Highlights

- We search for the Mediterranean-Atlantic gateway that delivered the marine salt during the Messinian Salinity Crisis
- All previously proposed late Miocene gateways through southern Spain and northern Morocco are shown to have closed during the latest Tortonian-earliest Messinian
- The Gibraltar Corridor is considered to sole candidate gateway and was most likely open during most of the Messinian Salinity Crisis
- The dimensions of the Gibraltar Corridor during the MSC are estimated based on Mediterranean salinity fluctuations using geophysical models
- A revised palaeogeographic evolution of the Gibraltar region is presented for the late Tortonian to early Zanclean.

The Gibraltar Corridor: Watergate of the Messinian Salinity Crisis

Wout Krijgsman[1], Walter Capella[1], Dirk Simon[1], Frits J. Hilgen[1], Tanja J. Kouwenhoven[1], Paul Th. Meijer[1], Francesco J. Sierro[2], Maria A. Tulbure[1], Bas C.J. van den Berg[2], Marlies van der Schee[2] and Rachel Flecker[3]*

[1]Department of Earth Sciences, Utrecht University, The Netherlands
[2]Department of Geology, University of Salamanca, 37008, Salamanca, Spain
[3]BRIDGE, School of Geographical Sciences and Cabot Institute, University of Bristol, Bristol, BS8 1SS, UK

**Corresponding author (W.Krijgsman@uu.nl)*

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.

Keywords: Miocene, Mediterranean, Atlantic, gateways, evaporites, paleoceanography

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,b). 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 ~1500m 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., 1973). 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/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., 2017; 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 less than 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 (Martin 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 der 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; Martin and Braga, 1994; Krijgsman et al., 1999a; Martin 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 this technique commonly has lower resolution and higher uncertainties (e.g., Garcés et al., 2001). It should especially be realized that the absence of evidence for marine sedimentation is no solid proof for the non-existence of a marine gateway. The interpretation of seaway closure therefore has to take into account the depositional history of all the connecting gateway basins, including inferred sedimentation rates, lateral facies development, and regional tectonics and geodynamics. Here, we present an overview of most recent dating results of the marine and continental sediments in the late Miocene gateways that may have played a role in the water exchange between Mediterranean and Atlantic during the MSC.

2.1 Connections through southern Spain

The Betic Corridor (or Iberial Portal sensu Benson et al., 1991) was a system of seaways forming four distinct connections through Southern Spain (Fig. 2). The northernmost connection (North-Betic Strait) already became restricted in the early Tortonian (Martin et al., 2009, 2014) following the onset of compression (Meijninger and Vissers, 2006) and causing the Tortonian Salinity Crisis (TSC) of the eastern Betics (Krijgsman et al., 2000). In its eastern part, Tortonian evaporites (gypsum and halite) of the Lorca and Fortuna basins are overlain by thick successions of late Tortonian and Messinian continental sediments (Garcés et al., 1998; 2001; Kruiver et al., 2002), indicating the marine connection through the northern Betics had ceased to exist. These successions were dated by integrated magneto-biostratigraphy (small mammals) and show that the marine to continental transition takes place at 7.6 Ma (Garcés et al., 2001). The Guadix Strait connected the eastern end of the Guadalquivir with the Mediterranean; it was open between 8.1 and 7.8 Ma (Betzler et al., 2006; Hüsing et al., 2010), and less than 2 km wide and around 70 m deep when the last marine sediments were deposited (Martin et al., 2014). A major hiatus separates its marine sediments from the continental deposits above (Hüsing et al., 2010, 2012; Minwer-Barakat et al., 2009), but so far no evidence exists that the Guadix seaway persisted during the Messinian. The Zagra strait connected the Guadalquivir Basin to the Mediterranean via the Granada Basin. In the Granada basin, the late Miocene sediments show a marine-continental transition, via a series of shallow-water evaporites, that is dated by biostratgraphic techniques at 7.37-7.24 Ma (Garcia-Garcia et al. 2009; Corbi et al 2012). Lastly, the Guadalhorce Strait was a 2-5 km wide and 30 km long passage that was thought to be the last Betic seaway and the only one open in the Messinian (Martin et al., 2001, 2014), although previous studies date these marine deposits as Tortonian (Lopez-Garrido and Sanz de Galdeano 1999). New age constraints on the fine portion of the sediments from the Arcos, Ronda and Antequera basins, on which the existence of this strait has been based, all revealed a late Tortonian age (Van den Berg, 2016; Van der Schee et al., 2018). A late Tortonian closure of the Guadalhorce connection is in agreement with the onset of compression and uplift of the area (Jimenez-Bonilla et al, 2015) and the changes in depositional environment in the Malaga region (Guerra-Merchán et al., 2010).

In summary, there is no evidence of any Mediterranean-Atlantic connection through Spain after the Tortonian.

2.2 Connections through northern Morocco

The Rifian gateway consisted of two distinct connections: the North and South Rifian Corridors (Fig. 2). Palaeogeographic reconstructions of depositional environments in the late Miocene sedimentary basins of Northern Morocco, based on surface–subsurface correlations, helped to elucidate the temporal and spatial evolution of the Rifian Corridor (Capella et al., 2017a;

2018). The restriction of the southern branch had already started in the late Tortonian-early Messinian (Krijgsman et al., 1999b; Ivanovic et al., 2013) and was driven by a phase of enhanced uplift along high angle faults (Capella et al., 2017b, 2018). Improved biostratigraphic dating of the continuous transition from marine to continental-lacustrine deposition shows that the South Rifian Corridor closed at 7.1-6.9 Ma (Capella et al., 2017a; 2018).

The closure age of the North Rifian Corridor is less well-constrained because the marine-continental transition is commonly missing in most of the scattered outcrops (Achalhi et al., 2016; Tulbure et al., 2017). The open and relatively deep marine sediments deposited in the North Rifian Corridor are all late Tortonian in age >7.35 Ma (Tulbure et al., 2017). The assemblages of planktonic foraminifera and calcareous nannoplankton reveal that the Messinian is not reached. The top parts of the marine successions may have been removed by erosion, but the observed high sedimentation rates in combination with the shallowing upward trend in the Tortonian suggests that marine sedimentation is likely to have ended in the earliest Messinian around 7.0 Ma (Tulbure et al., 2017). We conclude that a connection through the northern basins could have persisted only for a short time after the enhanced rates of uplift that started during the late Tortonian.

In summary, there is also no evidence of a Mediterranean-Atlantic connection through Morocco after 6.9 Ma.

3. SOLVING THE GATEWAY CONUNDRUM

3.1 The evidence for an Atlantic connection during the MSC

The large volume of evaporites preserved in the Mediterranean necessitates that one or more marine connections with the Atlantic remained, at least until the end of the halite stage (5.55 Ma; Roveri et al., 2014a), and possibly during the entire MSC (Roveri et al., 2014b). The onset of the Messinian Salinity Crisis occurred at 5.97 Ma (Manzi et al., 2013) with synchronous precipitation of the Primary Lower Gypsum (PLG) in marginal basins around the Mediterranean during MSC Stage 1 (Krijgsman et al., 1999a, 2001; 2002; Roveri and Manzi, 2006; Manzi et al., 2007). The PLG successions are all sufficiently similar in terms of number, vertical facies distribution and overall stacking pattern of cycles and can be used for basin-wide correlations on a bed-to-bed scale (Lugli et al., 2010). The stratigraphic similarities combined with the characteristic Sr isotope values, close to open ocean values, indicate the PLG precipitated from a relatively homogeneous Atlantic-fed water body with a restricted outflow (Lugli et al., 2007, 2010). The restricted outflow scenario implies that Mediterranean water level remained equal to the Atlantic at a level substantially higher than the Gibraltar sill (Krijgsman and Meijer, 2008).

The halite deposits of Stage 2 only developed in the deep Mediterranean basins and are commonly linked to the last two peak glacials TG12–14 of the Messinian glacial interval (Hilgen et al., 2007; Roveri et al., 2014a). The observed thickness of the halite unit in the seismic profiles of the western Mediterranean basin is 600–1000 m, while at least 1500 m have been reported from the eastern Mediterranean basin (Lofi et al., 2005). Quantitative box model analyses indicate that a scenario of Atlantic inflow with blocked Mediterranean outflow and the evaporative loss of freshwater, results in the precipitation of a volume of salt that is comparable to the thickness and extent of the seismic interpretations (Krijgsman and Meijer, 2008). In any case, a Mediterranean-Atlantic gateway is still required to feed the Mediterranean with salt during halite deposition, although this connection may have been episodic during salt precipitation.

