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A record of the Messinian salinity crisis in the eastern Ionian tectonically active domain (Greece, eastern Mediterranean)

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**A record of the Messinian Salinity Crisis in the eastern
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3 **A record of the Messinian Salinity Crisis in the eastern Ionian tectonically-active**
4 **domain (Greece, eastern Mediterranean)**
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Abstract

This integrated study of the Messinian-Zanclean deposits on Zakynthos Island (Ionian Sea) reveals the effect of the Messinian salinity crisis (MSC) in a transitional area between the eastern and the western Mediterranean. The proposed paleogeographic model incorporates new paleontologic, sedimentologic, biostratigraphic, paleomagnetic, and geochemical data. In the Kalamaki-Agassi section, the selenite

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3 gypsum is assigned to the Primary Lower Gypsum (PLG) unit deposited during the
4 first MSC stage (5.971-5.60 Ma). In the Agios Sostis section, the gypsum is clastic in
5 origin, derived from the dismantlement and re-sedimentation during the second MSC
6 stage (5.60-5.55 Ma) of PLG deposits formed in a western basin.
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9 In the Kalamaki pre-evaporitic sequence, nine planktonic foraminifer bioevents are
10 recognized. Five planktonic foraminifer bioevents, nine lithological cycles, and ten
11 oxygen isotope stages are identified within the Pliocene Trubi Formation.
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13 Sedimentologic and paleoecologic analysis indicates a shallow water environment,
14 less than 300 m before the onset of evaporite deposition. Oxygen and carbon isotopic
15 analyses in the upper part of the pre-evaporitic sequence provide evidence for
16 increased isotopically-light carbon input from bacterial sulfate reduction, due to
17 increasing stagnation conditions at the beginning of sulfate deposition. Two intervals
18 are distinguished through the paleoenvironmental reconstruction of the pre-evaporitic
19 Messinian in Kalamaki area: a) 6.45-6.122 Ma and b) 6.122-5.97 Ma. Both the
20 planktonic foraminifer and fish assemblages indicate a cooling phase punctuated by
21 hypersalinity episodes at around 6.05 Ma.
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23 Field observations, borehole data, and seismic profiles indicate that the deposition of
24 Messinian gypsum took place in marginal sub-basins, which formed during the late
25 Messinian in the Pre-Apulian foreland basin before the main phase of the tectonic
26 emplacement of the Ionian zone. In this foreland basin, the Neogene formations over
27 the Ionian zone (east of the westernmost Triassic diapir) formed in the wedge-top
28 depozone, while those overlying Pre-Apulian zone correspond to the main foredeep
29 and the foreland ramp to the foredeep. Erosion of PLG evaporites in the forebulge and
30 wedge-top areas, supplied the foreland basin depocenter with gypsum turbidites.
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44 **Keywords**

45 Gypsum; foreland basin; evaporites; Zakynthos; paleogeography
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49 **1. Introduction**

50 The Messinian salinity crisis (MSC; Selli, 1954), the greatest Mediterranean
51 paleoenvironmental perturbation, still offers a fascinating story tale, which inspired
52 researchers for more than fifty years. Despite the fact that certain aspects have been
53 investigated to great extent, major questions still remain open regarding the
54 mechanisms operating during this event (see Roveri *et al.*, 2014a). The scope of the
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3 present study is to describe, in detail, the Messinian-Zanclean deposits and their
4 inclusive fauna in Zakynthos Island (Ionian Sea), a pivotal area located at the
5 transition between the eastern and the western Mediterranean. The MSC-associated
6 environmental changes are revealed through high-resolution integrated stratigraphy.
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8 Furthermore, a new tectono-sedimentary evolution model is proposed incorporating
9 new paleontologic, sedimentologic, biostratigraphic, paleomagnetic, and geochemical
10 data.
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15 16 **2. The Messinian salinity crisis**

17 Since the early Messinian (7.251 Ma), the gradual restriction of the marine
18 connections between the Mediterranean Sea and the Atlantic Ocean was combined
19 with long-term orbital forcing (Hilgen *et al.*, 2007) to significantly alter the
20 paleoenvironmental conditions in the entire basin. A series of events has been
21 recorded as a result: a) a reduction of deep-water ventilation at 7.15 Ma
22 (Kouwenhoven *et al.*, 1999; 2003; 2006; Kouwenhoven and Van der Zwaan, 2006)
23 associated with diatom-rich and opal-rich sediment deposition between 7.15-6.7 Ma,
24 b) a sudden drop in calcareous plankton diversity at 6.7 Ma (Sierro *et al.*, 1999; 2003;
25 Blanc-Valleron *et al.*, 2002), c) the intensification of bottom-water stagnation and
26 stratification (Kouwenhoven *et al.*, 1999; Sierro *et al.*, 1999; Blanc-Valleron *et al.*,
27 2002; Sierro *et al.*, 2003; Van Assen *et al.*, 2006), d) calcareous sediment
28 precipitation between 6.3-5.97 Ma, and e) the complete disappearance of planktonic
29 foraminifers during summer insolation minima (Sierro *et al.*, 1999; Bellanca *et al.*,
30 2001; Blanc-Valleron *et al.*, 2002; Sierro *et al.*, 2003; Manzi *et al.*, 2007; 2011; 2013;
31 Gennari *et al.*, 2013).
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34 According to the three-step model for the development of the salinity crisis proposed
35 by Roveri *et al.* (2008a; 2014a), the MSC Stage 1 commenced synchronously at 5.97
36 Ma throughout the Mediterranean basin (Krijgsman *et al.*, 1999a; 2002; Manzi *et al.*,
37 2013). It is recorded by evaporite deposition, the Primary Lower Gypsum (PLG), in
38 the marginal areas (including basins with water depth less than 200 m) and by
39 evaporite-free dolomites and organic-rich shales, in the intermediate and deeper
40 basins (Manzi *et al.*, 2007; 2011; De Lange and Krijgsman, 2010; Dela Pierre *et al.*,
41 2012). The deposition of gypsum took place subaqueously, in shallow water settings
42 with moderate oxygenation (Lugli *et al.*, 2010). The deposition of up to 16
43 precession-induced gypsum-marl cycles comprising PLG continued until ~5.6 Ma
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3 (Vai 1997; Krijgsman *et al.*, 1999b; Hilgen *et al.*, 2007; Lugli *et al.*, 2010), and was
4 concluded by a major subaerial exposure event creating the Messinian Erosional
5 Surface (MES) in the marginal basins.
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8 During MSC stage 2 (5.6 – 5.55 Ma; Roveri *et al.*, 2014a), the Messinian Erosional
9 Surface (MES) developed across the Mediterranean margins due to subaerial erosion.
10 Two intense glacial periods (TG14 and TG12) further limited fresh-water input and
11 probably stopped the outflow of Mediterranean water to the Atlantic (Meijer and
12 Krijgsman, 2005; Hilgen *et al.*, 2007; Roveri *et al.*, 2014a). Primary halite
13 occasionally precipitated in the marginal basins (Manzi *et al.*, 2012) as well as in the
14 sub-basins (Lugli *et al.*, 1999). In the margins, tectonic activity, in conjunction with
15 general slope instability, led to the erosion and resedimentation of the PLG and the
16 widespread deposition of clastic evaporites (Resedimented Lower Gypsum; RLG
17 *sensu* Roveri *et al.*, 2008b) throughout the Mediterranean (Ricci Lucchi, 1973;
18 Robertson *et al.*, 1995; Kontopoulos *et al.*, 1997; Fortuin and Krijgsman, 2003;
19 Roveri *et al.*, 2003; Manzi *et al.*, 2005; Roveri and Manzi, 2006; Manzi *et al.*, 2011;
20 Omodeo-Salé *et al.*, 2012; Lugli *et al.*, 2013; Roveri *et al.*, 2014a; Manzi *et al.*, 2015).
21 On Sicily, RLG deposited in adjacent depocenters as a result of tectonic activity
22 (Butler *et al.*, 1995; Roveri *et al.*, 2008a; Manzi *et al.*, 2011) and is associated with
23 hydrocarbon migration (Iadanza *et al.*, 2013).
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26 The MSC stage 3 (5.55 – 5.33 Ma; Manzi *et al.*, 2009; Roveri *et al.*, 2014a) was
27 characterized by selenite and cumulate gypsum precipitation in the shallow-water sub-
28 basins of Sicily and Cyprus (Rouchy, 1982; Roveri *et al.*, 2008a; Manzi *et al.*, 2009;
29 2015); mostly clastic sediments were deposited in the northern and western
30 Mediterranean. Typical of this stage is the Lago-Mare facies (Gignoux, 1936;
31 Ruggieri, 1967; Orszag-Sperber, 2006), brackish to fresh-water sediments with
32 Paratethyan fauna, indicating surface-water dilution which may have been locally
33 interrupted by evaporitic events (Upper Gypsum; UG; Manzi *et al.*, 2009). The most
34 widely accepted scenario so far hypothesizes a complete isolation of the
35 Mediterranean from the Atlantic, with occasional connection to the Paratethys
36 (Orszag-Sperber, 2006; Rouchy & Caruso, 2006; Roveri *et al.*, 2008b). However, the
37 fossil fish record of northern Italy (Carnevale *et al.*, 2006; 2008), as well as biomarker
38 evidence (Mezger, 2012), suggests that the Mediterranean retained its connection to
39 the Atlantic, although maybe not continuously (Roveri *et al.*, 2014a,b,c).
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3 The end of the MSC and the return to fully marine conditions is considered to have
4 taken place at 5.33 Ma through a catastrophic event, flooding the entire Mediterranean
5 basin (Hsu *et al.*, 1973; Blanc-Valleron, 2002; Meijer & Krijgsman, 2005; Garcia-
6 Castellanos *et al.*, 2009). Lithologic and paleontologic observations generally concur
7 to this hypothesis. The Messinian/Zanclean boundary commonly includes a
8 transitional interval, rich in organic matter (Roveri *et al.*, 1998; 2008b; Gennari *et al.*,
9 2008), and it is followed by the typical early Pliocene marine deposits of the ‘Trubi’
10 or ‘Argille Azzurre’ Formations.

17 18 **3. Geological setting**

19 The Zakynthos Island’s alpine sequence belongs (Fig. 1) to the Pre-Apulian and partly
20 to the Ionian zone – separated by the Ionian thrust – whose emplacement took place
21 during the early Pliocene (BP, 1971; Sorel, 1976; Nikolaou, 1986; Underhill, 1989,
22 Karakitsios & Rigakis, 2007). The Pre-Apulian zone of Zakynthos comprises Upper
23 Cretaceous to Pleistocene sediments, while the Ionian zone is represented by Triassic
24 breccias and microcrystalline gypsum corresponding to the lower stratigraphic unit of
25 this zone. Cretaceous to Oligocene carbonates outcrop on Marathonisi Islet (2.5 km
26 east of Keri; Fig. 1) and probably represent a transitional facies between the Ionian
27 and Pre-Apulian domains (Nikolaou, 1986). Numerous reverse faults cut the Pre-
28 Apulian sequence along the NW-SE direction, exposing late Miocene sandstones and
29 marls along the coastal sections between Agios Sostis and Keri (Fig. 1); these are
30 significantly folded, indicating a post-Miocene age for the Ionian thrust emplacement
31 (Underhill, 1989; Karakitsios, 2013).

32 The Ionian sequence is unconformably overlain by Neogene and Quaternary deposits
33 outcropping mainly in southeastern Zakynthos. These are similar to those of the Pre-
34 Apulian zone, but thinner and characterized by unconformities (Dermitzakis, 1977;
35 Nikolaou, 1986), and they consist of early Miocene clastic sediments outcropping in
36 the Skopos area, followed by late Messinian marls and shales (30-100 m thick)
37 intercalated by gypsum (Fabricius *et al.*, 1998). The early Pliocene deposits include
38 calcareous pelagic marls (Trubi limestone) and sandstone intercalations (Kontopoulos
39 *et al.*, 1997). The late Pliocene to Pleistocene deposits comprise a transgressive clastic
40 sequence recording sea-level changes concurrent with intense tectonic movements
41 (Triantaphyllou, 1996; Triantaphyllou *et al.*, 1997; Duermeijer *et al.*, 1999; Zelilidis
42 *et al.*, 1998; Agiadi *et al.*, 2010; Papanikolaou *et al.*, 2011).

4. Methods

4.1 Field geology, borehole, and seismic data

Field observations were combined with detailed sampling along the Kalamaki-Argassi and Agios Sostis areas, in the south-eastern part of Zakynthos Island. A main concern was to distinguish the Ionian zone Triassic gypsum (Karakitsios, 1995) from the Messinian gypsum, both expressed in this area. The Ionian thrust's cartographic position and the Neogene deposits' distribution were based on new tectonic, stratigraphic, and sedimentologic observations, in conjunction with a reinterpretation of the available boreholes and onshore seismic data.

4.2 Planktonic Foraminifera

In the Kalamaki and Agios Sostis sections, 198 samples were collected. In the Kalamaki section, 175 samples were obtained at 0.05 to 0.50-meter intervals in the west (pre-MSC) and the east subsection (Messinian-Zanclean), representing 37.1 m of sediment thickness. In the Agios Sostis section (Fig. 7), 23 samples were collected at 0.05 to 1-meter intervals for a total thickness of 20 m. A total of 14 samples (AS 1-14) were studied from the 16.5 m of the pre-evaporitic sequence (sampling step about 0.30 to 1 m), and nine samples were examined from the 20 m of the post-evaporitic sequence. Three samples (AS 15-17) were obtained from the first 1.20 m of the post-evaporitic sequence, which are rich in gypsum crystals, six samples (AS 18-23) were taken from the last 1.5 m of the Agios Sostis section.

The samples were washed through a 63- μm sieve. Biostratigraphy is based on the semi-quantitative analysis of planktonic foraminifers. The bioevents considered in this study were based on the changes in the planktonic foraminiferal assemblage observed in the fraction larger than 125 μm . The recognition of zonal boundaries was based on the biozonal scheme of Iaccarino *et al.* (2007) and through correlation to the astronomically calibrated succession of the Mediterranean area (Krijgsman *et al.*, 1999b; Sierro *et al.*, 2001; Iaccarino *et al.*, 1999; Gennari *et al.*, 2008).

The planktonic foraminifer paleoecological remarks are based on the quantitative abundance distribution of the species, identified in the section, and their modern ecological affinities (Bè & Tolderlund, 1971; Hemleben *et al.*, 1989).

4.3 Calcareous nannofossils

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3 Smear slides were prepared following the standard technique described by Perch
4 Nielsen (1985) and Bown & Young (1998). The taxonomy of the determined
5 calcareous nannofossil species was in accordance with Aubry (1984, 1988, 1989,
6 1990, and 1999) and Perch-Nielsen (1985). Biostratigraphic analysis was based on the
7 standard biozonal scheme of Martini (1971). Biochronology and the numerical ages of
8 the biozone boundaries were assigned according to Lourens *et al.* (2004), Raffi *et al.*
9 (2006), and Backman *et al.* (2012).

10 Nannofossil biostratigraphy incorporated qualitative and semiquantitative analyses.
11 Qualitative methods are traditionally based on the estimation of index-species
12 presences, obtained through a rough scan of the sample. Concerning semiquantitative
13 methods, these were mainly used to overcome the very terrigenous and relatively
14 shallow nature of the studied samples, in which nannofossils are rather scarce. To
15 obtain accurate biostratigraphic estimations, up to 100 fields of view were
16 investigated per slide, using a Leica DMLSP optical polarizing light microscope at
17 1250x magnification. Semiquantitative abundances of the identified taxa were
18 categorized as follows: A. abundant, more than one specimen in every field of view;
19 C. common, one specimen in every ten fields of view; R. rare, one specimen in every
20 50 fields of view; P. present, one specimen in more than 100 fields of view; and RW.
21 reworked specimens.

