

The two-step scenario of the Messinian Crisis (Clauzon *et al.*, 1996): a specification supported by new data

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Abstract – Many papers refer in a revised way to the two-step scenario of the Messinian Crisis conceived by Clauzon *et al.* (1996). The present paper recalls the basis for the two-step scenario and discrepancies with the later modified version, completed by new data supported by extensive micropaleontological analyses. Our interpretation of the Sicilian Eraclea Minoa section as belonging to a peripheral basin is the centre of the debate. We show the great amplitude of fluvial erosion during the peak of the crisis, which for the Rhône River, exceeded 400 km upstream of the present shoreline. Based on dinoflagellate cysts, we also recall the reasons for supporting the occurrence of three successive Lago Mare episodes of two different origins. The first and third episodes constitute phases of high sea-level exchanges between the Mediterranean and the Paratethys respectively just before the onset of paroxysm and after it. The second episode is due to overflowing Paratethyan waters from the Aegean Basin just before the end of paroxysm. Similarly, the demonstration of the marine reflooding of the Mediterranean Basin prior to the Zanclean is repeated. We emphasize dissimilarity between basins, focussing in particular on those, isolated or perched ones, which were continuously filled by waters during the desiccation phase: western part of the Alboran Sea and southeastern part of the Levantine Basin (marine waters), Apennine Foredeep (fresh waters), and Aegean Basin (brackish waters). The Apennine Foredeep cannot be the reference for the entire Mediterranean with respect to its evolution during the crisis. During the crisis, water exchanges between the Aegean Basin and the Eastern Paratethys (Dacic Basin, Black Sea) were impossible through the Marmara region because of the development of two opposed fluvial networks. Such exchanges existed thanks to a gateway that was probably located within the Balkans. Investigations around the Levantine Basin point to areas submitted to fluvial erosion during the crisis paroxysm and nearby areas, which might have received marine waters from the Red Sea. Much information is still to be discovered and that more progress is still needed in order to fully decipher this outstanding event.

Keywords: Two-steps of the Messinian Crisis / diachronous peripheral-central evaporites / wide sea-level drop / subaerial erosion / multiple Lago Mare episodes / disparity of isolated basins

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Résumé – Le scénario en deux temps de la Crise messinienne (Clauzon *et al.*, 1996): une précision appuyée par de nouvelles données. De nombreux articles se réfèrent opportunément mais sous une forme révisée au scénario en deux temps de la Crise messinienne de Clauzon *et al.* (1996). Cet article rappelle les fondements de ce scénario et les dissemblances avec les autres versions, le tout appuyé par de nouvelles données riches en analyses micropaléontologiques. Notre interprétation de la coupe d'Eraclea Minoa (Sicile) comme relevant d'un bassin périphérique est au centre du débat. Nous montrons l'ampleur de l'érosion fluviale pendant le paroxysme de la crise qui, pour le Rhône, s'est propagée jusqu'à 400 km en amont de l'actuel littoral. Nous rappelons les arguments en faveur de l'existence de trois épisodes Lago Mare distincts chronologiquement et de nature différente mis en évidence par les kystes de dinoflagellés. Les premier et troisième épisodes résultent des phases d'échanges réciproques à haut niveau marin entre Méditerranée et Paratéthys peu avant le déclenchement du paroxysme et après celui-ci. Le second épisode est dû au déversement des eaux paratéthysiennes issues du bassin égéen peu avant la fin du paroxysme. De même, la démonstration du réennoiment du bassin méditerranéen antérieurement au Zancéen est réitérée. L'accent est mis sur la disparité entre bassins, notamment ceux qui sont restés isolés ou perchés et alimentés en eau pendant la phase de dessiccation: partie occidentale de la Mer d'Alboran et partie sud-est du bassin levantin (eau marine), avant-fosse apenninique (eau douce), et bassin égéen (eau saumâtre). Il est évident que le processus qu'a connu l'avant-fosse apenninique ne peut plus servir de modèle pour l'ensemble du bassin méditerranéen. Les échanges entre bassin égéen et Paratéthys orientale (bassin dacique, Mer Noire) ne pouvaient s'effectuer par la région de Marmara, siège pendant la crise de deux réseaux fluviaux de sens opposé, mais par un corridor probablement intra-balkanique. Les résultats sur le pourtour du bassin levantin laissent entrevoir des secteurs soumis à l'érosion fluviale lors du paroxysme de la crise à côté de secteurs ayant pu bénéficier d'entrées d'eaux marines de la Mer Rouge. Il reste encore beaucoup à découvrir et à comprendre pour démystifier complètement cet événement hors normes.

Mots-clés : Deux stades de la Crise messinienne / évaporites périphériques-centrales diachrones / érosion subaérienne / épisodes Lago Mare multiples / disparité des bassins isolés

1 Introduction

The Messinian Crisis (MC) was a huge and brief event in the latest Miocene, which impacted the entire Mediterranean Basin and its paleo-appendices such as the Eastern Paratethys (Black Sea and Dacic Basin), the Aegean Basin and the Apennine Foredeep, caused by severe restriction of connection between the Mediterranean Sea and the Atlantic Ocean (Fig. 1; Hsü *et al.*, 1973; Hsü and Giovanoli, 1979-1980; Clauzon *et al.*, 2005; Jolivet *et al.*, 2006; Ryan, 2023; Krijgsman *et al.*, 2024; Roveri *et al.*, 2025). The main characteristics of this outstanding event were the deposition of a salt giant and intense erosion from the margins to the deep basins. Immediate and postponed consequences of this event affected the regional paleogeography, the sedimentary filling of basins, and biogeography at a large scale. Aiming to close more than forty years of debate about the diverse scenarios of the MC, the CIESM meeting held in Almería in 2007 validated the recognition of the Clauzon *et al.* (1996) two-step scenario and the paper that resulted from the discussions presented agreement on main points and discussed various controversial items (CIESM, 2008). Then, Roveri *et al.* (2014a) published a scenario presented as being inspired by Clauzon *et al.*'s (1996) scenario. However, this new scenario shows many critical divergences with the Clauzon *et al.*'s scenario.

Being challenged by the extensive reference made to the Roveri *et al.*'s (2014a) scenario, often presented as the scenario agreed in general (e.g.: Roveri *et al.*, 2019, 2025; Andreotto *et al.*, 2021; van Dijk *et al.*, 2023; Krijgsman *et al.*, 2024), we aim at clarifying how much the two-step scenario (Clauzon *et al.*, 1996), successively further developed by Bache *et al.* (2012, 2015), Popescu *et al.* (2015, 2021) and Suc *et al.* (2023),

differs from the Roveri *et al.*'s (2014a) scenario. As detailed below (Fig. 2), the two scenarios (Roveri vs. Clauzon) mainly differ (1) in the environmental context (marginal to deep vs. marginal) of the Sicilian Basin and the resulting estimated chronology of its Messinian units, (2) in the nature (subaerial to submarine vs. only subaerial) erosion caused by the sea-level drop and its resulting estimated chronology, and (3) in the chronology of the Lago Mare (only one event vs. three distinct episodes) and the significance of this biofacies (Paratethys overflow during the sea-level lowstand vs. two Mediterranean-Paratethys crossed exchanges during highstands of sea level with an intercalated Paratethys overflow during the sea-level lowstand).

In addition, here we report on new data, discuss how the data are consistent with the two-step scenario, and illustrate the great differences between responses of the various types of basins to the MC (Fig. 1).

2 The scenarios

2.1 The Clauzon *et al.* (1996) scenario

The two-step scenario (Clauzon *et al.*, 1996; Bache *et al.*, 2012, 2015; Popescu *et al.*, 2015, 2021; Suc *et al.*, 2023) clearly differentiates in space and time the peripheral (shallow to relatively deep) basins from the central (deep) basins (Fig. 2). The central basins benefit from a refined terminology of the seismic units (Lofi *et al.*, 2011). The Sicilian Caltanissetta Basin, although relatively deep in its southern part, was assigned to the peripheral basins (Fig. 2) as supported by chronological data (Gautier *et al.*, 1994), paleoenvironmental considerations (Grasso and Pedley, 1988), geomorphological-sedimentological observations (Butler *et al.*, 1995;

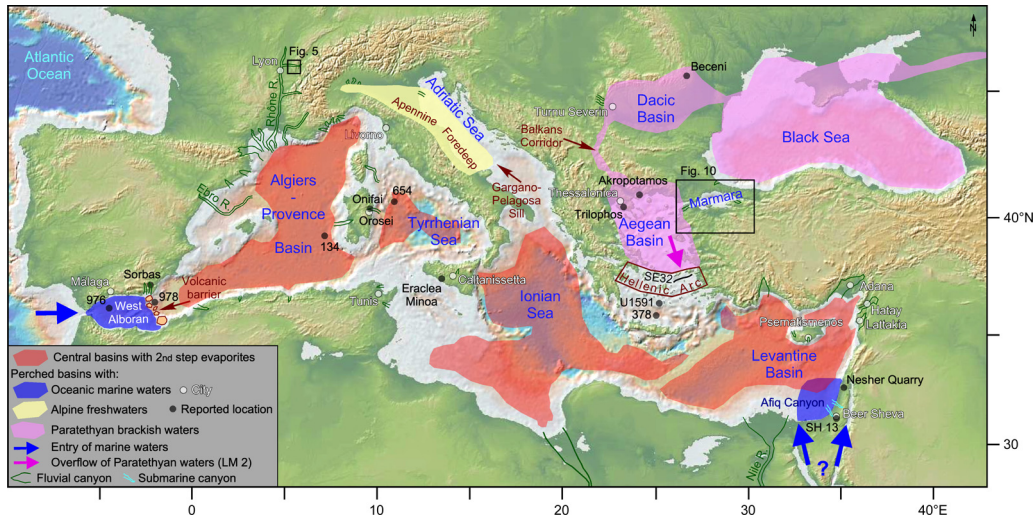


Fig. 1. Map of the Mediterranean Basin s.l. with a sketch of the paleogeographic context during the second (paroxysmal) step of the Messinian Crisis, with a focus on the evaporites in the central basins (Haq *et al.*, 2020), the isolated (perched) basins (West Alboran: Booth-Rea *et al.*, 2018; Apennine Foredeep: Pellen *et al.*, 2017, 2021; Eastern Paratethys including the Aegean Basin: Popescu *et al.*, 2015; Suc *et al.*, 2015a), the fluvial canyons (Bache *et al.*, 2012; Pellen *et al.*, 2019; addition references in the Supplementary material), and the submarine canyons in the Southeastern Levantine Basin (Buchbinder and Zilberman, 1997; Moneron and Gvirtzman, 2022). The map is elaborated using GeoMapApp (Ryan *et al.*, 2009).

Fig. 1. Carte de la Méditerranée s.l. dans le contexte paléogéographique du second stade (paroxysmal) de la Crise messinienne.

Bache *et al.*, 2012), seismic stratigraphy and regional correlations (Haq *et al.*, 2020; El Euch-El Koundi *et al.*, 2009; Popescu *et al.*, 2021), and palinspastic reconstructions (Pellen *et al.*, 2021). Chronology of this scenario has progressively been updated thanks to successive new data (Fig. 2; Bache *et al.*, 2012; Do Couto *et al.*, 2014; Clauzon *et al.*, 2015a; Popescu *et al.*, 2015, 2021; Suc *et al.*, 2023). In addition to the thoroughness in separating peripheral from central basins, the specific attributes of the scenario are:

- the critical place of the Messinian erosion in a strict subaerial sense (e.g.: Rubino *et al.*, 2010; Clauzon *et al.*, 2015a-b; Do Couto *et al.*, 2014, 2015, 2024; Osman *et al.*, 2021; Dromart *et al.*, 2024);
- the notable involvement of biostratigraphy (e.g.: Melinte-Dobrinescu *et al.*, 2009; Popescu *et al.*, 2017);
- the consideration of three Lago Mare (LM) distinct episodes, clearly marked by the Paratethyan dinoflagellate cysts (e.g.: Clauzon *et al.*, 2005; Popescu *et al.*, 2009, 2015; Do Couto *et al.*, 2014; Atik *et al.*, 2024);
- the age of the marine reflooding of the Mediterranean Basin which significantly predated the Zanclean Stage (Bache *et al.*, 2012; Popescu *et al.*, 2021).

2.2 The Roveri *et al.* (2014a) scenario

This scenario arises from the consideration of the Sicilian Caltanissetta Basin within both reference basin types, the marginal (= our peripheral) basins and the deep (= our central) basins (Fig. 2). This concept is based on (1) the interpretation of the Sicilian Eraclea Minoa section (Roveri *et al.*, 2008a) as a continuous marginal Messinian-Zanclean succession that is discussed hereafter, and (2) the fact to consider the Apennine Foredeep representative of the whole Mediterranean

(Roveri *et al.*, 2001). As consequences of these assumptions, the Sicilian Upper Evaporites has become the equivalent to the Upper Unit (UU: Lofi *et al.*, 2011) of the central basins, the Salt Member of Sicily has been correlated with the Mobile Unit of the central basins, and only one Lago Mare event has been considered, which is identified by dreissenids and limnocyprids, and usually by ostracods (Roveri *et al.*, 2019). The meaning of the Messinian Erosional Surface (MES) in the Roveri *et al.*'s (2014a) scenario is a serious concern because (1) it is indicated in both marginal basins and deep basins, where it is overlain by the evaporites, and (2) the presence of erosion at the same time at different depths implies a bivalent or even unclear nature, being subaerial in marginal areas and submarine in deeper areas (Roveri *et al.*, 2014b-c, 2019).

2.3 Elements of agreement and disagreement between the two scenarios

To summarize, agreement between the two scenarios exists on two points (Fig. 2):

- the age of the onset of the MC in the early paleomagnetic Chron C3r (Gautier *et al.*, 1994; Krijgsman *et al.*, 1999), now exactly placed at 5.97 Ma (Manzi *et al.*, 2013);
- the development of subaerial erosion from inner lands (e.g.: Clauzon, 1982; Gargani, 2004; Gargani *et al.*, 2010; Clauzon *et al.*, 2015b; Dromart *et al.*, 2024) to peripheral basins (e.g.: Clauzon *et al.*, 2015a; Suc *et al.*, 2015a; Pellen *et al.*, 2017; Roveri *et al.*, 2019).

The major subjects of disagreement are the estimated amplitude of the Mediterranean Sea-level fall at the peak of the MC and the duration of the peak (Fig. 2):

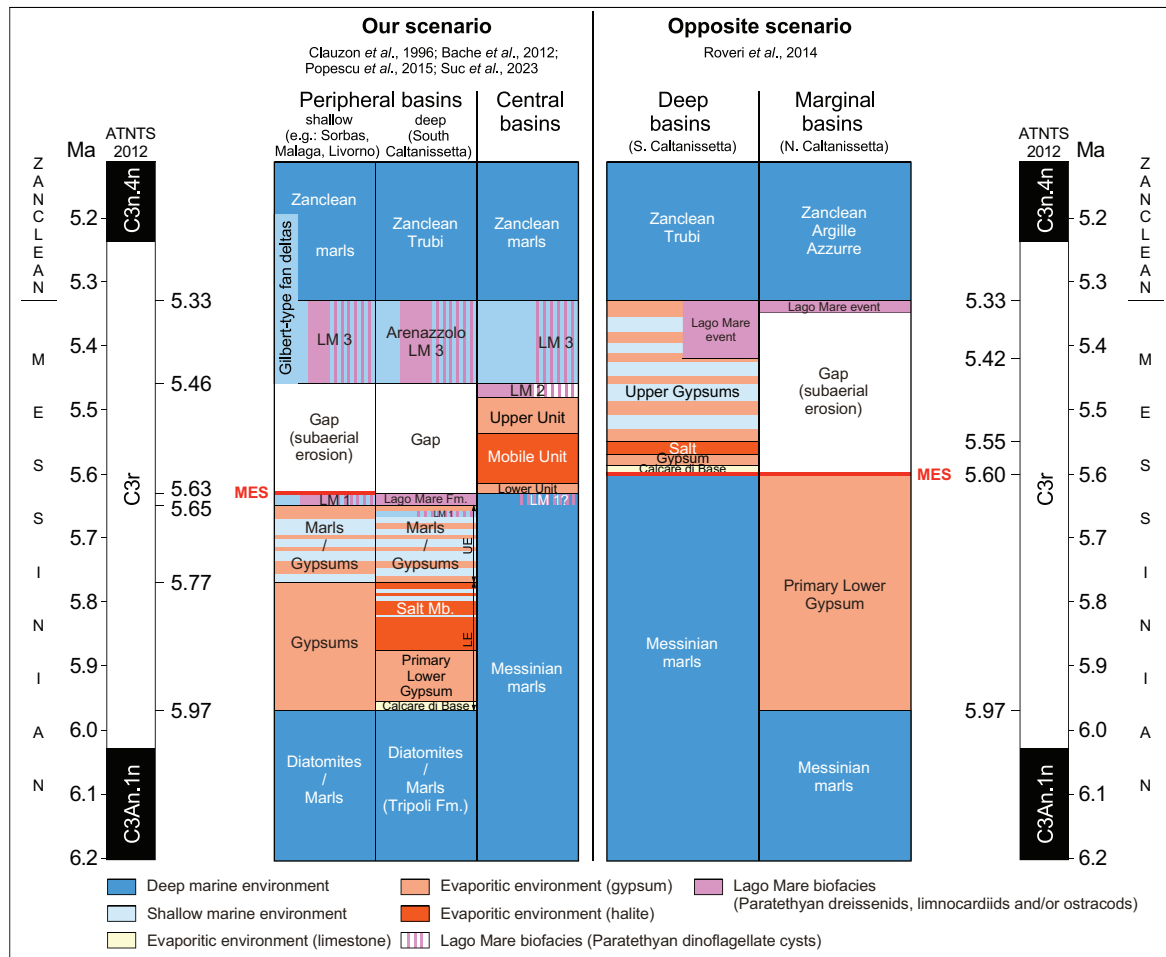


Fig. 2. Compared scenarios with their own chronology. MES: Messinian Erosional Surface. LM 1, LM 2, LM 3: successive Lago Mare episodes. LE: Sicilian Lower Evaporites. UE: Sicilian Upper Evaporites. The central basin units refer to Lofi *et al.* (2011).

