Mediterranean Geoscience Reviews
https://doi.org/10.1007/s42990-019-0002-5

REVIEW ARTICLE

The Messinian salinity legacy: 50 years later

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Received: 5 March 2019 / Revised: 8 June 2019 / Accepted: 11 June 2019

Abstract

The so-called Messinian salinity crisis, which dramatically affected the Mediterranean Sea at the end of Miocene, and resulted in the accumulation of important quantities of both layered and massive salt deposits within the basin, also generated a thick pile of research papers, as well as endless debates within the scientific community. We believe that the body of evidence available from geological, hydrological, and geochemical data collected during the last 50 years provides a basis to identify a relatively coherent scenario to explain this extraordinary event, which led to the Mediterranean Sea being partly desiccated and which has strongly impacted its post Miocene evolution. We also stress how the late, or the limited understanding of several fundamental parameters, such as evidence of deep outflows of salty waters, or of realistic paleogeographic reconstructions of the Messinian basins or of recognition of their frequent syn-tectonic origin, has contributed to delay a general agreement by the scientific community of a coherent global model.

Keywords Mediterranean Sea · Messinian crisis · Evaporites

Introduction

Near the end of the 1960s, the world of academic geosciences became aware of numerous salt structures (already known by oil industry companies) detected in the deep Mediterranean basins thanks to seismic refection profiling. Initially attributed to Triassic formations (Glangeaud et al. 1966), a Late Miocene age (Messinian, Pontian) was soon proposed (Cornet 1968; Montadert et al. 1970; Auzende et al. 1971; Ryan et al. 1973) and confirmed during the first drilling operations within the Mediterranean Sea (DSDP Leg 13 in 1971).

The term “Messinian” was first defined for the Latest Messinian (post-Tortonian) by Mayer-Eymar in 1867, based on his research on a small sedimentary basin located near Messina (Fig. 1). This term was hardly used, however, even in Sicily, where geologists were rather referring to “*formazione gessoso–solfifera*”. Such formations in the Mediterranean region became the subject of more various detailed researches such as: (1) paleontological analysis, particularly on fish fauna from the so-called “*tripoli*” deposits from Licata, in Sicily, and Oran in Algeria, which demonstrated their evident pelagic marine environment (Arambourg 1925, 1927); (2) structural analyses highlighting the syn-tectonic character of the sedimentation in Sicily (Ogniben 1954) and in the Southern Apennines (Mostardini et al. 1966); (3) petrological (Ogniben 1957) and stratigraphic studies, which allowed the definition of a more complete neostratotype in the Central–Sicilian Caltanissetta Basin than in the Messina region (Selli 1960); and (4) and even economic, including an evaluation of the industrial potential of the sulphur deposits within the Central-Sicilian basin (Regione Siciliana 1962–1964).

Recognizing the Messinian record

The scientific excitement generated by the discoveries of underwater salt structures led to avalanches of academic papers as well as of various theories and models, sometimes esoteric, on the “*Messinian episode*”. Over the decades, this body of researches produced some major results (see a summary in CIESM 2008 and in Roveri et al. 2014a):

(1) The Messinian geological stage was definitively validated; its base and its summit (GSSP) were, respec-

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Fig. 1 Localization map of main Messinian basins in Sicily (superimposed on Google Earth image). Broken white lines show the main Messinian to Pliocene basins: Caltanissetta Central basin, West Sicilian (Belice) basin (WS), Central Ciminna basin (C), Littoral basins of Himera (H), Messina basin (M), and Noto-Pachino basin (NP)

tively, characterized in the sections of the Oued Akrech in Morocco (Hilgen et al. 2000a, b) and of Eraclea Minoa in Sicily (Van Couvering et al. 2000).

(2) It has been possible to establish a quite precise chronology of the events (Fig. 2), thanks to robust coupling between astrochronology, paleomagnetism, micro and nano-paleontology, and some radiochronological dating (Hilgen et al. 2000a, b, 2007; Krijgsman et al. 1999, 2004; Krijgsman 2001; Hilgen et al. 2007; Manzi et al. 2013). The Messinian stage initiated at 7.246 Ma and ended at 5.33 Ma; the salinity crisis started itself around 5.96–5.97 Ma; a clear discontinuity, occurring around 5.6 Ma, separates two different Messinian sections (Decima and Wezel 1971, 1973; Roveri et al. 2008): the Lower and Upper evaporites.

(3) A large set of seismic profiles has made possible the imaging of various Messinian sequences (Fig. 3) deposited within the different Mediterranean basins; these data facilitated an evaluation of the volumes of Messinian formations, demonstrated the existence of wide areas of intra-Messinian erosion, and showed that a strong unconformity is observed between an Upper and a Lower units almost everywhere within the deep Mediterranean basins as illustrated by Lofi et al. (2005, 2011a, b, 2019).

Competing models for the Messinian crisis

The largest part of the literature was attempting to explain the genesis and the evolution of the Messinian events. It has been thus well established that:

1. The water balance of the Mediterranean (evaporation vs. inflows by rainfall and Mediterranean rivers) was (and is still) quite deficient; this disequilibrium is today compensated by a strong inflow (1.5 m/s) of less salty Atlantic waters through the Strait of Gibraltar, a phenomenon known since ancient times.
2. The total evaporation of the actual Mediterranean would only result in an evaporite layer about 30 m thick, far less than the observed masses of salt, which may locally exceed 1 km in thickness.

Taking into account these two important constraints, different models of formation have been proposed:

- A first model assumed that the evaporitic sections were deposited in shallow basins that subsequently collapsed (Nesteroff 1973). This hypothesis was soon rejected as being incompatible with both the subsidence history of the Algeria–Provence Basin on one hand, and on the other hand with the history of the Eastern Mediterranean, which was known to have been a deep basin a long time before the Messinian stage.
- Subsequent models can be grouped in two main types (Fig. 4):

  1. Shallow evaporite basins deposited within deep depressions. This *“Sebkha”*-type model, involving shallow water salty sedimentation on the floor of deep depressions, implies either a recurrent feeding mechanism of these depressions, including alternation of dewatering and filling events, or, a system of basins located at different altitudes but connected by waterfalls. One may effectively observe, within the

