above the erosional surface produced during stage 2. A global sea-level rise is known to have occurred during stage 3, which suggests that the Mediterranean could have been connected with the Atlantic and that the two shared the same base level. With a closed Strait of Gibraltar, the base-level rise could be explained only by a regional climate and precipitation regime. With an open Strait of Gibraltar, the input of Atlantic waters as underflow would promote a threefold-stratified structure of the Mediterranean, with Lago Mare freshwater on top, normal marine water at intermediate depths, and possibly denser, residual hypersaline waters at the bottom. This could explain the possible presence of normal marine water that has often been documented, especially for substage 3.2, based on paleontological (Popescu et al. 2007, Carnevale et al. 2018) and/or organic–geochemical proxies (long-chain alkenones from marine calcareous nannoplankton; Vasiliev et al. 2017, Pilade et al. 2023). Moreover, a high sea level could also easily explain the extremely homogeneous character of the stage 3 succession in terms of the number of evaporite cycles and geochemical signatures of both evaporites and fossils (^{87}Sr/^{86}Sr; see **Figure 2**), in either marginal or deep settings all along the Mediterranean (Roveri et al. 2014a,c; Gvirtzman et al. 2017).

This scenario, despite some important differences with other scenarios, may be partially in agreement with the idea of a reconnection of the Mediterranean Basin with the Atlantic Ocean well before the Zanclean base (Bache et al. 2012). Moreover, it could provide an alternative interpretation for the origin of the Arenazzolo sandstones that does not imply catastrophic processes. These deposits, interpreted as shallow-water contourites related to a Messinian terminal flood (van Dijk et al. 2023), occur at the top of a Lago Mare succession, showing an overall transgressive trend, and include deltaic sandstone lobes in the underlying Upper Gypsum formation (Manzi et al. 2009). We argue that the Arenazzolo sandstones could have been deposited in somewhat deeper waters and in a less topographically constrained setting than the underlying deposits and therefore were more influenced by normal basinal processes, such as longshore drift or shelf currents.

5.2.5. Zanclean base (end of the Messinian salinity crisis): 5.33 Ma.

The initial subsidence in the Gibraltar Arc area and the progressive vanishing of the African monsoon would have led, toward the end of substage 3.2, to the increase of Atlantic water input and the concurrent reduction of the Lago Mare freshwater layer in the Mediterranean, the latter of which was also a result of the enlargement of the basin due to the rise in base level. These factors could have caused the collapse of the hydrological structure of the Atlantic–Mediterranean exchange. Thus, what we consider the abrupt end of the MSC could simply be related to the reversal of the general circulation pattern in the Mediterranean with surface Atlantic water and the reactivation of the deep MOW, as evidenced by the onset of bottom current activity in the Cadiz Basin. This would have caused the progressive mixing of Mediterranean waters and consequent sea-bottom ventilation. The timing of these changes appears to be instantaneous, thus promoting the idea of a catastrophic event. What we consider instantaneous in geology should be considered relative to the available stratigraphic resolution, which in this case is on the order of several thousand years. This is also confirmed by the frequent occurrence at the Messinian–Zanclean boundary of a dark, organic-rich layer, suggesting a transitional phase still characterized by water stratification and anoxia at depth (Bulian et al. 2023), at least locally (**Figure 6*g***). The activation of vigorous vertical water circulation and of strong deep-water currents was a gradual process completed during the early Zanclean, in agreement with the activation of MOW-related contourite systems in the Atlantic margin of Iberia (**Figure 6*b***).

It is worth noting that the lowermost precessional cycles of the Zanclean successions are characterized by a very rare occurrence of benthic foraminifers, often interpreted as Messinian reworked species (Iaccarino & Bossio 1999), suggesting that the reestablishment of fully marine conditions did not immediately follow the return of Atlantic waters to the Mediterranean. In this scenario, due to the ongoing subsidence of the Gibraltar Arc and the consequent increase of its cross-sectional area, the Strait of Gibraltar likely underwent a drastic drop in the energy and velocity of its currents. This resulted in the transition from a mainly erosional to a mainly depositional regime, with erosion much more localized and weaker than it was during the Messinian.

6. CONCLUSIONS

The end of the MSC, one of the most distinctive of the geological events that have punctuated Earth's history, may not have necessarily been caused by a catastrophic event, as is commonly thought. The increasing independent evidence for a Strait of Gibraltar that was open before and during the MSC leaves open the possibility that normal strong marine erosional processes, like those characterizing modern straits and seaways connecting marine basins, may have dominated the Strait of Gibraltar throughout the crisis. In this respect, it appears that the knowledge of present-day and recent oceanographic processes is not adequately incorporated into the reconstruction of the events of the past. This is obviously largely due to the temporal scale issue, which always challenges an actualistic interpretation of the paleoceanographic events. We do not know to what extent the seasonal to pluriannual variability of marine processes can be recorded in sedimentary successions, nor do we know the real meaning of the paleoceanographic events that we have reconstructed through geochemical, paleontological, and sedimentological proxies. However, the complexity that we see today in extremely dynamic environments like the Mediterranean Sea and its Atlantic gateway suggests that future studies should seek to bridge the gap of knowledge in this specific field between modern and past environments.

Relative to the human scale of comprehension, something extraordinary occurred in the Mediterranean Basin during the Messinian. Perhaps it will someday be demonstrated that a great, catastrophic waterfall or megaflood did indeed end the MSC, in which case this scientific hypothesis will become fact; it could also eventually be shown that the story was different, and that the Zanclean flood is a wonderful myth. Whatever the case, the Gibraltar stamp celebrating this great and fascinating event would significantly increase in value.

NOTE ADDED IN PROOF

Maria Bianca Cita, one of the scientists who in the early 1970s discovered the large evaporite deposits in the deep Mediterranean basins and formulated the desiccation model of the Messinian salinity crisis, passed away while this publication was in the final stages of preparation. Our tribute goes to Maria Bianca for her passion for geology and for the encouragement she always provided, despite the diversity of ideas, to continue research on one of the most fascinating and debated geological problems in the history of the Earth.

DISCLOSURE STATEMENT

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