Fig. 2. Comparaison entre les scénarios avec leur propre chronologie.

- moderate sea-level drawdown, about 500 m, for Roveri *et al.* (2014a), versus huge sea-level drop, about 1,500 m, for Clauzon *et al.* (1996) leading to an almost completely desiccated basin;
- duration of ca. 270 kyrs for the peak of the MC for the Roveri *et al.* (2014) scenario, versus ca. 170 kyrs for the Clauzon *et al.* (1996) scenario.

The divergence is also great about only one Lago Mare event claimed by Roveri *et al.* (2014) versus three Lago Mare episodes corresponding to two different contexts proposed by Clauzon *et al.* (2005). In addition to the above points of disagreements, the Gilbert-type fan deltas, developed in many peri-Mediterranean Messinian fluvial valleys, which illustrate the suddenness and amplitude of the marine reflooding (Bache *et al.*, 2012; Clauzon *et al.*, 2015a-b; Suc *et al.*, 2015a) have not been considered in the Roveri *et al.* (2014a) scenario.

3 Material and methods

Our work first results from field stratigraphic investigations with a chief task: the recognition of the MES, most often beneath Zanclean deposits. Such contacts are usually neglected

or unidentified, often interpreted as faults even if they show a meander morphology (e.g.: Clauzon *et al.*, 2015b). Two examples are shown in Figure 3 (Onifai, near Orosei, East Sardinia: Giresse *et al.*, 2015; Suc *et al.*, 2019; Maillard *et al.*, 2020; Trilophos near Thessalonica, North Greece: Suc *et al.*, 2015a; Fig. 1) where the MES is similarly overlain by foreset beds of a nested Gilbert-type fan delta, the bottomset beds of which are dated from 5.35 to 5.28 Ma based on our record in both locations of the calcareous nannofossils *Ceratolithus acutus* and *Orthorabdus* (ex. *Triquetrorhabdulus*) *rugosus* (see the bio-chronostratigraphy of calcareous nannoplankton in Fig. S2).

Our second important task is (1) to date deposits using planktonic foraminifera and/or calcareous nannofossils, and (2) to reconstruct paleoenvironments using dinoflagellate cysts. Several new results are presented in this paper, which used the classical methods for preparing samples (see Supplementary material). Biostratigraphic events of planktonic foraminifera are based on Lirer *et al.* (2019), and those of calcareous nannofossils refer to Martini (1971), Perch-Nielsen (1985), Young (1998), and Raffi *et al.* (2006) (Fig. S2). Dinoflagellate cyst taxa are grouped according to their surface-water tolerance, nutritional strategy, and geographical provenance based on Warny and Wrenn (2002), Londeix *et al.* (2007), and Popescu *et al.* (2009) with modifications.

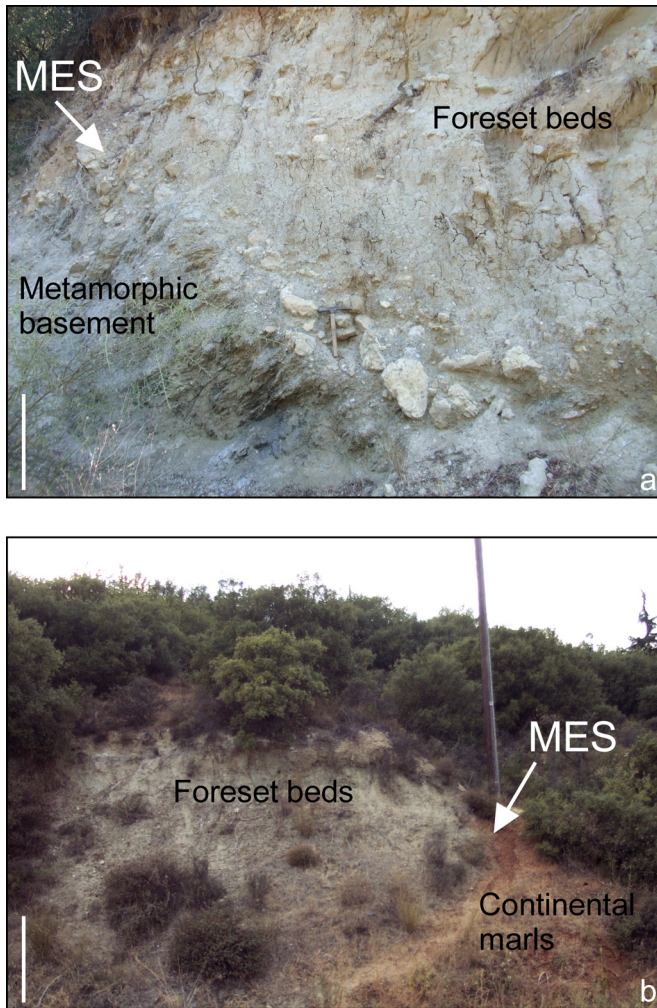


Fig. 3. Exposed Messinian Erosional Surface and nested Zanclean deposits. a, Onifai (Orosei), East Sardinia. b, Trilophos (Thessalonica), North Greece. Vertical scale bar = 1 m. Photographs by J.-P. Suc.

Fig. 3. Exemples de la Surface d'érosion messinienne à l'affleurement et de dépôts zancléens emboîtés

The observation of Gilbert-type fan deltas similarly overlying the MES is a strong argument for a sudden, large-scale marine flooding, and some authors have questioned the identification of *Ceratolithus acutus*, claiming to have been confused for destructed fragments of ascidian spicules (Golovina *et al.*, 2019; Krijgsman *et al.*, 2020b). Nevertheless, only very few specimens of spicules fragments illustrated by Golovina *et al.* (2019: see Fig. 8 in that paper) might resemble *C. acutus*. Strangely, *Ceratolithus acutus*-shaped ascidian spicules would have proliferated exactly when *C. acutus* appeared! The probability is very low that all the fragmented spicules of ascidians may have an indisputable shape of *C. acutus* and the confusion is easy to avoid when mastered by specialists, particularly with the plethora of *C. acutus* records in the Mediterranean (Popescu *et al.*, 2017 and references herein).

4 Major matters of debate

Four major points concentrate the debate between the two scenarios. They concern (1) the Sicilian Eraclea Minoa section whose the chronostratigraphic interpretation significantly differs, (2) the nature of erosion, subaerial and/or submarine, (3) the Lago Mare as a single episode or multiple episodes in different paleoenvironmental contexts, and (4) the age of the marine reflooding at 5.46 Ma or 5.33 Ma.

4.1 Continuity vs. discontinuity at the Messinian-Zanclean contact in Sicily

Eraclea Minoa is a key-section from southern Sicily (Fig. 1) showing a well-exposed succession of the Sicilian Upper Evaporites overlain by the Lago Mare Formation, the Arenazzolo Unit, and the Zanclean Trubi (Fig. 4a, b, d). The Zanclean GSSP (Global Boundary Stratotype Section and Point) at 5.33 Ma is placed at the base of the latter formation that is supposed to be in a continuous chronological succession with the underlying Messinian deposits (Fig. 4c; Van Couvering *et al.*, 2000). There, the Sicilian Upper Evaporites overlie the Lower Evaporitic Unit (rich in halite), the contact between the two successions being assigned to a fault and to an erosional surface (Roveri *et al.*, 2009). This discontinuity is assigned to the MES because it separates the Primary Lower Gypsum from overlying reworked gypsarenites (Roveri *et al.*, 2008). The latter unit is greatly deformed hence its chaotic aspect (Fig. 4c), which makes it very difficult to appreciate if the inferred erosional surface is relevant. Its ascription to the MES only depends on the correlation with the Apennine Foredeep succession (Roveri *et al.*, 2008b). We disagree with the inclusion of the chaotic Primary Gypsum, dislocated by a submarine collapse, to the MES. This interpretation results in placing the Sicilian halite in the second step of the MC (Manzi *et al.*, 2021a). The northern part of the Caltanissetta Basin exhibits at thick deltaic construction following a fluvial erosion by the Salso River (Butler *et al.*, 1995; Maniscalco *et al.*, 2019). These deltaic conglomerates are rich in pebbles of reworked gypsum that has been assigned to the Sicilian Lower Evaporites (Butler *et al.*, 1995; Maniscalco *et al.*, 2019). However, these reworked gypsum pebbles could otherwise be assigned to the Sicilian Upper Evaporites, which are abundantly exposed in the area (Tzevahirtzian *et al.*, 2023).

On the other side of the present Sicily-Tunisia Strait, offshore Tunisia, provided evidence of two peripheral evaporitic sequences of similar composition and thickness to the Sicilian Messinian series (El Euch-El Koundi *et al.*, 2009). This Tunisian succession is cut by a deep fluvial canyon filled by Zanclean clays (El Euch-El Koundi *et al.*, 2009). Our investigations along the Eraclea Minoa section established a gap in sedimentation and some erosion at the top of the Lago Mare Formation, showing moreover the transgressive status of the overlying Arenazzolo Unit (Fig. 3f; Bache *et al.*, 2012). This discontinuity is considered to illustrate the marine reflooding of the Mediterranean that is, in addition, supported by dinoflagellate cyst records (Popescu *et al.*, 2009, 2021; Bache *et al.*, 2012). Collectively these data are supportive of the peripheral status that we propose for the Sicilian



Fig. 4. The controversial Eraclea Minoa section. a, Google Earth 3D overview of the area with location of the photographs. b, Upper part of the Messinian succession overlain by Zanclean Trubi (location of photographs is indicated by rectangles). c, Chaotic Lower Gypsum. d, Detailed stratigraphic succession from the last gypsum to Trubi. e, Zanclean GSSP. f, Section showing the transgressive ravinement surface. LM 1, LM 3: Lago Mare episodes. Photographs: b, c, d, e by T. Rigaudier; f by J.-P. Suc.

Fig. 4. La coupe d'Eraclea Minoa sujette à controverse.

Caltanissetta Basin (Fig. 2), the Messinian-Zanclean history of which might have been symmetric to that of Northern Tunisia (El Euch-El Koundi *et al.*, 2009; Popescu *et al.*, 2021). This interpretation is consistent with the subaerial erosion evidenced along the Malta Escarpment (Micallef *et al.*, 2019).

4.2 Nature of the Messinian erosion

Roveri *et al.* (2014c) have questioned the Zanclean age and the marine character of the sedimentary infill of the Nile canyon south of the Aswan Dam (Egypt), *i.e.* more than 1,000 km upstream of the modern seashore, which, contrarily to Chumakov (1967, 1973), has been considered to have not been cut during the peak of the MC. This discredit of the Nile canyon being transformed into a funnel-shaped marine ria, has induced as a corollary some uncertainty about the Rhône

canyon cutting and its sedimentary fill, which were not really well-constrained at that time (Clauzon, 1982). Finally, Roveri *et al.* (2014c) have concluded that the Messinian erosion cannot be exclusively attributable to subaerial process instead of submarine cascading (Roveri *et al.*, 2014c).

Recently, intensive researches concerned the Rhône Valley (Dromart *et al.*, 2024; Do Couto *et al.*, 2024). In addition, we obtained new data upstream Lyon, in the area of Ambérieu-en-Bugey, at more than 400 km from the shoreline along the modern Rhône course (Fig. 5a). The hereafter detailed results validate the marine context of the early Zanclean sediments and demonstrate the long-distance invasion by the Zanclean Sea. There, thick marly-sandy sediments were deposited at the outlet of the Cluse des Hôpitaux (Fig. 5b-c), a 49 km long valley today occupied by two small opposite rivers, the Albarine R. (western part) and the Furans R. (eastern part),

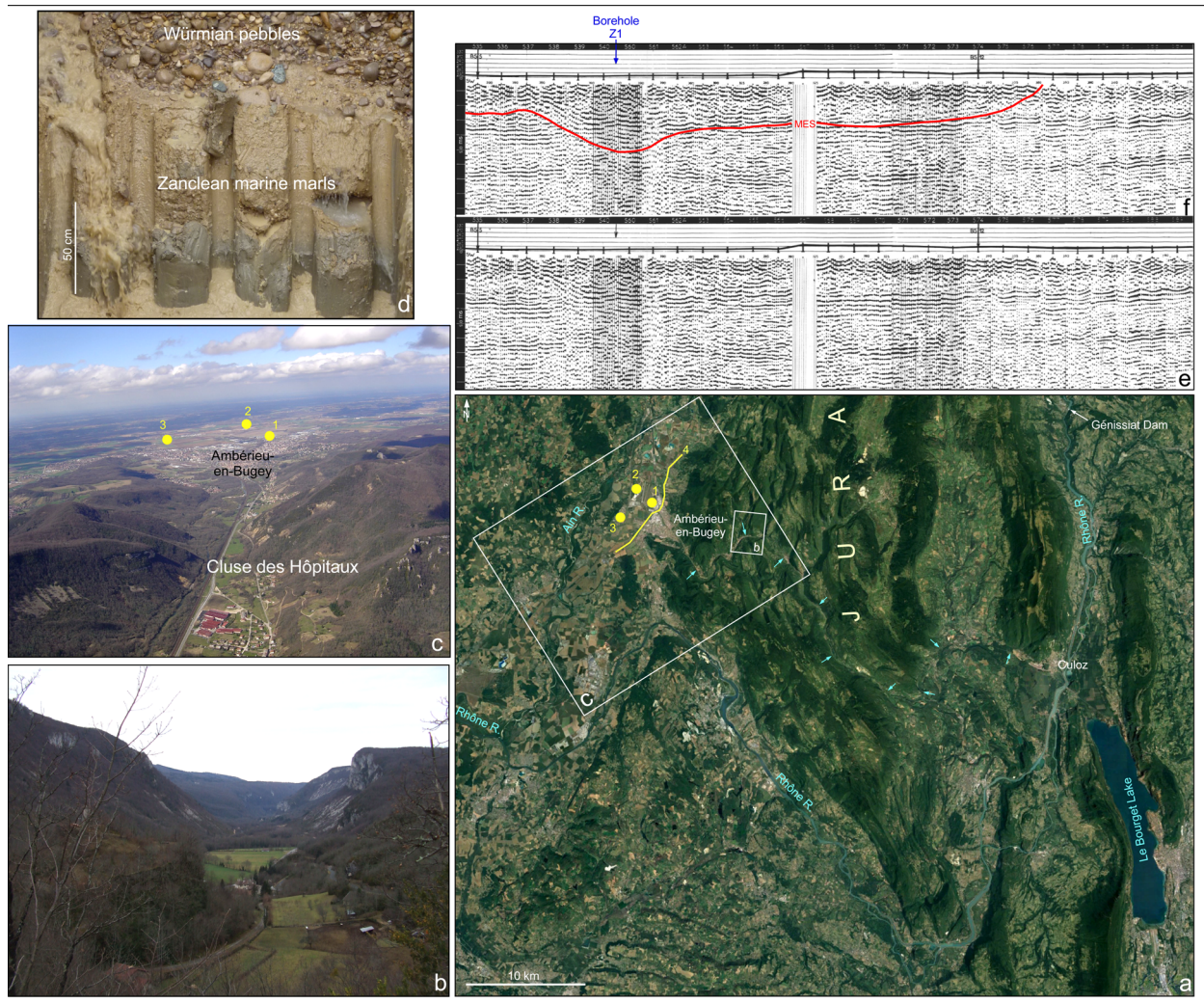


Fig. 5. New data from the Rhône Messinian Erosional Surface far in the hinterland. a, Google Earth view in the southern Jura Mountains area (see Fig. 1). The Messinian paleovalley is tagged by blue arrows. 1, Borehole Z1 in the Air Base 278; 2, Château-Gaillard Quarry; 3, Cormoz 1 borehole; 4, Location of the seismic profile 14 from the 16-0184 survey. b, Transverse view of the Cluse des Hôpitaux. The Messinian erosion should correspond to the uppermost 30-40 metres of the uplifted Jurassic cliffs. c, Aerial view of the outlet of the Cluse des Hôpitaux. Legend: see Fig. a. d, Section of the Château-Gaillard Quarry. e, Uninterpreted seismic profile 14. f, Interpreted seismic profile 14. Red line: Messinian Erosional Surface (MES). Photographs: b by J.-P. Suc; c by B. Chirol; d by P. Sorrel.

Fig. 5. Données nouvelles sur la Surface d'érosion messinienne du Rhône loin à l'intérieur des terres.

unscaled with the cutting of such a wide valley (Fig. 5a-c). Near Ambérieu-en-Bugey, three main locations informed on the Zanclean age of the marine sediments (Fig. 5a, 5c):

- the well Cormoz 1 (45° 57' 48" N, 5° 18' 00" E, z=235 m. asl), document 06757X0043/CMZ-1 from the infoterre website;
- the borehole Z1 in the Air Base 278 (45° 58' 33" N, 5° 20' 30" E, z=254 m asl), document 06758X0004/MB1/Z1 from the infoterre website;
- the Château-Gaillard Quarry (45° 59' 7.42" N, 5° 19' 7.38" E).