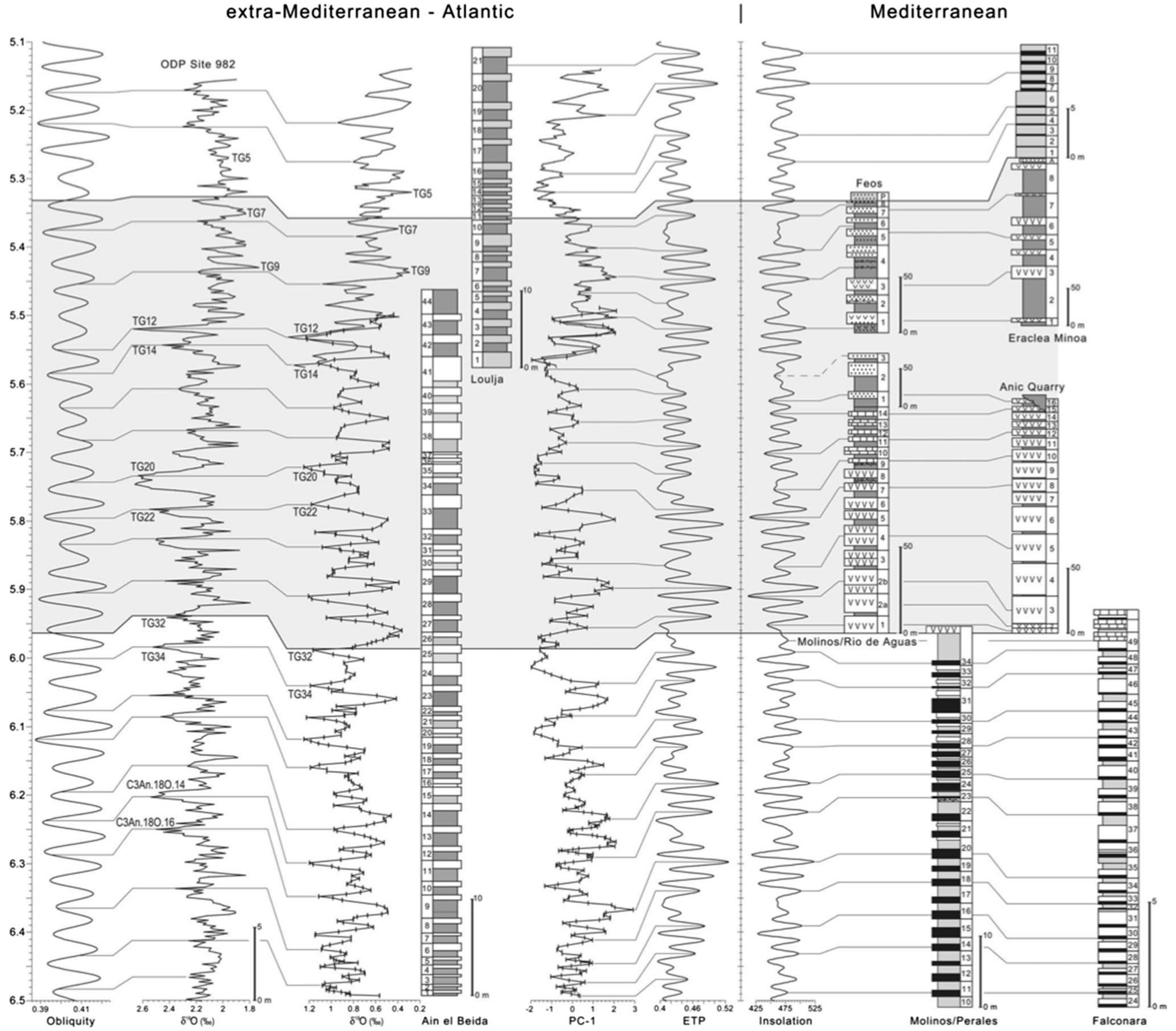


Fig. 2 Example of dating and correlations of Messinian sequences (After Hilgen et al. 2007)

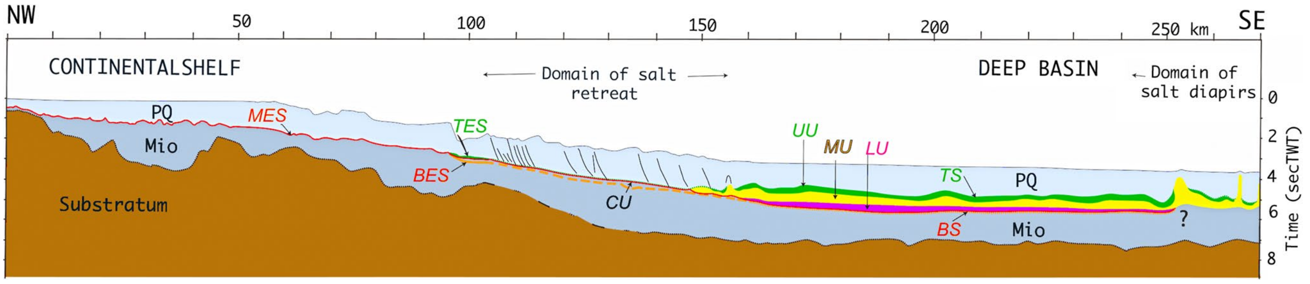


Fig. 3 Gulf of Lion margin synthetic profile (after Lofi et al. 2011a, b). MES: Messinian erosion surface; CU and LU: infra-salt units; MU: mobile unit (massive salt); UU: Upper unit (Upper evaporites); BS and TS: basal and top surfaces; BES and TES: *id*. However, including erosion; PQ: Plio-Quaternary; Mio: Intra-Messinian Miocene

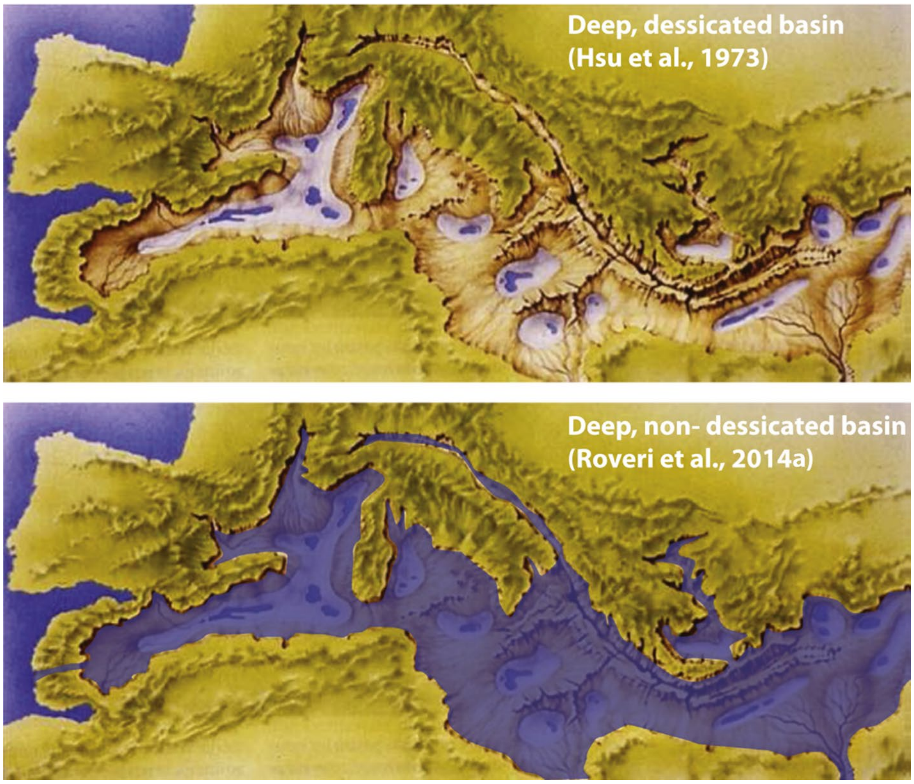


Fig. 4 Illustration of the two different models for the Messinian evaporitic basins according to Krijgsman et al. (2018). Although the two maps clearly stress the strong difference between desiccated and non-desiccated possibilities, the schemes fail due to the use of the present-day configuration of the basins (see discussion below)

Upper evaporites of Sicily, repetitive cycles of marls and gypsum (already reported by Ogniben 1954 and 1957) and interpretable in terms of alternating flooding and dewatering. However, the Lower unit does not generally display such characteristics except when syn-sedimentary tectonism occurred as in the Apennines (Mostardini et al. 1966; Ricci Lucchi 1973) or in Sicily (Ogniben 1954, 1957). Moreover, chronological correlations, established at the scale of the entire Mediterranean domain, do not support such a complex system of connected basins (Lofi et al. 2011a, b, 2019).