22 The biostratigraphic framework for the Trubi deposits was based on the
23 paleoecological affinities of the following calcareous nannofossil species. Small
24 *Gephyrocapsa* spp. $<3 \mu\text{m}$, are considered upper photic-zone opportunistic taxa,
25 indicating eutrophic conditions (e.g., Flores *et al.*, 2005). Discoasterids, generally
26 preferring warm and oligotrophic waters, are lower photic-zone inhabitants, which
27 increase their abundance with deep pycnocline (Flores *et al.*, 2005). *Helicosphaera*
28 *carteri* is commonly found in warm waters (e.g., Baumann *et al.*, 2005), associated
29 with moderately-elevated nutrient levels (e.g., Ziveri *et al.*, 2004). It is commonly
30 accepted as a species tolerant of low salinities and high terrigenous input
31 (Triantaphyllou *et al.*, 2009a,b); it is highly frequent in regions influenced by riverine
32 discharge (e.g., Cros, 2001), as a coastal-water taxon (e.g., Dimiza *et al.*, 2014).
33 In addition, Rhabdosphaeraceae prefer warm and oligotrophic waters (Triantaphyllou
34 *et al.*, 2004; Dimiza *et al.*, 2008; Malinverno *et al.*, 2009) and *Scyphosphaera* spp. are
35 common in tropical-subtropical regions (Rade, 1975).
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4.4 Fish otoliths

The same samples collected for the biostratigraphic analysis were also examined for the fish otolith content. In addition, several 25 kg bulk samples were obtained throughout the pre-evaporitic interval and the upper part (Trubi Formation) of Kalamaki section, as well as from each of the marl beds alternating with the gypsum (Fig. 2). The purpose was to identify the fish fauna in the area before, during, and after the MSC; to determine the timing of the reestablishment of a purely marine fauna after the crisis (Carnevale *et al.*, 2006); and to estimate the paleoenvironmental conditions especially just before the onset of evaporite deposition. Fish otoliths were described according to the criteria set by Nolf (1985) and systematically identified based on the scheme of Nelson (2006). The methodology of Nolf & Brzobohaty (1994), as readjusted by Agiadi *et al.*, (2010), was applied to estimate the paleodepth. The paleoecological analysis was based on the fish's present-day distribution and ecological data acquired through the FishBase database (Froese & Pauly, 2014).

4.5 Magnetostratigraphy

The magnetostratigraphy of the Kalamaki section is based on a subset of the same samples used for biostratigraphy, 61 samples in total (Fig. 2). Core samples were obtained with a water-cooled diamond-head corer installed on an electric driller. The standard specimens were thermally demagnetized in an ASC oven and the natural remanent magnetization (NRM) was measured on a 2G-Enterprises DC SQUIDS cryogenic magnetometer, in a magnetically shielded room at the ALP Laboratory of Peveragno (Italy). Samples were first heated to 90°C, and, then, successive 30°C steps were applied up to a maximum of 560°C. The magnetic susceptibility was monitored during heating to detect mineralogical changes. The NRM dataset was processed using the Remasoft software (Chadima & Hrouda, 2006) to calculate the direction of the characteristic remanent magnetization (ChRM) and the Virtual Geomagnetic Pole (VGP) for each sample.

4.6 Oxygen and carbon stable isotopes

The isotopic composition of bulk sediments and planktonic foraminifers focused on investigating the degree of evaporation before the commencement of evaporite deposition, as well as the system inertia after the MSC. The oxygen and carbon

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3 isotopic compositions were measured on both the bulk sediment (late Miocene
4 deposits; $\delta^{18}\text{O}_{\text{carb}}$, $\delta^{13}\text{C}_{\text{carb}}$) as well as on the planktonic foraminifers *Turborotalita*
5 *multiloba*, *Orbulina universa* (late Miocene; $\delta^{18}\text{O}_{\text{foram}}$, $\delta^{13}\text{C}_{\text{foram}}$) and
6 *Globigerinoides obliquus* (Pliocene; Trubi Formation; $\delta^{18}\text{O}_{G.obliquus}$, $\delta^{13}\text{C}_{G.obliquus}$),
7 using a mass spectrometer VG SIRA 9 and a KIEL-IV carbonate device coupled
8 online to a Delta V Advantage IRMS (Thermo Scientific), respectively. The CO_2
9 extraction was attained through reaction of powder samples (50-100 mg) with
10 anhydrous orthophosphoric acid, at 50°C. The values were expressed in per mil
11 relative to the Vienna PDB (V-PDB) standard reference. Long-term analytical
12 precision reached $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}_{\text{carb}}$, $\pm 0.05\text{‰}$ for $\delta^{13}\text{C}_{\text{carb}}$, $\pm 0.08\text{‰}$ for $\delta^{18}\text{O}_{\text{foram}}$
13 and $\delta^{18}\text{O}_{G.obliquus}$, and $\pm 0.05\text{‰}$ for $\delta^{13}\text{C}_{\text{foram}}$ and $\delta^{13}\text{C}_{G.obliquus}$.

24 4.7 Strontium isotopes

25 Two gypsum samples (Fig. 2) were analyzed for strontium isotope content in order to
26 distinguish the stage 1 PLG deposits from the stage 3 UG (Flecker *et al.*, 2002; Roveri
27 *et al.*, 2014b). Strontium isotope analyses were carried out at the Scottish Universities
28 Environmental Research Centre in East Kilbride, Scotland (SUERC). Samples were
29 leached in 1M ammonium acetate prior to acid digestion with HNO_3 . Strontium was
30 separated using Eichrom Sr Spec resin. Matrix elements were eluted in 8M HNO_3 and
31 3M HNO_3 , before elution of Sr in 0.01M HNO_3 . Total procedure blank for Sr
32 samples prepared using this method was b200 pg. In preparation for mass
33 spectrometry, Sr samples were loaded onto single Re filaments with a Ta-activator
34 similar to that described by Birck (1986). Sr samples were analyzed with a VG Sector
35 54-30 multiple collector mass spectrometer. A ^{88}Sr intensity of 1V (1Å~ 10 – 11A) \pm
36 10% was maintained. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was corrected for mass fractionation using
37 $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and an exponential law. The mass spectrometer was operated in the
38 peak-jumping mode, with data collected as 15 blocks of 10 ratios providing an
39 internal uncertainty of b0.000020 (2 S.E.). For this instrument NIST SRM 987 gave
40 0.710249 ± 0.000008 (1 S.D., $n = 17$) during the course of the present study.

54 5. Results

55 5.1 Field observations

56 5.1.1 Kalamaki–Argassi area

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3 The Neogene sequence of the Kalamaki-Argassi area lies unconformably over the
4 Ionian zone basement. The following stratigraphic units are recognized (Fig. 2):

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6 Pre-evaporitic unit
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8 The lower 14.5 m of the succession consist of alternating massive and laminated
9 marls with rare calcareous-marl and calcarenite intercalations. From 5 to 13 m,
10 bivalves, *Discospirina*, pteropods, echinoids, and molluscs are observed. Between
11 14.5 to 17.5 m, some slumps and chaotic horizons occur. The rest of the pre-
12 evaporitic sequence is partially covered by Quaternary detritus (Fig. 3a).
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16 Evaporitic unit
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18 The previous unit is followed in stratigraphic continuity by a 108 m-thick evaporite
19 succession (Figs. 2 and 4). Eight gypsum-marl cycles are identified (A to H),
20 exhibiting different gypsum depositional facies: massive, massive stratified, banded,
21 laminite, and branching selenite (Lugli *et al.*, 2010); thin gypsrudite and gypsarenite
22 intercalations appear in the upper one-third of the succession (Fig. 3c,d,e,f, and 4).
23 Based on these evaporitic facies and on the conformable superposition on the pre-
24 MSC succession, these deposits can be ascribed to the Primary Lower Gypsum unit
25 (PLG; Roveri *et al.*, 2008a) accumulated during the MSC stage 1 (5.971-5.60;
26 CIESM, 2008; Manzi *et al.*, 2013). The uppermost eight meters of the gypsum
27 succession are clastic deposits, comprising laminated greenish marls; interrupted,
28 after the fourth meter of the succession, by a dm-thick gypsarenite bed (cycle H of
29 depositional gypsum type; Fig. 2). These sediments originate from the hanging wall of
30 a small normal fault separating the lower from the uppermost part of the succession.
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39 Post-evaporitic unit
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41 The uppermost part of the gypsum unit is capped by an angular unconformity (Fig.
42 3b) that can be correlated with the MES (CIESM, 2008; Roveri *et al.*, 2014a). The
43 unconformity is sealed by a four m-thick unit consisting of alternating greenish and
44 discontinuous calcareous marl beds that can be assigned to the uppermost Messinian
45 Lago-Mare 3b). This unit in turn is sharply overlain by the Trubi Formation, which
46 begins with three meters of whitish massive marly limestones, overlain by an
47 alternation of decametric marly limestones and laminated marl beds. The Trubi
48 Formation can be subdivided into nine lithological cycles (Figs. 3b and 5).
49

50 In the Argassi area (Fig. 1), the PLG is well-recorded (Fig. 8a,b), and it comprises
51 eight gypsum-marl cycles that can be correlated with those of the Kalamaki section
52 (Fig. 6). However, in Argassi area, it is not possible to observe the stratigraphic
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3 transition of the evaporitic succession to the overlying and the underlying formations,
4 due to tectonics and the Quaternary debris cover.

5 6 *5.1.2 Agios Sostis area*

7
8 The Neogene succession of Agios Sostis area lies over the Pre-Apulian zone
9 sequence. The following stratigraphic units are recognized:

10 11 *Pre-evaporitic unit*

12
13 In the Agios Sostis section, the lowermost part of this unit consist of decameter-thick
14 shale and sandstone alternations, exhibiting upward decrease in clastic input (Figs. 7
15 and 8c). These deposits are overlain by 3.5 m of thin sandstone beds with marl
16 intercalations, which in turn are capped by 3 m of laminated green shale and marl
17 alternations.

18 19 *Evaporitic unit*

20
21 In the Agios Sostis area, two parallel linear gypsum outcrops are observed, the
22 Ploumari outcrop and the Panagia (Machairado) outcrop (Fig. 1). The western outcrop
23 (Ploumari) consists of primary bottom-growth selenite (PLG) deposited in shallow-
24 water settings (less than 200 m; Lugli *et al.*, 2010) and is exposed for about three km.
25 The PLG succession is here incomplete and represented only by one or two gypsum
26 beds consisting of very large crystals that are typically found in the two lowermost
27 PLG cycles (Lugli *et al.*, 2010).

28
29 Conversely, the eastern outcrop (Panagia) exposes mainly clastic gypsum deposits
30 that derive from the re sedimentation of older PLG deposits. Moving from Panagia to
31 Agios Sostis, in a NNW-SSE direction (Fig. 1), it is possible to observe a down-slope
32 transition of different gravity-flow deposits: from chaotic deposits including dm-thick
33 resedimented gypsum blocks to gypsum turbidites alternated with primary gypsum
34 cumulate. These deposits are well exposed in the Agios Sostis section.

35
36 This suite of evaporite-bearing gravity-flow deposits suggests that the Panagia
37 sediments derived from the erosion of PLG located to the west, like those outcropping
38 in Ploumari. Unfortunately, the basal contact of the evaporitic unit is not visible in
39 this sector. Thus, it cannot be excluded that the PLG deposits are actually blocks slit
40 downslope from a more western position; e.g., from the backbulge basin on top of the
41 Apulian terrains. Westward, these PLG deposits were completely eroded during the
42 late Messinian, as indicated by the angular unconformity between the early Pliocene
43 conglomerates - sandstones and the early-middle Miocene marls, which was first
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3 observed by Nikolaou (1986) in the Perlakia area (about one km north of the Keri
4 village; Fig. 1).

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6 Along the Agios Sostis shoreline, a 16 m-thick gypsum unit lies above an erosional
7 surface developed on top of the pre-evaporitic succession (Fig. 7 and 8c). It consists
8 of several alternations of primary (cumulate) and clastic gypsum (gypsrudite,
9 gypsarenite, and gypsiltite; Figs. 7 and 8d, f), commonly showing high-angle cross-
10 and convolute lamination (Figs. 7 and 8e). This succession is mostly characterized by
11 clastic gypsum deposits and lacks the *in situ* shallow-water selenite described in the
12 Kalamaki–Argassi area. This evaporitic unit derives from the dismantlement and
13 resedimentation of PLG deposits and, thus, can be ascribed to the RLG unit, deposited
14 during the stage 2 of the salinity crisis (5.60-5.55; CIESM, 2008; Roveri *et al.*,
15 2008a). The entire RLG unit shows an upward increase of the siliciclastic component
16 and is divided into four units, each topped by a centimetric marly bed. Approximately
17 two meters of hybrid sandstones are capping the clastic evaporite unit. The urban
18 fabric of Agios Sostis Community (harbour) does not allow further observations.
19 Nevertheless, the section's continuity is observed in the Agios Sostis islet (Fig. 1),
20 which is separated from the main coastal section by a fault; the two sections are
21 located approximately 130 m apart. In this islet, about eleven meters of interbedded
22 graded sandstones and marls are observed (level 6 of Fig. 7), exhibiting an upward
23 decrease in siliciclastic material. At approximately 37-38 m above the base of the
24 Agios Sostis composite section, a normal fault with a throw of about two meters is
25 observed (lower level 6 of Fig. 7). The last seven meters of the section (levels 46-53
26 m) are well observed in the rocky elevation of the Agios Sostis harbor, some 130
27 meters NNW of the islet (upper level 6 and level 7 of Fig. 7). They comprise a six m-
28 thick succession of graded sandstone and marl alternations, followed by 1.5 m of
29 whitish marls belonging to the post-evaporitic Trubi Formation.
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48 **5.2 Borehole and seismic reflection data**

49 Correlation of the available borehole logs (Fig. 9) shows that the Neogene deposits
50 (Messinian gypsum included), deposited over the Pre-Apulian basement, increase
51 their thickness east-to-southeastward, following the dipping of the Alikanas
52 monocline. The Neogene sediment thickness ranges from 800 m in the west to 1350
53 m in the east. This eastward thickening, toward the depocenter of the basin, is
54 confirmed by the Alikanas basin onshore seismic profile (Fig. 10). Furthermore, the
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3 seismic profile suggests that the Ionian thrust is located west of the western Ionian
4 Triassic diapir (Agia Dynati diapir; Fig. 1), more to the west than previously
5 considered. In addition, in the Agios Kyrikos-1 well (Fig. 9; AK1), at the Alikanas
6 basin's depocenter, an increase in the salinity of the drilling mud was recorded, when
7 the drilling penetrated the Messinian evaporites. This fact, combined with the
8 observation of a simultaneous speed reversal of the seismic waves at the same
9 stratigraphic level (C. Nikolaou, personal communication), is an indirect indication of
10 the presence of halite in the Messinian evaporitic unit at the basin's depocenter zone.
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18 **5.3 Planktonic Foraminifera**

19 *5.3.1 Kalamaki section*

20 The abundance of planktonic foraminifers varies throughout the section. In the pre-
21 evaporitic sequence, several samples are barren or contain only benthic foraminifers.
22 The preservation is generally good in the lower part of the section, up to 14 m from
23 the base, and it becomes moderate upward. Planktonic foraminifers within the Trubi
24 Formation are very abundant and preserved well.
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29 *a) Western subsection*

30 In the pre-evaporitic part of the Kalamaki section (Fig. 2), the following species are
31 identified: *Turborotalita multiloba*, *Turborotalita quinqueloba*, *Globigerinita*
32 *glutinata*, *Globigerina bulloides*, *Globigerina obesa*, *Orbulina universa*, and
33 *Neogloboquadrina acostaensis* (dextral and sinistral forms). *Turborotalita multiloba*
34 occurs from 0.6 m (sample KAL 5) up to 7.2 m (KAL 41), and it is found together with
35 rare specimens of *Globigerinoides* spp., *O. universa*, and *T. quinqueloba*. In the
36 lowermost two meters of the section (KAL 7 -KAL 10), *T. multiloba* represents the
37 totality of the assemblage, making it monospecific. A paracme interval, within its
38 abundance distribution, is recognized between 1.95-4.3 m (KAL 11-KAL 23), where
39 the species is very rare or absent. The paracme end of this interval (bioevent 3a, fig.
40 15) is also recognized in Sorbas Basin, in the upper part of cycle UA23, and in
41 Caltanissetta Basin, just above the influx of *G. scitula*. The distribution of *T. multiloba*
42 is similar in Kalamaki and Falconara sections and is probably related to the
43 paleoecological requirements of the species and the basin's configuration during this
44 period. The species becomes the main planktonic foraminifera faunal component up
45 to 7.2 m. Upward, it exhibits two significant peaks at 9 and 10.5 m (KAL 56 and KAL
46 64) corresponding to its highest abundance.
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3 *Turborotalita quinqueloba* and *G. glutinata* are rare in the lower part of the section
4 and dominate the assemblages, in the thick massive marly interval from 7 to 8.5 m
5 (KAL 39 through KAL 49).
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8 *Neogloboquadrina acostaensis* is generally rare in the section, displaying a relative
9 abundance fluctuation between sinistral and dextral specimens. Sinistral forms are
10 more abundant from the base up to 1.5 m (KAL 9), whereas dextral representatives are
11 prevalent in the 2.7 - 8.4 m interval (KAL 15-KAL 49). Sinistral forms prevail again in
12 the interval between 8.8 and 9.2 m (KAL 54-KAL 57; 60-70%) and at 10.5 m (KAL 64;
13 40%).
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18 *Globorotalia scitula* is present with two short influxes at 3.7 and 9.3 m (KAL 20 and
19 KAL 58), between the two peaks of *T. multiloba*. The upper part of the section, from
20 10.5 m until just below the slumped interval (KAL 65-89), is characterized by the
21 dominance of *O. universa*, *G. bulloides*, and *G. obesa*, which reach their maximum
22 abundance in sample KAL 89 (14.3 m). Above the slumped interval, planktonic
23 Foraminifera are absent up to sample KAL 105, where few representatives of *N.*
24 *acostaensis* are present. Benthic foraminifera are very abundant in the samples before
25 the first gypsum.
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28 *b) Central subsection*