Marine dinoflagellate cysts including *Impagidinium patulum* were found in marls from the Château-Gaillard Quarry. Well Cormoz 1 also yielded marine dinoflagellate cysts between 90 m and 35 m depth, including two Paratethyan specimens (one assigned to *Spiniferites cruciformis*). At 35 m

depth, this well provided a calcareous nannoplankton assemblage including, among other taxa, *Helicosphaera sellii*, *Reticulofenestra minutula* (3.92-1.93 Ma) and *Amaurolithus delicatus* (7.42-3.9 Ma). The marine context of these deposits is thus unquestionable. According to the occurrence of Paratethyan taxa (LM 3: Fig. 2), the sediment at 90 m depth in the Cormoz 1 well dates from the marine reflooding of the Mediterranean that is estimated at 5.1 Ma in the Lyon area (Dromart *et al.*, 2024). The sample at 35 m depth from the same borehole is dated ca. 3.9 Ma (Young, 1998). We must add that the Château-Gaillard and Cormoz 1 samples contain a typical pollen flora from the Zanclean in Southeastern France. Méon-Vilain (1970) indicated marine conditions from 20 m to 138.50 m depth in the borehole Z1 from the Air Base 278. This well is located along the seismic profile 14 of the 16-0184 campaign (Fig. 5a), which reveals a well-marked erosional

surface interpreted as the MES, exactly in the deepest part of the Zanclean sediments (Fig. 5e-f). Westward, the banks of the Ain River (Fig. 5a) are rich in exposed deposits that we also ascribe to the early Zanclean because they contain marine dinoflagellate cysts consistently with the record of a shark tooth (Combémourel *et al.*, 1970). These results demonstrate the validity of the interpretation of Clauzon (1999) who described the Cluse des Hôpitaux as the Messinian valley of the Rhône River, constituting an unquestionable argument supporting a powerful fluvial erosion in agreement with the desiccated deep-basin model of the MC (Hsü *et al.*, 1973). We consider that this valley was first cut during the MC peak, then uplifted during the Pliocene-Pleistocene orogenic phase (Dromart *et al.*, 2024) and finally shaped by the Pleistocene glaciers (Buoncrisiani and Campy, 2011). The intense karstification within the Cluse des Hôpitaux (Chirol, 2005) and upstream in the area of the Génissiat Dam (the famous “Pertes du Rhône”: Le Strat, 2005; Chirol, 2022) is another feature probably linked to the Messinian erosion (Fig. 5a).

These new data and the revisited previous studies fully validate the long-distance fluvial erosion caused by the MC peak and the following marine incursion more than 400 km within the hinterland.

4.3 Significance of Lago Mare: one or several events

Two contrasted concepts have been developed about the Lago Mare, the definition of which is based on the intrusion within the Mediterranean Basin of brackish species from the Paratethys (Fig. 1; Ruggieri, 1962; Cita and Colombo, 1979). Based on the occurrence of benthic faunas (mollusks, ostracods), only one Lago Mare event has been described as an unidirectional overflow of Paratethyan waters into the desiccated or not Mediterranean Basin (Cita *et al.*, 1978; Krijgsman *et al.*, 2010; Andreetto *et al.*, 2021). The discovery of Paratethyan dinoflagellate cysts within Messinian to Zanclean deposits (Corradini and Biffi, 1988; Bertini *et al.*, 1995) contributed to change our view by differentiating deep water Lago Mare biofacies (marked by dinoflagellates, living in surface waters) from shallow water Lago Mare biofacies (marked by mollusks and/or ostracods) (Popescu *et al.*, 2009, 2015; Do Couto *et al.*, 2014). Accordingly, we considered that Paratethyan dinoflagellate cysts are the actual markers of invading Paratethyan waters. Critical observations were revealed: (1) the marine context of most of the Lago Mare deposits (co-occurrence of marine dinoflagellate cysts and calcareous nannofossils: Popescu *et al.*, 2009, 2015; Do Couto *et al.*, 2014; co-occurrence of marine fishes: Carnevale *et al.*, 2006, 2008, 2018, 2019); (2) evidence of Lago Mare biofacies with dinoflagellate cysts below and above the MES or its discontinuity equivalent (see for details: Popescu *et al.*, 2009, 2015; Do Couto *et al.*, 2014).

The arrival into the Eastern Paratethys of marine calcareous nannofossils and/or planktonic foraminifers and/or dinoflagellate cysts coming from the Mediterranean Basin before and after the peak of the MC were convincing proofs of crossed water exchanges during episodes of high sea-level (LM 1 and LM 3: Fig. 2; Clauzon *et al.*, 2005; Suc *et al.*, 2011; Atik *et al.*, 2024). These water exchange events have recently been endorsed by Marzocchi *et al.* (2016), Stoica *et al.* (2016),

and Krijgsman *et al.* (2020a), closing previous contrasted conclusions (Krijgsman *et al.*, 2020a, 2024; Andreetto *et al.*, 2021).

With the Paratethyan waters pooled in the Aegean Basin flowing over the Hellenic Arc (see Section 5.3), the LM 2 episode was tracked in boreholes from the central basins (Popescu *et al.*, 2015). New results from ODP (Ocean Drilling Program) Hole 654A (Tyrrhenian Sea; Fig. 1) are provided hereafter. Figure 6 shows the key species of planktonic foraminifera and calcareous nannofossils used for the biostratigraphic subdivision of this cored succession. These new data allow to specify the boundary between Messinian and Zanclean sediments (Fig. 6) almost at the same place where it has been previously identified by Müller (1990) and Cita *et al.* (1990). The new information on this hole, revealed by dinoflagellate cysts, is the record of two separated Lago Mare episodes, in the latest Messinian and earliest Zanclean, respectively (Fig. 6). These episodes occurred in a marine environment: the first one is obviously the LM 2 event (*i.e.*, intercalated between gypsum of the UU) while the second one is the LM 3 (Fig. 6). Figure 7 gathers some sites published by Popescu *et al.* (2015) and Hole 654A and shows several discontinuous Lago Mare episodes recorded in central basins of the Western Mediterranean Sea: LM 1 or LM 3 were potentially recorded at Hole 976B (West Alboran Basin), LM 2 at Hole 978A (East Alboran Basin), LM 2 and LM 3 at holes 134B (West Sardinia) and 654A (Tyrrhenian Basin). At Hole 976B, the LM 2 episode is believed to have been unable by the volcanic barrier that separated the Eastern from the Western Alboran basins (Booth-Rea *et al.*, 2018), where holes 978A and 976B were respectively drilled (Fig. 1).

4.4 End of the Messinian Crisis

The debate about the understanding of the Arenazzolo Unit as a marginal marine deposit was started by Brolsma (1975, 1976). Then, a marine transgressive interval has been evidenced below the Trubi Formation in Calabria by Cavazza and DeCelles (1998). Micropaleontological studies both in Sicily and Calabria led us to the conclusion that the post-crisis marine reflooding occurred significantly before the beginning of the Zanclean Stage (Londeix *et al.*, 2007; Popescu *et al.*, 2009, 2021; Bache *et al.*, 2012). Using cyclostratigraphy, the age of 5.46 Ma was proposed by Bache *et al.* (2012) (Fig. 2). This conclusion has been revived by van Dijk *et al.* (2023), then typified by the Krijgsman's (2024) reconstructed global sea-level curve with significant high values between 5.45 and 5.40 Ma in agreement with the conclusions of Suc *et al.* (2023). However, if placing the latest evaporites from the Mediterranean central basins (UU) before 5.46 Ma (Fig. 7; Popescu *et al.*, 2015), it is clear that the global sea-level rise contributed to end the MC. The Zanclean GSSP cannot be considered as marking the end of the MC.

5 Divergences in paleogeography

In addition to the chronology of the successive events that occurred during the MC, another critical aspect is our knowledge of paleogeography, which is the focus of the following regional reconstructions.

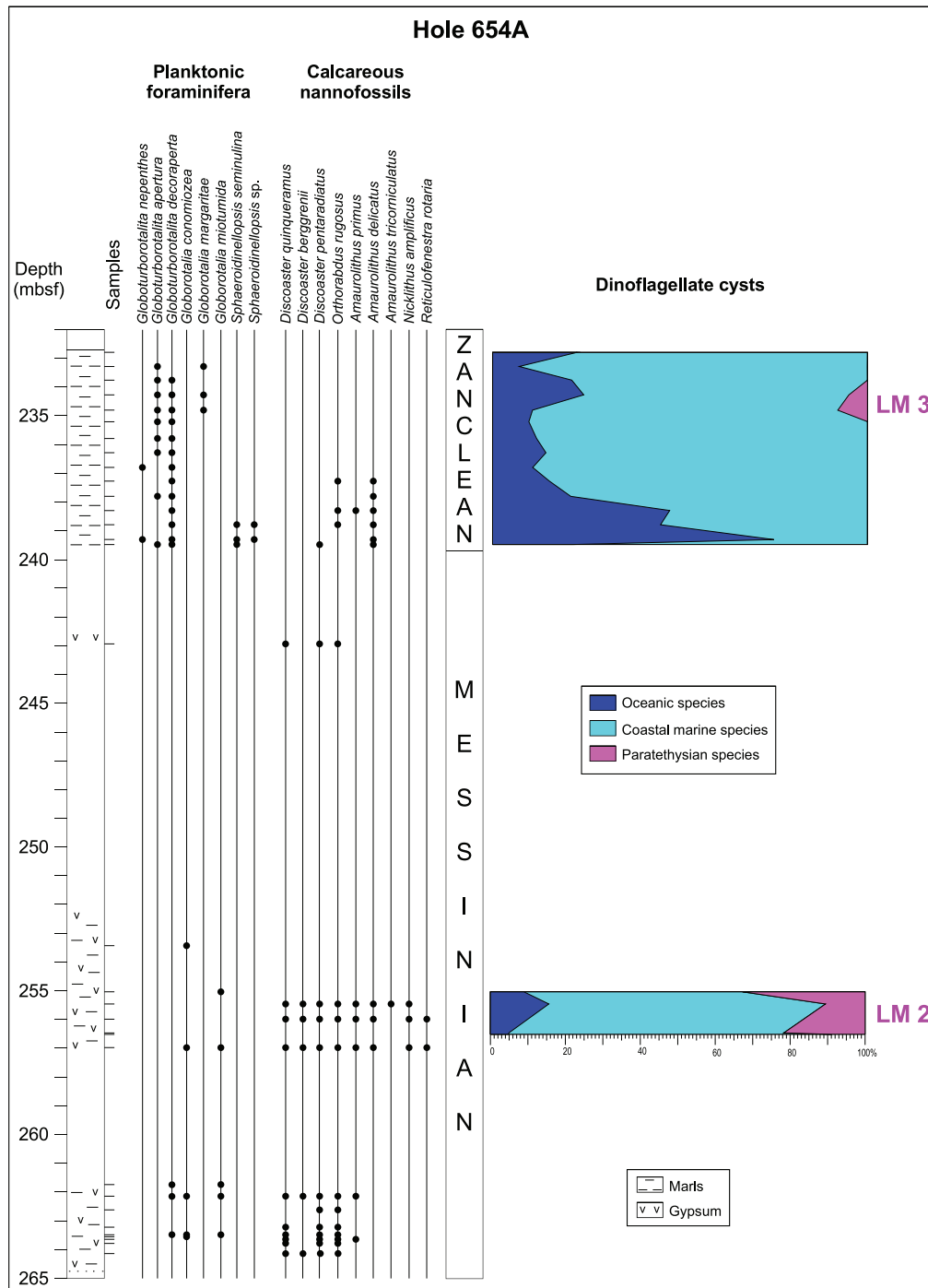


Fig. 6. New results on biostratigraphy (planktonic foraminifera and calcareous nannofossils) and environment (dinoflagellate cysts) of the latest Messinian and earliest Zanclean deposits of ODP Hole 654A. Evidence of two distinct Lago Mare episodes.

Fig. 6. Nouveaux résultats sur la biostratigraphie et l'environnement messiniens à zancléens du forage 654A, épisodes Lago Mare successifs.

5.1 Alboran Sea

Booth-Rea *et al.* (2018) proposed the uplift of a volcanic arc in the Eastern Alboran Sea, giving rise to an archipelago that helped to almost completely isolate the Western Alboran Basin from the rest of the Mediterranean (Fig. 1). Such a barrier is an explanation for the survival of Mediterranean

marine benthic fauna during the desiccation phase (Néraudeau *et al.*, 1999, 2001; Néraudeau, 2007). In addition, this paleogeographical context may have provided a passageway for land mammals (Agustí *et al.*, 2006; Gibert *et al.*, 2013), illustrating once again the extent to which land bridges provide opportunities for mammal migrations (Aslanian *et al.*, 2023).

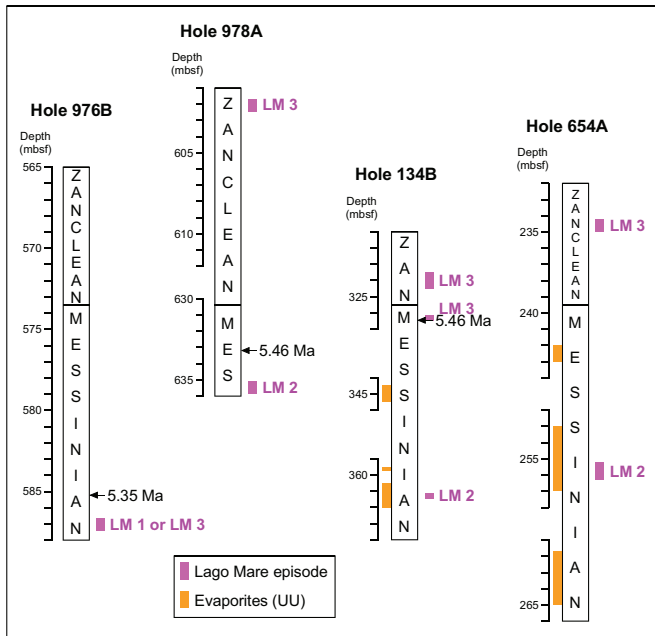


Fig. 7. Compared chronostratigraphy of four holes from the Western Mediterranean with respect to the Messinian and Zanclean boundary (5.33 Ma) and location of the Lago Mare episodes revealed by dinoflagellate cysts (LM 1 to LM 3), from Popescu *et al.* (2015) modified. The location of the Zanclean–Messinian boundary in Hole 976B takes into account the new data from Bulian *et al.* (2021). The Upper Evaporites (UU) topping the second step of the Messinian Crisis are indicated. ZAN = Zanclean; MES = Messinian. 5.35 Ma: first record of *Ceratolithus acutus*. 5.46 Ma: estimated location of the marine reflooding.

Fig. 7. Comparaison entre quatre forages de Méditerranée occidentale où les épisodes Lago Mare sont situés par rapport à la limite Messinien–Zancléen.

Indeed, the western part of the Alboran Basin was probably affected by the sea-level drop that occurred at the beginning of the second step of the MC with a weakly marked MES on both sides of its shorelines (Suc *et al.*, 2023), as it was relatively isolated by the volcanic arc in relation to the isostatic readjustment due to almost complete evaporation in the Mediterranean (Sternai *et al.*, 2017; Booth-Rea *et al.*, 2018). Although not entirely conclusive, the modelling carried out by Heida *et al.* (2024) suggested the occurrence of several volcanic islands, reducing the entry of Atlantic waters into the almost completely dried-up Mediterranean Basin. Anyway, a sudden and briefly emersion of volcanic island(s) cannot be discarded (*e.g.*, the present-day process in the Comores Archipelago: Masquelet *et al.*, 2022; Gargani, 2024). Contrarily to Zanclean samples, the Messinian samples at Hole 978A (Fig. 1) were rich in pollen grains among which bisaccate pollen grains (*Pinus* mostly), advantaged in air and water transport (Beaudouin *et al.*, 2007), were not the most abundant (Popescu *et al.*, 2015). This unusual weakness of pine pollen in a marine environment can be due to proximity of islands.

5.2 Apennine Foredeep

Thanks to an extensive stratigraphic and micropaleontological work, it has been shown by Pellen *et al.* (2017, 2022) that the Apennine Foredeep cannot henceforth be regarded as representative of the entire Mediterranean Basin contrarily to the Roveri *et al.*'s (2001) assumption. This shallow to deep basin experienced the first step of the MC with the deposition of evaporites, during its connection with the Mediterranean. It became isolated at the beginning of the second step of the MC (with an obvious MES of subaerial nature), and evolved as a perched basin, separated by the uplifted Gargano–Pelgosa Sill from the almost completely desiccated Mediterranean. However, the basin was filled by fresh waters from the Po River and the other Alpine rivers at that time (Fig. 1). The Apennine Foredeep then received several surface marine inflows over the sill from 5.36 Ma up to its complete renewal as a marine basin at 5.33 Ma. During the interval 5.36–5.33 Ma, the basin was a very propitious area for the development of Paratethyan species, repeatedly supplied by marine incursions (for details, see: Popescu *et al.*, 2007; Pellen *et al.*, 2017, 2022). Our scenario for the Apennine Foredeep has been validated by the modelled reconstruction performed by Amadori *et al.* (2018).

5.3 Aegean Basin and Marmara region

Two topics associate these nearby regions: the Messinian subaerial erosion and the relationships with the Paratethys.

5.3.1 Aegean Basin

In the Northern Aegean Basin, the Akropotamos location (Fig. 1) deserves attention because the Messinian evaporites are there exposed and overlain by a Zanclean Gilbert-type fan delta (Fig. 8; Suc *et al.*, 2015a). Ages of these formations have been established by Snel *et al.* (2006a) and Suc *et al.* (2015a). Ostracods found by Karakitsios *et al.* (2017) have identified a Lago Mare biofacies above the evaporites. Consistently with the Roveri *et al.* (2014) scenario (Fig. 2), Karakitsios *et al.* (2017) have conceived an erosional surface attributed to the MES between the evaporites and the Lago Mare Unit. This is a minor discontinuity signing the onlap of the Lago Mare strata (see Fig. 7J of Karakitsios *et al.*, 2017). In fact, the MES is above the travertine layer emphasized by the Zanclean Akropotamos Gilbert-type fan delta, channeled of about 100 m within the Messinian deposits (Fig. 8a, c-e; Suc *et al.*, 2015a). The Karakitsios *et al.*'s (2017) interpretation has resulted in minimizing the impact of the Messinian subaerial erosion in the Aegean Basin, which was established both onland (Suc *et al.*, 2015a) and offshore (Proedrou and Papaconstantinou, 2004; Anastasakis *et al.*, 2006; Varesis and Anastasakis, 2021; Rodriguez *et al.*, 2023).