2. Already deep and *hypersaline* (*brine*-type), basins.

Such a deep, *hypersaline,* basin model, was inspired by a concept already proposed by Schmalz (1969), but for the Devonian evaporites of Alberta in Canada. Using the Schmalz's hypothesis of a deep hypersaline basin was applied to the Mediterranean Messinian event by Cita (1973) and Hsü et al. (1973a, b, b), who faced a strong skepticism, and even categorical rejection, from many scientists, chiefly based on the absence of any modern analogue (uniformitarianism) as emphasized by Selli (1973).

Clauzon et al. (1996) proposed an alternative two-step version of this last model: during a first period, evaporitic sequences were deposited, particularly in shallow basins (similar to the Sorbas Basin in Spain), as a consequence of a relatively modest sea-level lowering. Later on, in a second stage, a total closure of the communications with the Atlantic water induced a very sudden sea-level drop, which in turn led to both the deposition of massive evaporites in the deepest part of the basins and to extensive erosion of their margins (Fig. 5).

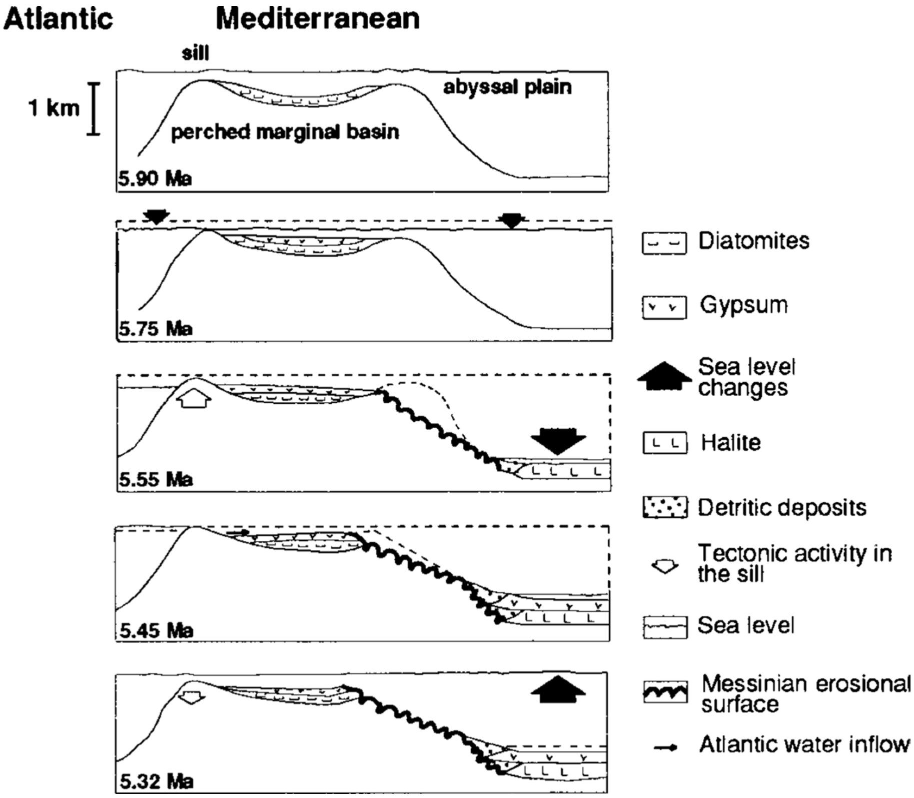
Recent modeling and detailed analysis (Ryan 2008; Christeleit et al. 2015; Simon and Meijer 2017; Meilijson et al. 2017) make it seems quite possible that a large volume of over-salty water existed within one or several deep basins of the Mediterranean Sea and that precipitation of salts could have occurred, supporting thus the Schmalz's model also considered by Roveri et al. (2014a).

Significance of the Gibraltar strait

In fact, the problem of water exchanges between the two oceanic spaces (Mediterranean Sea and World ocean) was not correctly addressed, since it was still not yet clearly understood in the 1990s that the present water balance within the Mediterranean is strongly connected to the existence of the Gibraltar undercurrent.

Today, this deep current flows at an approximate depth of 300 m (Figs. 6 and 7), and exfiltrates, at a speed of 1.5 m/s, the saltier (38‰) and warmer (12.82 °C) Mediterranean water; it allows thus the establishment of a double

Fig. 5 Two-step model for the Messinian episode proposed by Clauzon et al. (1996)



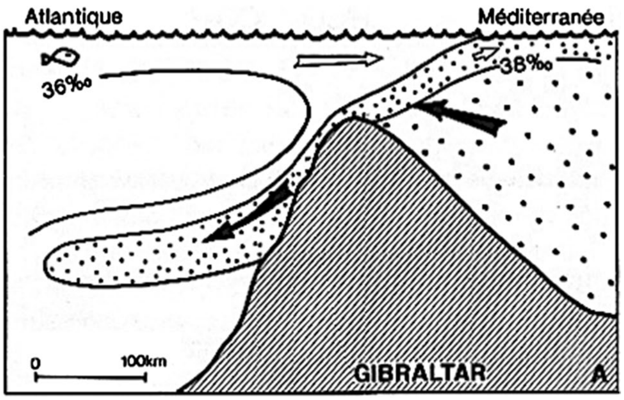


Fig. 6 Gibraltar underflow, (after Biju-Duval 1994)

equilibrium: inflow of Atlantic surface waters to restore the hydrological balance and outflow of more salty Mediterranean water at depth to restore the saline balance. The Gibraltar current, only discovered in 1928 but previously known by several military Navies, who used using it for their submarines, facilitates the continuous evacuation of an important volume of relatively warm and salty water (Mediterranean Outflow Water: MOW, Fig. 7), which becomes interstratified, between 700 and 1100 m depth, in the western Atlantic waters (Sverdrup et al. 1942; Madelain 1970; Knauss 1978; Levitus et al. 1994; Pérez-Asensio et al. 2012). A similar

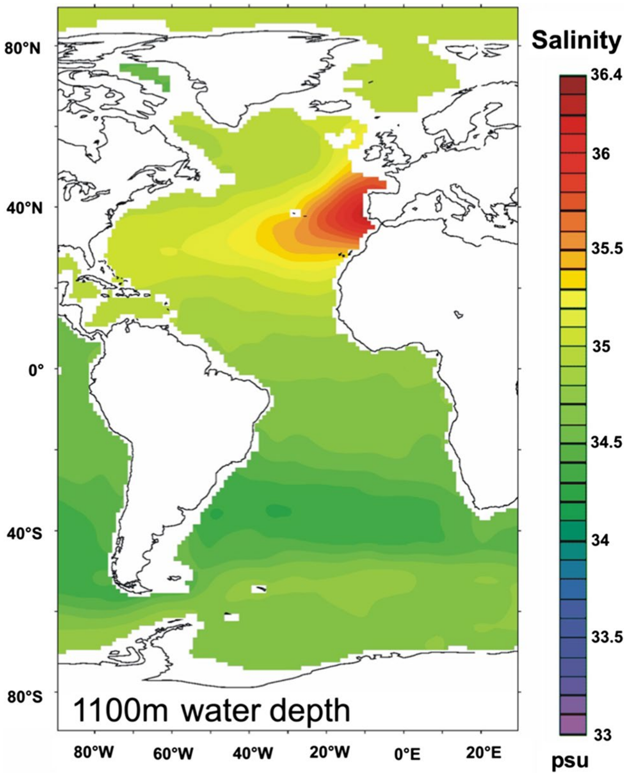


Fig. 7 Characterization of the Mediterranean Outflow Water (in red) in the Atlantic Ocean, (after Levitus et al. 1994)

constant Pliocene-to-Quaternary current activity is well supported by the presence of contourites detected at the base of the Gulf of Cadiz continental slope and studied, since the 1980s (Faugères et al. 1984, 1999; Hernandez-Molina et al. 2014).