29 The upper part of the PLG succession in the Kalamaki section (gypsum cycle H; Figs.
30 2, 3b, and 4) is characterized by the sporadic presence of the planktonic foraminifera:
31 *Globoturborotalita nepenthes*, *Globigerinoides*, *G. bulloides*, *Sphaeroidinellopsis*
32 spp., and *O. universa*.
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39 *c) Eastern subsection*

40 The Lago-Mare unit is characterized by the scattered presence of *Sphaeroidinellopsis*
41 spp., *G. nepenthes*, and *N. acostaensis*. Just below Trubi Formation (KAL 134) the
42 planktonic foraminifer assemblage is well-diversified mainly containing
43 *Sphaeroidinellopsis*, *G. obliquus*, *O. universa*, and *N. acostaensis* dextral specimens.
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48 *d) Trubi Formation*

49 Planktonic foraminifers become continuously abundant and well preserved from the
50 base of the Trubi Formation upward (Figs. 2, 3b, and 5); they are mainly represented
51 by *Sphaeroidinellopsis* spp., *G. obliquus*, *N. acostaensis* (dextral and sinistral),
52 *Globorotalia margaritae*, *G. bulloides*, and *O. universa*. *Neogloboquadrina*
53 *acostaensis* sinistral-coiling specimens exhibit an influx in samples KAL 142 and KAL
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3 149. *Sphaeroidinellopsis* spp. show an acme interval from KAL 147 through KAL 160.
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5 *Globorotalia margaritae* first commonly occurs in KAL 171.
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8 5.3.2 Agios Sostis section

9 a) Pre-evaporitic unit

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11 The samples from the pre-evaporitic sediments of Agios Sostis coastal section are
12 barren of foraminifera. The complete sequence is characterized by the presence of
13 gypsum crystals, possibly of diagenetic origin; gypsum was also recovered from the
14 sieved residual.
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17 b) Post-evaporitic unit

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19 The lower 1.2 m of the post-evaporitic sequence, in the coastal elevation of Agios
20 Sostis harbor, are barren of foraminifera, whereas the uppermost 1.5 m contains a rich
21 planktonic fauna. Samples AS 18 and 19 yield specimens of *Globorotalia conomiozea*
22 (Fig. 7). This species disappeared from Mediterranean during the pre-evaporitic phase
23 of the MSC, at 6.52 Ma (Krijgsman *et al.*, 1999; Sierro *et al.*, 2001). Therefore, its
24 presence in the post-evaporitic sequence of Agios Sostis may be assumed due to
25 reworking. The last four samples of the section (AS 20-23), collected one meter below
26 the Trubi Formation, are characterized by the presence of *G. obliquus*, *G. trilobus*, *G.*
27 *decoraperta*, *G. nepenthes*, *G. bulloides*, *G. falconensis*, *T. quinqueloba*, *Orbulina* sp.,
28 *Sphaeroidinellopsis* spp., and *N. acostaensis*.
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38 5.4 Calcareous nannoplankton

39 a) Western subsection

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41 The lower part of the Kalamaki sequence (KAL 10-50) features an abundant
42 nannofossil assemblage in good preservation state (Fig. 2). The prevailing species are
43 *Helicosphaera carteri*, *Calcidiscus leptoporus*, *Umbilicosphaera jafari*, and small
44 *Reticulofenestra* spp. (*R. haqii*, *R. minutula*). Six-rayed discoasters are very rare, and
45 *Discoaster quinqueramus* is practically absent. Nearly monospecific assemblages of
46 *Sphenolithus abies* are observed upward. The upper part of the sequence is
47 characterized by the sporadic presence of *Amaurolithus delicatus*, *A. primus*, *A.*
48 *tricorniculatus*, and rare *Nicklithus amplificus*.
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55 b) Central subsection

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57 The upper part of the PLG in Kalamaki section (KAL 114-125; Fig. 2) is characterized
58 by intense reworking and contains rare nannofossil specimens, in bad preservation,
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3 mostly reworked assemblages of Oligocene-Miocene age also including Cretaceous
4 taxa.
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6
7 *c) Eastern subsection*

8 The Lago-Mare facies unit (KAL 120-134), beneath the Trubi Formation of Kalamaki
9 section (Fig. 2), displays rare to common well-preserved small *Gephyrocapsa* spp.
10 coccoliths (1.5-3.0 μm) within a rich but reworked assemblage. Just below the Trubi
11 Formation (KAL 134), the rare presence of *Ceratolithus acutus* together with
12 specimens of *Reticulofenestra zancleana* is recorded.
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18 **5.5 Fish remains**

19 Sixteen fish taxa are identified in the pre-evaporitic sediments of Kalamaki section
20 based on the otolith remains (Table 1; Fig. 11). The samples obtained from the marls
21 in between the evaporites, as well as from the upper part of Kalamaki section,
22 including the Trubi Formation, did not yield otolith remains. The Kalamaki pre-
23 evaporitic teleost fauna resembles those identified by Girone *et al.* (2010) in the pre-
24 evaporitic successions of northern Italy. Indeed the great diversity of the benthic-
25 benthopelagic group is asserted here as well. *Gadiculus labiatus* is the most frequent
26 benthic species in the assemblages, although the overall abundance of gobiids is
27 higher. However, the gobiid specimens are very small and indeterminable to the
28 specific, or even generic, level. The pelagic realm is dominated by myctophids,
29 particularly those belonging to the genus *Diaphus*, which is much diversified; five
30 different species are identified, with high abundance in the studied samples. Notably,
31 *Diaphus rubus* and *Myctophum coppa*, two fossil species first reported by Girone *et*
32 *al.* (2010) in the pre-evaporitic sequence of northern Italy, are also found in pre-
33 evaporitic succession of Kalamaki section (samples KAL 6, KAL 13, KAL 15, KAL 26,
34 KAL 27, KAL 31, KAL 41, KAL 81, KAL 87, KAL 89, KAL 95). In biogeographic
35 terms, six of the fourteen fish, identified at the specific level, are extinct today; the
36 remaining still inhabit the Mediterranean Sea, apart from *Physiculus huloti*, which
37 occurs only in the Atlantic Ocean (Cohen *et al.*, 1990). *Diaphus* cf. *pedemontanus*, *D.*
38 *rubus*, and *Myctophum coppa* are absent in the so far studied Pliocene and Pleistocene
39 assemblages of the eastern Mediterranean (Agiadi *et al.*, 2010; Agiadi *et al.*, 2013a;
40 Agiadi, 2013).
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42 During the time interval preceding the onset of the MSC, the Kalamaki area presents a
43 well-diversified fish fauna, comprising both abundant pelagic and benthic-
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3 benthopelagic fish. The continuous presence of gobiids throughout the basal part of
4 the section and the occurrence of *Buglossidium* sp. in sample *KAL* 31 suggest rather
5 shallow water-depths before the onset of gypsum deposition. In fact, the occurrence of
6 benthopelagic *Physiculus* aff. *huloti* (bulk sample *KAL* base) indicates depths less
7 than 320 m (OBIS, 2006). However, the great diversity and abundance of the genus
8 *Diaphus* and the presence of gadids (*Gadiculus argenteus* and *Gadiculus labiatus*) in
9 the upper part of the basal sequence (just prior to the gypsum deposits, samples *KAL*
10 27, *KAL* 28, *KAL* 38, *KAL* 39, *KAL* 45), suggest the area was not secluded, and depths
11 certainly greater than 50 m may be expected. In addition, *Maurolicus muelleri* is
12 present in almost all the samples examined and in great abundances. Although this
13 bathypelagic species has a large bathymetric distribution today, between 0-1524 m
14 according to Wheeler (1992), it is usually found between 300-400 m depth
15 (Mauchline, 1988). Combining the above results, the paleodepth is estimated less than
16 300 m for the basal sequence of Kalamaki section.

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18 Considering the modern ecological data for the extant species present in the Kalamaki
19 fish assemblage (Table 1), as well as the high occurrence of the extinct Mediterranean
20 species *Diaphus cavallonis*, *D. rubus*, *D. cf. pedemontanus*, *Myctophum coppa*, and
21 *Gadiculus labiatus*, which are typically recorded in the Miocene and Pliocene
22 (Girone, 2007; Carnevale *et al.*, 2008; Girone *et al.*, 2010; Agiadi *et al.*, 2013a), the
23 Kalamaki area was probably situated on the tropical-subtropical climatic zone border.
24 Significant, in this respect, are the occurrences of tropical present-day extra-
25 Mediterranean species *Physiculus* aff. *huloti* and *Diaphus taaningi*.

41 5.6 Magnetostratigraphy

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43 The thermal demagnetization patterns and the trend of the magnetic susceptibility
44 with increasing temperature clearly show two different behaviors in the pre-evaporitic
45 unit and in the Trubi Formation of Kalamaki section (Fig. 2). The demagnetization
46 patterns of both groups indicate that a low temperature component, probably of
47 viscous origin, is sometimes demagnetized at 120°C. A second, normally-oriented
48 component is demagnetized up to 210°-330° C and generally contributes with 70-80%
49 to the initial magnetization in the pre-evaporitic interval and with 50%-70% in the
50 Trubi Formation. This component is interpreted as an overprint of the present day
51 field; in fact, in geographic coordinates, its mean declination is 0.7° N and the
52 inclination is 54.5° (N=52; A95=2.7°), which are values very close to the present day
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3 field direction in the area of Zakynthos (3.79° N of declination and 54.05° of
4 inclination). Samples collected in the pre-evaporitic sequence have a weak
5 magnetization, showing a mean normal remanent magnetization (NRM) of $4.07 \text{ E-}04$
6 A/m (with a standard deviation of $6.02 \text{ E-}04$). Usually, an abrupt increase in magnetic
7 susceptibility to $350^\circ\text{-}420^\circ \text{ C}$ is detected, concomitant with an increase of the
8 remanent magnetization, both indicative of authigenic sulphides. Besides the low-
9 temperature components, a higher temperature component is rarely isolated in this
10 group above 210°C . In several samples, the characteristic component (ChRM) is
11 isolated between 230 and 350° C . This component exhibits both normal and reversed
12 polarities (Fig. 12). Normal polarities are identified in the following intervals: a) from
13 the base of the section to 0.6 m , the Zijderveld diagrams for this samples display a
14 linear decay towards the origin; b) at 2.55 m ; c) from 8.58 to 12.03 m . Sample with
15 reversed polarities are identified at 6.53 m , at 14.02 m , and at 20.15 m . The Zijderveld
16 diagrams of interval b) and c) and of reversed polarity samples all show a cluster of
17 demagnetization steps. Mean direction for normal and reversal polarities were
18 calculated by mean of Fisher's statistics and are $64.3^\circ/39.8^\circ$ ($N=12$, $k=21.6^\circ$ and
19 $\alpha_{95}=9.6^\circ$) and $230.1^\circ/50.0^\circ$ ($N=4$, $k=13.9^\circ$ and $\alpha_{95}=25.6^\circ$). The second group of
20 samples, collected in the Trubi section, displays a higher mean NRM ($2.25 \text{ E-}03 \text{ A/m}$,
21 with a standard deviation of $1.92 \text{ E-}03$). Here, the demagnetization patterns show
22 much more stable trends with respect to the pre-evaporitic samples. The ChRM is
23 successfully recognized in all the samples between $210\text{-}230^\circ\text{C}$ and a maximum of
24 560°C . Both reversed ($KAL 142$ to $KAL 154$; $194.3^\circ/ -64.7^\circ$, $N=5$, $k=9.17$ and
25 $\alpha_{95}=26.7^\circ$) and normal ($KAL 156$ to $KAL 174$; $39.5^\circ/42.2^\circ$, $N=15$, $k=38.8$ and
26 $\alpha_{95}=6.2^\circ$) polarities are recognized and the reversal is identified between 9.6 and
27 10.4 m .

5.7 Stable oxygen and carbon isotopes

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29 In the pre-evaporitic sequence of Kalamaki section, bulk sediment and planktonic
30 foraminiferal δ values vary widely ($-2.71 < \delta^{18}\text{O}_{\text{carb}}\text{‰} < 7.45$; $-4.32 < \delta^{13}\text{C}_{\text{carb}}\text{‰} < 1.94$; $-$
31 $1.44 < \delta^{18}\text{O}_{\text{foram}}\text{‰} < 3.73$; $-2.90 < \delta^{13}\text{C}_{\text{foram}}\text{‰} < 0.95$), with heavier values measured in the
32 massive and calcareous marls (Fig. 14). Oxygen- and carbon-isotope compositions are
33 consistent with the major late Miocene-early Pliocene paleoclimatic and
34 paleoceanographic phases in the eastern Mediterranean Sea (Blanc-Valleron *et al.*,
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2002; Krijgsman *et al.*, 2002; Kouwnhoven *et al.*, 2006), yet they present certain differentiations attributed to local factors. The background $\delta^{13}\text{C}_{\text{carb}}$ value is $\sim 1.5\text{‰}$; up to 14 m from the section base, the values increase only once, at the upper part of the massive marls, reaching values up to 2‰ . From 15 m until the end of the pre-evaporitic sequence, $\delta^{13}\text{C}$ values exhibit no particular trend. The $\delta^{18}\text{O}_{\text{carb}}$ record displays some positive shifts, revealing a “pulse” of higher salinity/evaporation that is more intense near the evaporitic unit. Additionally, there is a simultaneous decrease in $\delta^{13}\text{C}_{\text{carb}}$ values and an increase in $\delta^{18}\text{O}_{\text{carb}}$ values at the same stratigraphic level.

Wacey *et al.* (2008) suggested that such a phenomenon may be the result of isotopically-light carbon influence from bacterial sulfate reduction, due to increased stagnation at the beginning of sulfate deposition. Similar trends in both carbon and oxygen isotopes were described in the Legnagnone section (Northern Apennines, Italy) by Gennari *et al.* (2013). There is a remarkable similarity between the $\delta^{18}\text{O}_{\text{carb}}$ and the $\delta^{18}\text{O}_{\text{foram}}$ isotope records of Kalamaki pre-evaporitic sequence, suggesting that $\delta^{18}\text{O}_{\text{foram}}$ values reflect the variability of salinity, evaporation, and fresh water input. In the upper part of the PLG (cycle H), $\delta^{13}\text{C}_{\text{carb}}$ values mostly fluctuate around -4‰ , while $\delta^{18}\text{O}_{\text{carb}}$ values range between -5 and 8‰ (Fig. 15). The most prominent change, linked to environmental phenomena, seems to be the positive $\delta^{18}\text{O}$ shift ($\sim 8\text{‰}$) recorded just below and above the gypsum bed, revealing high salinity that is consistent with the evaporite deposition (cycles A-G). The observed negative $\delta^{18}\text{O}_{\text{carb}}$ shifts of more than 1‰ are considered indicative of increased freshwater input. Sharp $\delta^{13}\text{C}_{\text{carb}}$ negative and positive shifts characterize rapid changes in the hydraulic budget and in the ventilation of the basin, from lacustrine to saline conditions (Shackleton *et al.*, 1995).