The scenarios that envisage a major drawdown of Mediterranean water level during the MSC generally place the peak desiccation during, or after, the halite unit (Lofi et al., 2005; Ryan, 2008; Bache et al., 2009, 2015). In terms of Mediterranean–Atlantic gateway exchange, the subsequent MSC Stage 3 is the most enigmatic phase, with mixed signals coming from the Upper Evaporites with gypsum beds and rare halite layers indicating high salinities and Lago-mare associations which contain fresh to brackish water fauna and flora (Londeix et al. 2007; Bassetti et al., 2003, 2006; Orszag-Sperber, 2006; Stoica et al., 2016). During MSC Stage 3 the Mediterranean may have been completely isolated from the open ocean until the return to normal open marine conditions after the Miocene–Pliocene boundary at 5.33 Ma (e.g. Hsü et al., 1973; Ryan, 2009). Alternatively, it may have experienced a two-step flooding (Bache et al., 2012) or (quasi) continuously received Atlantic inflow (Roveri et al., 2014; Marzocchi et al., 2016). The occurrence of marine fish (Carnevale et al., 2006, 2008) and long chain alkenones (Vasiliev et al., 2017) strongly hint at the possible persistence, continuous or episodic, of an Atlantic connection, which could also explain the sporadic occurrence of anomalously small or "dwarf" foraminifers (Iaccarino et al., 2008) and the presence of marine dinoflagellates (Pellen et al., 2017) in Stage 3 deposits.

3.2 The Gibraltar remedy

The Strait of Gibraltar is the modern day connection between the Atlantic and the Mediterranean. The assumption of a catastrophic, early Pliocene opening of this strait is based upon (i) the requirement of a closed connection during the final phase of the MSC (Hsü et al., 1973, 1978) and (ii) the seismic evidence of an incised channel that dips gently from the Gibraltar sill towards the Alborán Sea. This incision is not dated directly, but can be followed for at least 300 km towards the east (Estrada et al., 2011; Fig. 3a) where it merges laterally with the Messinian erosional surfaces and it is locally filled with Plio-Quaternary sediments (Garcia-Castellanos et al., 2009). The only evidence for a Pliocene opening comes from seismic profiles that show two canyons cutting into Miocene reflectors in the Alborán Basin (Esteras et al., 2000). The deep erosional incision of this channel, which is particularly well imaged on the Atlantic side of the Alborán basin, indicates that lowering of the base level on the Mediterranean side must have taken place (Garcia-Castellanos et al., 2009). An accurate age determination for these channel reflectors is lacking, implying that it cannot be completely ruled out that they could have been (partly) formed earlier during the MSC. In the deepest part of the Western Alborán basin, at site ODP 976 (Comas et al. 1999), this reflector separates lower Messinian pelagic deposits from lower Pliocene sediments, indicating that this erosion could have formed at the base of the Pliocene or anytime between the early Messinian and the base of the Pliocene. Anyway, (re-)opening of the Strait of Gibraltar at the Miocene-Pliocene boundary does not exclude that the gateway was open during earlier phases of the Messinian, and that the erosional features (partly) formed during stage 2 of the MSC.

The area of the Gibraltar Corridor lacks clear evidence for crustal extension as a driving mechanism for its Pliocene opening; consequently, erosional processes are preferred (see review in Loget and Van Den Driessche, 2006). However, the Messinian Gibraltar Corridor was likely to be influenced by the evolution of the contiguous Western Alborán Basin, which is thought to record the constant pull of the Gibraltar slab throughout the Miocene (Do Couto et al., 2016). During the Tortonian, the Western Alborán Basin documented partial inversions and transpressional structures accompanied by localised subsidence (Comas et al., 1999; Do Couto et al., 2016). Models showed that slab sinking would lead to dynamic subsidence (Govers and Wortel, 2005), which can occur coevally with regional uplift trends and without requiring surface extension. Slab-sinking in the Gibraltar area has therefore been proposed as the main mechanism to provide the required topographic lowering for the modern Gibraltar Straits to form (Govers, 2009). Given the western Alborán was always affected by the slab-sink (Do Couto et al., 2016), which steepened after the cessation of slab-roll back around ca. 8 Ma (Govers, 2009), we propose that shallow connections through the Gibraltar Corridor could have been always present from a dynamic topography perspective. The paleo-channel may have been subdivided in a northern and southern strait, as suggested by reconstructed stratigraphy from drill cores (Esteras et al., 2000; Fig 3b). These two straits are filled with ca. 300 m of undated, mud and flysch breccia, void of recognizable foraminifera (Sierro, unpublished data).

3.3 Dimensions of the Messinian Gibraltar Corridor

The conclusion that the Gibraltar Corridor was the only, but previously ignored, Mediterranean-Atlantic gateway during MSC times raises the question if there is anything that can be deduced about its depth, width and length. All numerical investigations on Messinian gateways (e.g., Meijer, 2006; Meijer, 2012; Rohling et al., 2008; Simon and Meijer, 2015; Simon et al., 2017; Topper et al., 2011; Topper and Meijer, 2013, 2015) agree that to increase the salinity of the Mediterranean Sea, its outflow into the Atlantic has to decrease greatly relative to the Atlantic inflow. One possibility to do so is by restricting the dimension of the Atlantic-Mediterranean connection. The exact geometry of the Messinian Gibraltar Corridor is arguably impossible to reconstruct, eroded subsequently by episodes of erosions and slumps (Blanc, 2002). However, given the longer (100-150 km) and narrower (10-15 km) morphology of the Corridor at depth (-200 m isobaths; Fig. 3), a possible option is that the region of the modern Mediterranean-Atlantic connection underwent a similar magnitude (~200 m) subsidence from the late Miocene to present day, driven by slab-pull (Govers, 2009).

The presence of an E-W oriented rectilinear incision, four times longer than today (following isobaths -200 m; Fig. 3b) suggests that the Gibraltar Corridor may have been a long, narrow and elongated channel. The buried strait is represented by isobaths -100 or -200 m; for these submarine features the reconstructed portion of straight line is much longer (ca. 40 and 80 km, respectively) than present-day, and trends approximately the same (N70E to N80E). The width of the paleo-channels spans 10-15 km at isobaths -100 m, and 10-30 km at -200 m. These rectilinear features may reflect hydrological incision during the formation of the Corridor (Blanc, 2002), caused by a relatively lower sea-level in the area.

If the palaeo-coastline was to be set at -200 m in Gibraltar bathymetry, and the sediment infill removed from the channels, then the strait would be ca. 80 km long and divided in two channels in a cross-section (Fig. 3b), with the southern one approximately two km wide and 400 m deep, and the northern one four km wide and 400 m deep.

Simon and Meijer (2015) indicated that Atlantic-Mediterranean exchange during the PLG was approximately 25-10% of the present-day value at the Strait of Gibraltar. Their correlation of exchange flux to gateway dimensions indicates that the gateway present prior to a potential disconnection from the Atlantic must have been relatively small (in the order of width ~2-5km and depth ~20-10 m, if length is taken to be short at ~25-50 km). However, (1) a longer gateway length allows for a greater cross-sectional area, while sustaining the same basin salinity due to friction (Simon and Meijer, 2015) and (2) a heavily stratified Mediterranean basin allows for more vigorous and therefore larger strait dimensions than previously thought (Simon and Meijer, 2017).

In the following we use the Mediterranean environmental constraints on salinity to reconstruct the possible dimensions of the Gibraltar Strait during the Messinian. Meijer (2012) used hydraulic control theory for a rectangular sill geometry in combination with a full Mediterranean Sea to calculate the exchange fluxes and basin salinity for a certain gateway depth and width. Figure 4 uses the same equations in reverse to estimate the gateway depth and width for the Mediterranean salinities associated with the different MSC stages (Roveri et al., 2014; Flecker et al., 2015; Kouwenhoven et al., 2003): pre-7.2 Ma, the Mediterranean salinity was similar to the present, only a couple of g/kg higher than open ocean salinity; at 7.2 Ma and 6.8 Ma the salinity stepped up, but did not reach gypsum saturation; around 6.0 Ma, gypsum saturation (~130 g/kg) was reached; at 5.6 Ma halite saturation (~350 g/kg) was reached; at 5.55 Ma the basin returned to gypsum saturation and at 5.33 Ma normal marine conditions were established. To estimate the gateway dimensions for these salinities we assume a constant mean Mediterranean freshwater forcing following recent estimates (Simon et al., 2017) and no additional input from Paratethys. Figure 4 clearly demonstrates that the gateway size needs to be drastically reduced; potentially by mechanisms described above. The estimates given here illustrate a lower dimensional bound; likely the gateway was slightly wider or deeper and effective restriction was caused by factors such as friction (Simon and Meijer, 2015) or basin stratification (Simon and Meijer, 2017). In addition, water may have been transported through extensive karst connections.