It is now well recognized that the interruption of this deep current, prohibiting the export of Mediterranean waters (and of its salt content), has led during the Messinian stage to over-salinity in the Mediterranean basins. Denser salty water accumulates at the bottom of the basins as brines until salt precipitation are reached; such a phenomenon is likely to have played a role in the initiation of the Messinian crisis: interruption of the deep salty Mediterranean waters outflow current, not necessarily involving interruption of Atlantic waters surface current. Despite having been suspected by Selli (1973), the fundamental importance of such a mechanism has only relatively recently been perceived (Krijgsman and Meijer 2008; Meijer 2012; Meijer et al. 2004; Hilgen et al. 2007; Ryan 2008; Roveri et al. 2014a).

An immediate corollary is that the level of the Mediterranean Sea remained practically identical to that of the Atlantic; in others words at this stage, the Mediterranean was not a series of deep and desert-like depressions! The salinity of the waters gradually increased, water stratification initiated, and finally, salt precipitation started within the deepest basins. This geochemical event occurred between 5.96 and 5.5 Ma. Meijer et al. (2004) and Hilgen et al. (2007) place the onset of salt deposition at 5.6 Ma.

This was followed by a real interruption of the Atlantic waters input current. This event occurred only around 5.55 Ma. A direct consequence was a very sudden and considerable sea-level drop, on the order of 1500 m; at that time were probably formed deep desiccated depressions.

This was also the period during which intense erosion of the suddenly emerged continental slopes took place; in particular, numerous submarine canyons at the mouth of rivers were dug or over-deepened during this stage, sometimes extending quite far onshore, such as the Nile canyon detected until Aswan (Chumakov 1973), or the Rhône canyon, which reached the area of Lyon (Clauzon 1982). Large amount of terrigenous material led to the creation of Gilbert deltas near the base of the continental slope, as observed for example offshore of the Provence domain (Bigot-Cormier et al. 2004; Sage et al. 2005). The bottoms of the deep basins were, however, still partially flooded without water concentration thanks to the contribution of peri-Mediterranean rivers fresh waters. This is well attested by strontium isotopes data (Topper et al. 2011; Roveri et al. 2014b) (Fig. 8) indicating values beyond sulfates precipitation. Such conditions, which prevailed between 5.55 and 5.33 Ma, correspond to the initial deposition of the Upper evaporites. It is, however, quite possible that water communications also existed with the Black Sea (domain not submitted to any important sea-level drop) as suggested by the presence of Pontic flora and fauna especially near the top of the series within the so-called "*Lagomare*" formations. However, it should be kept in mind that both wind and running waters could have played a significant role in the dispersion of pollen and, similarly, that dispersion of mollusks and ostracods may have been effective by birds.

Finally, one may consider that both types of models are relevant: between 5.96 and 5.55 Ma, the Lower Unit and the massive salt are sedimented in deep basins (Schmalz's type). Between 5.55 and 5.33 Ma, the Upper Unit is deposited in a *sebkha*-type environment on the bottom of some basins in Sicily, Crete, and Cyprus now at shallow levels. Note

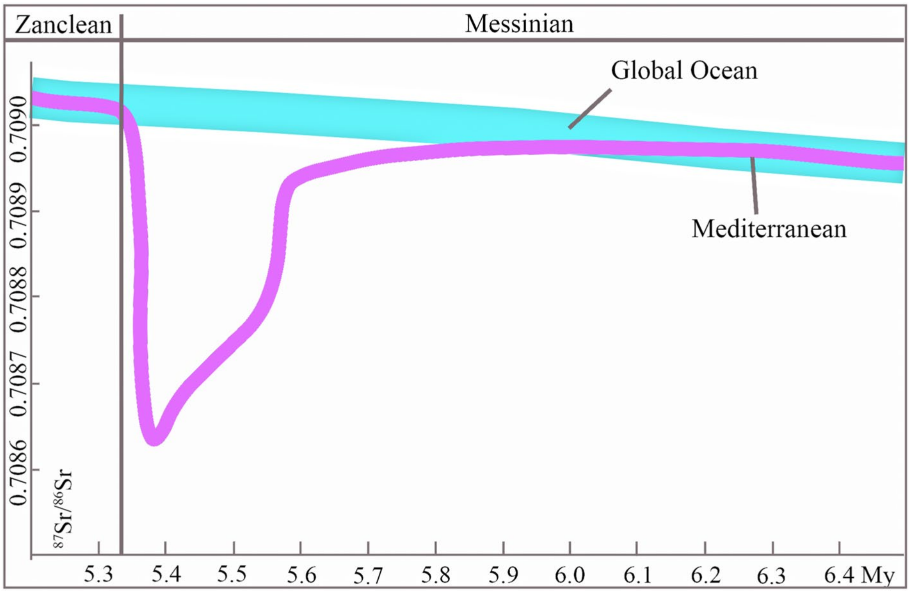


Fig. 8 Strontium isotopic variations during the Messinian (Simplified after Roveri et al. 2014a)

that this sequence of events is somewhat similar to that proposed by Clauzon et al. (1996), although it differs in several respects, for example, the upholding of the Atlantic sea level within the Mediterranean realm during the first stage. Such chronological evolution leads, however, to various consequences. First, the very short duration (about 200 ka) of the drying event precludes stable isostatic equilibrium being reached. As a consequence of water weight disappearing, or at least its important reduction, the Central Mediterranean uplifted, and consequently, the surrounding lands started subsiding, but without reaching a stable equilibrium. In this perspective, all previous attempts to evaluate the real depth of basins and the subsidence of their margins require revision. The elevation reached during the Early Pliocene transgression in stable areas, for example, the Languedoc in southern France (160 m), may reflect the amount of the isostatic variations on land.

A second consequence regards the climatic evolution during Messinian times. There is no real justification for a durable climatic crisis during the whole Messinian. If a strong climatic change occurred in the Mediterranean area, it was a very short one and only during about 200 ky before the Pliocene re-inundation.

Paleogeographic reconstructions and tectonic movements

Another important problem concerning many of the proposed models for the Messinian is that almost all of them were, and until recently, remain based on basin boundaries more or less identical to the present-day ones (for example, see Rouchy and Caruso 2006; Krijgsman et al. 2010 or Lugli et al. 2015 and Roveri et al. 2016, 2019). Indeed, we know that during Messinian times, the paleogeography of the Mediterranean basins was quite different from that of the present days (Fig. 9).

Only the Late Miocene Algeria–Provence Basin shows by that time a paleoconfiguration, almost similar to that of the present day, at least for its deeper part, where evaporites were deposited (Fig. 10). During the Messinian, the Tyrrhenian Basin was almost non-existent, expressed only as a narrow rift zone gradually widening between eastern Sardinia and west of the Selli Central Fault. Indeed, the creation of oceanic crust within the Tyrrhenian Sea started only around 3.5 Ma in the central Vavilov basin and later on, only around 1.8 Ma, in the Marsili basin southeast of the Tyrrhenian Sea (Kastens et al. 1988).