We consider that the Aegean Basin was connected to the Mediterranean during the first step of the MC (peripheral evaporites) and connected to the Dacic Basin at its termination (LM 1 episode). It was then affected by the subaerial erosion at the beginning of the second step of the MC before the beginning of the isolation, and it was supplied by Paratethyan

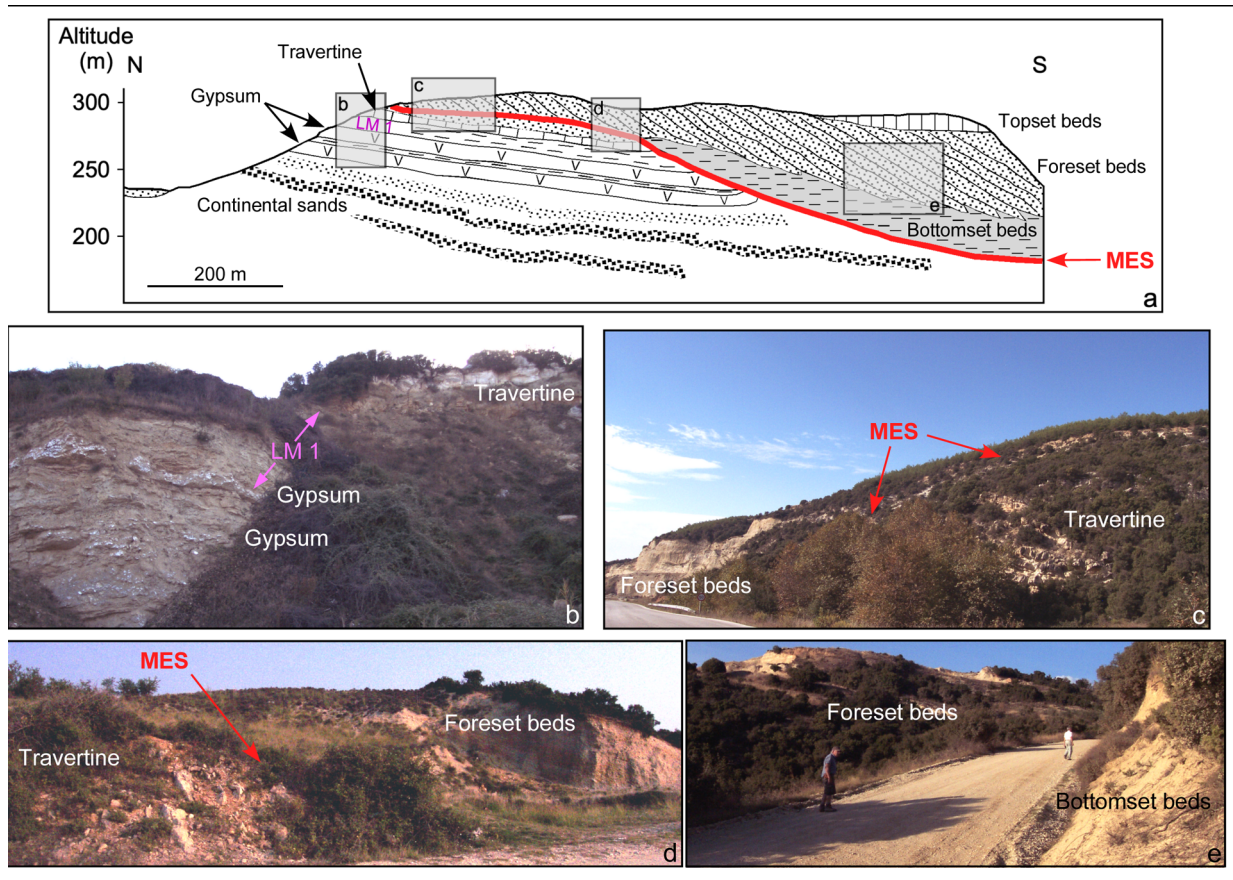


Fig. 8. Updated stratigraphy interpretation of the Akropotamos succession (Suc *et al.*, 2015a; Karakitsios *et al.*, 2017). a, Completed cross-section from Suc *et al.* (2015a) with location of the cartoons b–e; b, The gypsum quarry northward of Akropotamos; c, The MES separating the travertine layers from the foreset beds of the Gilbert-type fan delta along the road to Kariani; d, The MES separating the travertine layers from the foreset beds of the Gilbert-type fan delta southward of Akropotamos; e, Distal part of the Akropotamos Gilbert-type fan delta. Photographs: b–e by J.-P. Suc.

Fig. 8. Mise au point sur la stratigraphie de la série d'Akropotamos et sur son interprétation.

brackish waters through the Balkans Corridor, which were probably at the origin of the LM 2 episode (Suc *et al.*, 2011, 2015a; Popescu *et al.*, 2015). The uplift of the Hellenic Arc may have formed a barrier isolating the Aegean as response to the Mediterranean drying up (Fig. 1). The second Lago Mare episode is considered to have resulted from the rush of the Paratethyan waters from the Aegean pool into the almost completely desiccated Mediterranean Basin resulting from the erosion of the previously uplifted sill (Fig. 1). A transverse seismic profile from the Southeastern Aegean to the south of the islands Ikaria–Petrokaravo–Samos documents this cataclysmic erosion and the spilling of the Aegean waters into the Mediterranean (Figs. 1). The profile SE32 from the SEISA Cruise (Fig. 9; Schuster *et al.*, 1978) displays a huge canyon (1225 m deep with ca. 2000 m/s mean seismic velocity) filled by chaotic seismic facies (yellow) interpreted as chaotic Messinian deposits (thick of about 400 m with the same mean seismic velocity) and overlain by a thick deformed unit interpreted as Zanclean marine marls (green). Two high amplitude and continuous reflectors (pink) underlie the chaotic unit just below the MES and could be interpreted as Messinian peripheral evaporites (first step of the MC) (Fig. 9). This

interpretation is supported by two nearby cored boreholes, which show evaporitic deposits beneath the Early Pliocene sediments (Fig. 1: Site 378: Hsü *et al.*, 1978; Site U1591: Druitt *et al.*, 2024).

5.3.2 Marmara region (Fig. 10)

Two contradicted views of the Dardanelles Strait remain in the recent literature: Melinte-Dobrinescu *et al.* (2009) argued in favour of Messinian erosion in this area while Krijgsman *et al.* (2020) promoted a scenario concluding that there was no effect of the MC in the Marmara Sea (Fig. 1). Krijgsman *et al.* (2020) used a biostratigraphic scheme based on Paratethyan ostracods and molluscs, despite their low value in terms of global marine correlations. Melinte-Dobrinescu *et al.* (2009) used marine microfossils, which have a greater potential for correlations at large geographical scale.

Krijgsman *et al.* (2020) studied a section, called Intepe-2, different from the Intepe section studied by Melinte-Dobrinescu *et al.* (2009) (Figs. 10, 11e), which was destroyed in early 2013 for building a new motorway (Fig. 11f). Krijgsman *et al.* (2020) based their interpretation by

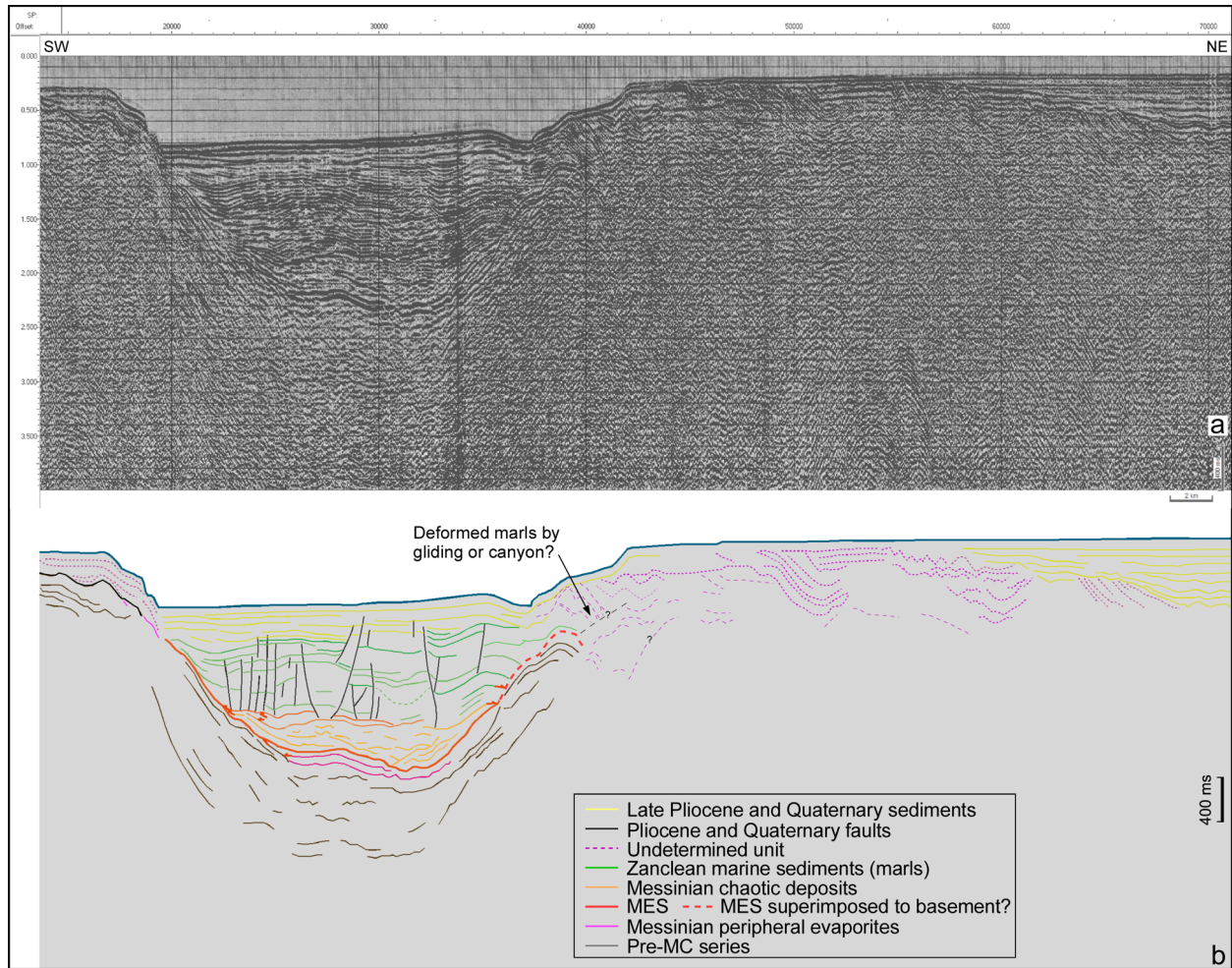


Fig. 9. Transverse seismic profile SE32 across the Southeastern Aegean Basin (SEISA Cruise; Schuster *et al.*, 1978). a, Non interpreted profile; b, Interpreted line-drawing of the profile.

Fig. 9. Profil sismique à travers le sud-est de la Mer Egée.

considering the Intepe-2 section equivalent to the “original” section, although distant from about 1,000 m (Fig. 11d). The Intepe-2 section shows critical insufficiencies to be elected as a suitable substitutive section because: (1) the original Intepe section is rich in marine microfossils (calcareous nannofossils and dinoflagellate cysts) that is not the case for the Intepe-2 section, and (2) the Intepe-2 section includes a lignite which is not immediately overlain by fired red clays (Krijgsman *et al.*, 2020: Fig. 5c), which is representative of an emersion event that we correlated with the paroxysmic phase of the MC (Fig. 11j; Melinte-Dobrinescu *et al.*, 2009). This area is heavily faulted making impossible to exactly duplicate the original Intepe section. The Intepe section topped a thick succession (Fig. 11e), which includes several lignite beds as those shown by Krijgsman *et al.* (2020) but none of these beds is topped by a fired clay. Our conclusion is that the Intepe-2 section does not constitute a stratigraphic equivalent to the original Intepe section. We believe that Krijgsman *et al.* (2020) may have studied an offset part of the lower Intepe succession. To conclude about this area, Krijgsman *et al.* (2020) wrote that they did not observe any Gilberttype fan delta. This is because the Intepe Gilbert delta is not observable in the Intepe area but

in the north, back to Güzelyalı (Fig. 11d; Melinte-Dobrinescu *et al.*, 2009). There, all the different components of the post-MC Gilbert-type fan deltas were recorded in several places (Fig. 11g–i), spotlighting the Messinian erosion and the following reflooding as sedimentary terrestrial key-systems (Clauzon, 1990; Bache *et al.*, 2012). Krijgsman *et al.* (2020) probably explored a high topographic location older than the original Intepe section (Fig. 11d).

At Seddülbahir, another key section, Krijgsman *et al.* (2020) assumed to have not identified a Gilbert-type fan delta. Here, a transverse section through the bottomset beds of the Dardanelles Gilbert-type fan delta, does not allow to identify such a sedimentary system without observing a longitudinal section showing sandy to gravelly foreset beds (see: Melinte-Dobrinescu *et al.*, 2009: Fig. 15). The analysis of calcareous nannofossils performed on this section by Krijgsman *et al.* (2020) appears to be preliminary, showing rare markers. Indeed, as already indicated by Popescu *et al.* (2017), biostratigraphic markers were recorded after a long analysis in association with abundant of long-range taxa (e.g., *Amaurolithus primus*, *Calcidiscus leptoporus*, *Calcidiscus macintyreii*, *Coccolithus pelagicus*, *Helicosphaera carteri*,

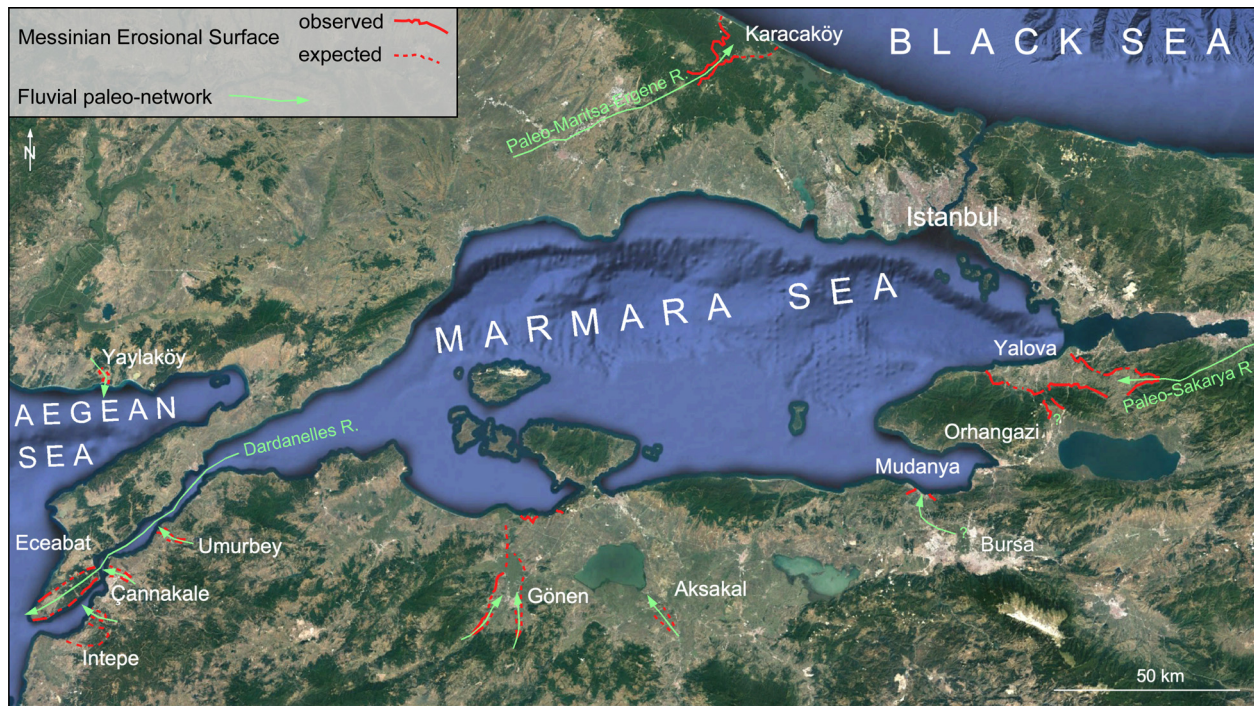


Fig. 10. Google Earth map of the Marmara region with the outline of the MES filled by Gilbert-type fan deltas and sketch of the fluvial network at the peak of the MC. The studied locations with calcareous nannoplankton age for most of them are shown in Figure S1. Sketch of the MES comes from Melinte-Dobrinescu *et al.* (2009) and Suc *et al.* (2015b). This figure includes the new data presented in this paper.

Fig. 10. Carte Google Earth de la région de Marmara avec dessin de la Surface d'érosion messinienne, des Gilbert deltas qui remplissent les vallées messiniennes et du réseau fluvial lors du paroxysme de la Crise messinienne.

Reticulofenestra pseudumbilicus, *Sphenolithus abies*). We recall how doubtful is the potential confusion of *Ceratolithus acutus* with a fragment of ascidian spicule when mastered by accepted specialists (de Leeuw *et al.*, 2018). In addition, questioning our results should consider the occurrence of the morphologically unquestionable nannofossil *Triquetrorhabdulus rugosus* (now: *Orthorhabdus rugosus*) usually recorded simultaneously with *C. acutus* in the Intepe and West Seddülbahir sections, the disappearance of which is dated at 5.28 Ma (Fig. S2), i.e. shortly after the first appearance of *C. acutus*, as observed in the Intepe succession (Melinte-Dobrinescu *et al.*, 2009: Fig. 12). Finally, Krijgsman *et al.* (2020) assumed that these rare species cannot be recorded in coastal shallow sediments. On the contrary, we think that the very exceptional context of the almost instantaneous reflooding of the Mediterranean Basin by marine waters closing the MC offered outstanding conditions for recolonizing a very large space including the (often deep) marine rias that replaced the fluvial canyons (as the Dardanelles area). In fact, these rare species were recorded in the lowermost marine sediments overlying the MES (Popescu *et al.*, 2017 and references herein; see also the recent papers by: Osman *et al.*, 2021; Atik *et al.*, 2024). The MES often shows a jagged outline (Fig. 11a; see also Fig. 12c) and there is the possibility that the lowermost part of the Krijgsman *et al.*'s section (2020: their samples SB1-SB5: Fig. 4b) was in fact below a jag of the MES (Fig. 11a). This would give an explanation to the land fauna (mammals, snails) reported by Krijgsman *et al.* (2020) from sample SB5.