4. EPILOGUE

The late Miocene-early Pliocene palaeogeographic evolution of Mediterranean-Atlantic connectivity took place in several distinct steps. During the late Tortonian numerous connections still existed through southern Spain and northern Morocco and probably also through the Gibraltar Corridor (Fig. 5a). Slab retreat in the western Mediterranean subduction zone underneath the Gibraltar Arc came to a hold in the late Tortonian (Van Hinsbergen et al., 2014) after which tectonic uplift processes took over in the Betic (at ~7.8 Ma; Betzler et al., 2006; Krijgsman et al., 2006) and slightly later in the Rif orogeny (at ~7 Ma; Capella et al., 2017a; Tulbure et al., 2017). During the early Messinian, all the Betic connections and the North Rifian Corridor were closed by Africa-Iberia convergence processes (e.g., Spakman et al., 2018). The South Rifian Corridor was still open during the earliest Messinian, but a marked transition to continental and lacustrine deposits dates its closure at <6.9 Ma (Capella et al., 2017b). A gap of one million year separates the last field evidence of marine connection and the onset of the MSC in the Mediterranean. Based on the new MEDGATE age constraints and gateway analyses, there is no direct evidence of a Mediterranean-Atlantic gateway through southern Spain or northern Morocco from 6.9 Ma until 5.33 Ma. Consequently, the Gibraltar Corridor became the sole Atlantic gateway during the Messinian and its paleogeographic reconstruction indicates a slightly different configuration than today, picturing a potential gateway with two small channels towards the Alboran basin (Fig. 5b, c). The Gibraltar Corridor probably delivered salt waters to the Mediterranean during all successive stages of the MSC, but it changed from an open marine two-way connection during PLG times (e.g. Simon and Meijer, 2017) towards a putative unidirectional flow into the Mediterranean during the halite and Lago-mare phases. The basal Zanclean re-flooding of the Mediterranean could then correspond to a dramatic change in the inflow-outflow balance, effectively starting a Mediterranean pump scenario conform Marzocchi et al. (2016). The re-enlargement of the gateway at 5.33 Ma does not correlate to a major deglaciation or sea level increase in the global paleoclimatic records (Van der Laan et al., 2006). The deepening of the Gibraltar Strait at the beginning of the Pliocene has most likely a geodynamic forcing, e.g., being related to slab dynamics in the upper mantle (Garcia-Castellanos and Villasenor, 2011; Spakman et al., 2018).

An early, pre-Pliocene connection through Gibraltar is in agreement with growing evidence that the Mediterranean Sea was principally a deep, non-desiccated basin during most of the MSC. A proper reconstruction of Mediterranean water level changes, especially during MSC stages 2 and 3, is currently one of the most crucial tipping points to finally resolve the complete story of water exchange between the Atlantic and Mediterranean during the MSC. We conclude that the Gibraltar Corridor being open during the Messinian is a more plausible scenario than several hundred km long and shallow straits through Morocco and/or Spain, although it still requires direct evidencing of a Messinian connection through Gibraltar to substantiate its exact configuration. We therefore suggest that future field and drilling campaigns should target the western Alborán and Gibraltar Strait regions directly in order to confirm the geological conundrum of a Messinian watergate.

ACKNOWLEDGMENTS

We thank the entire MEDGATE team for many fruitful workshops, meetings and discussions. The research leading to these results has received funding from the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/ under REA Grant Agreement No. 290201 MEDGATE and from the Netherlands Geosciences Foundation (ALW) of the Netherlands Organization for Scientific Research (NWO) program through the VICI grant of WK. We furthermore acknowledge the constructive comments of two anonymous reviewers and journal editor Michele Rebesco.

REFERENCES

Achalhi, M., Münch, P., Cornée, J.J., Azdimousa, A., Melinte-Dobrinescu, M., Quillévéré, F., Drinia, H., Fauquette, S., Jiménez-Moreno, G., Merzeraud, G. and Moussa, A.B., 2016. The late Miocene Mediterranean-Atlantic connections through the North Rifian Corridor: New insights from the Boudinar and Arbaa Taourirt basins (northeastern Rif, Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *459*, 131-152.

Bache, F., Popescu, S.M., Rabineau, M., Gorini, C., Suc, J.P., Clauzon, G., Olivet, J.L., Rubino, J.L., Melinte-Dobrinescu, M.C., Estrada, F. and Londeix, L., 2012. A two-step process for the reflooding of the Mediterranean after the Messinian Salinity Crisis. *Basin Research*, *24*(2), 125-153.

Bache, F., Olivet, J.L., Gorini, C., Rabineau, M., Baztan, J., Aslanian, D. and Suc, J.P., 2009. Messinian erosional and salinity crises: view from the Provence Basin (Gulf of Lions, Western Mediterranean). *Earth and Planetary Science Letters*, *286*(1), 139-157.

Bache, F., Gargani, J., Suc, J.P., Gorini, C., Rabineau, M., Popescu, S.M., Leroux, E., Do Couto, D., Jouannic, G., Rubino, J.L. and Olivet, J.L., 2015. Messinian evaporite deposition during sea level rise in the Gulf of Lions (Western Mediterranean). *Marine and Petroleum Geology*, *66*, 262-277.

Bassetti, M.A., Miculan, P. and Lucchi, F.R., 2003. Ostracod faunas and brackish-water environments of the late Messinian Sapigno section (northern Apennines, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *198*(3), 335-352.

Bassetti, M.A., Miculan, P. and Sierro, F.J., 2006. Evolution of depositional environments after the end of Messinian Salinity Crisis in Nijar basin (SE Betic Cordillera). *Sedimentary Geology*, *188*, 279-295.

Benson, R.H., Bied, R.E. and Bonaduce, G., 1991. An important current reversal (influx) in the Rifian Corridor (Morocco) at the Tortonian-Messinian boundary: The end of Tethys Ocean. *Paleoceanography*, *6*(1), 165-192.

Betzler, C., Braga, J.C., Martín, J.M., Sanchez-Almazo, I.M. and Lindhorst, S., 2006. Closure of a seaway: stratigraphic record and facies (Guadix basin, Southern Spain). *International Journal of Earth Sciences*, *95*(5), 903-910.

Blanc, P.L., 2002. The opening of the Plio-Quaternary Gibraltar Strait: assessing the size of a cataclysm. *Geodinamica acta*, *15*(5-6), 303-317.

Booth-Rea, G., Ranero, C. R., Grevemer, I. 2016. Role of the Alboran Sea volcanic arc choking the Mediterranean to the Messinian salinity crisis and foundering biota diversification in North Africa and Southeast Iberia, EGU General Assembly 2016, EPSC2016-16376

Capella, W., Matenco, L., Dmitrieva, E., Roest, W.M., Hessels, S., Hssain, M., Chakor-Alami, A., Sierro, F.J. and Krijgsman, W., 2017a. Thick-skinned tectonics closing the Rifian Corridor. *Tectonophysics*, *710*, 249-265.

Capella, W., Hernández-Molina, F.J., Flecker, R., Hilgen, F.J., Hssain, M., Kouwenhoven, T.J., van Oorschot, M., Sierro, F.J., Stow, D.A.V., Trabucho-Alexandre, J. and Tulbure, M.A., 2017b. Sandy contourite drift in the late Miocene Rifian Corridor (Morocco): Reconstruction of depositional environments in a foreland-basin seaway. *Sedimentary Geology*, *355*, 31-57.

Capella, W., Barhoun, N., Flecker, R., Hilgen, F.J., Kouwenhoven, T.E., Matenco, L., Sierro, F.J., Tulbure, M., Yousfi, Z., Krijgsman, W. 2018. Palaeogeographic evolution of the Late Miocene Rifian Corridor (Morocco): reconstructions from surface and subsurface data, *Earth Science Reviews*, 180, 37-59.

Carnevale, G., Landini, W. and Sarti, G., 2006. Mare versus Lago-mare: marine fishes and the Mediterranean environment at the end of the Messinian Salinity Crisis. *Journal of the Geological Society*, *163*(1), 75-80.

Carnevale, G., Longinelli, A., Caputo, D., Barbieri, M. and Landini, W., 2008. Did the Mediterranean marine reflooding precede the Mio–Pliocene boundary? Paleontological and geochemical evidence from upper

Messinian sequences of Tuscany, Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *257*(1), 81-105.

Chumakov, I.S., 1973. Pliocene and Pleistocene deposits of the Nile valley in Nubia and upper Egypt. *Initial Reports of the Deep Sea Drilling Project*, *13*(part 2), 1242-1243.

Clauzon, G., 1982. Le canyon messinien du Rhone; une preuve decive du" desiccated deep-basin model"(Hsue, Cita and Ryan, 1973). *Bulletin de la Société géologique de France*, *7*(3), 597-610.

Clauzon, G., Suc, J.P., Gautier, F., Berger, A. and Loutre, M.F., 1996. Alternate interpretation of the Messinian salinity crisis: Controversy resolved? *Geology*, *24*(4), 363-366.

Comas, M.C., Platt, J.P., Soto, J.I. and Watts, A.B., 1999. 44. The origin and tectonic history of the Alboran Basin: insights from Leg 161 results. In *Proceedings of the Ocean Drilling Program Scientific Results*, 161, 555-580).

Corbí, H., Lancis, C., García-García, F., Pina, J.A., Soria, J.M., Tent-Manclús, J.E. and Viseras, C., 2012. Updating the marine biostratigraphy of the Granada Basin (central Betic Cordillera). Insight for the Late Miocene palaeogeographic evolution of the Atlantic–Mediterranean seaway. *Geobios*, *45*(3), 249-263.

Do Couto, D., Gorini, C., Jolivet, L., Lebret, N., Augier, R., Gumiaux, C., d'Acremont, E., Ammar, A., Jabour, H. and Auxietre, J.L., 2016. Tectonic and stratigraphic evolution of the Western Alboran Sea Basin in the last 25Myrs. *Tectonophysics*, *677*, 280-311.

Esteras, M. Izquierdo, J. Sandoval, N. G. & Bahmad, A., 2000. Evolución morfológica y estratigrafía Plio-Cuaternaria del Umbral de Camarinal (Estrecho de Gibraltar) basada en sondeos marinos. *Rev. Soc. Geol. Esp*. 13, 539–550.