The M/P boundary is marked by the first excursion toward higher δ values ($\delta^{18}\text{O}_{G. obliquus} = -0.75\text{‰}$, $\delta^{13}\text{C}_{G. obliquus} = 0.91\text{‰}$) that occurs at the base of the Trubi Formation (Fig. 15). In contrast to the presence of abundant planktonic assemblages above the M/P boundary level, the freshwater influence remains significant over an interval corresponding to five cm of sediment marked by negative $\delta^{18}\text{O}$ values (black shale just below the Trubi). This development reflects the rapid transition to marine conditions at the onset of the Pliocene. The establishment of stable normal marine conditions is recorded 20 cm above the M/P boundary. Above this level, $\delta^{18}\text{O}_{G. obliquus}$ oscillations correspond to the ten (I to X) cycles of the Trubi Formation (Shackleton *et al.*, 1995; Di Stefano & Sturiale, 2010), with $\delta^{18}\text{O}$ values varying at a range of

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3 approximately 1.5‰ in each cycle. The overlying early Pliocene sediments rapidly
4 stabilize at positive $\delta^{13}\text{C}$ values ($0.32 < \delta^{13}\text{C} \text{‰} < 1.39$), characteristic of an open-
5 marine, stable, and well-ventilated environment. Moreover, the $\delta^{13}\text{C}$ signal follows
6 the same frequency changes as the $\delta^{18}\text{O}$, with the transitions to lighter $\delta^{13}\text{C}$ values
7 coinciding with high shifts to heavier $\delta^{18}\text{O}$ values (Fig. 13). The simultaneous $\delta^{18}\text{O}$
8 increase and $\delta^{13}\text{C}$ decrease are possibly related to sea surface temperature variations
9 and reveal that the glacial cycles (Sprovieri *et al.*, 2006) also influenced the eastern
10 Mediterranean during the early Pliocene.
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18 **5.8 Strontium isotopes**

19 The results of the strontium isotope analyses in the Kalamaki section gypsum unit are
20 presented in Fig. 2. Selenite samples yield $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.708993 for
21 (2 σ = 0.0014) and 0.709007 (2 σ = 0.0015). These values correspond to PLG deposits
22 from stage 1 of the salinity crisis (Roveri *et al.*, 2014a,b).
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28 **6. Discussion**

29 **6.1 Chronostratigraphic framework**

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32 The observed distributions of planktonic foraminifer and calcareous nannofossil
33 species were used to recognize astronomically-tuned bioevents that are already
34 defined in lower Messinian Mediterranean sections (Krijgsman *et al.*, 1999; Hilgen &
35 Krijgsman, 1999; Sierro *et al.*, 2001; Blanc-Valleron *et al.*, 2002; Manzi *et al.*, 2011;
36 Manzi *et al.*, 2013) (Figure 14). The first peak of *T. multiloba* is recognized one meter
37 from the base of the western Kalamaki subsection and can be correlated with its first
38 abundant occurrence dated at 6.415 Ma in the Perales section (Sierro *et al.*, 2001). The
39 first abundant occurrence of dextral *N. acostaensis*, identified also in the Perales
40 section and dated at 6.339 Ma, is recorded at 2.7 m. This biostratigraphic event is
41 considered more reliable than the *N. acostaensis* coiling change as no sinistral
42 specimens were observed below this level. The presence of *G. scitula* at 3.7 m can be
43 correlated with its first influx and dated between 6.291-6.287 Ma. The interval
44 between 8.8-9.2 m, dominated by sinistral *N. acostaensis*, is correlated with the
45 relevant interval found in the Metochia section (Gavdos Island; Drinia *et al.*, 2007)
46 and in the Perales composite section (Sierro *et al.*, 2001; Manzi *et al.*, 2013), and it is
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3 dated between 6.140-6.108 Ma. The influx of *T. multiloba* at 9 m can be correlated
4 with a relevant influx of this species at Perales section, which falls in the upper part of
5 cycle UA28, dated at 6.121 Ma. The influx of *G. scitula* at 9.3 m correlates well with
6 the second known influx of this species, dated between 6.105 and 6.099Ma (Sierro *et*
7 *al.*, 2001). The dominance of sinistral *N. acostaensis* identified at 10.4 m can be
8 correlated with the second influx of sinistral *N. acostaensis* dated between 6.078 and
9 6.08 Ma, approximately at the same level of the influx of *T. multiloba* at 10.5 m,
10 which could correspond to the last prominent influx of the species in the Perales
11 section. The oligotypic assemblage recorded below the slumped interval and the high
12 abundance of planktonic foraminifera at 14.3 m were also observed in the Sorbas
13 basin and in the Northern Apennines (Sierro *et al.*, 2003; Gennari *et al.*, 2013)
14 preceding the last eccentricity maximum centered at ca. 6.01 Ma, before the onset of
15 the MSC.
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18 Based on this biostratigraphic framework, the normal polarity at the lower part of the
19 Kalamaki pre-evaporitic sequence (up to 0.68 m) is correlated with subchron
20 C3An.2n (6.733-6.436 Ma after Lourens *et al.*, 2004), below the first abundant
21 occurrence of *T. multiloba*. The reverse magnetic signal at 6.53 m falls within
22 subchron C3An.1r. This interval is confirmed by the position of the *N. acostaensis*
23 dextral-coiling specimens' abundant occurrence and the *G. scitula* first influx. The
24 normal polarities between 8.58 and 12.03 m correlate with subchron C3An.1n (6.252-
25 6.033 Ma) and the reversal polarities at 14.02-20.15 m fall within the lower part of
26 subchron C3r.
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29 As for the calcareous nannofossil, the typical specimens of *D. quinquerramus*, usually
30 recorded in other pre-evaporitic deposits (e.g. Gavdos Island; Triantaphyllou *et al.*,
31 1999), is not found in the Kalamaki sequence, probably due to the establishment of a
32 semi-closed, neritic, littoral environment (Wade *et al.*, 2006). However, the presence
33 of *N. amplificus* supports the biostratigraphic assignment of the Kalamaki pre-
34 evaporitic unit within the NN11 biozone, dated between 6.82-5.98 Ma (Raffi *et al.*,
35 2006; Backman *et al.*, 2012).
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38 Reworked planktonic foraminifera and nannofossil specimens characterize the upper
39 part of the PLG succession and the Lago Mare deposits in the Kalamaki section.
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41 *Gephyrocapsa* spp. specimens, although suggesting an age within the early Pliocene
42 (subbottom of *Gephyrocapsa* spp. at 4.33 Ma; Lourens *et al.*, 2004), were also
43 observed in the late Messinian pre-evaporitic diatomites of Gavdos (Triantaphyllou *et*
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3 *al.*, 1999). Thus, their presence in the Kalamaki sequence contributes to the limited
4 knowledge on the precise stratigraphic and geographic distribution of these early
5 representatives of the genus in the SE Mediterranean region.
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8 Just before the Trubi Formation (Fig. 15), the planktonic foraminifera assemblages in
9 both Kalamaki and Ag. Sostis sections are assigned to the Transitional Unit identified
10 in the ODP sections by Iaccarino *et al.* (1999). In sample *KAL* 134, the rare presence
11 of calcareous nannofossil *Ceratolithus acutus*, together with specimens of
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13 *Reticulofenestra zancleana*, implies an age within the base of the NN12 biozone, in
14 the early Zanclean (5.36 Ma; Di Stefano & Sturiale, 2010; Backman *et al.*, 2012).
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17 The M/P boundary (5.33 Ma) is defined by the distribution of dextral and sinistral
18 forms of *N. acostaensis* and the *Sphaeroidinellopsis* Acme Base, further supported by
19 the increasing of the oxygen and carbon isotope values, and it is placed at the base of
20 the Trubi Formation. The recognized bioevents and the polarity reversal identified in
21 the lower part of Trubi Formation of Kalamaki section are correlated with the upper
22 part of subchron C3r and the normal polarity at the C3r/C3n boundary is placed in the
23 9.6-10.4 m interval midpoint (event IV; Fig. 15) dated at 5.235 Ma (Lourens *et al.*,
24 2004), below the *Sphaeroidinellopsis* Acme End (5.21 Ma). The sinistral shifts of *N.*
25 *acostaensis* at 7.8 and 8.52 m are ascribed to the first and second *N. acostaensis*
26 sinistral shifts that are reported from several Mediterranean Lower Pliocene sections
27 (Di Stefano *et al.*, 1996; Lourens *et al.*, 1996; Iaccarino *et al.*, 1999; Pierre *et al.*,
28 2006; Gennari, 2007; Drinia *et al.*, 2008), dated at 5.330 and 5.281 Ma (Lourens *et*
29 *al.*, 2004) and correlated with the base of cycle 2-top cycle 1 and the base of cycle 2-
30 top cycle 3, respectively. The base of the *Sphaeroidinellopsis* Acme Zone, recorded at
31 8.3 m, and its top, at 11.3 m, correspond to the cycle 2 and the base of cycle 6,
32 respectively. The first common occurrence of *Globorotalia margaritae* (FCO) is
33 recorded in *KAL* 171 and marks cycle 10, dated at 5.08 Ma (Lourens *et al.*, 2004).
34 Consequently, the studied Trubi Formation sediments belong to the MPL1 biozone –
35 lower part of the MPL2 biozone; its base may be correlated with the base of the
36 Zanclean, as defined in the Eraclea Minoa GSSP at 5.33 Ma (Van Couvering *et al.*,
37 2000). The presences of *Sphenolithus* spp. (abundance >5%), *Reticulofenestra*
38 *pseudoumbilicus* (abundance 1-2%, possibly representing the *R. pseudoumbilicus*
39 Pliocene Paracme Zone; Di Stefano & Sturiale, 2010), rare *Reticulofenestra*
40 *zancleana*, and several discoasterid species (*D. brouweri*, *D. pentaradiatus*, *D.*
41 *surculus*, *D. intercalaris*, *D. variabilis*); in conjunction with the common occurrence
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3 of *Amaurolithus* spp.; document the biostratigraphic correlation with the nannofossil
4 biozone NN12 (Martini, 1971), or MNN12a-b (Rio *et al.*, 1990). Therefore, the Trubi
5 sediments of Kalamaki section (Fig. 15) have an early Zanclean age, ranging between
6 5.36-5.0 Ma.
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11 **6.2 Kalamaki paleoenvironmental reconstruction**

12 The fish assemblage identified in the pre-evaporitic Messinian of Kalamaki section
13 (Fig. 2) is indicative of a coastal marine area, with easy access to the open ocean, not
14 exceeding 300 m in its deeper parts. The great diversity of the fauna, along with the
15 fact that it incorporates deep-water pelagic species, such as *Maurolicus muelleri*,
16 *Gadiculus argenteus* and *Physiculus* aff. *huloti*, as well as shallow-water inhabitants,
17 such as gobiids, suggests that fossils from different adjacent underwater domains were
18 combined during deposition. This light transport effect is commonly observed in the
19 otolith faunas (Agiadi *et al.*, 2013b), and it is the result of a high bathymetric gradient
20 in the area of deposition. Thus, the Kalamaki area paleogeographic scheme proposed
21 here is further supported by this observation. Several paleoenvironmental changes can
22 be recognized by the variations of the faunal and isotopic markers resulted to a step-
23 wise progression towards the evaporitic conditions.
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33 *6.2.1 Pre-evaporitic sequence*

34 Interval 6.45-6.121 Ma (0-9 m)

35 In the pre-evaporitic sequence of Kalamaki (KAL 10-50; Figure 2), the nannofossil
36 assemblage of *H. carteri*, *C. leptoporus*, *U. jafari*, *R. haqii*, and *R. minutula* is mostly
37 represented by whole coccospheres, indicating high productivity and fresh-water input
38 to the surface waters (e.g., Triantaphyllou *et al.*, 2009). In addition, the impressive
39 monospecific assemblages of *Sphenolithus abies* in the upper part of the pre-
40 evaporitic sequence (samples KAL 45-55 and 85-92) suggest marine mesotrophic
41 environments (Wade *et al.*, 2006).
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49 In this basal part of the pre-evaporitic sequence, the bulk sediment $\delta^{18}\text{O}$ values range
50 between 0-2.1‰, reflecting marine conditions with slight salinity and/or temperature
51 fluctuations (Fig. 13). The positive trend of $\delta^{13}\text{C}$ reveals high productivity related to
52 cold waters. The oligotypic planktonic foraminifera record is characterized by levels
53 with 60-100% dominance of *T. multiloba*. This species is related to progressive
54 isolation of the Mediterranean, and it is thought to be tolerant to increased salinity
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3 (Sierro et al., 2001). Its occurrence together with *T. quinqueloba* and *G. glutinata* in
4 this part of the section is related to cold and nutrient rich surface waters (Tolderlund
5 and Bè, 1971; Sierro *et al.*, 2003). The almost complete absence of planktonic
6 foraminifera 2-4 m from the base is associated with increased riverine input causing a
7 reduction of the sea surface salinity. This is further supported by the $\delta^{18}\text{O}$ negative
8 excursions and nannofossil assemblages indicative of high productivity and fresh-
9 waters input. At around 3.7 m, normal marine conditions are inferred by the oxygen
10 isotope positive values around 1‰ accompanied by the *G. scitula* influx, which is a
11 deep-dwelling species (Bè and Tolderlund, 1971). The return to positive $\delta^{18}\text{O}$ values
12 suggest that the negative values recorded below this level are due to a temporary
13 restriction of the Atlantic connection, during a sea level-fall, or excess precipitation in
14 the Mediterranean area at this time. Maximum $\delta^{18}\text{O}$ values, corresponding to
15 hypersalinity episodes, alternate with values near 0‰ (between 7-9 m), which reflect
16 periods when normal marine conditions prevailed. In these high-salinity levels, the
17 planktonic foraminiferal assemblage is dominated by *G. glutinata* and *T. quinqueloba*;
18 the sporadic presence of *T. multiloba* is also noted. High abundance of these species
19 usually occurs under conditions of environmental stress and is also related to
20 decreased food availability and low water-temperatures, reflecting the climatic
21 variability toward a cooling phase around 6.121 Ma (Van der Laan *et al.*, 2005;
22 Gennari *et al.*, 2013). It is hypothesized that stressful conditions for the marine
23 meiofauna were induced by an increase of surface-water salinity.

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The foraminiferal isotopic composition ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) is related to the ecological
affinities of the species involved. *Turborotalita multiloba* is considered a morphotype
of *T. quinqueloba* with more chambers in the final whole. The former species
proliferates near river-influenced, low temperature, and nutrient-rich waters, and it
tolerates increased salinities (Bè and Tolderlund, 1971). Hence, its isotopic
composition directly reflects salinity and/or temperature variations. The parallel low
 $\delta^{13}\text{C}$ values with high $\delta^{18}\text{O}$ values may be related to an average increase of salinity in
the lower part of sequence.

Interval 6.122-5.97 Ma (9-22 m)

The nannoflora assemblages are indicative of marine mesotrophic environments in the
upper part of the basal Kalamaki sequence. Toward the top and before the deposition
of the gypsum, $\delta^{18}\text{O}$ varies between -4 and 8‰, suggesting that salinity fluctuates

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3 rapidly between highly evaporated and diluted conditions (Bellanca *et al.*, 2001).
4 Foraminiferal carbon and oxygen isotopes of this interval were analyzed on *Orbulina*
5 *universa*. Since this species proliferates in mixed-layer surface waters during surface
6 water stratification, the isotopic compositions reflect changes in temperature, fresh
7 water input, or trophic content (Sierro *et al.*, 2003). There is a 4‰ difference between
8 the $\delta^{13}\text{C}$ values in the upper and lower part of the basal Kalamaki interval. This
9 probably reflects the contrast between nutrient-depleted waters of the stratified
10 summer mixed layer, recorded in the upper part of the basal sequence, and the
11 increased nutrient availability of the basal interval ($\delta^{13}\text{C}$ in *T. multiloba*). A cooling
12 phase punctuated by hypersaline conditions is centered at 12 m, and may be delimited
13 by the levels of increased fresh-water input and the warmer phases evidenced by the
14 fish fauna and planktonic foraminifera assemblages. Indeed, the fish fauna is
15 dominated by warm-water species, notably *Diaphus taaningi* and *Physiculus* aff.
16 *huloti* in the intervals below and over this cooling phase, whereas these taxa are
17 completely absent in the cooling phase, which is characterized by the presence of
18 *Maurolicus muelleri* mostly preferring temperate conditions. The onset of MSC is
19 accompanied by the disappearance of plankton assemblages, heavier oxygen isotopic
20 values and a sharp negative carbon isotope shift.

33 Post-evaporitic sequence

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35 The establishment of rather eutrophic conditions may be hypothesized, based on the
36 presence of small placoliths, along with the siliciclastic nature of the sediments at the
37 uppermost part of the Kalamaki Lago-Mare unit, just before the onset of Trubi
38 Formation (e.g., Young, 1994). The samples from approximately one meter below the
39 Agios Sostis Trubi Formation (Fig. 7) contain (AS 20-23) moderately preserved
40 nannofossil assemblages and more reworked material with respect to the Kalamaki
41 samples, indicating greater land proximity.