In the Dardanelles area, the MES often tops red beds that makes easier its recognition and we must concede that the calcareous nannoplankton is a very efficient guide (Fig. 11b-c).

We extended new investigations along the Southern Marmara shoreline where outstanding complete Gilbert-type fan deltas were identified, overlying the MES (Fig. 12a). These include the ones at Mudanya (Fig. 12c-d, f, j) and Yalova (Fig. 12c-d, f, j), and partly recognized near Umurbey, Gönen (Fig. 12b) and Aksakal (Figs. 10 and S1). Most of their bottomset beds provided calcareous nannofossils that resulted in a robust bio-chronostratigraphy (Fig. S2; Tab. S1).

Because of its morphology, the region of İstanbul has usually been considered as a passageway for exchanges between the Eastern Paratethys and the Mediterranean Sea (e.g.: Krijgsman *et al.*, 2020, 2024). This is established for the Paleogene (Okay *et al.*, 2019) but this connection was interrupted during the Middle-Late Miocene while some uncertainty is expressed for the Messinian time (Görür *et al.*, 1997; Çağatay *et al.*, 2006). Despite the strong tectonics due to the propagation of the North Anatolian Fault, which considerably impacted the regional landscapes and strata arrangement, the obvious conclusion of our work is the development of two opposed fluvial networks during the peak of the MC (Suc *et al.*, 2015b; Fig. 10). This paleogeographic configuration, supported by strong fluvial erosion both in the Southwestern Black Sea (northeastward oriented) and in the Marmara area (westward to southwestward oriented), prevents any connection through the İstanbul Sill (Fig. 10).

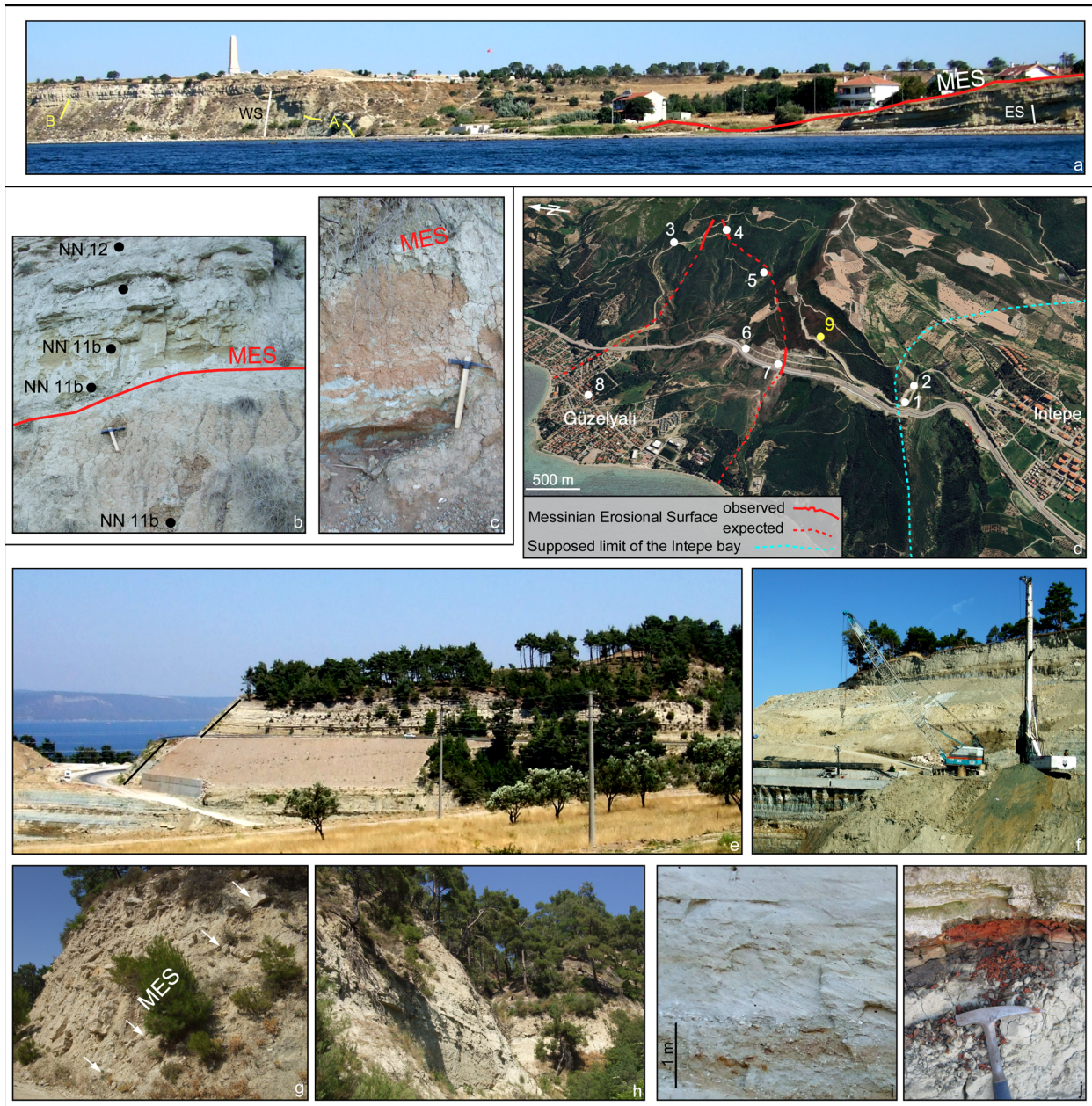


Fig. 11. Selection of locations in the Dardanelles Strait (Fig. S1). a, Seddülbahir: white lines, sections studied by Melinte-Dobrinescu *et al.* (2009): ES, East Seddülbahir; WS, West Seddülbahir. Yellow lines: sections A–B studied by Krijgsman *et al.* (2020b). b–c, The Karanfil T. section (Table S1): a, showing the MES and chronological calibration by calcareous nannoplankton; c, Karanfil T. section: lithological detail around the MES. d–j, The Intepe area. d, Google Earth relief map with the key-locations: 1–2, the Intepe section of Melinte-Dobrinescu *et al.* (2009) (Table S1): 1, the studied section; 2, place of the lignite overlain by fired clays; 3–8, representative sections of the Güzelyalı nested Gilbert-type fan delta: 3, deposits prior to the Messinian erosion northward of the MES; 4, block debris flow in contact with the MES; 5, foreset beds; 6, foreset-beds; 7, foreset beds in contact with the MES; 8, bottomset beds; 9, the Intepe-2 section studied by Krijgsman *et al.* (2020b). e, The Intepe section studied (black lines) by Melinte-Dobrinescu *et al.* (2009) as available in 2007. f, The same section destroyed in 2013 for building a motorway. g, Messinian sediments (to the right) cut by the MES, overlain by nested block debris flow (location 4 in Figure 11d). h, Foreset beds of the Gilbert-type fan delta (location 5 in Figure 11d). i, Zoom on the foreset beds of the Gilbert-type fan delta (location 7 in Figure 11d). j, The Intepe lignite overlain by fired clays (location 2 in Figure 11d). Photographs: a–c and e–i by J.-P. Suc, j by Ç. Karakaş.

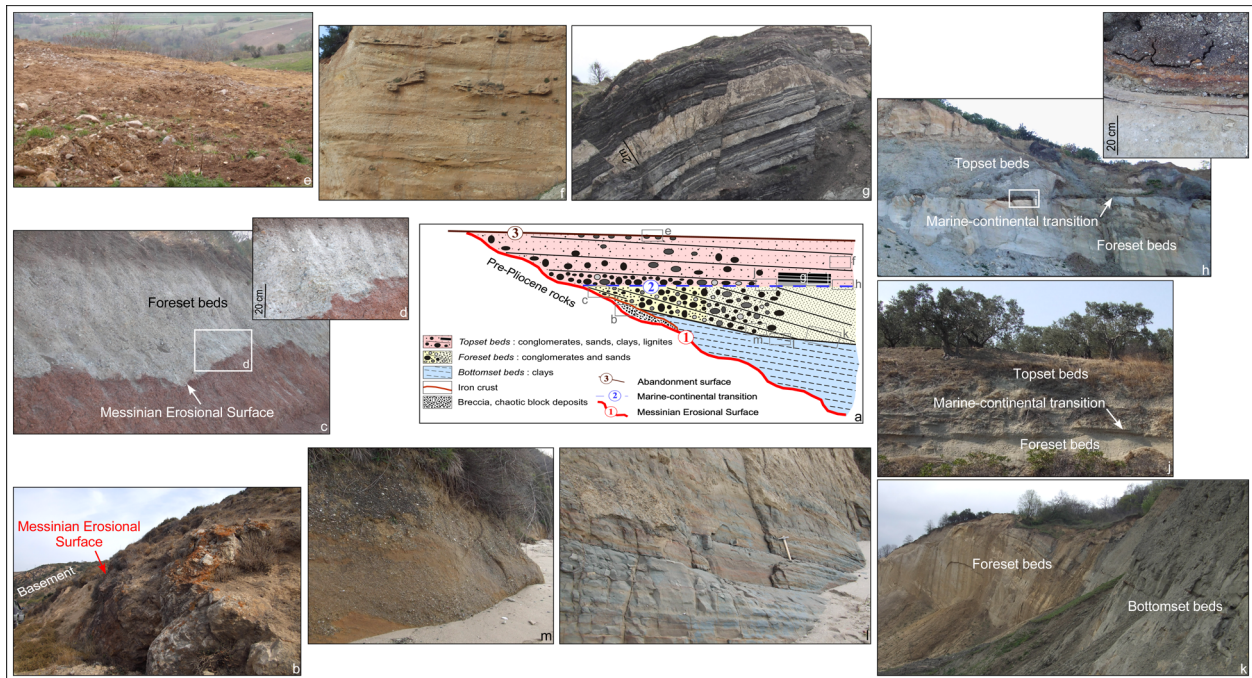


Fig. 12. New elements of post-MC Gilbert-type fan deltas in the southern Marmara Sea region (the number into brackets refers to [Figure S1](#) for location, and to [Table S1](#) for calcareous nannoplankton ages). a, Concept of post-MC Gilbert-type fan deltas with constituent bodies and reference surfaces ([Clauzon, 1990](#); [Bache et al., 2012](#)). b, Salzıdere (19): cemented breccia (debris flow) with iron crust overlying the MES. c, Mudanya (20): sandy to gravelly foreset beds overlying the MES cutting granitic weathered clays. d, Detail of the previous view. e, Yalakdere (27): abandonment surface. f, Mudanya (20): sandy to gravelly topset beds. g, Soğuçak (24): clayey and lignitic topset beds. h, Soğuçak (24): marine-continental transition. i, Detail of the previous view. j, Mudanya (20): marine-continental transition. k, Soğuçak (24): sigmoid passage from sandy foreset beds to clayey bottomset beds. l, Koruköy (26): clayey bottomset beds. m, Koruköy (26): sandy to gravelly foreset beds.

Fig. 12. Nouveaux éléments constitutifs des Gilbert deltas du sud de la Mer de Marmara.

5.4 Relationship with the Paratethys

Among the data from the Dacic Basin (Eastern Paratethys) ([Fig. 1](#)), the occurrence of Zanclean Mediterranean marine plankton in sediments nested within the basement or the Miocene and even older sediments is of the highest importance. [MăruŃeanu and Papaianopol \(1995,1998\)](#) attracted attention in showing the occurrence of calcareous nannofossils in many places that illustrated the marine connection between the Mediterranean and the Dacic Basin. Based on magnetostratigraphy, [Snel et al. \(2006b\)](#) has provided evidence that two of these marine connections occurred during the Late Miocene and the Early Pliocene, *i.e.* before and after the MC, respectively. The nested Gilbert-type fan deltas of Turnu Severin with bottomset beds ascribed to the calcareous nannofossil Zone NN12 and to Chron C3r (for chronostratigraphy, see [Fig. S2](#)) and including planktonic foraminifera, have started to show the impact of the MC in the Eastern Paratethys ([Clauzon et al., 2005](#); [Popescu et al., 2006](#); [Suc et al., 2011](#)). It is encouraging that the MC sea-level fall, surrounded by two phases of marine connection with the Mediterranean, was admitted in the Dacic Basin ([Krijgsman et al., 2010](#); [Leever et al., 2010](#)) without considering the subaerial erosion and the nesting of the post-MC deposits ([ter Borgh et al., 2014](#)).

An illustrative example exists near Beceni ([Fig. 1](#): 45° 22'30"N, 26°47'45"E) where cyclic marls that yielded calcareous plankton taxa including, among others,

Ceratolithus acutus, *Orthrhabdus rugosus* (calcareous nannofossils) and *Sphaeroidinellopsis seminulina* (planktonic foraminifer), unconformably overlie marls with *Orthrhabdus rugosus*, *Reticulofenestra rotaria*, and *Amaurolithus tricorniculatus*, among others ([Clauzon et al., 2008](#); [Fig. 13](#)). According to the record of *R. rotaria* (6.91–5.94 Ma), the lower marls were assigned to the Messinian. The upper marls were assigned to the early Zanclean (ca. 5.30 Ma), based on co-occurrence of *C. acutus* and *O. rugosus* (see [Fig. S2](#) for the calcareous nannoplankton biochronology). The discontinuity separating those two marl units shows an angle of 29° southward oriented while the dip of the overlying marls is 18° E: such a feature is characteristic of an erosion that, considering the datings, was attributed to the MES ([Fig. 13a](#); [Clauzon et al., 2008](#)).

5.5 Levantine Basin

The Easternmost part of the Mediterranean Basin ([Fig. 1](#)) is imperfectly known but has benefited of extensive research during the two last decades thanks to important hydrocarbon discoveries. Unfortunately, both the discovery of hydrocarbons and the political context of the area have made the investigations very difficult, even sometimes not possible.

Two major problems still concern the erosional features and the chronostratigraphy of this basin. The fluvial erosion during the sea-level drop has been clearly established, forced



Fig. 13. Beceni (SE Romania). a, The MES between Miocene marine marls and Zanclean marine marls. b, The overlying marls which recorded the Zanclean marine microplankton.

Fig. 13. Surface d'érosion messinienne à Beceni (SE Roumanie) surmontée par des dépôts à microplankton marin zancéen.

by three orthogonal systems (Nile River, Levantine shoreline, Southern Turkey: Gorini *et al.*, 2015; Madof *et al.*, 2019; Ben Moshe *et al.*, 2020). The onshore Messinian fluvial valleys have been shown for long for the Nile drainage area (Chumakov, 1967, 1973; Barber, 1980, 1981; Palmieri *et al.*, 1996; Dalla *et al.*, 1997; Dolson *et al.*, 2005) and were shown by recent studies in Cyprus (Psematisimos: Mocochain *et al.*, 2015, 2024), Syria (Lattakia: Mocochain *et al.*, 2015) and Southeastern Turkey (Hatay: Mocochain *et al.*, 2015; Adana: Hippolyte *et al.*, in progress). The only available chronostratigraphy proposed by Meilijson *et al.* (2019) is still fragile since it relies on cyclostratigraphy, based on a supposed correlation with the Apennine Foredeep, Eraclea Minoa and Sorbas successions, the interpretations of which being themselves questionable as explained above. A biostratigraphy has been established for the onshore and offshore Nile Delta wells but it is only partly published (Farouk *et al.*, 2014) and the drilled materials remain unattainable for international investigations. Paleocanyons also exist perpendicular to the Israel coastline, such as the Afiq Canyon (Fig. 1),

extensively documented between Beer Sheva and Gaza (Druckman *et al.*, 1995; Buchbinder and Zilberman, 1997). This paleocanyon resulted from submarine cutting mainly made during the Mid-Miocene and was mostly filled by Upper Miocene sediments including Messinian peripheral evaporites but would have possibly been submitted to subaerial erosion during the MC peak (Druckman *et al.*, 1995). However, the Messinian fluvial erosion offshore was challenged by Moneron and Gvirtzman (2022) who conceived a submarine channel system in a Mediterranean Basin filled by marine waters during the central evaporite deposition.