Estrada, F., Ercilla, G., Gorini, C., Alonso, B., Vázquez, J.T., García-Castellanos, D., Juan, C., Maldonado, A., Ammar, A. and Elabbassi, M., 2011. Impact of pulsed Atlantic water inflow into the Alboran Basin at the time of the Zanclean flooding. *Geo-Marine Letters*, *31*(5-6), 361-376.

Flecker, R., Krijgsman, W., Capella, W., de Castro Martíns, C., Dmitrieva, E., Mayser, J.P., Marzocchi, A., Modestu, S., Ochoa, D., Simon, D., Tulbure, M., van den Berg, B., van der Schee, M., de Lange, G., Ellam, R., Govers, R., Gutjahr, M., Hilgen, F., Kouwenhoven, T., Lofi, J., Meijer, P., Sierro, F.J., Bachiri, N., Barhoun, N., Alami, A.C., Chacon, B., Flores, J.A., Gregory, J., Howard, J., Lunt, D., Ochoa, M., Pancost, R., Vincent, S. and Yousfi, M.Z., 2015. Evolution of the Late Miocene Mediterranean–Atlantic gateways and their impact on regional and global environmental change. *Earth-Science Reviews*, *150*, 365-392.

Garcés, M., Krijgsman, W., and Agustí, J. 1998. Chronology of the late Turolian deposits of the Fortuna basin: implications for the Messinian evolution of the eastern Betics, *Earth Planet. Sci. Lett*., 163, 69-81.

Garcés, M., Krijgsman, W., Agustí, J. 2001. Chronostratigraphic framework and evolution of the Fortuna Basin (Eastern Betics) since the Late Miocene, *Basin Res*., 13(2), 199-216.

Garcia-Castellanos, D., Estrada, F., Jiménez-Munt, I., Gorini, C., Fernández, M., Vergés, J. and De Vicente, R., 2009. Catastrophic flood of the Mediterranean after the Messinian salinity crisis. *Nature*, *462*, 778-781.

Garcia-Castellanos, D., Villaseñor, A., 2011. Messinian salinity crisis regulated by competing tectonics and erosion at Gibraltar arc. *Nature,* 480, 359–363

Garcia-Garcia, F., Soria, J.M., Viseras, C., Fernandez, J. 2009. High frequency rythmicity in a mixed siliciclastic-carbonate shelf (Late Miocene, Guadix basin, Spain): A model of interplay between climatic oscillations, subsidence, and sediment dispersal. *Journal of Sedimentary Research*, 79, 302–315.

Govers, R. and Wortel, M.J.R., 2005. Lithosphere tearing at STEP faults: response to edges of subduction zones. *Earth and Planetary Science Letters*, *236*(1), 505-523.

Govers, R., 2009. Choking the Mediterranean to dehydration: the Messinian salinity crisis. *Geology*, *37*(2), 167-170.

Grunert, P., Harzhauser, M., Rosenthal, Y., Carnevale, G., 2016. Estuarine Lago Mare fauna from the Tertiary Piedmont Basin indicates episodic Atlantic/Mediterranean exchange during the final stage of the Mediterranean salinity crisis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 457, 70–79.

Guerra-Merchán, A., Serrano, F., Garcés, M., Gofas, S., Esu, D., Gliozzi, E., Grossi, F., 2010. Messinian Lago-Mare deposits near the Strait of Gibraltar (Malaga Basin, S Spain). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 285, 264–276.

Hilgen, F.J., Kuiper, K.F., Krijgsman, W., Snel, E., Van der Laan, E., 2007. Astronomical tuning as the basis for high resolution chronostratigraphy: the intricate history of the Messinian Salinity Crisis, *Stratigraphy*, 4, 231-238.

Hsü, K.J., Ryan, W.B.F. and Cita, M.B., 1973a. Late Miocene desiccation of the Mediterranean. *Nature*, *242*(5395), 240-244.

Hsü, K.J., Cita, M.B., Ryan, W.B.F., 1973b. The origin of the Mediterranean evaporites.In: Ryan,W.B.F., Hsü, K.J., Cita, M.B. (Eds.), Initial Reports of the Deep Sea Drilling Project 13, Part 2. U.S. Government Printing Office, Washington D.C., 1203–1231.

Hsü, K.J., et al., 1978. History of the Mediterranean salinity crisis. *Nature* 267, 399–403.

Hüsing, S.K., Oms, O., Agustí, J., Garcés, M., Kouwenhoven, T.J., Krijgsman, W. and Zachariasse, W.J., 2010. On the late Miocene closure of the Mediterranean–Atlantic gateway through the Guadix basin (southern Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *291*(3), 167-179.

Hüsing, S.K., Oms, O., Agustí, J., Garcés, M., Kouwenhoven, T.J., Krijgsman, W. and Zachariasse, W.J., 2012. On the Late Miocene continentalization of the Guadix Basin: More evidence for a major Messinian hiatus. *Geobios*, *45*(6), 617-620.

Iaccarino, S.M., Bertini, A., Di Stefano, A., Ferraro, L., Gennari, R., Grossi, F., Lirer, F., Manzi, V., Menichetti, E., Ricci Lucchi, M., Taviani, M., Sturiale, G., Angeletti, L., 2008. The Trave section (Monte dei Corvi, Ancona, Central Italy): an integrated paleontological study of the Messinian deposits. *Stratigraphy*, 5, 281–306.

Ivanovic, R.F., Flecker, R., Gutjahr, M. and Valdes, P.J., 2013. First Nd isotope record of Mediterranean–Atlantic water exchange through the Moroccan Rifian Corridor during the Messinian salinity crisis. *Earth and Planetary Science Letters*, *368*, 163-174.

Jiménez-Bonilla, A., Expósito, I., Balanyá, J.C., Díaz-Azpiroz, M. and Barcos, L., 2015. The role of strain partitioning on intermontane basin inception and isolation, External Western Gibraltar Arc. *Journal of Geodynamics*, *92*, 1-17.

Kouwenhoven, T.J., Hilgen, F.J. and Van der Zwaan, G.J., 2003. Late Tortonian–early Messinian stepwise disruption of the Mediterranean–Atlantic connections: constraints from benthic foraminiferal and geochemical data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *198*(3), 303-319.

Kouwenhoven, T.J., Morigi, C., Negri, A., Giunta, S., Krijgsman, W. and Rouchy, J.-M., 2006. Paleoenvironmental evolution of the eastern Mediterranean during the Messinian: Constraints from integrated microfossil data of the Pissouri Basin (Cyprus), *Mar. Micropal*, 60, 17-44.

Krijgsman, W., 2002. The Mediterranean: Mare Nostrum of Earth Sciences, *Earth Planet. Sci. Lett.*, 205, 1-12.

Krijgsman, W. and Meijer, P.T., 2008. Depositional environments of the Mediterranean "Lower Evaporites" of the Messinian salinity crisis: constraints from quantitative analyses. *Marine Geology*, *253*(3), 73-81.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J. and Wilsonk, D.S., 1999a. Chronology, causes and progression of the Messinian salinity crisis. *Nature*, *400*, 652-655.

Krijgsman, W., Langereis, C.G., Zachariasse, W.J., Boccaletti, M., Moratti, G., Gelati, R., Iaccarino, S., Papani, G. and Villa, G., 1999b. Late Neogene evolution of the Taza–Guercif Basin (Rifian Corridor, Morocco) and implications for the Messinian salinity crisis. *Marine Geology*, *153*(1), 147-160.

Krijgsman, W., Garcés, M., Agustı, J., Raffi, I., Taberner, C. and Zachariasse, W.J., 2000. The ‘Tortonian salinity crisis’ of the eastern Betics (Spain). *Earth and Planetary Science Letters*, *181*(4), 497-511.

Krijgsman, W., Fortuin, A.R., Hilgen, F.J. and Sierro, F.J., 2001. Astrochronology for the Messinian Sorbas basin (SE Spain) and orbital (precessional) forcing for evaporite cyclicity. *Sedimentary Geology*, *140*(1), 43-60.

Krijgsman, W., Blanc-Valleron, M.M., Flecker, R., Hilgen, F.J., Kouwenhoven, T.J., Merle, D., Orszag-Sperber, F. and Rouchy, J.M., 2002. The onset of the Messinian salinity crisis in the Eastern Mediterranean (Pissouri Basin, Cyprus). *Earth and Planetary Science Letters*, *194*(3), 299-310.

Krijgsman, W., Leewis, M.E., Garcés, M., Kouwenhoven, T.J., Kuiper, K.F., and Sierro, F.J., 2006. Tectonic control for evaporite formation in the Eastern Betics (Tortonian; Spain), *Sedimentary Geology*, 188-189, 155-170.

Kruiver, P.P., Krijgsman, W., Langereis, C.G. and Dekkers, M.J. 2002. Cyclostratigraphy and rock-magnetic investigation of the NRM signal in late Miocene palustrine-alluvial deposits of the Librilla section (SE Spain), *J. Geophys. Res.*, 107, B12, 2334.