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43 In the interval 5.6-5.33 Ma (1.4-7.5 m), from the top of the gypsum unit to the
44 beginning of the Trubi Formation, the bulk sediment $\delta^{18}\text{O}$ values vary widely from
45 8‰ in the gypsum to -6‰ in the upper part of the sequence. The calcite $\delta^{13}\text{C}$ values
46 fluctuate between -6 and -1‰ (Fig. 13). These isotopic values reflect wide variations
47 of the paleoenvironmental conditions from hypersaline conditions to fresh and
48 brackish water.
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3 The total nannofossil content in the interval just above the Miocene/Pliocene (M/P)
4 boundary in the Kalamaki section implies warm surface-water conditions in a pelagic
5 environment. In particular, the presence of discoasterids, *Rhabdosphaera* spp.,
6 *Sphenolithus* spp., *Scyphosphaera* spp., *Amaurolithus* spp. is indicative of warm
7 subtropical conditions (e.g., Rio & Sprovieri, 1986). Relatively increased productivity
8 is inferred by the presence of *Helicosphaera carteri*, a species preferring warm waters
9 and moderately-elevated nutrient-levels. The faunal assemblages as well as the
10 isotope analyses reveal stable paleoenvironmental conditions settled at the beginning
11 of the Zanclean, due to the restoration of normal marine conditions.
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20 **6.3 Zakynthos Neogene paleogeographic and structural evolution**

21 Field observations suggest that the Neogene sediments in the main part of Zakynthos
22 Island were deposited over the Pre-Apulia zone formations, whereas those in the
23 southeastern part were deposited over the Ionian zone. The correlation of the field
24 observations with the available borehole data and the onshore seismic section (Figs. 1,
25 9, and 10) reveals that the Neogene formations over the Pre-Apulia zone sediments,
26 east of the Vrahionas anticline (Fig. 1), form a monocline dipping approximately 30°
27 ESE. Borehole stratigraphy (Fig. 9) indicates that the Neogene deposits (gypsum
28 included) increase their thickness toward the dipping monocline.
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34 The Neogene sediments exhibit their maximum thickness (800-1350 m) within the
35 largest depocenter zone, extending eastward from the Agios Sostis area. The
36 westernmost gypsum outcrops (Ploumari) consist of eroded PLG blocks, whereas
37 the easternmost ones (Panagia) contain gypsum turbidites and gypsum cumulates
38 (Fig. 1). Consequently, the PLG deposits accumulated in a shallow marine basin (Fig.
39 13), which was located in the western part of the Zakynthos (Alikanas) basin (west of
40 the Ploumari outcrops; Fig. 1), and they were almost completely eroded during late
41 Messinian. Indeed, about one km north of the Keri village (Fig. 1), in the Perlakia
42 location, early Pliocene conglomerates and sandstones lie over the early-middle
43 Miocene marls through an angular unconformity. Thus, the eroded PLG deposits
44 provided the clastic material that was deposited as gypsum turbidites (RLG) along the
45 Messinian basin slope (Panagia outcrops) and in its depocenter.
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54 On the contrary, Neogene sediments over the Ionian zone formations in the south-
55 easternmost part of the island are considerably thinner (200-300 m). Gypsum deposits
56 in Kalamaki and Argassi areas correspond to MSC stage 1 PLG unit; to the east
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3 (Skopos area, Fig. 1), only some rare and small gypsum outcrops can be observed,
4 mainly reworked gypsum and occasionally gypsum turbidites. These differences
5 suggest that the Zakynthos Neogene basin was not uniform, but subsidence in the
6 monocline area (over Pre-Apulian basement) was more rapid as compared with the
7 eastern area (over Ionian basement).
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11 The above observations are explained by a simple model of continental foreland-
12 directed migration of the Hellenide (Alpine) thrusting, during the late Neogene and
13 Pliocene. The Ionian thrust foreland basin can be modeled according to the foreland
14 basin systems proposed by DeCelles & Giles (1996), although it is necessary to take
15 into consideration the particular role of the Ionian Triassic evaporites diapiric
16 movements (Karakitsios, 1995). The Neogene formations over the Pre-Apulian zone
17 correspond to the foredeep, the forebulge and flank between them; those overlying
18 Ionian zone rocks correspond to the wedge-top (Fig. 14). The greater subsidence
19 characterizing the foredeep and flank-to-forebulge areas is reflected in the increased
20 thickness of the clastic Neogene formations over the Pre-Apulian zone (between 800-
21 1350 m), which partially derived from the eroded Pre-Apulian forebulge.
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24 Simultaneously, the diapiric movement of the Ionian Triassic evaporites prevented
25 substantial subsistence to occur. As a result, the eastern part of the Neogene basin
26 over the Ionian zone basement corresponds to a slowly-subsiding wedge-top. This is
27 reflected in the observed thin clastic Neogene sediments derived from the Ionian
28 orogen's erosion.
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30 During the Messinian, the shallow depths in the wedge-top and forebulge area of the
31 basin, together with the upper Messinian overall negative hydrological balance
32 (Mertz-Kraus *et al.*, 2009) led to the deposition of the PLG. The subsequent PLG
33 erosion produced clastic gypsum that was deposited through gravity-flows in the
34 slope and the depocenter. In addition, PLG mass-flows were accumulated in the distal
35 Zakynthos foreland slope. By the end of the Messinian, the PLG unit was completely
36 eroded at the forebulge zone, probably due to subaerial exposure. The MES (Fig. 14)
37 is located directly above the pre-evaporitic sequence west of the Ploumari gypsum
38 outcrops (Fig. 1), and it passes over the remaining PLG in the proximal slope
39 (Ploumari gypsum outcrops). In the distal slope and the foreland depocenter, the MES
40 becomes a correlative conformity.
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56 The wedge-top zone was characterized by shallower depths, mainly due to the diapiric
57 uplift of the Ionian Triassic evaporites (Karakitsios, 1995). Indeed, the sea depth in
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3 the Kalamaki area, prior to the PLG deposition, is estimated around 300 m, based on
4 the fish assemblages. Consequently, the Kalamaki area, placed over the external
5 Ionian Triassic diapir (Agia Dynati diapir; Figs. 1 and 14), received PLG deposits.
6 Eroded gypsum material from the wedge-top PLG also supplied clastic gypsum to the
7 foredeep RLG unit, which was located to its west (Fig. 14).
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11 In the Argassi area, PLG was also deposited over the Agios Ioannis diapir; the upper
12 PLG part was subsequently eroded. Quaternary erosion obscures the continuation of
13 the deposited sediments of this area. Possibly the Argassi and Kalamaki sections
14 during PLG deposition belonged to the same evaporitic basin that was separated by an
15 early activation of the Agios Ioannis diapir (Fig. 14 A).
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19 The proposed paleogeographic scheme for the last period of the Trubi Formation's
20 deposition is presented in Fig. 14 B. The Lago-Mare unit lies unconformably over the
21 MES in the wedge-top (Kalamaki area), whereas in the distal slope and in the
22 depocenter it was deposited with a correlative conformity. The Trubi Formation
23 succeeds the Lago-Mare unit, in stratigraphic continuity. The onset of the Trubi
24 Formation at 5.33 Ma, corresponding to the Pliocene flooding of the Mediterranean
25 basin, is recorded well on Zakynthos Island.
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29 The present results indicate that the Messinian gypsum units of Zakynthos Island were
30 deposited in a Mediterranean peripheral/marginal sub-basin context (*sensu* Roveri *et*
31 *al.*, 2014a), formed during the late Messinian in the Pre-Apulian foreland basin,
32 before the early Pliocene main deformation phase responsible for the tectonic
33 emplacement of the Ionian zone over the Pre-Apulian zone.
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41 **7. Conclusions**

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43 The present detailed study identifies the Messinian evaporitic basins on Zakynthos
44 Island, whose dynamics were controlled by the inherent substratum properties and the
45 regional tectonic regime. The development and distribution of the depositional
46 environments, before the Ionian thrust activation, was mainly influenced by the
47 Triassic evaporites diapiric movements in the foreland basin. The Zakynthos
48 Messinian evaporites were deposited in Mediterranean peripheral/marginal sub-
49 basins. The PLG was accumulated in the shallower parts (<300 m) of the Zakynthos
50 foreland basin, formed over the Pre-Apulian and the Ionian Alpine basement. In the
51 areas over Pre-Apulian basement, the Neogene sequence consists of mass-wasting
52 Messinian gypsum, which passes to mainly gypsum turbidites indicating a deeper
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3 environment. These deposits derived from the dismantlement and re-sedimentation of
4 the PLG unit and correspond to the RLG.

5 Planktonic foraminifera and calcareous nannoplankton biostratigraphy,
6 magnetostratigraphic analysis, and correlation with astronomically-tuned
7 Mediterranean sections provide the chronostratigraphic framework for the studied
8 sequences. The pre-evaporitic sequence in Kalamaki section is dated between 6.415-
9 6.01 Ma. Nine planktonic foraminiferal bioevents are distinguished. In Kalamaki
10 section, PLG was deposited during the first MSC stage, between 5.971-5.60 Ma. The
11 re-sedimented PLG deposits observed in Agios Sostis area correspond to the second
12 MSC stage (5.6-5.55 Ma). The M/P boundary is placed at the base of the Trubi
13 Formation, dated at 5.33 Ma. The Kalamaki section Trubi Formation, corresponds to
14 the interval between 5.33-5.08 Ma, in which five planktonic foraminiferal bioevents
15 were distinguished.

16 Two intervals are distinguished through the paleoenvironmental reconstruction of the
17 pre-evaporitic Messinian in Kalamaki area: a) 6.45-6.122 Ma and b) 6.122-5.97 Ma.
18 During the first interval (6.45-6.122 Ma), marine conditions prevailed, with slight
19 salinity and temperature variations. The positive $\delta^{13}\text{C}$ trend and the oligotypic
20 planktonic foraminiferal assemblage, dominated by *T. multiloba*, indicate high-
21 productivity cold waters. Between approximately 6.2-6.14 Ma (7-9 m), high $\delta^{18}\text{O}$
22 corresponding to hypersalinity episodes alternate with normal salinity conditions with
23 decreased food availability and low temperature. Between 6.122-5.97 Ma, marine
24 mesotrophic conditions are well established; the isotopic record suggests nutrient-
25 depleted waters of the stratified summer mixed layer. Both the planktonic
26 foraminifera and the fish assemblage indicate a cooling phase punctuated by
27 hypersalinity episodes around 6.05 Ma (12 m). In the upper part of the pre-evaporitic
28 sequence, the observed synchronous decrease in the carbon isotopic ratio, and
29 increase in the oxygen isotopic ratio may be caused by isotopically-light carbon
30 input from bacterial sulfate reduction, due to increasing stagnation conditions at the
31 beginning of sulfate deposition. After the MSC, eutrophic conditions are indicated at
32 the uppermost part of the Lago-Mare facies unit, just before the onset of Trubi
33 limestone Formation.

34 A new paleogeographic and structural model, integrating all the observed data, is
35 proposed. In the Zakynthos foreland basin, the Neogene formations over Ionian zone
36 correspond to the wedge-top, consistently with the diapiric movements of the Ionian
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3 Triassic evaporites, whereas those overlying the Pre-Apulian zone correspond to the
4 foredeep and the flank, between foredeep and forebulge. PLG erosion, both at the
5 forebulge and the wedge-top, supplied the foreland basin's depocenter with gypsum
6 turbidites. The PLG unit at the forebulge zone was totally eroded and the MES is now
7 located directly above the pre-evaporitic sequence, while, it is over the remaining
8 PLG in the slope area, and it became a correlative conformity for subsequent
9 sediments at the depocenter zone of the foreland basin. In the wedge-top zone, the
10 MES over the upper part of PLG unit is overlapped by the Lago-Mare unit, over
11 which the Trubi Formation lies in stratigraphic continuity.
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26
27
28
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32 **References**

- 33
34
35 AGIADI, K. (2013) *Investigation of the Plio-Pleistocene eastern Mediterranean*
36 *Ichthyofauna and paleoenvironmental representations on Rhodes and Crete Islands*,
37 PhD Thesis, University of Athens.
38
39
40
41 AGIADI, K., TRIANTAPHYLLOU, M., GIRONE, A., KARAKITSIOS, V. &
42 DERMITZAKIS, M. (2010) Paleobathymetric interpretation of the fish otoliths from
43 the lower - middle quaternary deposits of Kephallonia and Zakynthos islands (Ionian
44 Sea, Western Greece). *Rivista Italiana di Paleontologia e Stratigrafia*, 116(1), 63-78.
45
46
47
48
49 AGIADI, K., KOSKERIDOU, E., TRIANTAPHYLLOU, M., GIRONE, A. &
50 KARAKITSIOS, V. (2013) Fish otoliths from the Pliocene Heraklion Basin (Crete
51 Island, Eastern Mediterranean). *Geobios*, 46, 461-472.
52
53
54
55 ANTONARAKOU, A., DRINIA, H., TSAPARAS, N. & DERMITZAKIS, M.D.,
56 (2007). Micropaleontological parameters as proxies of late
57
58
59
60

1
2
3 Miocene surface water properties and paleoclimate in Gavdos Island, eastern
4 Mediterranean. *Geodiversitas*, 29(3), 379-399.

5
6
7 AUBRY, M.-P. (1984, 1988, 1989, 1990, 1999) *Handbook of Cenozoic Calcareous*
8 *Nannoplankton*. Vol. 1-5, Micropress, American Museum of Natural History, New
9 York.

10
11
12
13 BACKMAN, J., RAFFI, I., RIO, D., FORNACIARI, E. & PÄLIKE, H. (2012)
14 Biozonation and biochronology of Miocene through Pleistocene calcareous
15 nanofossils from low and middle latitudes. *Newsletters on Stratigraphy*, 45(3), 221-
16 244.

17
18
19
20
21 BAUMANN, K.-H., ANDRULEIT, H., BÖCKEL, B., GEISEN, M. & KINKEL, H.
22 (2005) The significance of extant coccolithophores as indicators of ocean water
23 masses, surface water temperature, and paleoproductivity: a review. *Paläontologische*
24 *Zeitschrift*, 79, 93-112.

25
26
27
28 BÈ, A.W.H., TOLDERLUND, D.S. (1971) *Distribution and ecology of living*
29 *planktonic foraminifera in surface waters of the Atlantic and Indian Oceans*. In:
30 Funnel, B.M., Riedel, W.R. (Eds.), *The Micropaleontology of Oceans*. Cambridge
31 University Press, Cambridge, pp. 105-149.

32
33
34
35
36 BELLANCA, A., CARUSO, A., FERRUZZA, G., NERI, R., ROUCHY, J.M.,
37 SPROVIERI, M. & BLANC-VALLERON, M.M. (2001) Transition from marine to
38 hypersaline conditions in the Messinian Tripoli Formation from the marginal areas of
39 the central Sicilian Basin. *Sedimentary Geology*, 140(1-2), 87-105.

40
41
42
43 BIRCK, J. (1986) Precision K–Rb–Sr isotope analysis: application to Rb–Sr
44 chronology. *Chemical Geology*, 56, 73-83.

45
46
47
48 BLANC-VALLERON, M.-M., PIERRE, C., CAULET, J.P., CARUSO, A.,
49 ROUCHY, J.-M., CESPUGLIO, G., SPROVIERI, R., PESTREA, S. & DI
50 STEFANO, E. (2002) Sedimentary, stable isotope and micropaleontological records
51 of paleoceanographic change in the Messinian Tripoli Formation (Sicily, Italy).
52 *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 185, 255-286.

- 1
2
3 BOWN, P.R., & YOUNG, J.R. (1998) Techniques. In: *Calcareous Nannofossil*
4 *Biostratigraphy* (Ed. by P.R. Bown), pp. 16–28, Kulwer Academic Publications,
5 Dordrecht.
6
7
8
9 BP CO. LTD. (1971.) *The Geological results of petroleum exploration in western*
10 *Greece. Institute for Geology and Subsurface Research (now I.G.M.E.). Special*
11 *Report, 10, Athens.*
12
13
14 BUTLER, R.W.H., LICKORISH, W.H., GRASSO, M., PEDLEY, H.M. &
15 RAMBERTI, L. (1995) Tectonics and sequence stratigraphy in Messinian basins,
16 Sicily: constraints on the initiation and termination of the Mediterranean salinity
17 crisis. *Geolog. Soc. America Bull.*, 107(4), 425-439.
18
19
20
21
22 CARNEVALE, G., LANDINI, W. & SARTI, G. (2006) Mare versus Lago-mare:
23 marine fishes and the Mediterranean environment at the end of the Messinian Salinity
24 Crisis. *Journal of the Geological Society London*, 163, 75-80.
25
26
27
28 CARNEVALE, G., LONGINELLI, A., CAPUTO, D., BARBIERI, M. & LANDINI,
29 W. (2008) Did the Mediterranean marine reflooding precede the Mio–Pliocene
30 boundary? Paleontological and geochemical evidence from upper Messinian
31 sequences of Tuscany, Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*,
32 257(1-2), 81-105.
33
34
35
36
37 CHADIMA, M., & HROUDA, F. (2006) Remas of t 3.0 a User friendly
38 Paleomagnetic Data Browser and Analyzer. *Travaux Géophysiques*, 27, 20-21.
39
40
41
42 CIESM (2008) The Messinian salinity crisis from mega-deposits to microbiology. A
43 consensus report. In: *33ème CIESM Workshop Monographs* (Edited by F. Briand), pp.
44 91-96, Monaco.
45
46
47
48 COHEN, D.M., INADA, T., IWAMOTO, T. & SCIALABBA, N. (1990) FAO
49 species catalogue. Vol.10. Gadiform fishes of the world (Order Gadiformes). An
50 annotated and illustrated catalogue of cods, hakes, grenadiers and other gadiform
51 fishes known to date. *FAO Fish. Synop.*, 125(1), pp. 442, FAO, Rome.
52
53
54
55
56 CROS, L. (2001) *Planktonic coccolithophores of the NW Mediterranean*, PhD thesis,
57 pp.181, Departament d'Ecologia, Universitat de Barcelona, Barcelona.
58
59
60

1
2
3 DERMITZAKIS M. (1977) Stratigraphy and sedimentary history of the Miocene of
4 Zakynthos (Ionian Islands, Greece). *Ann. Geol. Pays Hell.*, 29, 47-186.