In order to contribute to document this crucial matter by new data, we searched for calcareous nannoplankton and dinoflagellate cysts from two sections already studied for planktonic foraminifera (Martinotti *et al.*, 1978; Zilberman *et al.*, 2010): the BH 13 hole drilled at Beer Sheva within the proximal part of the Afiq Canyon and the Nesher Quarry located near Haifa at the foot of the Carmel Mount (Fig. 1). In both locations, foraminifera indicated an undefined Upper Miocene to Lower Pliocene succession (Fig. 14) based on the occurrence of *Globoturborotalita nepenthes* (first occurrence at 11.6 Ma) and *Sphaeroidinellopsis* spp. (first occurrence at about 8 Ma). Calcareous nannofossils indicate that the lower part of the section has deposited during the Messinian (occurrence of *Reticulofenestra rotaria* and *Orthorhabdus rugosus* in both sections, of *Discoaster quinqueramus* in the Nesher Quarry only) (Fig. 14). The occurrence of *Ceratolithus acutus* indicates that the upper part of both sections have deposited during the early Zanclean (Fig. 14). The four samples from the Nesher Quarry were barren in dinoflagellate cysts while the upper part of the SH 13 borehole (167-213 m asl) was rich in dinoflagellate cysts indicating an open marine environment (*Spiniferites membranaceus*, *S. hyperacanthus*, *S. mirabilis*, *Impagidinium patulum*, etc.; Fig. 14). In the Nesher Quarry, a debris flow below the first record of *C. acutus* may indicate some erosion (Zilberman *et al.*, 2010). In the SH 13 borehole, there is no clear lithological change below the first record of *C. acutus* (Buchbinder and Zilberman, 1997). It is surprising that the subaerial erosion during the MC peak was so weak along the Israel shoreline (Buchbinder and Zilberman, 1997), compared with the other coastal regions of the Levantine Basin (Nile Delta: Barber, 1980, 1981; Palmieri *et al.*, 1996; Dalla *et al.*, 1997; Dolson *et al.*, 2005; Southern Turkey: Poisson *et al.*, 2011; Mocochain *et al.*, 2015; Hippolyte *et al.*, in progress; Cyprus: Mocochain *et al.*, 2024; Syria: Mocochain *et al.*, 2015). Such a striking contrast has been attributed to the absence of fluvial stream only from the Israelian coastal range because of arid climatic conditions limiting water transport (Buchbinder and Zilberman, 1997). On the contrary, pollen records showed that arid climatic conditions existed around the entire Eastern Mediterranean before and after the MC (Fauquette *et al.*, 2006; Jiménez-Moreno *et al.*, 2007), but this context did not avoid strong fluvial erosion during the MC peak in areas other than Israel, considering also that a East-West drainage network was developed there at the end of Zanclean (Ginat *et al.*, 2000). If it is possible that these first layers of the lower Zanclean illustrate the marine reflooding of the Mediterranean Basin after a weak phase of local erosion, then the possibility that they express some momentary water inflow from the Red Sea preceding the Zanclean must be taken into account (Fig. 15; Pensa *et al.*, 2025). Such a marine gateway through the Gulf of Suez (Gargani *et al.*,

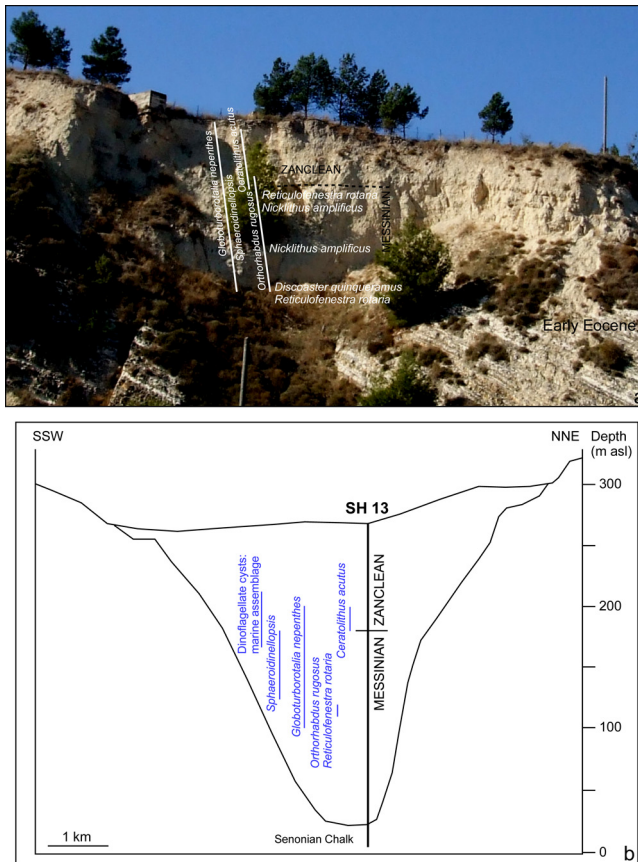


Fig. 14. Biostratigraphic (planktonic foraminifera and our new results on calcareous nannoplankton) and paleoenvironmental (dinoflagellate cysts) information from two sections from Israel. a, Nesher Quarry (Zilberman *et al.*, 2010); b, Borehole SH 13 (foraminifera from: Martinotti *et al.*, 1978).

Fig. 14. Biostratigraphie de deux coupes en Israël incluant les résultats nouveaux sur le nannoplankton calcaire.

2008) or the southern Dead Sea would lighten the following contrasted contexts (Fig. 1):

- (1) fluvial erosion in front of Lebanon–Syria (Nar Menashe complex: Madof *et al.*, 2019) and of Northern Israel (Ben Moshe *et al.*, 2020), and in front of the Nile Delta (Barber, 1980, 1981; Gargani and Rigollet, 2007; Gargani *et al.*, 2010);
- (2) submarine erosion in an isolated basin in front of Southern Israel (Moneron and Gvirtzman, 2022).

In addition, this assumption would provide a reliable explanation to the occurrence of tropical fishes (sharks and rays) originating from the Indian Ocean in lowermost Zanclean deposits from Lybia rather than their survival within the almost completely desiccated Mediterranean as hypothesized by Pawellek *et al.* (2012).

6 Conclusive remarks

In its initial sense, the two-step MC scenario, inherited from Clauzon *et al.* (1996), was mainly based on a high

amplitude of the sea-level drop (ca. 1,500 m) and the resulting widespread fluvial erosion in the entire Mediterranean region (e.g., and references herein: Alboran Sea: Do Couto *et al.*, 2016; Gulf of Lions: Lofi *et al.*, 2005; Bache *et al.*, 2009, 2012; Leroux *et al.*, 2017; offshore Algeria: Capron *et al.*, 2011; Tyrrhenian Sea: Thinon *et al.*, 2016; Levantine Basin: Gorini *et al.*, 2015; Madof *et al.*, 2019). Our studies onland, offshore seismic profiles and land-sea relationship allow to conclude that (1) the peripheral evaporites, and (2) the onset of fluvial cutting and the deposition of central evaporites were succeeding in time (Bache *et al.*, 2015; Clauzon *et al.*, 2015a; Gorini *et al.*, 2015; evaluation: 5.97–5.65 Ma for the peripheral evaporites, 5.63–5.48 Ma for the erosion progression and the central evaporites deposition; Fig. 2).

We recognize three distinct Lago Mare episodes of different origin and age, based on the record of Paratethyan dinoflagellate cysts (Clauzon *et al.*, 2005; Popescu *et al.*, 2015):

- high sea-level in Mediterranean-Dacic basins with two-way exchanges at ca. 5.65–5.63 Ma and ca. 5.46–5.33 Ma, respectively LM 1 and LM 3, both recorded in peripheral and central Mediterranean sections;
- discharge of Paratethyan brackish waters *via* the perched Aegean Basin into the almost completely desiccated Mediterranean at ca. 5.48–5.46 Ma (LM 2), only recorded in the central Mediterranean wells.

At last, we claim a marine reflooding of the Mediterranean Basin at 5.46 Ma, significantly before the beginning of the Zanclean Stage (5.33 Ma) (Bache *et al.*, 2012; Popescu *et al.*, 2021).

In complement to the chronological scheme shown in Figure 2, the two-step scenario of the MC is illustrated in one longitudinal and three latitudinal Mediterranean transects (Fig. 15) which, in addition to sea-level changes and isostatic readjustments resulting in water exchanges or overflows, take into account the paleogeographic disparities between basins, particularly the water storage in isolated (perched) basins (Western Alboran: marine waters; Apennine Foredeep: fresh waters; Aegean Basin: brackish waters; Fig. 1). The possibly isolated southeastern part of the Levantine Basin is not delineated in Figure 15 because it is not really on the A–B transect and it overall needs to be confirmed by future research.

Is it necessary to recall that our scenario results from both onshore and offshore intensive investigations supported by outstanding micropaleontology-based chronostratigraphy. Our behaviour in deciphering the MC puzzle was to consider all the data, whatever their relevance with the hypotheses, which guided our interpretation independently from any preconceived concept.

The reader must understand that the Clauzon *et al.* (1996) two-step scenario significantly differs from the scenario of Roveri *et al.* (2014a). The two prevalent scenarios discussed in this paper perpetuate several reciprocal crucial discrepancies, including the synchronicity or not of peripheral vs. central evaporites, the chronology and nature of erosion (subaerial? submarine?) (for comparison, see Manzi *et al.*, 2021b and Krijgsman *et al.*, 2024).

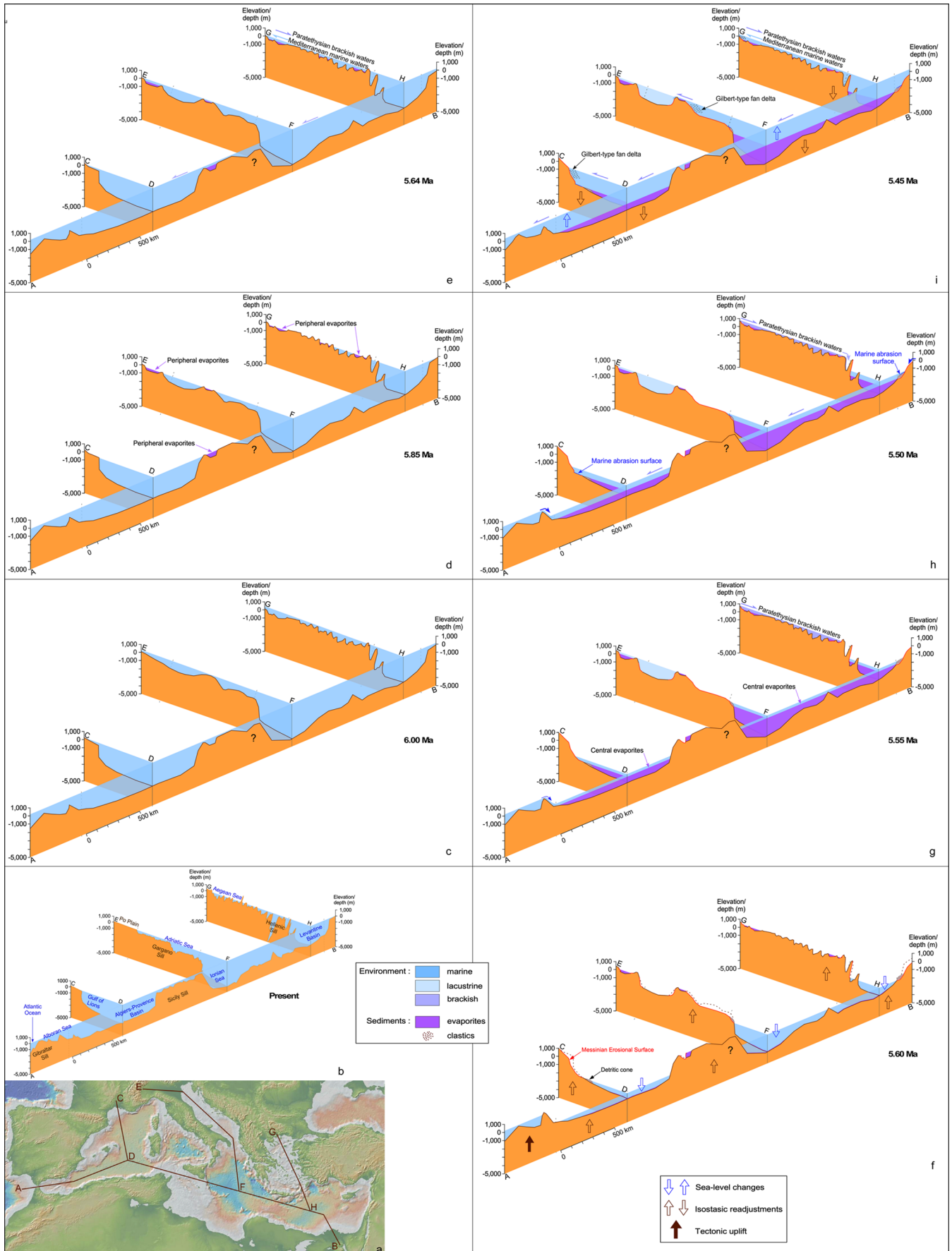


Fig. 15. Reconstructed paleogeography of the Mediterranean region through some transects in agreement with the two-step scenario of the MC (Clauzon *et al.*, 1996, 2005; Bache *et al.*, 2012, 2015; Gorini *et al.*, 2015; Popescu *et al.*, 2015, 2021; Haq *et al.*, 2020). a, Location of the transects. b, Present-day bathymetry along a longitudinal transect and three transverse transects. c–i, Environmental changes in the Mediterranean (bathymetry, deposition, erosion) from 6.00 to 5.45 Ma through four similar transects: c, 6.00 Ma: before the MC onset; d, 5.85 Ma: first step of the MC (peripheral evaporites); e, 5.64 Ma: high sea level closing the first step of the MC (LM 1); f, 5.60 Ma: beginning of the second step of the MC (subaerial erosion, deposition of detritic cones); g, 5.55 Ma: ongoing second step of the MC (central evaporites); h, 5.50 Ma: end of the second step of the MC (slow sea-level rise, marine abrasion surface, transfer of Aegean waters into the Mediterranean: LM 2); i, 5.45 Ma: after the catastrophic marine reflooding (edification of Gilbert-type fan deltas, LM 3).

Fig. 15. Paléogéographie méditerranéenne reconstituée à travers quelques transects conformément au scénario en deux temps de la Crise messinienne.

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Supplementary material

Fig. S1. Google Earth map with the studied locations in the Marmara region.

Fig. S2. Chronostratigraphy of the studied locations in the Marmara region with respect to the calcareous nannoplankton events and to late Messinian events.

Table S1. Information on the studied locations in the Marmara region. The Supplementary Material is available at <https://www.bsgf.org/10.1051/bsgf/2025021/olm>.

References

- Agustí J, Garcés M, Krijgsman W. 2006. Evidence for African-Iberian exchanges during the Messinian in the Spanish mammalian record. *Palaeogeogr Palaeoclimatol Palaeoecol* 238: 5–14.
- Amadori C, García-Castellanos D, Toscani G, *et al.* 2018. Restored topography of the Po Plain-Northern Adriatic region during the Messinian base-level drop-Implications for the physiography and compartmentalization of the palaeo-Mediterranean basin. *Bas Res* 30: 1247–1263.
- Anastasakis G, Piper DJW, Dermitzakis MD, Karakitsios V. 2006. Upper Cenozoic stratigraphy and paleogeographic evolution of Myrtoon and adjacent basins, Aegean Sea, Greece. *Mar Pet Geol* 23: 353–369.
- Andreotto F, Aloisi G, Raad F, *et al.* 2021. Freshening of the Mediterranean Salt Giant: controversies and certainties around the terminal (Upper Gypsum and Lago-Mare) phases of the Messinian Salinity Crisis. *Earth-Sci Rev* 216:103577.
- Aslanian D, Pellen R, Rabineau M, *et al.*, 2023. The postulation of intermittent land bridges as an explanation for reiterated colonization events of Madagascar by African vertebrates: an in-depth review and novel insights in honour of the late Judith Masters and Fabien Génin. *Earth-Sci Rev* 246:104585.
- Atik A, Mansouri MEH, Bessedik M, Osman MK, *et al.* 2024. New insights on the latest Messinian-to-Piacenzian stratigraphic series from the Dahra Massif (Lower Chelif Basin, Algeria): Lago Mare, reflooding and bio-events. *BSGF - Earth Sci Bull* 195:2.
- Bache F, Gargani J, Suc J-P, *et al.* 2015. Messinian evaporite deposition during sea level rise in the Gulf of Lions (Western Mediterranean). *Mar Pet Geol* 66: 262–277.
- Bache F, Olivet J-L, Gorini C, *et al.* 2009. Messinian erosional and salinity crises: view from the Provence basin (Gulf of Lions, Western Mediterranean). *Earth Planet Sci Lett* 286: 139–157.
- Bache F, Popescu S-M, Rabineau M, *et al.* 2012. A two step process for the reflooding of the Mediterranean after the Messinian Salinity Crisis. *Basin Res* 24: 125–153.
- Barber PM. 1980. Palaeogeographic evolution of the Proto-Nile delta during the Messinian salinity crisis. *Géol Méd* 7(1): 13–18.
- Barber PM. 1981. Messinian subaerial erosion of the proto-Nile Delta. *Mar Geol* 44:253–272.
- Beaudouin C, Suc J-P, Escarguel G, Arnaud M, Charmasson S. 2007. The significance of pollen signal in present-day marine terrigenous sediments: the example of the Gulf of Lions (western Mediterranean sea). *Geobios* 40: 159–172.
- Bellucci M, Leroux E, Aslanian D, Moulin M, Pellen R, Rabineau M. 2024. Salt tectonics evolution in the Provençal Basin, Western Mediterranean Sea. *Earth Sci Bull* 195:16.
- Ben Moshe L, Ben-Avraham Z, Enzel Y, Schattner U. 2020. Estimating drawdown magnitudes of the Mediterranean Sea in the Levant basin during the Lago Mare stage of the Messinian Salinity Crisis. *Mar Geol* 427:106215.
- Bertini A, Corradini D, Suc J-P. 1995. On *Galeacysta etrusca* and the connection between the Mediterranean and the Paratethys. *Romanian J Stratigr* 76(7): 141–142.
- Booth-Rea G, Ranero CR, Grevenmeyer I. 2018. The Alboran volcanic-arc modulated the Messinian faunal exchange and salinity crisis. *Sci Rep* 8:13015.