Lofi, J., Gorini, C., Berné, S., Clauzon, G., Dos Reis, A.T., Ryan, W.B. and Steckler, M.S., 2005. Erosional processes and paleo-environmental changes in the Western Gulf of Lions (SW France) during the Messinian Salinity Crisis. *Marine Geology*, *217*(1), 1-30.

Loget, N., Van Den Driessche, J. and Davy, P., 2005. How did the Messinian salinity crisis end? *Terra Nova*, *17*(5), 414-419.

Loget, N. and Van Den Driessche, J., 2006. On the origin of the Strait of Gibraltar. *Sedimentary Geology*, *188*, 341-356.

Londeix, L., Benzakour, M., Suc, J.P. and Turon, J.L., 2007. Messinian palaeoenvironments and hydrology in Sicily (Italy): the dinoflagellate cyst record. *Geobios*, 40(3), 233-250.

López-Garrido, A. and Sanz de Galdeano, C., 1999. Neogene sedimentation and tectonic-eustatic control of the Malaga Basin, South Spain: *Journal of Petroleum Geology*, 22, 81–96.

Lugli, S., Manzi, V., Roveri M. and Schreiber C.B., 2010. The Primary Lower Gypsum in the Mediterranean: a new facies interpretation for the first stage of the Messinian salinity crisis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *297*(1), 83-99.

Lugli, S., Bassetti, M.A., Manzi, V., Barbieri, M., Longinelli, A. and Roveri, M., 2007. The Messinian ‘Vena del Gesso’evaporites revisited: characterization of isotopic composition and organic matter. *Geological Society, London, Special Publications*, *285*(1), 179-190.

Manzi, V., Gennari, R., Hilgen, F., Krijgsman, W., Lugli, S., Roveri, M. and Sierro, F.J., 2013. Age refinement of the Messinian salinity crisis onset in the Mediterranean. *Terra Nova*, *25*(4), 315-322.

Manzi, V., Lugli, S., Lucchi, F.R. and Roveri, M., 2005. Deep-water clastic evaporites deposition in the Messinian Adriatic foredeep (northern Apennines, Italy): did the Mediterranean ever dry out? *Sedimentology*, *52*(4), 875-902.

Manzi, V., Roveri, M., Gennari, R., Bertini, A., Biffi, U., Giunta, S., Iaccarino, S.M., Lanci, L., Lugli, S., Negri, A. and Riva, A., 2007. The deep-water counterpart of the Messinian Lower Evaporites in the Apennine foredeep: the Fanantello section (Northern Apennines, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, *251*(3), 470-499.

Martín, J. and Braga, J.C., 1994. Messinian events in the Sorbas Basin in southeastern Spain and their implications in the recent history of the Mediterranean. *Sedimentary Geology*, *90*(3-4), 257-268.

Martín, J.M., Braga, J.C. and Betzler, C., 2001. The Messinian Guadalhorce corridor: the last northern, Atlantic–Mediterranean gateway. *Terra Nova*, *13*(6), 418-424.

Martín, J.M., Braga, J.C., Aguirre, J. and Puga-Bernabéu, Á., 2009. History and evolution of the North-Betic Strait (Prebetic Zone, Betic Cordillera): a narrow, early Tortonian, tidal-dominated, Atlantic–Mediterranean marine passage. *Sedimentary Geology*, *216*(3), 80-90.

Martín, J.M., Puga-Bernabéu, Á., Aguirre, J. and Braga, J.C., 2014. Miocene Atlantic-Mediterranean seaways in the Betic Cordillera (Southern Spain), *Revista Soc. Geol. España*, 27(1), 175-186.

Marzocchi, A., Flecker, R., Van Baak, C.G., Lunt, D.J. and Krijgsman, W., 2016. Mediterranean outflow pump: An alternative mechanism for the Lago-mare and the end of the Messinian Salinity Crisis. *Geology*, *44*(7), 523-526.

Meijer, P.T., 2006. A box model of the blocked-outflow scenario for the Messinian Salinity Crisis. *Earth and Planetary Science Letters*, *248*(1), 486-494.

Meijer, P.T., 2012. Hydraulic theory of sea straits applied to the onset of the Messinian Salinity Crisis. *Marine Geology*, *326*, 131-139.

Meijninger, B.M.L. and Vissers, R.L.M., 2006. Miocene extensional basin development in the Betic Cordillera, SE Spain revealed through analysis of the Alhama de Murcia and Crevillente Faults. *Basin Research*, *18*(4), 547-571.

Micallef, A., Camerlenghi, A., Garcia-Castellanos, Cunarro Otero, D., Gutscher, M.A., Barreca, G., Spatola, D., Facchin, L., Geletti, R., Krastel, S., Gross, F., Urlaub, M., 2018. Evidence of the Zanclean megaflood in the eastern Mediterranean Basin, Scientific Reports, 8:1078.

Minwer-Barakat, R., García-Alix, A., Agustí, J., Suárez, E.M. and Freudenthal, M., 2009. The micromammal fauna from Negratín-1 (Guadix Basin, Southern Spain): new evidence of African-Iberian mammal exchanges during the Late Miocene. *Journal of Paleontology*, *83*(6), 854-879.

Orszag-Sperber, F., 2006. Changing perspectives in the concept of "Lago-Mare" in Mediterranean Late Miocene evolution. *Sedimentary Geology*, *188*, 259-277.

Pellen, R., Popescu, S.M., Suc, J.P., Melinte-Dobrinescu, M.C., Rubino, J.L., Rabineau, M., Marabini, S., Loget, N., Casero, P., Cavazza, W. and Head, M.J., 2017. The Apennine foredeep (Italy) during the latest Messinian: Lago Mare reflects competing brackish and marine conditions based on calcareous nannofossils and dinoflagellate cysts. *Geobios*. 50(3), 237-257.

Rohling, E.J., Schiebel, R. and Siddall, M., 2008. Controls on Messinian lower evaporite cycles in the Mediterranean. *Earth and Planetary Science Letters*, *275*(1), 165-171.

Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F.J., Bertini, A., Camerlenghi, A., De Lange, G. and Govers, R., 2014a. The Messinian Salinity Crisis: past and future of a great challenge for marine sciences. *Marine Geology*, *352*, 25-58.

Roveri, M., Manzi, V., Bergamasco, A., Falcieri, F.M., Gennari, R., Lugli, S. and Schreiber, B.C., 2014b. Dense shelf water cascading and Messinian canyons: a new scenario for the Mediterranean salinity crisis. *American Journal of Science*, *314*(3), 751-784.

Roveri, M. and Manzi, V., 2006. The Messinian salinity crisis: Looking for a new paradigm? *Palaeogeography, Palaeoclimatology, Palaeoecology*, *238*(1), 386-398.

Ruggieri, G., 1967. The Miocene and later evolution of the Mediterranean Sea. In: Adams, C.G., Ager, A.V. (Eds.), Aspects of Tethyan Biogeography, 7. Systematics Association Publ., London, pp. 283–290.

Ryan, W.B.F., 2009. Decoding the Mediterranean salinity crisis. *Sedimentology*, 56, 95–136.

Ryan, W.B.F., 2008, Modeling the magnitude and timing of evaporative drawdown during the Messinian salinity crisis. *Stratigraphy,* 5, 227-243.

Ryan, W.B., 1978. Messinian badlands on the southeastern margin of the Mediterranean Sea. *Marine Geology*, *27*(3-4), 349-363.

Selli, R., 1954. Il Bacino del Metauro. *Giornale di Geologia* 24, 1–294.

Selli, R., 1960. Il Messiniano Mayer-Eymar 1867. Proposta di un neostratotipo. *Giornale di Geologia* 28, 1–33.

Simon, D. and Meijer, P., 2015. Dimensions of the Atlantic–Mediterranean connection that caused the Messinian Salinity Crisis. *Marine Geology*, *364*, 53-64.

Simon, D., Marzocchi, A., Flecker, R., Lunt, D.J., Hilgen, F.J. and Meijer, P.T., 2017. Quantifying the Mediterranean freshwater budget throughout the late Miocene: New implications for sapropel formation and the Messinian Salinity Crisis. *Earth and Planetary Science Letters*, *472*, 25-37.

Simon, D. and Meijer, P.T., 2017. Salinity stratification of the Mediterranean Sea during the Messinian crisis: A first model analysis. *Earth and Planetary Science Letters,* 479, 366-376.

Spakman, W., Chertova, M.V., Van den Berg, A., Van Hinsbergen, D.J.J., 2018. Puzzling features of western Mediterranean tectonics explained by slab dragging. *Nature Geosciences*, 11, 211-216

Stoica, M., Krijgsman, W., Fortuin, A. and Gliozzi, E., 2016. Paratethyan ostracods in the Spanish Lago-Mare: More evidence for interbasinal exchange at high Mediterranean sea level. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *441*, 854-870.

Topper, R.P.M., Flecker, R., Meijer, P.T. and Wortel, M.J.R., 2011. A box model of the Late Miocene Mediterranean Sea: Implications from combined 87Sr/86Sr and salinity data. *Paleoceanography*, *26*(3).

Topper, R.P.M. and Meijer, P.T., 2013. A modeling perspective on spatial and temporal variations in Messinian evaporite deposits. *Marine Geology*, 336, 44-60.