It is clear that during Messinian times, the Eastern Mediterranean Sea was much wider than today and in open connections westward with the Ionian and Adriatic basins; the Mediterranean ridge, running in its middle, did not interrupt deep water circulation between the Levantine Basin and the Ionian Sea, while a seawater connection was open with the Adana Basin in Turkey (Cipollari et al. 2013; Radeff et al. 2016). In fact, by Latest Miocene, the Eastern Mediterranean Sea was about twice as wide than today (Fig. 10) (Mascle 2008). This, relatively wide, oceanic space was bounded by two active subduction zones: a northern one, linking the Adana gulf to the Adriatic Sea, and a western one extending between Tunisia and Tuscany; both subduction zones were bordered by accretionary wedges. In the present-day Caltanissetta basin,

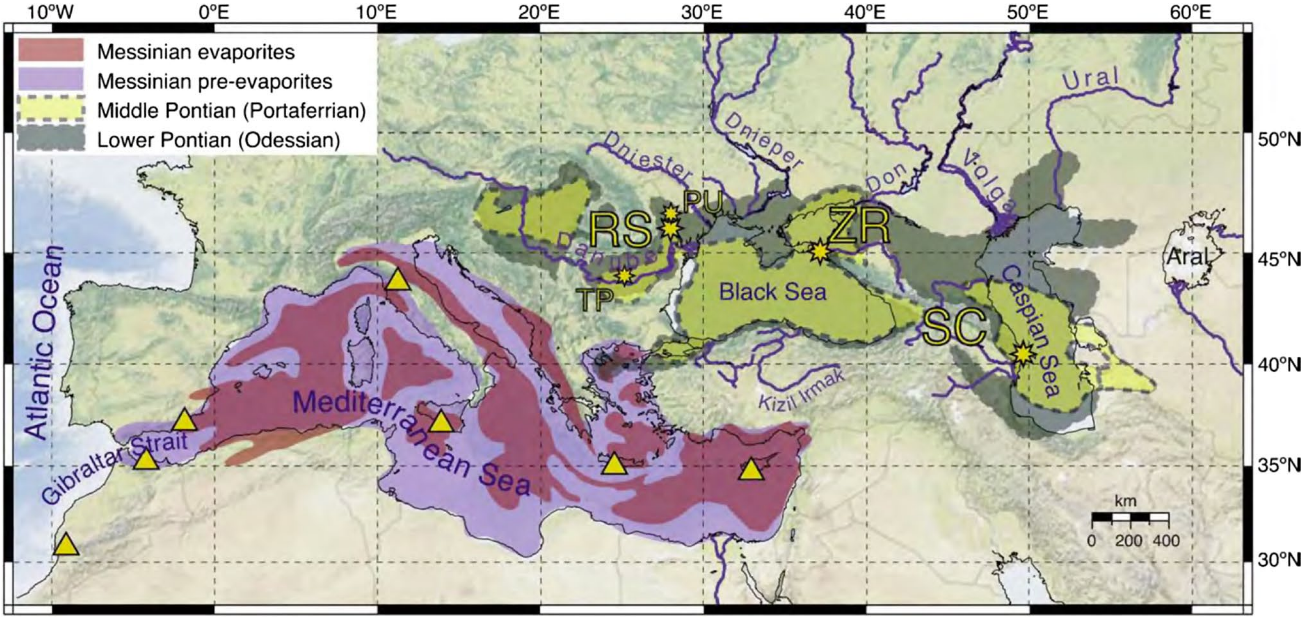


Fig. 9 Messinian paleogeography (after Krijgsman et al. 2010)

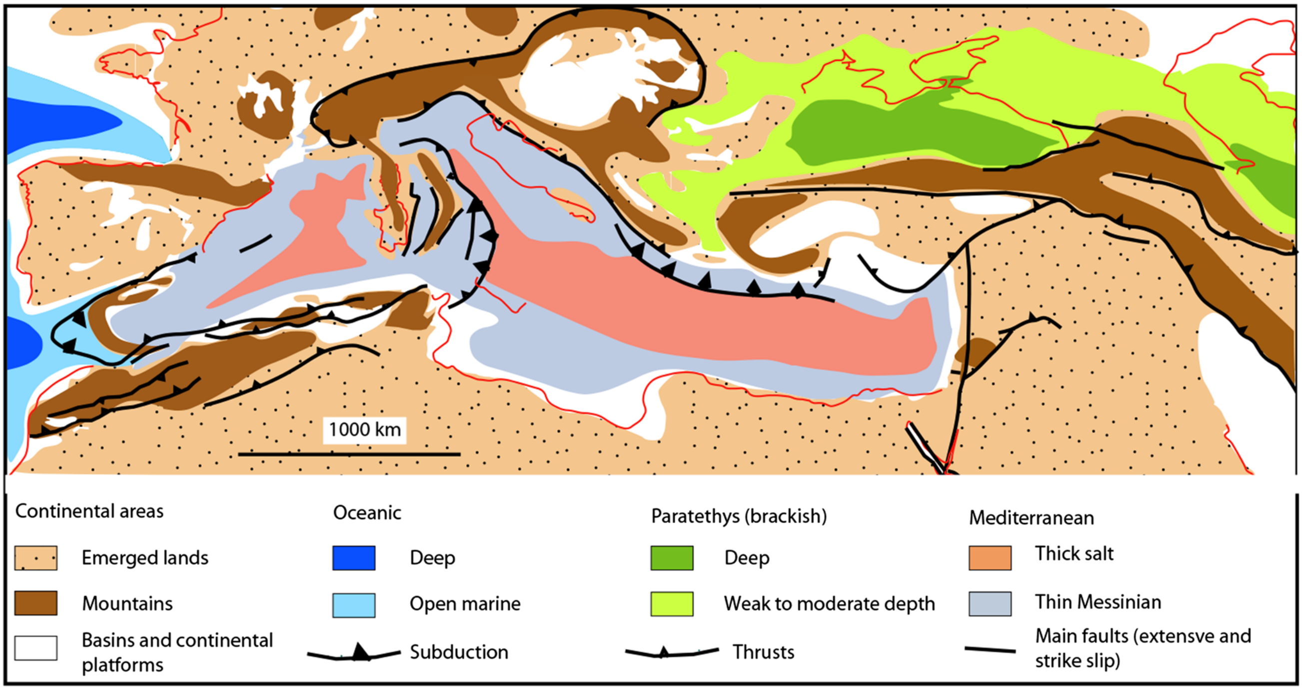


Fig. 10 Mediterranean Sea during Messinian time (modified after Mascle 2008)

in Sicily, numerous tectonic intercalations made of chaotic allochthonous materials are observed within the Messinian sequences (Ogniben 1954) and their occurrence indicates that the area was a portion of an accretion complex that connected northward with the Bradanic Trench in Southern and Central Apennines. Therefore, the salt sequences from the Caltanissetta basin, and similarly from Calabria, may indicate a continuity of the deep Ionian Basin rather than a tectonic setting related to potential perched basins. The Messinian sequences were simply progressively incorporated within the accretionary wedge, either during Messinian times or even later on during the Pliocene. Such mechanisms are clearly occurring today along the southern borders of both the Calabria external arc and the Mediterranean Ridge, respectively, in the Central and Eastern Mediterranean Sea. Evidence for this can easily be observed on the "Geological and Morpho-Tectonic Map of the Mediterranean Domain" published by Mascle and Mascle (2012). Puzzling that such a fundamental paleogeographic constraint (Fig. 10) has remained more or less unaddressed, since it first assessment more than 10 years ago (Mascle 2008). Recently, however, it has finally been taken into account (see Krijgsman et al. 2018).