- Brolsma MJ. 1975. Lithostratigraphy and foraminiferal assemblages of the Miocene–Pliocene transitional strata of Capo Rossello and Eraclea Minoa (Sicily, Italy). *Proc Konink Neder Akad Van Wetensch* 78 (B): 341–380.
- Brolsma MJ. 1976. Discussion on the arguments concerning the palaeoenvironmental interpretation of the Arenazzolo in Capo Rossello and Eraclea Minoa (S. Sicily, Italy). *Mem Soc Geol Ital* 16: 153–157.
- Buchibinder B, Zilberman E. 1997. Sequence stratigraphy of Miocene–Pliocene carbonate–siliclastic shelf deposits in the eastern Mediterranean margin (Israel): effects of eustasy and tectonics. *Sedim Geol* 112: 7–32.
- Bulian F, Sierro FJ, Ledesma S, Jiménez-Espejo F, Bassetti M-A. 2021. Messinian West Alboran Sea record in the proximity of Gibraltar: early signs of Atlantic-Mediterranean gateway restriction. *Mar Geol* 434:106430.
- Buoncrisiani J-F, Campy M., 2011, Quaternary glaciations in the French Alps and Jura. In: Ehlers J, Gibbard PL, Hughes PD, eds. *Developments in quaternary science* 15, Amsterdam, pp. 117126.
- Butler RWH, Lickorish WH, Grasso M, Pedley HM, Ramberti L. 1995. Tectonics and sequence stratigraphy in Messinian basins, Sicily: constraints on the initiation and termination of the Mediterranean “Salinity crisis”. *Geol Soc Amer Bull* 107: 425–439.
- Çağatay MN, Görür N, Flecker R, *et al.* 2006. Paratethyan-Mediterranean connectivity in the Sea of Marmara region (NW Turkey) during the Messinian. *Sedim Geol* 188–189: 171–187.
- Capron A, Déverchère J, Gaullier V, Le Roy P, Mercier de Lépinay B, Yelles K. 2011. Algerian margin. In: Lofi J, Déverchère J, eds. *Seismic atlas of the Messinian salinity crisis markers in the offshore Mediterranean domain*. Paris: Mémoire de la Société géologique de France and Commission for the Geological Map of the World, 179,p. 72.
- Carnevale G, Dela Pierre F, Natalicchio M, Landini W. 2018. Fossil marine fishes and the ‘Lago Mare’ event: has the Mediterranean ever transformed into a brackish lake? *Newslett Stratigr* 51(1): 57–72.
- Carnevale G, Gennari R, Lozar F, Natalicchio M, Pellegrino L, Dela Pierre F. 2019. Living in a deep desiccated Mediterranean Sea: an overview of the Italian fossil record of the Messinian salinity crisis. *Boll Soc Paleontol Ital* 58(1): 109–140.
- Carnevale G, Landini W, Sarti G. 2006. Mare versus Lago-mare: marine fishes and the Mediterranean environment at the end of the Messinian salinity Crisis. *J Geol Soc London* 163: 75–80.
- Carnevale G, Longinelli A, Caputo D, Barbieri M, Landini W. 2008. Did the Mediterranean marine reflooding precede the Mio-Pliocene boundary? Paleontological and geochemical evidence from upper Messinian sequences of Tuscany, Italy. *Palaeogeogr Palaeoclimatol Palaeoecol* 257: 81–105.
- Cavazza W, DeCelles PG. 1998. Upper Messinian siliciclastic rocks in southeastern Calabria (southern Italy): paleotectonic and eustatic implications for the evolution of the central Mediterranean region. *Tectonophysics* 298: 223–241.
- Chirol B. 2005. Genèse et evolution de la Cluse des Hôpitaux (Bugey de l’Ain). Apport des formes et formations karstiques. Master 1 thesis, Université de Savoie.
- Chirol B. 2022. La perte du Rhône. Librairie de la Bibliothèque de la Société Suisse de Spéléologie, Granges, Switzerland.
- Chumakov IS. 1967. Pliocene and Pleistocene deposits of the Nile Valley: Nubia and Upper Egypt. *Academy of Science of the U.S.S.R., Geological Institute transactions* 170, 113 pp. (in Russian).
- Chumakov IS., 1973, Pliocene and Pleistocene deposits of the Nile Valley in Nubia and Upper Egypt. In: Ryan WBF, Hsü KJ, Cita MB, *et al.* eds. *Leg 13. Initial Reports of the Deep Sea Drilling Project* 13(1), U.S. Government Printing office, pp. 1242–1243.
- CIESM 2008. The Messinian Salinity Crisis from mega-deposits to microbiology – A consensus report. *CIESM Workshop Monographs* 33: 7–28.
- Cita MB, Colombo L. 1979. Sedimentation in the latest Messinian at Capo Rossello. *Sedimentology* 26: 497–522.
- Cita MB, Santambrogio S, Melillo B, Rogate F. 1990. Messinian paleoenvironments: new evidence from the Tyrrhenian Sea (ODP Leg 107). In: Kastens KA, Mascle J, *et al.* eds. *Proceedings of the ocean drilling program, scientific results*, TX: College Station, 107, pp. 211–227.
- Cita MB, Wright RC, Ryan WBF. 1978. Messinian paleoenvironments. In: Ryan WBF, Hsü KJ, Montadert L, eds. *Leg 42A. Initial Reports of the Deep Sea Drilling Project* 42(1), U.S. Government Printing office, pp. 1003–1035.
- Clauzon G. 1982. Le canyon messinien du Rhône: une preuve décisive du “desiccated deep–basin model” [Hsü, Cita et Ryan, 1973]. *Bull Soc Géol France* 24(3)(S7): 597–610.
- Clauzon G. 1990. Restitution de l’évolution géodynamique néogène du bassin du Roussillon et de l’unité adjacente des Corbières d’après les données écostratigraphiques et paléogéographiques. *Paléobiol Cont* 17: 125–155.
- Clauzon G. 1999. L’impact des variations eustatiques du bassin de Méditerranée occidentale sur l’orogène alpin depuis 20 Ma. *Ét Géogr Phys* 28: 1–8.
- Clauzon G, Le Strat P, Duvail C, *et al.* 2015b. The Roussillon Basin (S. France): a case-study to distinguish local and regional events between 6 and 3 Ma. *Mar Pet Geol* 66: 18–40.
- Clauzon G, Suc J-P, Do Couto D, *et al.* 2015a. New insights on the Sorbas Basin (SE Spain): the onshore reference of the Messinian Salinity Crisis. *Mar Pet Geol* 66: 71–100.
- Clauzon G, Suc J-P, Gautier F, Berger A, Loutre M-F. 1996. Alternate interpretation of the Messinian salinity crisis: controversy resolved? *Geology* 24: 363–366.
- Clauzon G, Suc J-P, Popescu S-M, *et al.* 2005. Influence of Mediterranean sea-level changes on the Dacic Basin (Eastern Paratethys) during the late Neogene: the Mediterranean Lago Mare facies deciphered. *Basin Res* 17: 437–462.
- Clauzon G, Suc J-P, Popescu S-M, *et al.* 2008. Chronology of the Messinian events and paleogeography of the Mediterranean region s.l. *CIESM Workshop Monographs* 33:31–37.
- Combémoré R, Guérin C, Méon-Vilain H. 1970. Un nouveau gisement de Vertébrés mio-pliocènes à Priay (Ain). *Bull Bur Rec Géol Min* 4(S2): 33–47.
- Corradini D, Biffi U. 1988. Etude des dinokystes à la limite Messinien-Pliocène dans la coupe Cava Serredi, Toscane, Italie. *Bull Centres Rech Explor-Prod Elf-Aquitaine* 12(1): 221–236.
- Dalla S, Harby H, Serazzi M. 1997. Hydrocarbon exploration in a complex incised valley fill: an example from the late Messinian Abu Madi Formation (Nile Delta Basin, Egypt). *The Leading Edge* 16: 1819–1824.
- De Leeuw A, Tulbure M, Kuiper KF, Melinte-Dobrinescu MC, Stoica M, Krijgsman W. 2018. New ⁴⁰Ar/³⁹Ar magnetostratigraphic and biostratigraphic constraints on the termination of the Badenian Salinity Crisis: indications for tectonic improvement of basin interconnectivity in Southern Europe. *Global Planet Change* 169: 1–15.

- Do Couto D, Cushing EM, Mocochain L, *et al.* 2024. Messinian canyons morphology of the Rhône and Ardèche rivers (south-east France): new insights from seismic profiles. *BSGF–Earth Sci Bull.* 195: 19.
- Do Couto D, Gorini C, Jolivet L, *et al.* 2016. Tectonic and stratigraphic evolution of the Western Alboran Sea Basin in the last 25 Myrs. *Tectonophysics* 677: 280–311.
- Do Couto D, Gumiaux C, Jolivet L, *et al.* 2015. 3D modelling of the Sorbas Basin (Spain): new constraints on the Messinian Erosional Surface morphology. *Mar Pet Geol* 66:101–116.
- Do Couto D, Popescu S-M, Suc J-P, *et al.* 2014. Lago Mare and the Messinian Salinity Crisis: evidence from the Alboran Sea (S. Spain). *Mar Pet Geol* 52: 57–76.
- Dolson JC, Boucher PJ, Siok J, Heppard PD. 2005. Key challenges to realizing full potential in an emerging giant gas province: Nile Delta/Mediterranean offshore, deep water, Egypt. In: Doré AG, Vining BA, eds. *Petroleum Geology: North-West Europe and global perspectives*. Proceedings of the 6th Petroleum Geology Conference. Geological Society of London, 2005, pp. 607–624.
- Dromart G, Suc J-P, Popescu S-M, Rubino J-L. 2024. The Pliocene succession of Lyon Metropolis (SE France): an overfill of a Messinian incised-valley. *BSGF – Earth Sci Bull* 19:6.
- Druckman Y, Buchbinder B, Martinotti GM, Siman Tov R, Aharon P. 1995. The buried Afik Canyon (eastern Mediterranean, Israel): a case study of a tertiary submarine canyon exposed in Late Messinian times. *Mar Geol* 123: 167–185.
- Druitt TH, Kutterolf S, Ronge TA, *et al.* 2024. Site U1591. In: Druitt TH, Kutteroff S, Ronge TA, *et al.* eds. *Proceedings of the international ocean discovery program*, 398, College Station, 105.
- El Euch-El Koundi N, Ferry S, Suc J-P, *et al.* 2009. Messinian deposits and erosion in northern Tunisia: inferences on Strait of Sicily during the Messinian Salinity Crisis. *Terra Nova* 21: 41–48.
- Farouk S, Ziko A, Eweda SA, Said AE. 2014. Subsurface Miocene sequence stratigraphic framework in the Nile Delta, Egypt. *J Afr Earth Sci* 91: 89–109.
- Fauquette S, Suc J-P, Bertini A, *et al.* 2006. How much did climate force the Messinian salinity crisis? Quantified climatic conditions from pollen records in the Mediterranean region. *Palaeogeogr Palaeoclimatol Palaeoecol* 238: 281–301.
- Gargani J. 2004. Modelling of the erosion in the Rhone valley during the Messinian crisis (France). *Quat Intern* 121: 13–22.
- Gargani J. 2024. Relative sea level and coastal vertical movements in relation to volcanic-tectonic processes at Mayotte Island, Indian Ocean. *GeoHazards* 5: 329–349.
- Gargani J, Moretti I, Letouzey J. Evaporite accumulation during the Messinian Salinity Crisis: the Suez Rift case. *Geophys Res Lett* 35: L02401.
- Gargani J, Rigollet C. 2007. Mediterranean Sea-level variations during the messinian salinity crisis. *Geophys Res Lett* 34:110–405.
- Gargani J, Rigollet C, Scarcelli S. 2010. Isostatic response and geomorphological evolution of the Nile Valley during the Messinian salinity crisis. *BSGF* 181: 19–26.
- Gautier F, Clauzon G, Suc J-P, Cravatte J, Violanti D. 1994. Age et durée de la crise de salinité messinienne. *CR Acad Sci Paris* 318 (S2): 1103–1109.
- Gibert L, Scott GR, Montoya P, *et al.* 2013. Evidence for an African-Iberian mammal dispersal during the pre-evaporitic Messinian. *Geology* 41: 691–694.
- Ginat H, Zilberman E, Avni Y. 2000. Tectonic and paleogeographic significance of the Edom River, a Pliocene stream that crossed the dead sea Rift Valley. *Isr J Earth Sci* 49: 159–177.
- Giresse P, Bassetti M-A, Chanier F, *et al.* 2015. Depositional environment and age of some key Late Pliocene to Early Quaternary deposits on the underfilled Cedrino paleovalley (Orosei): insight into the Neogene geodynamic evolution of Sardinia. *Quat Intern* 357: 220–236.
- Golovina LA, Radionova EP, van Baak CGC, Krijgsman W, Palcu DV. 2019. A Late Maeotian age (6.7–6.3 Ma) for the enigmatic “Pebbly Breccia” unit in DSDP Hole 380A of the Black Sea. *Palaeogeogr Palaeoclimatol Palaeoecol* 533:109269.
- Gorini C, Montadert L, Rabineau M. 2015. New imaging of the salinity crisis: dual messinian lowstand megasequences recorded in the deep basin of both the eastern and western Mediterranean. *Mar Pet Geol* 66: 278–294.
- Görür N, Çağatay MN, Sakinc M, *et al.* 1997. Origin of the Sea of Marmara deduced from Neogene to Quaternary paleogeographic evolution of its frame. *Int Geol Rev* 39: 342–352.
- Grasso M, Pedley HM. 1988. The sedimentology and development of Terravecchia Formation carbonates (Upper Miocene) of north central Sicily: possible eustatic influence on facies development. *Sedim Geol* 57: 131–149.
- Haq B, Gorini C, Baur J, Moneron J, Rubino J-L. 2020. Deep Mediterranean’s Messinian evaporite giant: how much salt? *Global Planet Change* 184:103052.
- Heida H, García-Castellanos D, Jiménez-Munt I, *et al.* 2024. Seaway restriction, sea level drop and erosion in the Alboran Basin from a paleotopographic reconstruction for the Messinian Salinity Crisis. *Mar Geol* 474:107300.
- Hilgen FJ, Lourens LJ, Van Dam JA. 2012. The Neogene Period. In: Gradstein FM, Ogg JG, Schmitz M, Ogg G, eds. *The geologic time scale 2012*, Elsevier, pp. 923–978.
- Hsü KJ, Montadert L, Bernoulli D, *et al.* 1978. Site 378: Cretan Basin. In: Ryan WBF, Hsü KJ, Montadert L, eds. *Leg 42A. Initial Reports of the Deep Sea Drilling Project 42(1)*, U.S. Government Printing office, pp. 321–357.
- Hsü KJ, Ryan WBF, Cita MB. 1973. Late Miocene desiccation of the Mediterranean. *Nature* 242: 240–244.
- Hsü KJ, Giovanoli F. 1979–1980. Messinian event in the Black Sea. *Palaeogeogr Palaeoclimatol Palaeoecol* 29: 75–93.
- Infoterre (BRGM) available from <http://www.infoterre.brgm.fr>.
- Jiménez-Moreno G, Popescu S-M, Ivanov I, Suc J-P. 2007. Neogene flora, vegetation and climate dynamics in southeastern Europe and the northeastern Mediterranean. In: Williams M, Haywood AM, Gregory FJ, Schmidt DN, eds. *Deep-time perspectives on climate change: marrying the signal from computer models and biological proxies*. London: The Micropalaeontological Society, Special Publications, The Geological Society, pp. 503–516.
- Jolivet L, Augier R, Robin C, Suc J-P, Rouchy JM. 2006. Lithospheric-scale geodynamic context of the Messinian salinity crisis. *Sedim Geol* 188–189: 9–33.
- Karakitsios V, Cornée J-J, Tsourou T, *et al.* 2017. Messinian salinity crisis record under strong freshwater input in marginal, intermediate, and deep environments: the case of the North Aegean. *Palaeogeogr Palaeoclimatol Palaeoecol* 485: 316–335.
- 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, Palcu DV, Andreotto F, Stoica M, Mandic O. 2020a. Changing seas in the late Miocene Northern Aegean: a Paratethyan approach to Mediterranean basin evolution. *Earth-Sci Rev* 210:103386.