Topper, R.P.M. and Meijer, P.T., 2015. Changes in Mediterranean circulation and water characteristics due to restriction of the Atlantic connection: a high-resolution ocean model. *Climate of the Past*, *11*(2), 233-251.

Tulbure, M.A., Capella, W., Barhoun, N., Flores, J.A., Hilgen, F.J., Krijgsman, W., Kouwenhoven, T., Sierro, F.J. and Yousfi, M.Z., 2017. Age refinement and basin evolution of the North Rifian Corridor (Morocco): No evidence for a marine connection during the Messinian Salinity Crisis. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 485, 416-432

Van Assen, E., Kuiper, K.F., Barhoun, N., Krijgsman, W. and Sierro, F.J., 2006. Messinian astrochronology of the Melilla Basin: stepwise restriction of the Mediterranean–Atlantic connection through Morocco. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *238*(1), 15-31.

Van Hinsbergen, D.J.J., Vissers, R.L.M. and Spakman, W., 2014. Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation, *Tectonics*, 10.1002/2013TC003349

Van den Berg, B.C.J., Sierro, F.J., Hilgen, F.J., Flecker, R., Larrasoaña, J.C., Krijgsman, W., Flores, J.A., Mata M.P., 2018. Imprint of Messinian Salinity Crisis events on the Spanish Atlantic margin, *Newslett. Strat.*, 51(1), 93-115.

Van den Berg, B.C.J., 2016. Late Miocene astrochronology and basin evolution of the Atlantic side of the Betic Corridor linked to the Messinian Salinity Crisis, Tesis Doctoral, University of Salamanca, 1-174.

Van der Laan, E., Snel, E., de Kaenel, E., Hilgen, F.J., Krijgsman, W., 2006. No major deglaciation across the Miocene–Pliocene boundary: integrated stratigraphy and astronomical tuning of the Loulja sections (Bou Regreg area, NW Morocco). Paleoceanography 21, PA3011.

Van der Schee, M., Sierro, F., Jimenez-Espejo, F., Hernández-Molina, F., Flecker, R., Flores, J., Acton, G., Gutjahr, M., Grunert, P., García-Gallardo, A. 2016. Evidence of early bottom water current flow after the Messinian Salinity Crisis in the Gulf of Cadiz. *Marine Geology,* 380, 315-329.

Van der Schee, M., Van den Berg, B.C.J., Capella, W., Simon, D., Krijgsman, W., Sierro, F.J., 2018. New age constraints on the western Betic intramontane basins: a late Tortonian closure of the Guadalhorce Corridor? *Terra Nova*, in press.

Vasiliev, I., Mezger, E.M., Lugli, S., Reichart, G.J., Manzi, V. and Roveri, M., 2017. How dry was the Mediterranean during the Messinian salinity crisis? *Palaeogeography, Palaeoclimatology, Palaeoecology*, *471*, 120-133.

FIGURE CAPTIONS

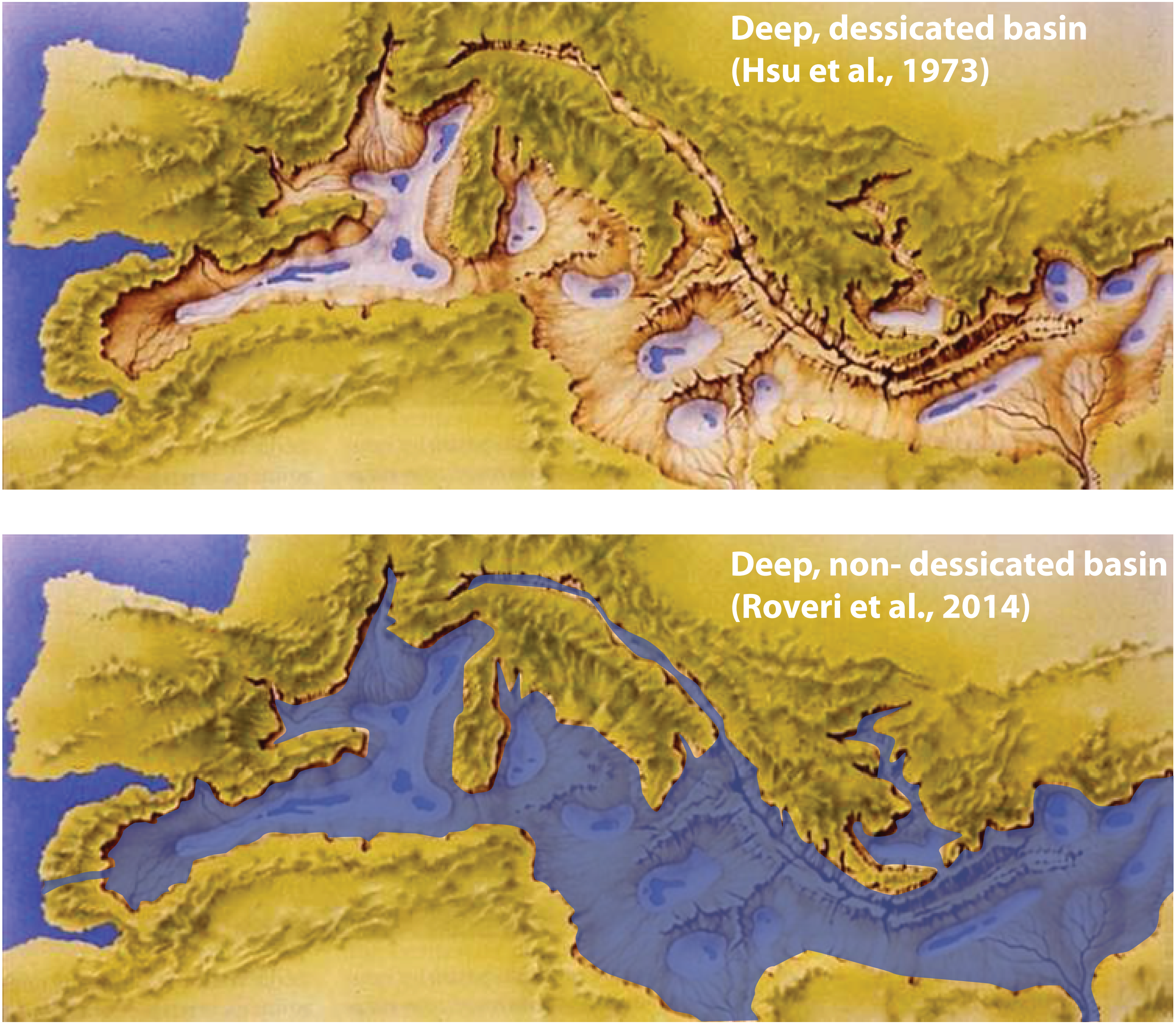
Figure 1: Map of the wider Mediterranean region. Two extreme MSC scenarios are shown; top panel: a 1500 m sea-level drop; bottom panel: deposition with normal sea-level. Modified after "The First Eden: The Mediterranean World and Man" by David Attenborough (1987).

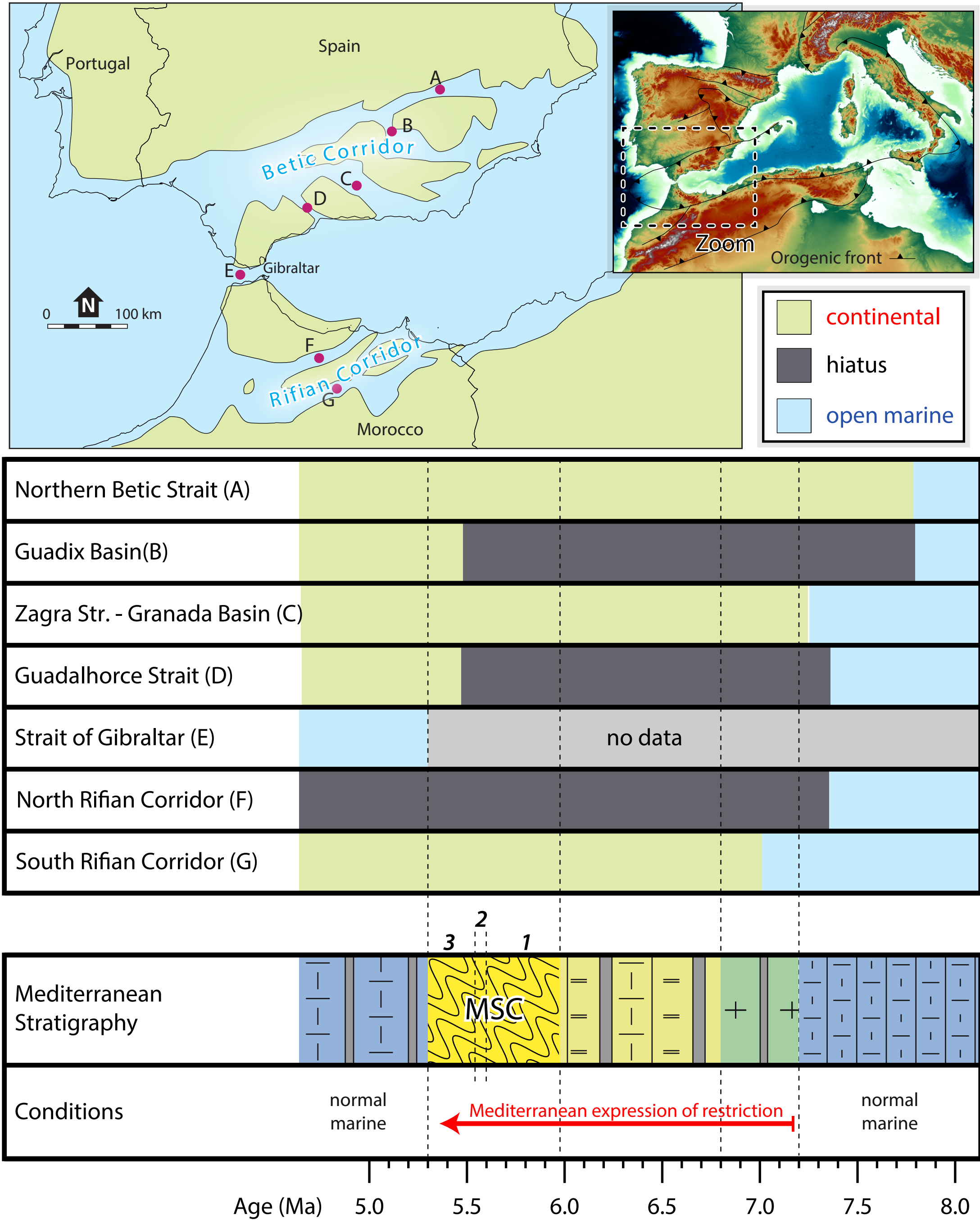
Figure 2: Top-right: Map of the western Mediterranean region with most relevant orogenic fronts. Top-left: Zoom into the Gibraltar region indicating locations of all known Mediterranean-Atlantic seaways that existed during late Miocene and Pliocene. Bottom: Temporal evolution of the marine-continental transitions of the gateways and a simplified Mediterranean sedimentary succession, following Flecker et al., 2015. The open marine nature of the Strait of Gibraltar since 5.3 Ma is based on the contourite record in the Atlantic Ocean to the west of the Strait, in the Gulf of Cádiz (Van der Schee et al., 2016).