5
6
7 DECELLES, P.G. & GILES, K.A. (1996) Foreland basin systems. *Basin Research*,
8 8(2), 105-123.

9
10
11 DE LANGE, G.J., & KRIJGSMAN, W. (2010) Messinian Salinity Crisis: a novel
12 unifying shallow gypsum/ deep dolomite formation mechanism. *Marine Geology*,
13 275, 273-277.

14
15
16
17 DELA PIERRE, F., CLARI, P., BERNARDI, E., NATALICCHIO, M., COSTA, E.,
18 CAVAGNA, S., LOZARA, F., LUGLI, S., MANZI, V., ROVERI, M. & VIOLANTI,
19 D. (2012) Messinian carbonate-rich beds of the Tertiary Piedmont Basin (NW Italy):
20 Microbially-mediated products straddling the onset of the salinity crisis.
21 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 344-345, 78-93.

22
23
24 DIMIZA, M.D., TRIANTAPHYLLOU, M.V., DERMITZAKIS, M.D. (2008)
25 Seasonality and ecology of living coccolithophores in E. Mediterranean coastal
26 environments (Andros Island, Middle Aegean Sea). *Micropaleontology*, 54, 159-175.

27
28
29 DIMIZA, M.D., TRIANTAPHYLLOU, M.V. & MALINVERNO, E. (2014) New
30 evidence for the ecology of *Helicosphaera carteri* in polluted coastal environments
31 (Elefsis Bay, Saronikos Gulf, Greece). *Journal of Nannoplankton Research*, 34,
32 special issue Coccolithophores 2014 INA workshop.

33
34
35 DI STEFANO, A. & STURIALE, G. (2010) Refinements of calcareous nannofossil
36 biostratigraphy at the Miocene/Pliocene Boundary in the Mediterranean region.
37 *Geobios*, 43, 5-20.

38
39
40 DI STEFANO, E., SPROVIERI, R. & SCARANTINO, S. (1996) Chronology of
41 biostratigraphic events at the base of the Pliocene. *Paleopelagos*, 6, 401-414.

42
43
44 DRINIA, H., ANTONARAKOU, A., TSAPARAS, N. & KONTAKIOTIS, G. (2007)
45 Palaeoenvironmental conditions preceding the MSC: a case study from Gavdos
46 Island. *Geobios*, 40, 251-265.

1
2
3 DRINIA, H., ANTONARAKOU, A., KONTAKIOTIS, G., (2008). On the occurrence
4 of Early Pliocene marine deposits in the Ierapetra Basin, Eastern Crete, Greece.
5
6 *Bulletin of Geosciences*, 83(1), 63-78.
7

8
9 DUERMEIJER, C.E., KRIJGSMAN, W., LANGEREIS, C.G., MEULENKAMP,
10 J.E., TRIANTAPHYLLOU, M.V. & ZACHARIASSE, W.J. (1999) A late Pleistocene
11 clockwise rotation phase of Zakynthos (Greece) and implications for the evolution of
12 the western Aegean arc. *Earth and Planetary Science Letters*, 173(3), 315-331.
13
14

15
16 FABRICIUS, F.H., HEIMANN, K.O. & BRAUNE, K. (1998) Comparison of site 274
17 with circum-Ionian land sections: implications for the Messinian “salinity crisis” on
18 the basis of a dynamic model. *Initial reports DSDP*, 42, 927-942.
19
20

21
22 FLECKER, R., DE VILLIERS, S. & ELLAM, R.M. (2002) Modelling the effect of
23 evaporation on the salinity–⁸⁷Sr/⁸⁶Sr relationship in modern and ancient marginal-
24 marine systems: the Mediterranean Messinian Salinity Crisis. *Earth and Planetary*
25 *Science Letters*, 203(1), 221-233.
26
27

28
29 FLORES, J.A., SIERRA, F.J., FILIPPELLI, G.M., BÁRCENA, M.A., PÉREZ-
30 FOLGADO, M., VÁZQUEZ, A. & UTRILLA, R. (2005) Surface water dynamics and
31 phytoplankton communities during deposition of cyclic late Messinian sapropel
32 sequences in the western Mediterranean. *Mar. Micropaleontol.*, 56, 50-79.
33
34
35

36
37 FROESE, R. & PAULY, D. (2014) *FishBase*. World Wide Web electronic
38 publication, www.fishbase.org, version (08/2014).
39
40

41
42 FORTUIN, A.R. & KRIJGSMAN, W. (2003) The Messinian of the Nijar Basin (SE
43 Spain): sedimentation, depositional environments and paleogeographic evolution.
44 *Sedimentary Geology*, 160(1-3), 213-242.
45
46

47
48 GARCIA-CASTELLANOS, D., ESTRADA, F., JIMÉNEZ-MUNT, I., GORINI, C.,
49 FERNÁNDEZ, M., VERGÉS, J. & DE VICENTE, R. (2009) Catastrophic flood of
50 the Mediterranean after the Messinian salinity crisis. *Nature*, 462, 778-781.
51
52

53
54 GENNARI, R. (2007) *Cause e modalità della formazione messiniana “LagoMare” e*
55 *passaggio al Pliocene*, Ph. D. Thesis, University of Parma, Parma, 126 pp.
56
57
58
59
60

1
2
3 GENNARI, R., IACCARINO S.M., DI STEFANO, A., STURIALE, G.,
4 CIPOLLARI, P., MANZI, V., ROVERI, M. & COSENTINO, D. (2008) The
5 Messinian – Zanclean boundary in the Northern Apennine. *Stratigraphy*, 5(3-4), 307-
6 322.
7
8

9
10 GENNARI, R., MANZI, V., ANGELETTI, L., BERTINI, A., BIFFI, U.,
11 CEREGATO, A., FARANDA, C. GLIOZZI, E. LUGLI, S., MENICHETTI, E.,
12 ROSSO, A. ROVERI, M. & TAVIANI, M. (2013) A shallow water record of the
13 onset of the Messinian salinity crisis in the Adriatic foredeep (Legnagnone section,
14 Northern Apennines). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 386,
15 145-164.
16
17

18
19 GIRONE, A., NOLF, D. & CAVALLO, O. (2010) Fish otoliths from the pre-
20 evaporitic (Early Messinian) sediments of northern Italy: their stratigraphic and
21 palaeobiogeographic significance. *Facies*, 56, 399-432.
22
23

24
25 GIGNOUX, M. (1936) *Géologie stratigraphique*. 2nd édition, pp. 709, Masson, Paris.
26
27

28
29 HEMLEBEN, CH., SPINDLER, M., ANDERSON, O.R. (1989) *Modern Planktonic*
30 *Foraminifera*. Springer, New York, pp. 1-363.
31
32

33
34 HILGEN, F.L. & KRIJGSMAN, W. (1999) Cyclostratigraphy and astrochronology of
35 the Tripoli diatomite formation (pre-evaporite Messinian, Sicily, Italy). *Terra Nova*,
36 11, 16-22.
37
38

39
40 HILGEN, F., KUIPER, K., KRIJGSMAN, W., SNEL, E. & VAN DER LAAN, E.,
41 (2007) Astronomical tuning as the basis for high resolution chronostratigraphy: the
42 intricate history of the Messinian Salinity Crisis. *Stratigraphy*, 4(2/3), 231-238.
43
44

45
46 HSU, K.J., RYAN, W.B.F. & CITA, M.B. (1973) Late Miocene desiccation of the
47 Mediterranean. *Nature*, 242, 240-244.
48
49

50
51 IACCARINO, S.M., PREMOLI SILVA, I., BIOLZI, M., FORESI, L.M., LIRER, F.,
52 TURCO, E., & PETRIZZO, M.R. (2007) *Practical manual of Neogene planktonic*
53 *foraminifera*, 1-180. Perugia: Università di Perugia Press International School on
54 Planktonic Foraminifera, (Neogene Planktonic Foraminifera).
55
56
57
58
59
60

1
2
3 IACCARINO, S.M., BERTINI, A., DI STEFANO, A., FERRARO, L., GENNARI,
4 R., GROSSI, F., LIRER, F., MANZI, V., MENICHETTI, E., RICCI LUCCHI, M.,
5 TAVIANI, M., STURIALE, G. & ANGELETTI, L. (2008) The Trave section (Monte
6 dei Corvi, Ancona, Central Italy): an integrated paleontological study of the
7 Messinian deposits. *Stratigraphy*, 5, 283-308.

8
9
10
11
12 IACCARINO, S., CASTRADORI, D., CITA, M.B., DI STEFANO, E., GABOARDI,
13 S., MCKENZIE, J.A., SPEZZAFERRI, S. & SPROVIERI, R. (1999) The Miocene–
14 Pliocene boundary and the significance of the earliest Pliocene flooding in the
15 Mediterranean. *Mem. Soc. Geol. Ital.*, 54, 109-131.

16
17
18
19
20 IADANZA, A., SAMPALMIERI, G., CIPOLLARI, P., MOLA, M. &
21 COSENTINO, D. (2013) The “Brecciated Limestones” of Maiella, Italy: Rheological
22 implications of hydrocarbon-charged fluid migration in the Messinian Mediterranean
23 Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 390, 130-147.

24
25
26
27
28 KARAKITSIOS, V. (1995). The influence of preexisting structure and halokinesis on
29 organic matter preservation and thrust system evolution in the Ionian basin,
30 northwestern Greece. *AAPG Bulletin*, 79, 960-980.

31
32
33
34 KARAKITSIOS, V. (2013) Western Greece and Ionian Sea petroleum systems.
35 *AAPG Bulletin*, 97(9), 1567-1595.

36
37
38 KARAKITSIOS, V. & RIGAKIS, N. (2007) Evolution and petroleum potential of
39 western Greece. *Journal of Petroleum Geology*, 30(3), 197-218.

40
41
42
43 KONTOPOULOS, N., ZELILIDIS, A., PIPER, D.J.W. & MUDIE, P.J. (1997)
44 Messinian evaporites in Zakynthos, Greece. *Palaeogeography, Palaeoclimatology,*
45 *Palaeoecology*, 129(3-4), 361-367.

46
47
48
49 KOUWENHOVEN, T.J. & VAN DER ZWAAN, G.J. (2006) A reconstruction of late
50 Miocene Mediterranean circulation patterns using benthic Foraminifera.
51 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 238(1-4), 373-385.

52
53
54
55 KOUWENHOVEN, T.J., SEIDENKRANTZ, M.-S. & VAN DER ZWAAN, G.J.
56 (1999) Deep-water changes: The near-synchronous disappearance of a group of
57
58
59
60

1
2
3 benthic Foraminifera from the late Miocene Mediterranean. *Palaeogeography,*
4 *Palaeoclimatology, Palaeoecology*, 152, 259-281.

6
7 KOUWENHOVEN, T.J., HILGER, F.J. & VAN DER ZWAAN, G.J. (2003) Late
8 Tortonian–early Messinian stepwise disruption of the Mediterranean–Atlantic
9 connections: constraints from benthic foraminiferal and geochemical data.
10 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 198(3-4), 303-319.

12
13 KOUWENHOVEN, T.J., MORIGI, C., NEGRI, A., GIUNTA, S., KRIJGSMAN, W.
14 & ROUCHY, J.-M. (2006) Paleoenvironmental evolution of the eastern
15 Mediterranean during the Messinian: Constraints from integrated microfossil data of
16 the Pissouri Basin (Cyprus). *Marine Micropaleontology*, 60(1), 17-44.

18
19 KRIJGSMAN, W., LANGEREIS, C.G., ZACHARIASSE, W.J., BOCCALETTI, M.,
20 MORATTI, G., GELATI, R., IACCARINO, S., PAPANI, G. & VILLA, G., (1999)
21 Late Neogene evolution of the Taza-Guercif Basin (Riffian Corridor, Morocco) and
22 implications for the Messinian salinity crisis. *Mar. Geol.*, 153(1-4), 147-160.

24
25 KRIJGSMAN, W., HILGEN, F.J., RAFFI, I., SIERRO, F.J. & WILSON, D.S.
26 (1999b) Chronology, causes and progression of the Messinian salinity crisis. *Nature*,
27 400, 652-655.

28
29 KRIJGSMAN, W., BLANC-VALLERON, M.-M., FLECKER, R., HILGEN, F.J.,
30 KOUWENHOVEN, T.J., MERLE, D., ORSZEG-SPERBER, F. & ROUCHY, J.-M.
31 (2002) The onset of the Messinian salinity crisis in the Eastern Mediterranean
32 (Pissouri Basin, Cyprus). *Earth and Planetary Science Letters*, 194(3-4), 299-310.

33
34 LUGLI, S., SCHREIBER, B.C. & TRIBERTI, B. (1999) Giant Polygons in the
35 Realmonte Mine (Agrigento, Sicily): Evidence for the Desiccation of a Messinian
36 Halite Basin. *Journal of Sedimentary Research, Section A: Sedimentary Petrology*
37 *and Processes*, 69(3), 764-771.

38
39 LUGLI, S., MANZI, V., ROVERI, M. & SCHREIBER, B.C. (2010) The Primary
40 Lower Gypsum in the Mediterranean: A new facies interpretation for the first stage of
41 the Messinian salinity crisis. *Palaeogeography Palaeoclimatology Palaeoecology*,
42 297, 83-99.

1
2
3 LUGLI, S., GENNARI, R., GVIRTZMAN, Z., MANZI, V. & ROVERI, M.,
4 SCHREIBER, B.C. (2013) Evidence of Clastic Evaporites In the Canyons of the
5 Levant Basin (Israel): Implications For the Messinian Salinity Crisis. *Journal of*
6 *Sedimentary Research*, 83(11), 942-954.
7
8

9
10 LOURENS, L.J., ANTONARAKOU, A., HILGEN, F.J., VAN HOOFF, A.A.M.,
11 VERGNAUD-GRAZZINI, C. & ZACHARIASSE, W.J. (1996) Evaluation of the
12 Plio-Pleistocene astronomical timescale. *Paleoceanography*, 11, 391-413.
13
14

15
16 LOURENS, L., HILGEN, F., SHACKLETON, N. J., LASKAR, J., & WILSON, J.
17 (2004) The Neogene period. In: *A Geologic Time Scale 2004* (Edited by F. M.
18 Gradstein *et al.*), p. 409-440, Cambridge University Press, Cambridge.
19
20

21
22 MALINVERNO, E., TRIANTAPHYLLOU, M.V., STAVRAKAKIS, S., ZIVERI, P.
23 & LYKOUSIS, V. (2009) Seasonal and spatial variability of coccolithophore export
24 production at the South-Western margin of Crete (Eastern Mediterranean). *Marine*
25 *Micropaleontology*, 71, 131-147.
26
27
28

29
30 MANZI, V., LUGLI, S., RICCI LUCCHI, F. & ROVERI, M. (2005) Deep-water
31 clastic evaporites deposition in the Messinian Adriatic foredeep (northern Apennines,
32 Italy): did the Mediterranean ever dry out? *Sedimentology*, 52(4), 875-902.
33
34
35

36
37 MANZI, V., ROVERI, M., GENNARI, R., BERTINI, A., BIFFI, U., GIUNTA, S.,
38 IACCARINO, S.M., LANCI, L., LUGLI, S., NEGRI, A., RIVA, A., ROSSI, M.E. &
39 TAVIANI, M. (2007) The deep-water counterpart of the Messinian Lower Evaporites
40 in the Apennine foredeep: The Fanantello section (Northern Apennines, Italy).
41 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 251(3-4), 470-499.
42
43
44

45
46 MANZI, V., LUGLI, S., ROVERI, M. & SCHREIBER, B.C. (2009) A new facies
47 model for the Upper Gypsum of Sicily (Italy): chronological and paleoenvironmental
48 constraints for the Messinian salinity crisis in the Mediterranean. *Sedimentology*, 56:
49 1937-1960.
50
51
52

53
54 MANZI, V., LUGLI, S., ROVERI, M., SCHREIBER, B.C. & GENNARI, R. (2011)
55 The Messinian "Calcare di Base" (Sicily, Italy) revisited. *Geological Society of*
56 *America Bulletin*, 123(1-2), 347-370.
57
58
59
60

1
2
3 MANZI, V., GENNARI, R., LUGLI, S., ROVERI, M., SCAFETTA, N. &
4 SCHREIBER, B.C. (2012) High-Frequency cyclicity in the Mediterranean Messinian
5 evaporites: evidence for solar-lunar climate forcing. *Journal of Sedimentary*
6 *Research*, 82(12), 991-1005.