Looking forward

- Differing tectonic configurations in the past will clearly have impacts on mass balance estimates. It is generally accepted (Warren 2010; Ryan *in* Lofi et al. 2011a, b) that the Messinian event resulted in the sequestration, within the Mediterranean Sea, of almost 5% of the salt of the world ocean. This corresponds to an estimated decrease of the average salinity of the world's ocean seawater on the order of 2 g/l. Considering a saltwater-phase diagram (Fig. 11), such a decrease in salinity implies an increase in the freezing temperature of the salt water on the order of 1 °C. This in turn implies an easier sea ice creation at high latitudes, and so major developments of ice pack in the polar areas, with drastic climatic and eustatic consequences. Accordingly, one may question the relations between the salinity crisis and climatic changes during Late Neogene and Quaternary times. Did the salinity crisis have induced global climatic alterations? Or did climatic alterations (initiating in high latitude glaciations) have caused the

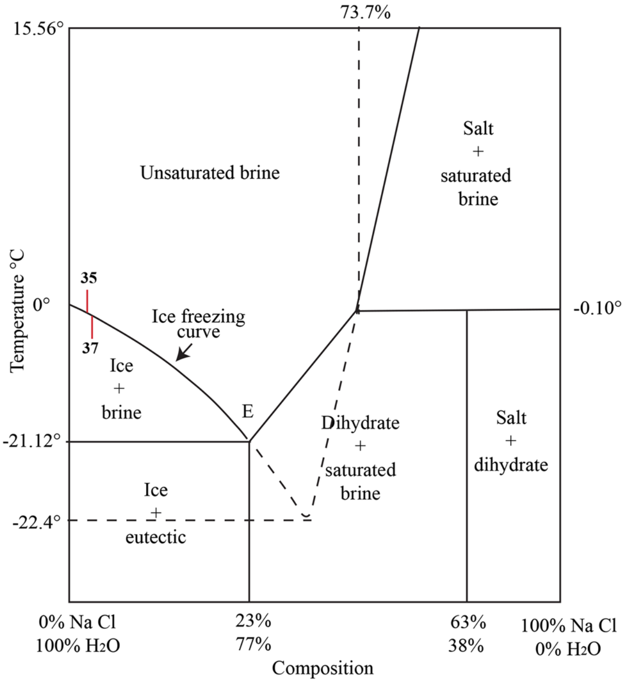


Fig. 11 Phase diagram of the mixture water/NaCl. The two small red lines indicate the variation of freezing temperature of sea ice for a salinity variation of 37–35‰

salinity crisis? Or finally was there a complex interaction between climatic alterations and salinity crisis? More data are needed to definitely answer these questions.

- Concerning the water connection between the Mediterranean Sea and the Atlantic, the model, proposed by Benson et al. (1991), based on a South-Rif entry corridor and a Betic exit corridor, remains valid, provided that it is in a restored Messinian geometry. On the path of the Betic corridor, the Upper Miocene series exhibits contourite features implying a westward current of up to 1.5 m/s (Hernandez-Molina et al. 2014). This corridor must have become ineffective, closed or not deep enough, around 5.96 Ma. It seems difficult to link the cause of this interruption to a simple ice-driven eustatic mechanism. Indeed, during the most recent glaciations, the about 120 m sea-level lowering did not interrupted the Gibraltar undercurrent. Therefore, a tectonic origin of the closure seems more likely. The South-Rif corridor, meanwhile, ceased being active around 5.5 Ma. Its closure may have been driven by differential vertical movements of the crust, which can themselves have resulted from a regional asthenospheric uplift at the origin of a magmatic axis known as "*Morocco Hot Line*" as proposed by Frizon de Lamotte et al. (2008).
- As for the re-flooding of the Mediterranean, occurring at 5.33 Ma, a model proposed by Blanc (2002, 2006) of a regressive erosion able to break the structural barrier at the level of the actual Strait of Gibraltar seems quite coherent, considering evidence that the region at that time was characterized by steep relief and strong erosive capacity. The Nile and Rhône canyons are good examples of very deeply incised valleys that imply extremely important regressive erosion rates occurring at that time. Similarly, a strong erosive capacity of rivers at the level of the Gibraltar strait has been supported by numerical modeling (Loget et al. 2005), as well as by seismic reflection data recorded in the western Alboran Sea (Garcia-Castellanos et al. 2009; Campillo et al. 1992; Martinez del Olmo and Comas 2008; Estrada et al. 2011).

Acknowledgements This paper has benefited from the critical reviews and improvements from Dr. D. Cosentino and an anonymous reviewer. We thank Dr. D. Praeg for both scientific and English wording improvements.

References

Arambourg C (1925) Révision des poissons fossiles de Licata (Sicile). Ann Paléontol 14:37–96

Arambourg C (1927) Les poissons fossiles d'Oran. *Mat Carte géol Algérie*, $1^{\text{ère}}$ série, *Paléontologie,* 6:1–298, atlas

Auzende JM, Bonnin J, Olivet JL, Pautot G (1971) Upper Miocene salt layer in the western Mediterranean. Nature 230:82–84

Benson RH, Bied RE, Bonaduce G (1991) An important current reversal (influx) in the Rifian corridor (Morocco) at the Tortonian-Messinian boundary: end of the Tethys Ocean. Paleoceanography 6:164–192

Bigot-Cormier F, Sage F, Sosson M, Déverchère J, Ferrandini M, Guennoc P, Popoff M, Stéphan JF (2004) Déformations pliocènes de la marge nord–Ligure (France): les conséquences d'un chevauchement crustal sud–alpin. Bull Soc Géol Fr 175:197–211

Blanc PL (2002) The opening of the Plio-Quaternary Gibraltar Strait: assessing the size of a cataclysm. Geodyn Acta 15:303–317

Blanc PL (2006) Improved modelling of the Messinian Salinity Crisis and conceptual implications. Palaeogeogr Palaeoclimatol Palaeoecol 238:349–372

Campillo A, Maldonado A, Mauffret A (1992) Stratigraphic and tectonic evolution of the western Alboran sea: late Miocene to recent. Geo–Mar Lett 12:165–172

Christeleit EC, Brandon MT, Zhuang G (2015) Evidence for deep–water deposition of abyssal Mediterranean evaporites during the Messinian salinity crisis. Earth Planet Sci Lett 427:226–235

Chumakov IS (1973) Pliocene and pleistocene deposits of the Nile valley in Nubia and upper Egypt. In: Ryan WBF, Hsu KJ et al (eds) Initial reports of the deep sea drilling project, 13. US Gov. Printing Office, Washington

CIESM (2008) The Messinian Salinity Crisis from me–ge–deposits to microbiology: a consensus report. In: Briand F (eds) CIESM workshop monographs, vol 33, Monaco, p 168

Cipollari P, Cosentino D, Radeff G, Schildgen TF, Faranda C, Grossi F (2013) Easternmost Mediterranean evidence of the Zanclean flooding event and subsequent surface uplift: Adana Basin, southern Turkey. Geol Soc Lond Spec Publ 372(1):473–494

Cita MB (1973) Mediterranean evaporite: paleotological arguments for a deep–basin desiccation model. In: Drooger CW (ed) Messinian events in the Mediterranean. North Holland Pub., Amsterdam, pp 226–228