Figure 3: A) Present-day coastline and bathymetric contours (200 m, 400 m, 800 m) of the Strait of Gibraltar region (after Blanc, 2002). B) N-S cross-section cutting through the Gibraltar Straits after Esteras et al. (2000) and Garcia-Castellanos et al. (2009). Location of transect in inset A. Combined, these two insets indicate two long paleo-strait-channels potentially active before the Zanclean flood.

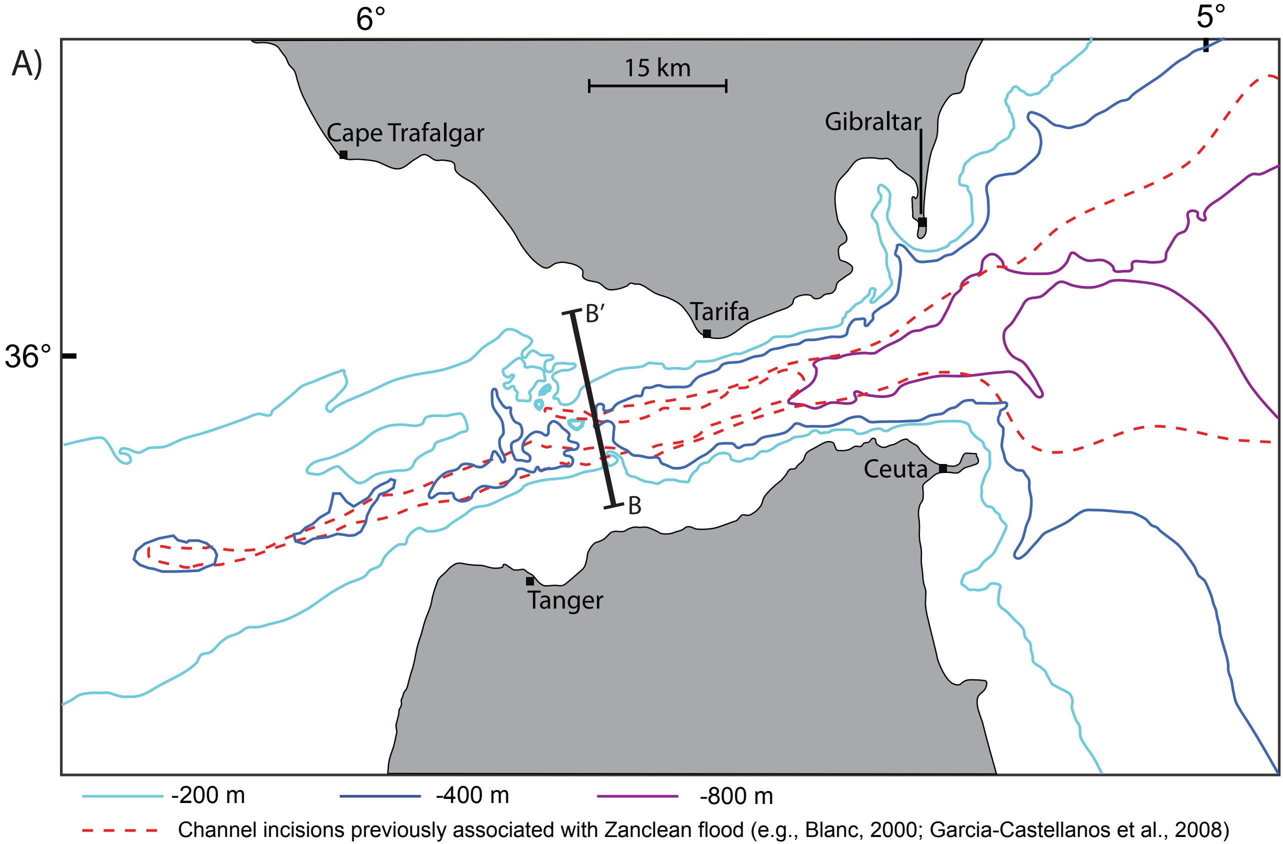
Figure 4: Correlation of Mediterranean salinity environments (A) to the gateway dimensions (B) throughout the late Miocene, following Meijer (2012).

Figure 5: Late Miocene Pliocene palaeogeographic evolution of the Mediterranean-Atlantic gateways updated with results of the present study. Blue arrows represent palaeocurrents derived from the literature (e.g., Martin et al., 2014; Capella et al., 2018). The eastern Alborán volcanic arc may have created a system of interconnected islands in the Messinian (Booth-Rea et al., 1016). The Strait of Gibraltar is here put forward as the last Messinian gateway. Sketch modified after Martin et al., 2001, 2009, 2014; Achalhi et al., 2016.

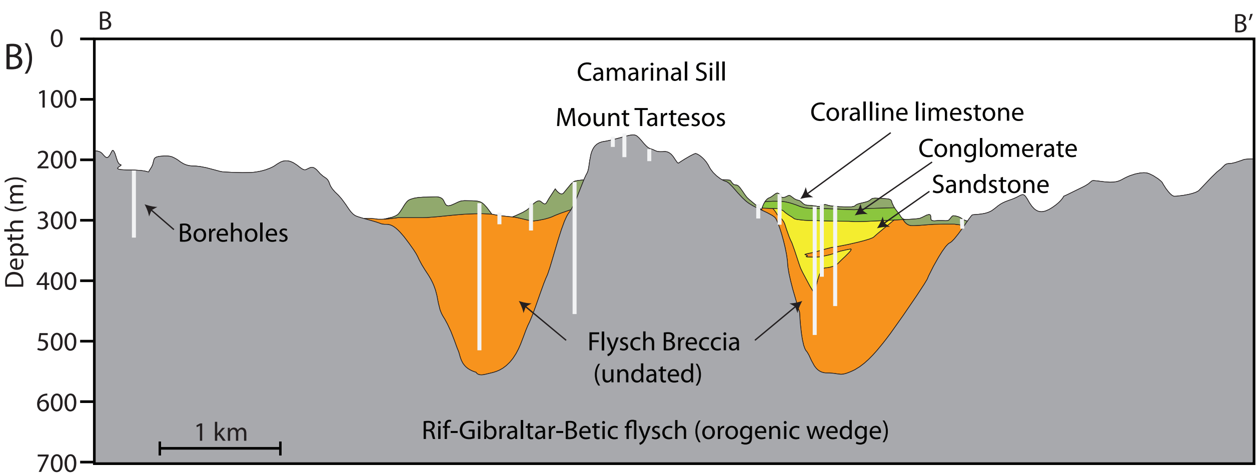

Deep, dessicated basin
(Hsu et al., 1973)
Deep, non- dessicated basin
(Roveri et al., 2014)