- Krijgsman W, Rohling EJ, Palcu DV, *et al.* 2024. Causes and consequences of the Messinian salinity crisis. *Nature Rev Earth Environ* 5: 335–350.
- Krijgsman W, Stoica M, Hoyle TM, *et al.* 2020b. The myth of the Messinian Dardanelles: Late Miocene stratigraphy and palaeogeography of the ancient Aegean-Black Sea gateway. *Palaeogeogr Palaeoclimatol Palaeoecol* 560:110033.
- 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.
- Leever KA, Matenco L, Rabagia T, Cloetingh S, Krijgsman W, Stoica M. 2010. Messinian sea level fall in the Dacic Basin (Eastern Paratethys): palaeogeographical implications from seismic sequence stratigraphy. *Terra Nova* 22: 12–17.
- Leroux E, Rabineau M, Aslanian D, *et al.* 2017. High-resolution evolution of terrigenous sediment yields in the Provence basin during the last 6 Ma: relation with climate and tectonics. *Bas Res* 29: 305–339.
- Le Strat P. 2005. Expertise géologique Gaz de France NACAP. Rapport final – BRGM/RC-53834-FR: 20 pp.
- Lirer F, Foresi L, Iaccarino SM, *et al.* 2019. Mediterranean Neogene planktonic foraminifer biozonation and biochronology. *Earth-Sci Rev* 196:102869.
- Lofi J, Gorini C, Berné S, *et al.* 2005. Erosional processes and paleoenvironmental changes in the Western Gulf of Lions (SW France) during the Messinian Salinity Crisis. *Mar Geol* 217: 1–30.
- Lofi J, Sage F, Déverchère J, *et al.* 2011. Refining our knowledge of the Messinian salinity crisis records in the offshore domain through multi-site seismic analysis. *Bull Soc géol France* 182(2): 163–180.
- Londeix L, Benzakour M, Suc J-P, Turon J-L. 2007. Messinian paleoenvironments and hydrology in Sicily (Italy): The dinoflagellate cyst record. *Geobios* 40(3): 233–250.
- Madof AS, Bertoni C, Lofi J. 2019. Discovery of vast fluvial deposits provides evidence for drawdown during the late Miocene Messinian salinity crisis. *Geology* 47: 171–174.
- Maillard A, Gaullier V, Lézin C, Chanier F, Odonne F, Lofi J. 2020. New onshore/offshore evidence of the Messinian Erosion Surface from key areas: the Ibiza-Balearic Promontory and the Orosei-Eastern Sardinian margin. *Earth Sci Bull* 191:9.
- Maniscalco R, Casciano CI, Distefano S, Grossi F, Di Stefano A. 2019. Facies analysis in the Second Cycle Messinian evaporites predating the early Pliocene reflooding: the Balza Soletta section (Corvillo Basin, central sicily). *Ital J Geosci* 138: 301–316.
- Manzi V, Gennari R, Hilgen FJ, *et al.* 2013. Age refinement of the Messinian salinity crisis onset in the Mediterranean. *Terra Nova* 25: 315–322.
- Manzi V, Gennari R, Lugli S, *et al.* 2021b. Synchronous onset of the Messinian salinity crisis and diachronous evaporite deposition: new evidences from the deep eastern Mediterranean basin. *Palaeogeogr Palaeoclimatol Palaeoecol* 584:110685.
- Manzi V, Roveri M, Argnani A, Cowan D, Lugli S. 2021a. Large-scale mass-transport deposits recording the collapse of an evaporitic platform during the Messinian salinity crisis (Caltanissetta basin, Sicily). *Sedim Geol* 424:106003.
- Martini E. 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In: Farinacci A, ed. *Proceedings of the 2nd International Conference on Planktonic Microfossils*, Roma 1970, vol. 2. Editura Tecnoscienza, Rome, pp. 739–785.
- Martinotti GM, Gvirtzman G, Buchbinder B. 1978. The Late Miocene marine transgression in the Be'er Sheva area. *Isr Journ Earth Sci* 27: 72–82.
- MăruŃeanu M, Papaianopol I. 1995. The connection between the Dacic and Mediterranean basins based on calcareous nannoplankton assemblages. *Rom J Stratigr* 76(7): 169–170.
- MăruŃeanu M, Papaianopol I. 1998. Mediterranean calcareous nannoplankton in the Dacic Basin. *Rom J Stratigr* 78: 115–121.
- Marzocchi A, Flecker R, van Baak CGC, Lunt DJ, Krijgsman W. 2016. Mediterranean outflow pump: an alternative mechanism for the lago-mare and the end of the Messinian Salinity Crisis. *Geology* 44: 523–526.
- Masquelet C, Leroy S, Delescluse M, *et al.* 2022. The East-Mayotte new volcano in the Comoros Archipelago: structure and timing of magmatic phases inferred from seismic reflection data. *CR Géoscience, Science de la Planète* 35(S2): A13.
- Meilijson A, Hilgen F, Sepúlveda J, *et al.* 2019. Chronology with a pinch of salt: integrated stratigraphy of Messinian evaporites in the deep eastern Mediterranean reveals long-lasting halite deposition during the Atlantic connectivity. *Earth-Sci Rev* 194: 374–398.
- Melinte-Dobrinescu MC, Suc J-P, Clauzon G, *et al.* 2009. The Messinian Salinity Crisis in the Dardanelles region: chronostratigraphic constraints. *Palaeogeogr Palaeoclimatol Palaeoecol* 278: 24–39.
- Méon-Vilain H. 1970. Palynologie des formations miocènes supérieures et pliocènes du bassin du Rhône. *Documents du Laboratoire de Géologie de la Faculté des Sciences de Lyon* 38, 167 pp.
- Micallef A, Camerlenghi A, Georgiopolou A, *et al.* 2019. Geomorphic evolution of the Malta Escarpment and implications for the Messinian evaporative drawdown in the eastern Mediterranean Sea. *Geomorphology* 327: 264–283.
- Mocochain L, Blanpied C, Revillon S, Suc J-P, Müller C, Melinte-Dobrinescu MC. 2024. The Psematismenos-Maroni Basin (South Cyprus): Cenozoic tectonic and sedimentary evolution. *BSGF – Earth Sci Bull*, 220020. <https://doi.org/10.1051/bsgf/2024020>.
- Mocochain L, Blanpied C, Suc J-P, *et al.* 2015. Some examples of peripheral basins affected by the Messinian salinity crisis in the Eastern Mediterranean: Paper 11387 presented at European Geophysical Union General Assembly, Vienna, Austria, 12-17 April.
- Moneron J, Gvirtzman Z. 2022. Late Messinian submarine channel system in the Levant Basin: challenging the desiccation scenario. *Geology* 50: 1366–1371.
- Müller C. 1990. Nannoplankton biostratigraphy and paleoenvironmental interpretations from the Tyrrhenian Sea, ODP Leg 107 (Western Mediterranean). In: Kastens KA, Mascle J, *et al.* eds. *Proceedings of the ocean drilling program, scientific results*, TX: College Station, 107, pp. 495–511.
- Néraudeau D. 2007. Les bioaccumulations néogènes (calcaires à algues, faluns) d'Europe occidentale et leurs relations avec la crise messinienne. *CR Palevol* 6: 59–71.
- Néraudeau D, Goubert E, Lacour D, Rouchy JM. 2001. Changing biodiversity of Mediterranean irregular echinoids from the Messinian to Present-Day. *Palaeogeogr Palaeoclimatol Palaeoecol* 175: 43–60.
- Néraudeau D, Roman J, Borghi E. 1999. Impact of the Messinian crisis on the Mediterranean echinoid fauna. In: Candia Carnevali M, Bonasoro F, eds. *Echinoderm research*. Rotterdam (The Netherlands): Balkema AA, pp. 355–360.
- Okay AI, Özcan E, Hakyemez A, *et al.* 2019. The Thrace Basin and the Black Sea: the Eocene-Oligocene marine connection. *Geol Mag* 156: 39–61.
- Osman MK, Bessedik M, Belkebir L, *et al.* 2021. Messinian to Piacenzian deposits, erosion, and subsequent marine bioevents in

- the Dahra Massif (Lower Chelif Basin, Algeria). *Arab Journ Geosci* 14:684.
- Palmieri G, Harby H, Marini JA, Hashem F, Dalla S, Shash M. 1996. Baltim fields complex: an outstanding example of hydrocarbon accumulations in a fluvial Messinian incised valley. In: Youssef M, ed. *Proceedings of the 13th petroleum conference*, Cairo, Egypt. The Egyptian General Petroleum Corporation, pp. 256–269.
- Pawellek T, Adnet S, Cappetta H, *et al.* 2012. Discovery of an earliest Pliocene relic tropical fish fauna in a newly detected cliff section (Sabratat Basin, NW Lybia). *N Jb Geol Paläont Abh* 266(2): 93–114.
- Pellen R, Aslanian D, Rabineau M, *et al.* 2019. The Messinian Ebro River incision. *Global Planet Change* 181:102988.
- Pellen R, Aslanian D, Rabineau M, *et al.* 2022. Structural and sedimentary origin of the Gargano - Pelagosa gateway and impact on sedimentary evolution during the Messinian Salinity Crisis. *Earth-Sci Rev* 232:104114.
- Pellen R, Gorini C, Aslanian D, *et al.* 2021. Implication des reconstructions palinspastiques dans l'évolution des seuils centraux méditerranéens durant la crise de salinité messinienne. 27th RST Lyon, T11.10, p. 646.
- Pellen R, Popescu S-M, Suc J-P, *et al.* 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: 237–257.
- Pensa T, Huertas AD, Afifi AM. 2025. Desiccation of the Red Sea basin at the start of the Messinian salinity crisis was followed by major erosion and reflooding from the Idian Ocean. *Comm Earth Environ* 6:649.
- Perch-Nielsen K, 1985. Cenozoic calcareous nannofossils. In: Bolli HM, Saunders JB, Perch-Nielsen K, eds. *Plankton stratigraphy*. Cambridge: Cambridge University Press, vol. 1, pp. 427–554.
- Poisson A, Orszag-Sperber F, Kosun E, *et al.* 2011. The Late Cenozoic evolution of the Aksu basin (Isparta Angle; SW Turkey). New insights. *Bull Soc géol Fr* 182(2): 133–148.
- Popescu S-M, Cavazza W, Suc J-P, Melinte-Dobrinescu MC, Barhoun N, Gorini C. 2021. Pre-Zanclean end of the Messinian Salinity Crisis: new evidence from central Mediterranean reference sections. *J Geol Soc* 178: jgs2020–183.
- Popescu S-M, Dalesme F, Jouannic G, *et al.* 2009. *Galeacysta etrusca* complex: dinoflagellate cyst marker of Paratethyan influxes to the Mediterranean Sea before and after the peak of the Messinian Salinity Crisis. *Palynology* 33: 105–134.
- Popescu S-M, Dalibard M, Suc J-P, *et al.* 2015. Lago Mare episodes around the Messinian–Zanclean boundary in the deep southwestern Mediterranean. *Mar Pet Geol* 66: 55–70.
- Popescu S-M, Krijgsman W, Suc J-P, Clauzon G, MăruŃeanu M, Nica T. 2006. Pollen record and integrated high-resolution chronology of the early Pliocene Dacic Basin (southwestern Romania). *Palaeogeogr Palaeoclimatol Palaeoecol* 238: 78–90.
- Popescu S-M, Melinte M-C, Suc J-P, Clauzon G, Quillévéré F, Sütö-Szentai M. 2007. Earliest Zanclean age for the “latest Messinian” northern Apennines: new palaeoenvironmental data from the Maccarone section (Marche province, Italy). *Geobios* 40: 359–373.
- Popescu S-M, Melinte-Dobrinescu MC, Suc J-P, Do Couto D. 2017. *Ceratolithus acutus* Gartner and Bukry 1974 (= *C. armatus* Müller 1974), calcareous nannofossil marker of the marine reflooding that terminated the Messinian Salinity Crisis: Comment on “Paratethyan ostracods in the Spanish Lago-Mare: More evidence for interbasinal exchange at high Mediterranean sea level” by Stoica, *et al.* 2016. *Palaeogeogr Palaeoclimatol Palaeoecol* 441: 854–870. *Palaeogeogr Palaeoclimatol Palaeoecol* 485: 986–989.
- Proedrou P, Papaconstantinou CM. 2004. Prinos Basin - a model for oil exploration. *Bull Geol Soc Greece* 36: 327–333.
- Raffi I, Backman J, Fornaciari E, *et al.* 2006. A review of calcareous nannofossil astrobiochronology encompassing the past 25 million years. *Quat Sci Rev* 25: 3113–3137.
- Rodriguez M, Sakellariou D, Gorini C, *et al.* 2023. Evolution of the North Anatolian Fault from a diffuse to a localized shear zone in the North Aegean Sea during the Plio–Pleistocene. *Geophys J Intern* 235: 2614–2639.
- Roveri M, Bassetti MA, Ricci Lucchi F. 2001. The Mediterranean Messinian salinity crisis: an Apennine foredeep perspective. *Sedim Geol* 140: 201–214.
- Roveri M, Flecker R, Krijgsman W, *et al.* 2014a. The Messinian Salinity Crisis: past and future of a great challenge for marine sciences. *Mar Geol* 352: 25–58.
- Roveri M, Gennari R, Ligi M, Lugli S, Manzi V, Reghizzi M. 2019. The synthetic seismic expression of the Messinian salinity crisis from onshore records: implications for shallow-to deep-water correlations. *Basin Res* 41:12361.
- Roveri M, Lugli S, Manzi V. 2025. The desiccation and catastrophic refilling of the Mediterranean: 50 years of facts, hypotheses, and myths around the Messinian Salinity Crisis. *Ann Rev Mar Sci* 17: 485–509.
- Roveri M, Lugli S, Manzi V, Gennari R, Schreiber BC. 2014b. High-resolution strontium isotope stratigraphy of the Messinian deep Mediterranean basins: implications for marginal to central basins correlation. *Mar Geol* 349: 113–125.
- Roveri M, Lugli S, Manzi V, Schreiber BC. 2008a. The Messinian Sicilian stratigraphy revisited: new insights for the Messinian salinity crisis. *Terra Nova* 20: 483–488.
- Roveri M, Manzi V, Bergamasco A, *et al.* 2014c. Dense shelf water cascading and Messinian canyons: a new scenario for the Mediterranean salinity crisis. *Am J Sci* 314: 751–784.
- Roveri L, Manzi V, Gennari R, Iaccarino SM, Lugli S. 2008b. Recent advancements in the Messinian stratigraphy of Italy and their Mediterranean-scale implications. *Boll Soc Paleontol Ital* 47(2): 71–85.
- Roveri M, Manzi V, Lugli S, *et al.* 2006. Clastic vs. primary precipitated evaporites in the Messinian Sicilian basins. *Acta Naturalia de L'Ateneo Parmense* 42(4): 125–199.
- Rubino J-L, Haddadi N, Camy-Peyret J, *et al.* 2010. Messinian Salinity Crisis expression along North African Margin. *SPE Conf., Le Caire, SPE 129526-PP*, 4 pp.
- Ruggieri G. 1962. La serie marine pliocenica e quaternaria della Val Marecchia. *Atti Acad Sci Lett Arti Palermo* 19: 1–169.
- Ryan WBF. 2023. 50th anniversary review of the Mediterranean desiccation hypothesis. *La Rivista del Nuovo Cimento* 42:9.
- Ryan WBF, Carbotte SM, Coplan JO, *et al.* 2009. Global multi-resolution topography synthesis. *Geochem Geophys Geosyst* 10: Q03014.
- Schuster JM, Auxietre J-L, Biju-Duval B, Letouzey J. 1978. CIDOG Mer Egée/Mer de Crète. Rapport interne IFP-SNEA.
- Snel E, MăruŃeanu M, Meulenkaamp JE. 2006a. Calcareous nannofossil biostratigraphy and magnetostratigraphy of the Upper Miocene and Lower Pliocene of the Northern Aegean (Orphanic Gulf-Strimon Basin areas), Greece. *Palaeogeogr Palaeoclimatol Palaeoecol* 238: 125–150.
- Snel E, MăruŃeanu M, Macalett R, Meulenkaamp JE, van Vugt N. 2006b. Late Miocene to Early Pliocene chronostratigraphic

- framework for the Dacic Basin, Romania. *Palaeogeogr Palaeoclimatol Palaeoecol* 238: 107–124.
- Sternai P, Caricchi L, Garcia-Castellanos D, Jolivet L, Sheldrake TE, Castelltort S. 2017. Magmatic pulse driven by sea-level changes associated with the Messinian salinity crisis. *Nat Geosci* 10: 783–787.
- Stoica M, Krijgsman W, Fortuin A, Gliozzi E. 2016. Paratethyan ostracods in the Spanish Lago-Mare: more evidence for basinal exchange at high Mediterranean sea level. *Palaeogeogr Palaeoclimatol Palaeoecol* 441: 854–870.
- Suc J-P, Do Couto D, Melinte-Dobrinescu MC, *et al.* 2011. The Messinian Salinity Crisis in the Dacic Basin (SW Romania) and early Zanclean Mediterranean-Eastern Paratethys high sea-level connection. *Palaeogeogr Palaeoclimatol Palaeoecol* 310: 256–272.
- Suc J-P, Fauquette S, Warny S, Jiménez-Moreno G, Do Couto D. 2023. Climate and Atlantic sea-level recorded in Southwestern Spain from 6.3 to 5.2 Ma. Inferences on the Messinian Crisis in the Mediterranean. *BSGF – Earth Sci Bull* 194:15.
- Suc J-P, Gillet H, Çağatay MN, *et al.* 2015b. The region of the Strandja Sill (North Turkey) and the Messinian events. *Mar Pet Geol* 66: 149–164.
- Suc JP, Gorini C, Rabineau M, *et al.* 2019. La Crise de salinité messinienne. *Géochronique* 151: 24–30.
- Suc J-P, Popescu S-M, Do Couto D, *et al.* 2015a. Marine gateway vs. fluvial stream within the Balkans from 6 to 5 Ma. *Mar Pet Geol* 66: 231–245.
- Ter Borgh M, Stoica M, Donselaar ME, Matenco L, Krijgsman W. 2014. Miocene connectivity between the Central and Eastern Paratethys: constraints from the western Dacian Basin. *Palaeogeogr Palaeoclimatol Palaeoecol* 412: 45–67.
- Thinon I, Guennoc P, Serrano O, Maillard A, Lasseur E, Réhault JP. 2016. Seismic markers of the Messinian Salinity Crisis in an intermediate-depth basin: data for understanding the Neogene evolution of the Corsica Basin (northern Tyrrhenian Sea). *Mar Pet Geol* 77: 1274–1296.
- Tzevahirtzian A, Caruso A, Andreetto F, Bonomo S, Krijgsman W. 2023. A bio-chronostratigraphic study of the upper Miocene from the northern Caltanissetta Basin, Sicily (core 3AGN2S04). Implications for dating the Messinian Salinity Crisis onset. *Sedim Geol* 445:106330.
- 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: 179–187.
- Van Dijk G, Maars J, Andreetto F, Hernández-Molina FJ, Rodríguez-Tovar FJ, Krijgsman W. 2023. A terminal Messinian flooding of the Mediterranean evidenced by contouritic deposits on Sicily. *Sedimentology* 70: 1195–1223.
- Varesis A, Anastasakis G. 2021. Cenozoic marine basin evolution in the Western North Aegean through margin: seismic stratigraphic evidence. *Water* 13:2267.
- Warny SA, Wrenn JH. 2002. Upper Neogene dinoflagellate cysts of the Atlantic coast of Morocco. *Micropaleontol* 48(3): 257–272.
- Young JR. 1998. Chapter 8: Neogene. In: Bown PR, ed. *Calcareous nannofossils biostratigraphy*. Kluwer, Dordrecht: British Micropaleontological Society Publications Series, pp. 225–265.
- Zilberman E, Siman-Tov R, Almogi-Labin A, *et al.* 2010. Late Miocene (Messinian) to earliest Pliocene submarine density flow sediments in the Nesher Quarry, and their implications on the timing of the Carmel Mountain uplift. *Rep Geol Surv Isr* 31: 44 pp.

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