Clauzon G, Suc JP, Gautier F, Berger A, Loutre MF (1986) Alternate interpretation of the Messinian salinity crisis: controversy resolved? Geology 24:363–366

Clauzon G (1982) Le canyon messinien du Rhône: une preuve définitive du « dessicated–deep model » (Hsü, Cita et Ryan, 1973). Bull Soc Géol France 24:597–610

Cornet C (1968) Le graben médian (zone A) de la Méditerranée occidentale pourrait être pontien. C R Somm Soc Géol France 5:149

Decima A, Wezel FC (1971) Osservazioni sulle evaporiti messiniane della Sicilia centro– meridionale. Riv Min Sicil 130–132:172–187

Decima D, Wezel FC (1973) Late Miocene evaporites of the central Sicilian Basin, Italy. Initial Rep Deep Sea Drill Proj 13:1234–1241

Estrada F, Ercilla G, Gorini C, Alonso B, Vasquez JT, Garcia-Castellanos D, Juan C, Maldonado A, Ammar A, Elabbassi M (2011) Impact f pulsed Atlantic water inflow into the Alboran basin at the time of Zanclean flooding. GeoMarine Lett 31:361–376

Faugères JC, Gonthier E, Stow DAV (1984) Contourite drift molded by deep Mediterranean outflow. Geology 12:296–300

Faugères JC, Stow DAV, Imbert P, Viana AR (1999) Seismic features diagnostic of contourite drifts. Mar Geol 162:1–38

Frizon de Lamotte D, Zizi M, Missenard Y, Hafid M, El-Azzouzi M, Maury RC, Charrière A, Taki Z, Benammi M, Michard A (2008) The Atlas system. In: Michard A, Saddiqui M, Chalouan A, Frizon de Lamotte D (eds) Continental evolution: the geology of Morrocco. Springer, Berlin, pp 133–202

Garcia-Castellanos D, Estrada F, Jimenez-Munt I, Gorini C, Fernandez M, Verges J, De Vicente R (2009) Catastrophic flood of the Mediterranean after the Messiniansalinity crisis. Nature 462:778–782

Glangeaud L, Alinat J, Polvèche J, Guillaume A, Leenhardt O (1966) Grandes structures de la mer Ligure et leurs relations avec les chaînes continentales. Bull Soc Géol France 7:921–937

Hernandez-Molina FJ, Stow DAK, Alvarez-Zarikian CA, Acton G, Bahr A, Balestra B, Ducassou E, Flood R, Flores JA, Furota S, Grunert P, Hodell D, Jimenez-Espero F, Kim JK, Krissek L, Kuroda J, Li BH, Llave E, Lofi J, Lourens L, Miller M, Nanayama F, Nishida N, Richter C, Roque C, Pereira H, Sanchez-Goni MF, Sierro FJ, Singh AD, Sloss C, Takashimizu Y, Tzanova A, Voelker A, Williams T, Xuan C (2014) Onset of Mediterranean outflow into the North Atlantic. Science 344:1244–1250

Hilgen FJ, Bissoli L, Iaccarino S, Krijgsman W, Meijer R, Negri A, Villa G (2000a) Integrated stratigraphy and astrochronology of the Messinian GSSP at Oued Akrech (Atlantic Morocco). Earth Planet Sci Lett 182:237–251

Hilgen FJ, Iaccarino S, Krijgsman W, Villa G, Langereis CG, Zachariasse WJ (2000b) The global boundary stratotype section and point (GSSP) of the Messinian stage (uppermost Miocene). Episodes 23:172–177

Hilgen FJ, Kuiper KF, Krijgsman W, Snel E, van der Laan E (2007) High-resolution integrated stratigraphy and astronomical tuning as prerequisites for deciphering the intricate history of the Messinian Salinity Crisis. Stratigraphy 4:231–238

Hsü KJ, Cita MB, Ryan WBF (1973a) The origin of the Mediterranean evaporites. In: Ryan WBF, Hsü KJ, Cita MB (eds) Initial reports of the deep sea drilling project 13, Part 2. U.S. Gov. Print. Office, Washington, pp 1203–1231

Hsü KJ, Ryan WBF, Cita MB (1973b) Late Miocene desiccation of the Mediterranean. Nature 242:240–244

Kastens K, Mascle J, Auroux C, Bonnati E, Broglia C, Channell J, Curzi P, Emeis KC, Glacon G, Hasegawa S, Hieke W, Mascle G, Mc Coy F, Mc Kenzie J, Mmendelson J, Muller C, Rehault JP, Robertson A, Sartori R, Sprovieri R, Torii M (1988) ODP leg 107 in the tyrrhenian sea: insights into passive margin and back-arc basin evolution. Geol Soc America Bull 100:1140–1156

Knauss JA (1978) Introduction to physical oceanography. Prentice-Hall, NJ, p 338

Krijgsman W (2001) Astrochronology for the Messinian Sorbas basin (SE Spain) and orbital (precessional) forcing for evaporite cyclicity. Sediment Geol 140(1–2):43–60

Krijgsman W, Meijer PT (2008) Depositional environments of the Mediterranean “Lower Evaporites” of the Messinian salinity crisis: constraints from quantitative analyses. Mar Geol 253:73–81

Krijgsman W, Hilgen FJ, Raffi I, Sierro FJ, Wilson DS (1999) Chronology, causes and progression of the Messinian salinity crisis. Nature 400:652–655

Krijgsman W, Gaboardi S, Hilgen FJ, Iaccarino S, de Kaenel E, van der Laan E (2004) Revised astrochronology for the Ain el Beida section (Atlantic Morocco): no glacio–eustatic control for the onset of the Messinian Salinity Crisis. Stratigraphy 1:87–101

Krijgsman W, Stoica M, Vasiliev I, Popov VV (2010) Rise and fall of the paratethys Sea during the Messinian Salinity Crisis. Earth Planet Sci Lett 290:183–191

Krijgsman W, Capella W, Simon D, Hilgen FJ, Kouwenhoven TJ, Meijer PTh, Sierro FJ, Tulbure MA, van den Berg BCJ, van der Schee M, Flecker R (2018) The gibraltar corridor: watergate of the messinian salinity crisis. Mar Geol 403:238–246

Levitus S, Burgett R, Boyer TP (1994) World Ocean Atlas 1994, Vol 3: salinity. In: NOAA Atlas NESDIS 3. U.S. Department of Commerce, Washington, DC

Lofi J, Gorini C, Berné S, Clauzon G, Dos Reis AT, Ryan WB, Steckler MS (2005) Erosional processes and paleo–environmental changes in the western Gulf of Lions (SW France) during the Messinian salinity crisis. Mar Geol 217:1–30

Lofi J, Deverchère J, Gaullier V, Gillet H, Gorini C, Guennoc P, Loncke L, Maillard A, Sage F, Thinon I (2011) Seismic atlas of the “Messinian Salinity Crisis” markers in the mediterranean and black seas, vol I. Commission for the Geological Map of the World, Paris, France. Mém. Soc. Géol. France, n.s., 179, 1 CD

Lofi J, Sage F, Deverchère J, Loncke L, Maillard A, Gaullier V, Thinon I, Gillet H, Guennoc P, Gorini C (2011b) Refining our knowledge of the Messinian salinity crisis records in the offshore domain through multi–site seismic analysis. Bull Soc Géol France 182:163–180