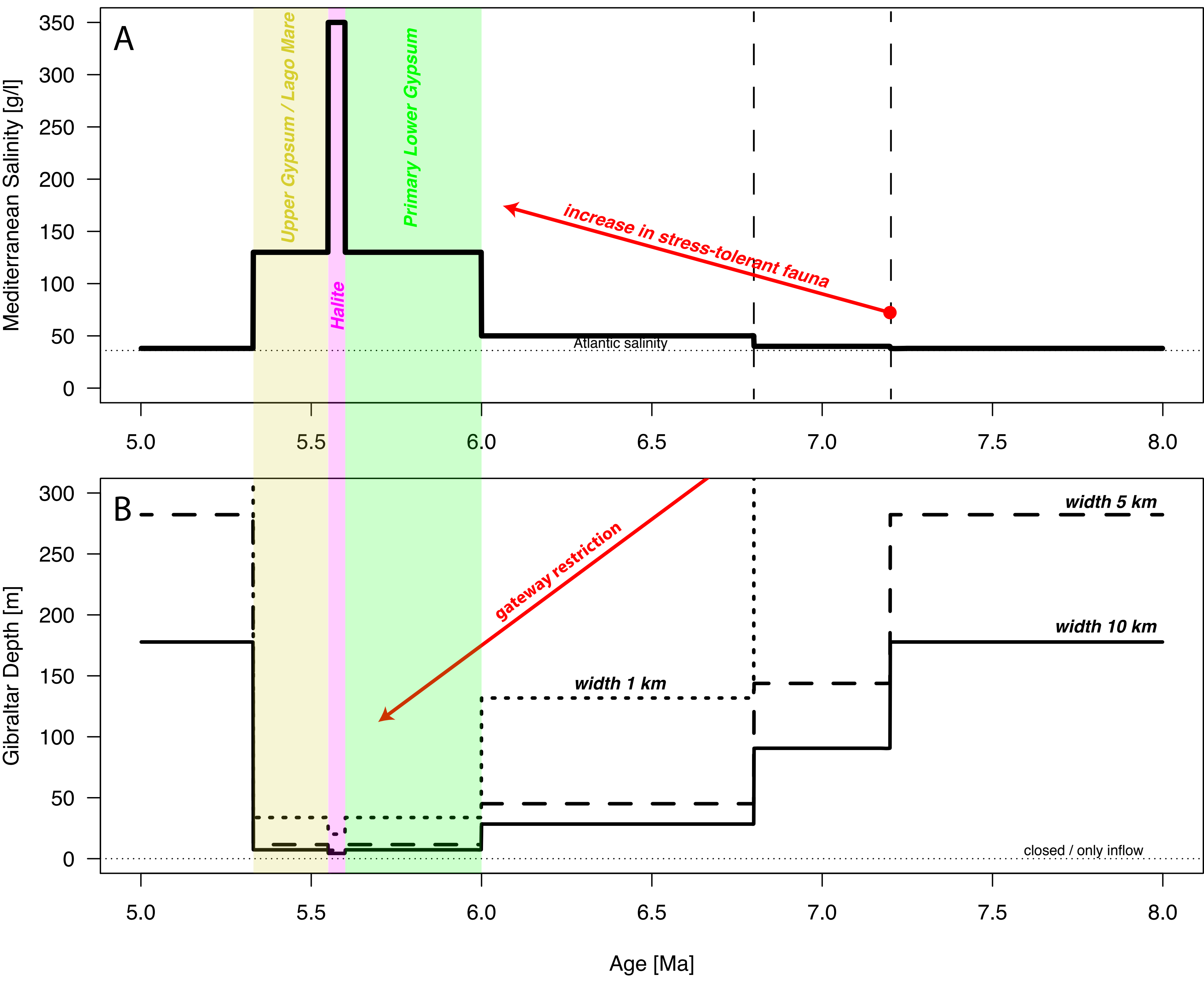
Portugal
Spain
A
B
Betic Corridor
C
D
E
Gibraltar
0
N
100 km
F
Rifian Corridor
G
Morocco
Zoom
Orogenic front
continental
hiatus
open marine
Northern Betic Strait (A)
Guadix Basin(B)
Zagra Str. - Granada Basin (C)
Guadalhorce Strait (D)
Strait of Gibraltar (E)
no data
North Rifian Corridor (F)
South Rifian Corridor (G)
3
2
1
Mediterranean Stratigraphy
MSC
Conditions
normal marine
Mediterranean expression of restriction
normal marine
Age (Ma)
5.0
5.5
6.0
6.5
7.0
7.5
8.0



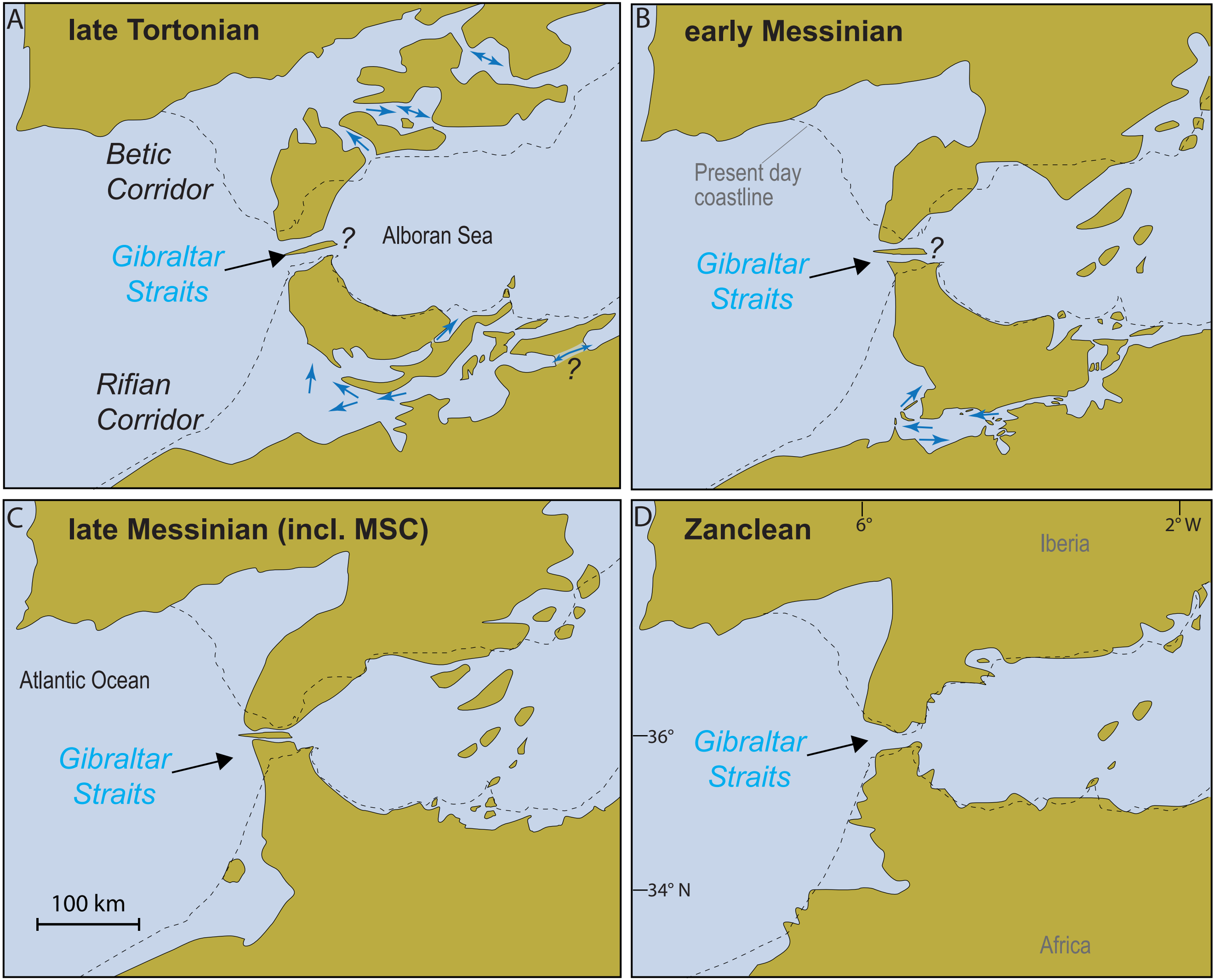
A)
6°
5°
36°
15 km
Cape Trafalgar
Gibraltar
Tarifa
B′
B
Ceuta
Tanger
-200 m
-400 m
-800 m
Channel incisions previously associated with Zanclean flood (e.g., Blanc, 2000; Garcia-Castellanos et al., 2008)



B)
B
B′
Depth (m)
0
100
200
300
400
500
600
700
Camarinal Sill
Mount Tartesos
Coralline limestone
Conglomerate
Sandstone
Boreholes
Flysch Breccia
(undated)
Rif-Gibraltar-Betic flysch (orogenic wedge)
1 km



A
B
Mediterranean Salinity [g/l]
Gibraltar Depth [m]
Age [Ma]
Upper Gypsum / Lago Mare
Halite
Primary Lower Gypsum
increase in stress-tolerant fauna
Atlantic salinity
gateway restriction
width 5 km
width 10 km
width 1 km
closed / only inflow



A
late Tortonian
Betic Corridor
?
Alboran Sea
Gibraltar Straits
?
Rifian Corridor
B
early Messinian
Present day coastline
?
Gibraltar Straits
C
late Messinian (incl. MSC)
Atlantic Ocean
Gibraltar Straits
100 km
D
Zanclean
6°
2° W
Iberia
36°
Gibraltar Straits
34° N
Africa