9
10 MANZI, V., GENNARI, R., HILGEN, F., KRIJGSMAN, W., LUGLI, S., ROVERI,
11 M. & SIERRO, F.J. (2013) Age refinement of the Messinian salinity crisis onset in
12 the Mediterranean. *Terra Nova*, 25(4), 315-322.

13
14 MANZI, V., LUGLI, S., ROVERI, M., DELA PIERRE, F., GENNARI, R. LOZAR,
15 F., NATALICCHIO, M., SCHREIBER, B.C., TAVIANI, M. & TURCO, E. (2015)
16 The Messinian salinity crisis in Cyprus: a further step toward a new stratigraphic
17 framework for Eastern Mediterranean. *Basin Research*, DOI: 10.1111/bre.12107.

18
19 MARTINI, E. (1971) Standard tertiary and quaternary calcareous nannoplankton
20 zonation. In: *Proceedings of the 2nd Planktonic Conference* (Edited by A. Farinacci),
21 p. 739-777, Edizioni Tecnioscienza, Rome.

22
23 MAUCHILNE, J. (1988) Growth and breeding of meso- and bathypelagic organisms
24 of the Rockall Trough, northeastern Atlantic Ocean and evidence of seasonality.
25 *Marine Biology*, 98, 387-393.

26
27 MEIJER, P.TH. & KRIJGSMAN, W. (2005) A quantitative analysis of the
28 desiccation and re-filling of the Mediterranean during the Messinian Salinity Crisis.
29 *Earth and Planetary Science Letters*, 240(2), 510-520.

30
31 MERTZ-KRAUS, R., BRACHERT, T.C., REUTER, M., GALER, S.J.G.,
32 FASSOULAS, C. & ILIOPOULOS, G. (2009) Late Miocene sea surface salinity
33 variability and paleoclimate conditions in the Eastern Mediterranean inferred from
34 coral aragonite $\delta^{18}\text{O}$. *Chemical Geology*, 262(3-4), 202-216.

35
36 MEZGER, E. (2012) *How dry was the Messinian salinity crisis? A molecular*
37 *biogeochemical study of the Eraclea Minoa (Sicily) section, Italy*, pp.34, M.Sc.
38 Thesis, Utrecht University, Utrecht.

39
40 NELSON, J.S. (2006) *Fishes of the World*, 4th ed., pp. 600, John Wiley and Sons Inc.,
41 New Jersey.

- 1
2
3 NIKOLAOU, C. (1986) *Contribution to the knowledge of the Neogene, the geology*
4 *and the Ionian and pre-Apulian limits in relation to the petroleum geology*
5 *observations in Strophades, Zakynthos and Kephallinia islands*, pp. 228, PhD
6 thesis, University of Athens, Athens.
7
8
9
10 NOLF, D. (1985) Otolithi Piscium, In: *Handbook of Paleoichthyology* (Edited by H.P.
11 Schultze), vol. 10, pp. 145, Stuttgart.
12
13
14 NOLF, D. & BRZOBOHATY, R. (1994) Fish otoliths as paleobathymetric indicators.
15 *Paleontologia i evolucion*, 24-25, 255-264.
16
17
18
19 OBIS (2006) *OBIS-extracted Depth Data*, Harvested by E.Agbayani July 2006 at
20 www.iobis.org.
21
22
23
24 OMODEO-SALE, S., GENNARI, R., LUGLI, S., MANZI, V. & ROVERI, M. (2012)
25 Tectonic and climatic control on the Late Messinian sedimentary evolution of the
26 Nijar Basin (Betic Cordillera, Southern Spain). *Basin Research*, 24(3), 314-337.
27
28
29
30 ORSZAG-SPERBER, F. (2006) Changing perspectives in the concept of “Lago-
31 Mare” in Mediterranean Late Miocene evolution. *Sedimentary Geology*, 188-189,
32 259-277.
33
34
35
36 PAPANIKOLAOU, M., TRIANTAPHYLLOU, M., PLATZMAN, E., GIBBARD, P.,
37 MACNIOCAILL, C. & HEAD, M.J. (2011) A well-established Early–Middle
38 Pleistocene marine sequence on SE Zakynthos island, Western Greece: magneto-
39 biostratigraphic constraints and palaeoclimatic implications. *Journal of Quaternary*
40 *Science*, 26, 523-540.
41
42
43
44
45 PERCH NIELSEN, K. (1985) Cenozoic calcareous nannofossils. In: *Plankton*
46 *Stratigraphy* (Edited by Bolli, H.M., Saunders, J.B. & Perch-Nielsen, K.), p. 427-554,
47 Cambridge Earth Science Series, Cambridge.
48
49
50
51 PIERRE, C., CARUSO, A., BLANC-VALLERON, M.-M., ROUCHY, J.M. &
52 ORZSAG-SPERBER, F. (2006) Reconstruction of the paleoenvironmental changes
53 around the Miocene-Pliocene boundary along a West-East transect across the
54 Mediterranean, *Sedimentary Geology*, 188-189, 319-340.
55
56
57
58
59
60

1
2
3 RADE, J. (1975) Scyphosphaera evolutionary trends with special reference to eastern
4 Australia. *Micropaleontology*, 21, 151-164.

6
7 RAFFI, I., BACKMAN, J., FORNACIARI, E., PÄLIKE, H., RIO, D., LOURENS, L.
8 & HILGEN, F. (2006) A review of calcareous nannofossil astrobiochronology
9 encompassing the past 25 million years. *Quaternary Science Reviews*, 25, 3113-3137.

11
12
13 RICCI LUCCHI, F. (1973) *Sedimentologia*. Parte I. Materiali e tessiture dei
14 sedimenti. Cooperativa libraria universitaria. Bologna.

16
17
18 RIO, D. & SPROVIERI, R. (1986) Biostratigrafia integrate del Pliocene-Pleistocene
19 inferire Mediterraneo in un'ottica di stratigrafia systematica. *Boll. Soc. Paleontol.*
20 *Italiana*, 25, 65-85.

22
23
24 ROBERTSON, A.H.F., EATON, S., FOLLOWS, E.J., PAYNE, A.S. (1995)
25 Depositional processes and basin analysis of Messinian evaporites in Cyprus. *Terra*
26 *Nova*, 7, 233-253.

28
29
30 ROUCHY, J.M. (1982) La genèse des évaporites messiniennes de Méditerranée.
31 *Mém. Mus. Nat. Hist. Nat.*, C, 50, Paris.

32
33
34 ROUCHY, J.M. & CARUSO, A. (2006) The Messinian salinity crisis in the
35 Mediterranean basin: a reassessment of the data and an integrated scenario.
36 *Sedimentary Geology*, 188, 35-67.

37
38
39 ROVERI, M. & MANZI, V. (2006) The Messinian salinity crisis: looking for a new
40 paradigm? *Palaeogeography, Palaeoclimatology, Palaeoecology*, 238, 386-398.

41
42
43 ROVERI, M., MANZI, V., BASSETTI, M.A., MERINI, M. & RICCI LUCCHI, F.
44 (1998) Stratigraphy of the Messinian post-evaporitic stage in eastern-Romagna
45 (northern Apennines, Italy). *Giornale di Geologia*, 60, 119-142.

46
47
48
49
50 ROVERI, M., MANZI, V., RICCI LUCCHI, F. & ROGLEDI, S. (2003) Sedimentary
51 and tectonic evolution of the Vena del Gesso Basin (Northern Apennines, Italy):
52 implications for the onset of the Messinian salinity crisis. *Geological Society of*
53 *America Bulletin*, 115, 387-405.

1
2
3 ROVERI, M., LUGLI, S., MANZI, V. & SCHREIBER, B.C. (2008a) The Messinian
4 Sicilian stratigraphy revisited: new insights for the Messinian salinity crisis. *Terra*
5 *Nova*, 20(6), 483-488.
6
7

8
9 ROVERI, M., BERTINI, A., COSENTINO, D., DI STEFANO, A., GENNARI, R.,
10 GLIOZZI, E., GROSSI, F., IACCARINO, S.M., LUGLI, S., MANZI, V. &
11 TAVIANI, M. (2008b) A high-resolution stratigraphic framework for the latest
12 Messinian events in the Mediterranean area. *Stratigraphy*, 5(3-4), 323-342.
13
14

15
16 ROVERI, M., FLECKER, R., KRIJGSMAN, W., LOFI, J., LUGLI, S., MANZI, V.,
17 SIERRO, F.J., BERTINI, A., CAMERLENGHI, A., DE LANGE, G., GOVERS, R.,
18 HILGEN, F.J., HÜBSCHER, C., MEIJER, P.T. & STOICA, M. (2014a) The
19 Messinian Salinity Crisis: Past and Future of a great challenge for marine sciences.
20 *Marine Geology*, 352, 25-58.
21
22

23
24 ROVERI, M., MANZI, V., BERGAMASCO, A., FALCIERI, F.M., GENNARI, R.,
25 LUGLI, S., SCHREIBER, B.C. (2014b) Dense shelf water cascading and Messinian
26 canyons: a new scenario for the Mediterranean salinity crisis. *American Journal Of*
27 *Science*, 314, 751-784.
28
29

30
31 ROVERI M., LUGLI S., MANZI V., GENNARI R. & SCHREIBER B.C. (2014c)
32 High-resolution strontium isotope stratigraphy of the Messinian deep Mediterranean
33 basins: implications for marginal to central basins correlation. *Marine Geology*, 349,
34 113-125.
35
36

37
38 RUGGIERI, G. (1967) The Miocene and later evolution of the Mediterranean Sea. In:
39 *Aspects of Tethyan Biogeography, Systematics Association* (Edited by Adams, C.G. &
40 Ager, A.V.), p. 283-290, London.
41
42

43
44 SHACKLETON, N.J., HALL, M.A. & PATE, D. (1995) Pliocene stable isotope
45 stratigraphy of Site 846. *ODP Proc.*, 138, 337-355.
46
47

48
49 SELLI, R. (1954) Il Bacino del Metauro. *Giornale di Geologia*, 24, 1-294.
50
51

52
53 SIERRO, F.J., FLORES, J.A., ZAMARREÑO, I., VAZQUEZ, A., UTRILLA, R.,
54 FRANCES, G., HILGEN, F.J. & KRIJGSMAN, W. (1999) Messinian pre-evaporite
55
56
57
58
59
60

1
2
3 spropels and precession-induced oscillations in western Mediterranean climate.

4 *Marine Geology*, 153, 137-146.

6
7 SIERRO, F.J., HILGEN, F.J., KRIJGSMAN, W. & FLORES, J.A. (2001) The Abad
8 composite (SE Spain): A Mediterranean reference section for the Mediterranean and
9 the APTS, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 168,141-169.

11
12
13 SIERRO, F.J., FLORES, J.A., FRANCÉS, G., VAZQUEZ, A., (2003) Orbitally
14 controlled oscillations in planktic communities and cyclic changes in western
15 Mediterranean hydrography during the Messinian. *Palaeogeography,*
16 *Palaeoclimatology, Palaeoecology*, 190, 289-316.

18
19
20 SOREL, D. (1976) *Etude néotectonique dans l'arc égéen externe occidental*, pp. 200,
21 Thèse 3^e c., Paris XI, Paris.

22
23
24 SPROVIERI, R., SPROVIERI, M., CARUSO, A., PELOSI, N., BONOMO, S. &
25 FERRARO, L. (2006) Astronomic forcing on the planktonic foraminifera assemblage
26 in the Piacenzian Punta Piccola section (southern Italy). *Paleoceanography*, 21,
27 PA4204.

28
29
30 TRIANTAPHYLLOU, M.V. (1996) Biostratigraphical and ecostratigraphical
31 observations based on calcareous nannofossils of the eastern Mediterranean Plio-
32 Pleistocene deposits. *GAIA* 1, pp. 229.

33
34
35 TRIANTAPHYLLOU, M.V., DRINIA, H. & DERMITZAKIS, M.D. (1997) The
36 Plio-Pleistocene boundary in the Gerakas section, Zakynthos (Ionian Islands). *Neues*
37 *Jahrbuch für Geologie und Paläontologie, Monatshefte*, 1, 12-30.

38
39
40 TRIANTAPHYLLOU, M.V., TSAPARAS, N., STAMATAKIS, M. &
41 DERMITZAKIS, M.D. (1999) Calcareous nannofossil biostratigraphy and
42 petrological analysis of the preevaporitic diatomaceous sediments from Gavdos
43 Island, southern Greece. *Neues Jahrbuch für Geologie und Paläontologie*
44 *Monatshefte*, 3, 161-178.

45
46
47 TRIANTAPHYLLOU, M.V., ZIVERI, P., GOGOU, A., MARINO, G., LYKOUSIS,
48 V., BOULOUBASSI, I., EMEIS, K.-C., KOULI, K., DIMIZA, M., ROSELL-MELE,
49 A., PAPANIKOLAOU, M., KATSOURAS, G. & NUNEZ, N. (2009a) Late Glacial-
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3 Holocene climate variability at the south-eastern margin of the Aegean Sea. *Marine*
4 *Geology*, 266, 182-197.
5
6
7 TRIANTAPHYLLOU, M.V., ANTONARAKOU, A., KOULI, K., DIMIZA, M.,
8 KONTAKIOTIS, G., PAPANIKOLAOU, M.D., ZIVERI, P., MORTYN, P.G.,
9 LIANOU, V., LYKOUSIS, V., DERMITZAKIS, M.D., (2009b). Late Glacial-
10 Holocene ecostratigraphy of the south-eastern Aegean Sea, based on plankton and
11 pollen assemblages. *Geo. Mar. Lett.*, 29(4), 249-267.
12
13
14 UNDERHILL, J.R. (1989) Late Cenozoic deformation of the Hellenide foreland,
15 western Greece. *Geol. Society of America Bull.*, 101, 513-634.
16
17
18 YOUNG, J.R. (1994) Functions of coccoliths, In: *Coccolithophores* (Edited by
19 Winter, A. & Siesser, W.G.), p. 63-82, Cambridge University Press, Cambridge.
20
21
22 VAI, G.B. (1997) Cyclostratigraphic estimate of the Messinian stage duration. In:
23 *Miocene stratigraphy: an integrated approach, Developments in Paleontology and*
24 *Stratigraphy* (Edited by Montanari, A. Odin, G.S. Coccioni, R.), 15, 463-476.
25
26
27 VAN ASSEN, E., KUIPER, K.F., BARHOUN, N., KRIJGSMAN, W. & SIERRO,
28 F.J. (2006) Messinian astrochronology of the Melilla Basin: Stepwise restriction of
29 the Mediterranean–Atlantic connection through Morocco. *Palaeogeography,*
30 *Palaeoclimatology, Palaeoecology*, 238, 15-31.
31
32
33 WACEY, D., KILBURN, M.R., MCLOUGHLIN, N., PARNELL, J., STOAKES,
34 C.A., GOVERNOR, C.R.M. & BRASIER, M. (2008) Use of NanoSIMS in the search
35 for early life on Earth: ambient inclusion trails in a c. 3400 Ma sandstone. *Journal of*
36 *the Geological Society London*, 165, 43-53.
37
38
39 WADE, B.S. & BOWN, P.R. (2006) Calcareous nannofossils in extreme
40 environments: The Messinian Salinity Crisis, Polemi Basin, Cyprus.
41 *Palaeogeography, Palaeoclimatology, Palaeoecology*, 233(3-4), 271-286.
42
43
44 WHEELER, A. (1992) A list of the common and scientific names of fishes of the
45 British Isles. *Journal of Fish Biology*, 41(1),1-37.
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 ZELILIDIS, A., KONTOPOULOS, N., AVRAMIDIS, P. & PIPER, D.J.W. (1998)
4 Tectonic and sedimentological evolution of the Pliocene-Quaternary basins of
5 Zakynthos Island, Greece: Case study of the transition from compressional to
6 extensional tectonics. *Basin Research*, 10(4), 393.
7
8

9
10 ZIVERI, P., BAUMANN, K.H., BÖCKEL, B., BOLLMANN, J. & YOUNG, J.
11 (2004) Biogeography of selected coccolithophores in the Atlantic Ocean, from
12 Holocene sediments. In: *Coccolithophores: From Molecular Processes to Global*
13 *Impact* (Edited by Thierstein, H. & Young, J.), p. 403-428, Springer Verlag.
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17 18 **Figure captions**