Lofi J, Camerlenghi A, Del Ben A, Do Couto D, Estrada F, Gallais F, Garcia M, Gaullier V, Maillard A, Micallef A, Rossi M, Sage F, Schattner U, Tass A, Urgeles R (2019) Seismic atlas of the “Messinian Salinity Crisis” markers in the mediterranean and black seas, vol II. Commission for the Geological Map of the World, Paris, France. Mém. Soc. Géol. France, n.s., 179, 1 CD

Loget N, Van den Driessche J, Davy P (2005) How did the Messinian salinity crisis end? Terra Nova 17:414–419

Lugli S, Manzi V, Roveri M, Schreiber CB (2015) The deep record of the Messinian salinity crisis: evidence of a non dessicated Mediterraneab Sea. Pal Pal Pal 433:201–218

Madelain F (1970) Influence de la topographie du fond sur l’écoulement méditerranéen entre le Détroit de Gibraltar et le Cap Saint-Vincent. Cah Oceanogr 22:43–61

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

Martinez del Olmo W, Comas MC (2008) Arquitectura sismica, olistostromas y fallas extensionales en el Norte de la cuenca oeste del Mar de Alboran. Rev Soc Geol Espana 21:151–167

Mascle G (2008) Les roches: mémoire du temps. Grenoble Sciences Ed, p 288

Mascle J, Mascle G (2012) Geological and morpho-tectonic map of the mediterranean domain. Publication CCGM/CGMW, Paris

Meijer PT (2012) Hydraulic theory of sea straits applied to the onset of the Messinian salinity crisis. Mar Geol 326–328:131–139

Meijer PTh, Slingerland R, Wortel MJR (2004) Tectonic control on past circulation of the Mediterranean Sea: a model study of the Late Miocene. Paleooceanography. https://doi.org/10.1029/2003PA000956

Meilijson A, Steinberg J, Hilgen F, Bialik OM, Waldmann ND, Makovsky Y (2017) Deep-basin evidence resolves a 50-year-old debate and demonstrates synchronous onset of Messinian evaporite deposition in a non-desiccated Mediterranean. Geology 46:243–246

Montadert L, Sancho J, Fial JP, Debyser J (1970) De l'âge tertiaire de la série salifère responsable des structures diapiriques en Méditerranée Occidentale (Nord–est des Baléares). CRAS 271:812–815

Mostardini F, Pieri M, Pirini C (1966) Stratigrafia del foglio 212, Montalbano Jonico. Boll Serv Geol Italia 87:541–547

Nesteroff W D (1973) The sedimentary history of the Mediterranean area during the Neogene. In: Ryan WBF, Hsu KJ et al (eds) Initial report of DSDP, vol 13, pp 1257–1261

Ogniben L (1954) Le « Argille brecciate » siciliane. Con i rilievi di dettaglio di Grottacalda (Valguarnera, Enna), Pasarello (Licata, Agrigento), Zubbi (San Cataldo, Caltanissetta). Mem Ist Geol Min Univ Padova 18:1–92

Ogniben L (1957) Petrografia della serie solfifera siciliana e considerazioni geologiche relative. Mem Descr Carta Geol Italia 33:1–275

Pérez-Asensio JN, Aguirre J, Schmiedl G, Civis J (2012) Impact of restriction of the Atlantic-Mediterranean gateway on the Mediterranean Outflow Water and eastern Atlantic circulation during the Messinian. Paleoceanography 27:PA3222

Radeff G, Cosentino D, Cipollari P, Schildgen TF, Iadanza A, Strecker M (2016) Stratigraphic architecture of the upper Messinian deposits of the Adana Basin (southern Turkey): implications for the Messinian salinity crisis and the Taurus petroleum system. Italian J Geosci 135(3):408–424

Regione Siciliana (1962–1964) Studi ed indagini per ricerche solfifere. Riv Min Siciliana, 76–78, 79–81, 85–87

Ricci Lucchi F (1973) Resedimented evaporites: indicators of slope instability and deep–basin conditions in Periadriatic Messinian (Apennines Foredeep, Italy). In: Drooger CW (ed) Messinian events in the Mediterranean. North–Holland Pub. Cie, Amsterdam, pp 142–149

Rouchy JM, Caruso A (2006) The Messinian salinity crisis in the Mediterranean basin: a reassessment of the data and an integrated scenario. Sed Geol 188–189:35–67

Roveri M, Manzi V, Gennari R, Iaccarino SM, Lugli S (2008) Recent advancements in the Messinian stratigraphy of Italy and their Mediterranean-scale implications. Boll Soc Pal Ital 47:71–85

Roveri M, Flecker R, Krijgsman W, Lofi J, Lugli S, Manzi V, Sierro FJ, Bertini A, Camerlenghi A, De Lange G, Govers R, Hilgen FJ, Hübscher C, Meijer PT, Stoica M (2014a) The Messinian salinity crisis: past and future great challenge for marine sciences. Mar Geol 352:25–58

Roveri M, Manzi V, Bergamasco A, Falcieri F, Gennari R, Lugli S (2014b) Dense shelf water cascading and Messinian canyons: a new scenario for the Mediterranean salinity crisis. Am J Sci 314:751–784

Roveri M, Gennari R, Ligi M, Lugli S, Manzi V, Minelli N, Reghizi M, Riva A, Rossi M, Schreiber C (2016) The Messinian salinity crisis: open problems and possible implications for Mediterranean petroleum systems. Petroleum Geosci 22:283–290

Roveri M, Gennari R, Lugli S, Manzi V, Reghizi M (2019) The synthetic seismic expression of the Messinian Salinity Crisis: implications for shallow—to deep-water correlations. Basin Res 32:1–32

Ryan WBF (2008) Modeling the magnitude and timing of evaporative drawdown during the Messinian salinity crisis. Stratigraphy 5:227–243

Ryan WBF, Hsu KJ, Cita MB, Dumitrica P, Lort JM, Maync W, Nesteroff WD, Pautot G, Stradner H, Wezel FC (1973) Initial reports of the deep sea drilling project, vol 13. US Government Printing Office, Washington

Sage F, Von Gronefeld G, Deverchère J, Gaullier V, Maillard A, Gorini C (2005) Seismic evidence for Messinian detrital deposits at the Western Sardinia margin, northwestern Mediterranean. Mar Petrol Geol 22:757–773

Schmalz RF (1969) Deep–water evaporite deposition: a genetic model. Bull Am Assoc Pet Geol 53:798–823

Selli R (1960) Il Messiniano Mayer Eymar 1867, proposta di un neostratotipo. Giorn Geol 2(28):1–33

Selli R (1973) An outline of the Italian Messinian. In: Drogger CW (ed) Messinian events in the Mediterranean. North–Holland Pub. Cie, Amsterdam, pp 124–141

Simon D, Meijer PT (2017) Salinity stratification of the Mediterranean Sea during the Messinian crisis: a first model analysis. Earth Plan Sci Lett 479:366–376

Sverdrup HU, Johnson MW, Fleming RH (1942) The oceans, their physics, chemistry, and general biology. Prentice-Hall, New York, p 1087

Topper RPM, Flecker R, Meijer PT, Wortel MJR (2011) A box model of the Late Miocene Mediterranean Sea: implications from combined 87Sr/86Sr and salinity data. Paleoceanography 26:PA3223

Van Couvering JA, Castradori D, Cita MB, Hilgen FJ, Rio D (2000) The base of the Zanclean stage and of the Pliocene series. Episodes 23:179–186

Warren JK (2010) Evaporites through time: tectonic, climatic and eustatic controls in marine and nonmarine deposits. Earth Sci Rev 98:217–268