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21 Fig. 1. Geological map of Zakynthos Island. The regional location is indicated in the
22 inset map. Boreholes: Z1 (Zakynthos-1); Z2 (Zakynthos-2), Z3 (Zakynthos-3); LA1
23 (Laganas-1); KB101 (Keri-well), AK1 (Agios Kyrikos-1), KY1 (Kypseli-1).
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28 Fig. 2. Kalamaki composite section with lithology, samples' location, macrofossils of
29 the pre-evaporitic sequence, the evaporitic unit (the PLG facies description is referred
30 in the key), the top of the evaporitic unit, and the post-evaporitic sequence, and two Sr
31 isotope values from the base and the top of the gypsum unit). M/P: Miocene/Pliocene
32 boundary, pre-MSC: pre-Messinian Salinity Crisis part of the section, MES:
33 Messinian Erosional Surface, samples *KAL* 1 to *KAL* 173 with their position in the
34 section.
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41 Fig. 3. The Kalamaki section's facies detail. a. Pre-evaporitic sequence, PLG: Primary
42 Lower Gypsum; b. Uppermost portion of the Primary Lower Gypsum unit topped by
43 the Lago-Mare unit, and by the Trubi Formation: Lago-Mare stratification is
44 overlapping (yellow arrow) the MES (Messinian Erosional Surface); c. Gypsum
45 laminite; d. Swallow-tail gypsum selenites; e. Bottom view of a branching selenite
46 cone; f. Branching selenite facies.
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53 Fig. 4. Primary Lower Gypsum (PLG) unit. Letters A to H: correspond to the eight
54 cycles of depositional gypsum types observed in the PLG unit. The last cycle H
55 corresponds to top of the PLG unit showed in figure 3 b, is overlain by the Lago-Mare
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3 (LM) unit through a low-angle unconformity. Evaporite facies of the PLG unit: EF1:
4 Shale, EF2: Limestone, EF3: Massive selenite, EF4: Banded selenite, EF5: Branching
5 selenite (EF5_L: Gypsum laminite), EF7: Gypsudite, EF8: Gypsarenite (see also key of
6 Fig. 2).
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11 Fig. 5. Kalamaki-Argassi Primary Lower Gypsum unit correlation.
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14 Fig. 6. Trubi Formation facies. Based on lithology, nine cycles (I to IX) of marly
15 limestones alternating with marls are observed.
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19 Fig. 7. Agios Sostis composite section: lithology, samples location, and facies
20 characteristics of the different stratigraphic levels.
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24 Fig. 8. Sedimentary facies details of the PLG and RLG units. Argassi area: a. selenite,
25 b. branching selenite. Agios Sostis area: c. pre-evaporitic sequence and MES
26 boundary with the overlying RLG unit, d. gypsum turbidites, e: convolute lamination,
27 f: alternations of primary cumulate gypsum (CU) and clastic gypsarenite (AR) and
28 gypsrudite (GR).
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34 Fig. 9. Zakynthos (Alikanas) basin wells positioned in a west-to-east direction (the
35 wells' locations are indicated in fig. 1). Correlation of the borehole logs shows that the
36 Neogene deposits (gypsum included) increase their thickness eastward. Agios
37 Kyrikos-1 well (AK-1) revealed indirect indices of halite accumulation in the
38 Messinian gypsum stratigraphic level.
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45 Fig. 10. Alikanas basin seismic profile (modified from the initial representation by
46 Marinescu; in Nikolaou, 1986). The seismic profile shows a) the position of the
47 Ionian thrust, b) the eastward increase in the thickness of the Neogene deposits. The
48 seismic line's location is indicated in Fig. 1. PL-PT: Pliocene-Pleistocene, Pl:
49 Pliocene, LPl: lower Pliocene, Mes-g: Messinian gypsum, M-UM: middle-upper
50 Miocene, LM: lower Miocene, P-Aps: pre-Neogene sequence of the Pre-Apulian
51 zone, P-Ions: pre-Neogene sequence of the Ionian zone (Triassic evaporites), ITF:
52 Ionian thrust front, Ne: undifferentiated Neogene, SP: shot point, sec: time in seconds.
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3 Fig. 11. Fish otoliths discovered in the pre-evaporitic sequence of Kalamaki section.
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6 Fig. 12. A: plots of VGP latitude of the West and East Kalamaki subsections. B: plots
7 of ChRM directions corrected for bed tilting, full and empty red and purple circles
8 represent normal and reversed mean direction for Kalamaki West and east subsection,
9 respectively. C: Zijderveld diagrams with demagnetization paths of selected samples
10 from the Kalamaki west subsection.
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16 Fig. 13. Pre-evaporitic sequence, Upper Evaporites, Lago-Mare, and Trubi Formation
17 carbon and oxygen stable isotopes.
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21 Fig. 14. Chronostratigraphic framework of Kalamaki section's pre-evaporitic sequence
22 and correlation with Perales section (Sorbas basin) (modified after Sierro *et al.*, 2001;
23 Manzi *et al.*, 2013) and Falconara section (Caltanissetta basin) (modified after Blanc-
24 Valleron *et al.*, 2002; Hilgen & Krijgsman, 1999; Manzi *et al.*, 2011) via the
25 astronomical Insolation summer curve of Laskar *et al.* 2004 and GPTS of Lourens *et*
26 *al.*, 2004. Bio-magnetostratigraphic events are: 1) FAO *T. multiloba*; 2) FAO dextral
27 *N. acostaensis*; 3) *G. scitula* influx; 4) *N. acostaensis* dominance sinistral; 5) *T.*
28 *multiloba* influx; 6) *G. scitula* influx; 7) dominance *N. acostaensis* sinistral; 8) Last
29 abundant influx *T. multiloba*; 9) HO planktonic Foraminifera; I) top C3An.1n; II)
30 boundary C3An.2n/C3r
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39 Fig. 15. Kalamaki section age model of the PLG top portion, Lago-Mare, and Trubi
40 Formation, correlated with insolation curve (based on Laskar *et al.*, 2004).
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44 Fig. 16. Paleogeographic reconstruction.

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46 A. During the Messinian, the Zakynthos (Alikanas) foreland basin was formed in
47 front of the Ionian thrust. The Neogene formations deposited over the Pre-Apulian
48 domain corresponded to the *foredeep* and the *flank* between foredeep and *forebulge*,
49 whereas those overlying the Ionian zone corresponded to the *wedge-top*, which was
50 uplifted due to the diapiric movements of the Ionian Triassic evaporites. In the 1st
51 *MSC stage*, PLG was deposited on both *forebulge* and *wedge-top*. In the 2nd *MSC*
52 *stage*, PLG was totally or partially eroded (creating the Messinian Erosional Surface;
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3 MES) and redeposited with *correlative conformity* mainly as gypsum turbidites (RLG
4 unit) in the depocenter of the foreland basin.

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6 B. During the end of the Messinian, in Kalamaki-Argassi *wedge-top area* the Lago-
7 Mare sediments were unconformably overlying the Primary Lower Gypsum above the
8 MES, while in the depocenter of the foreland basin they were conformably deposited
9 over the Resedimented Lower Gypsum. The Zanclean flood was recorded on both
10 areas by the conformable deposition of the Trubi Formation.

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14 *With red ruffled and continuous line the unconformity and the correlative conformity*
15 *of the MES, respectively.*
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21 Table 1.

22
23 The identified Teleost fish taxa in the pre-evaporitic Messinian of Kalamaki section.
24 Taxa in bold are not present in the modern Mediterranean. Taxa marked with an
25 asterisk are presently extinct. Present-day ecological data and the corresponding
26 references are presented for the extant taxa. Climatic zone distributions are
27 abbreviated as follows: Tr. Tropical, ST. Subtropical, Te. Temperate, SP. Subpolar.
28 The modern ecology of *Buglossidium* sp. refers to its only present-day representative,
29 *B. luteum* (Risso, 1810).
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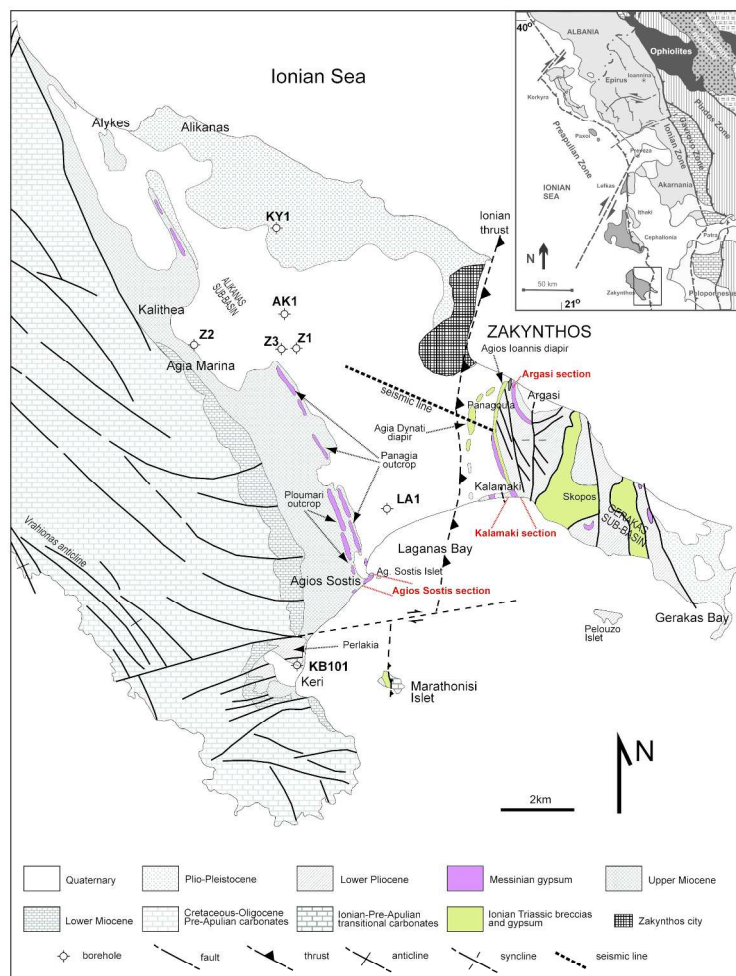


Fig. 1. Geological map of Zakynthos Island. The regional location is indicated in the inset map. Boreholes: Z1 (Zakynthos-1); Z2 (Zakynthos-2), Z3 (Zakynthos-3); LA1 (Laganas-1); KB101 (Keri-well), AK1 (Agios Kyrikos-1), KY1 (Kypseli-1).
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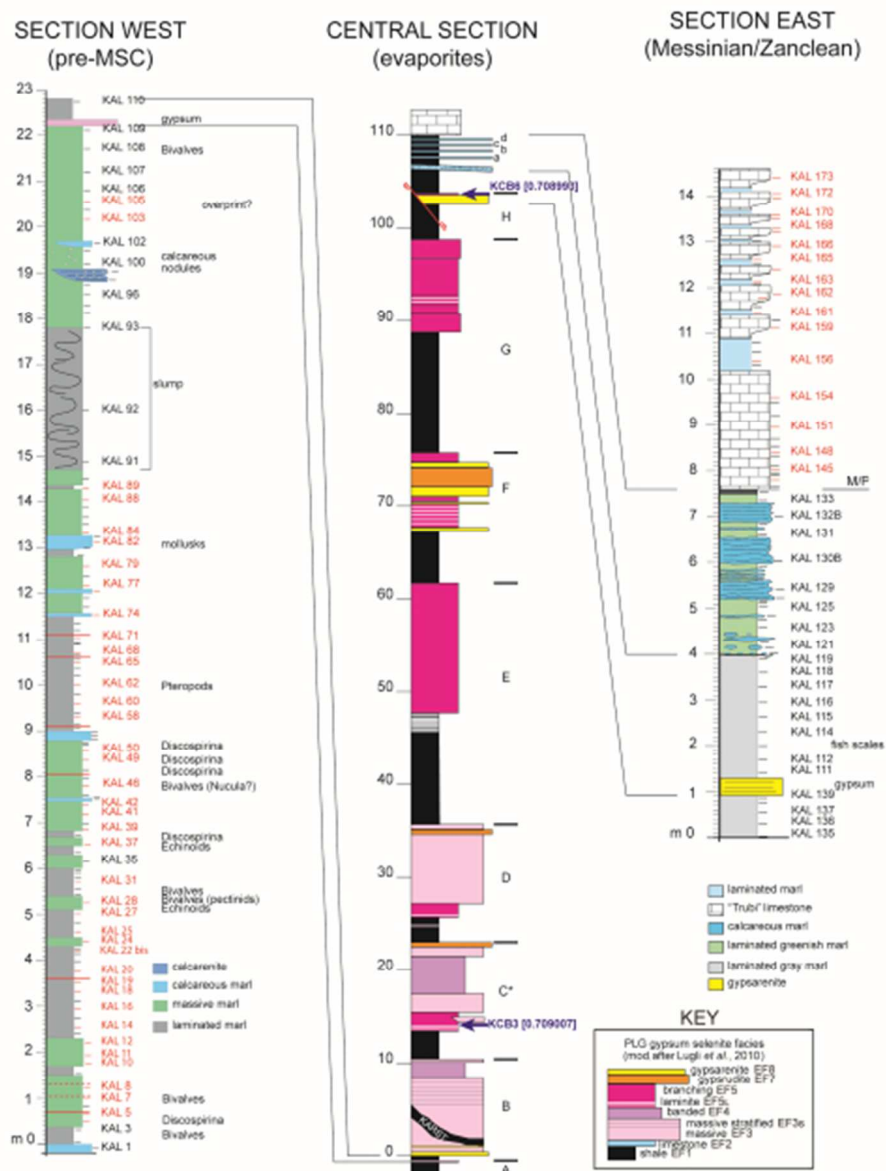


Fig. 2. Kalamaki composite section with lithology, samples' location, macrofossils of the pre-evaporitic sequence, the evaporitic unit (the PLG facies description is referred in the key), the top of the evaporitic unit, and the post-evaporitic sequence, and two Sr isotope values from the base and the top of the gypsum unit). M/P: Miocene/Pliocene boundary, pre-MSC: pre-Messinian Salinity Crisis part of the section, MES: Messinian Erosional Surface, samples KAL 1 to KAL 173 with their position in the section. 40x54mm (300 x 300 DPI)

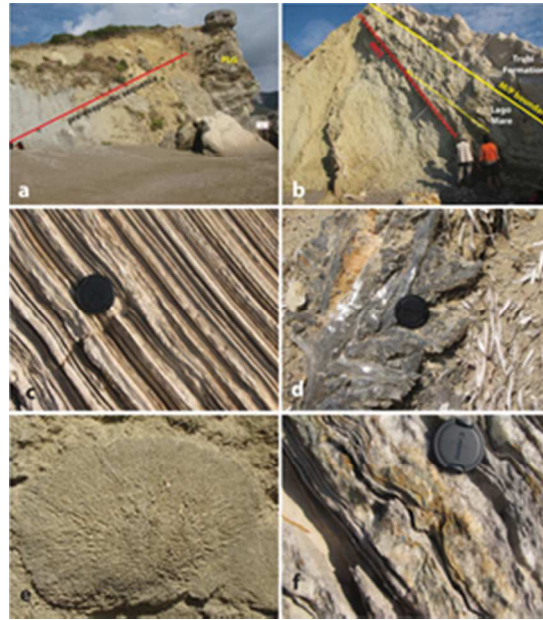


Fig. 3. The Kalamaki section's facies detail. a. Pre-evaporitic sequence, PLG: Primary Lower Gypsum; b. Uppermost portion of the Primary Lower Gypsum unit topped by the Lago-Mare unit, and by the Trubi Formation: Lago-Mare stratification is overlapping (yellow arrow) the MES (Messinian Erosional Surface); c. Gypsum laminite; d. Swallow-tail gypsum selenites; e. Bottom view of a branching selenite cone; f. Branching selenite facies.
22x25mm (300 x 300 DPI)

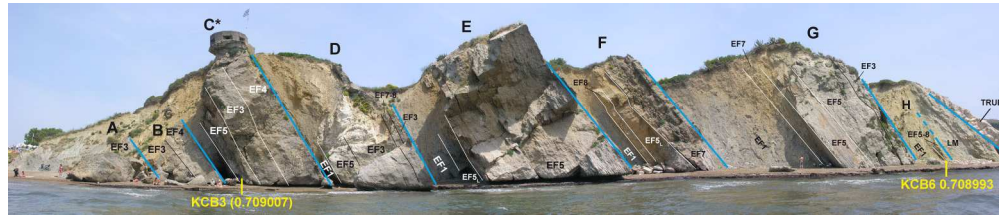


Fig. 4. Primary Lower Gypsum (PLG) unit. Letters A to H: correspond to the eight cycles of depositional gypsum types observed in the PLG unit. The last cycle H corresponds to top of the PLG unit showed in figure 3 b, is overlain by the Lago-Mare (LM) unit through a low-angle unconformity. Evaporite facies of the PLG unit: EF1: Shale, EF2: Limestone, EF3: Massive selenite, EF4: Banded selenite, EF5: Branching selenite (EF5L: Gypsum laminite), EF7: Gypsudite, EF8: Gypsarenite (see also key of Fig. 2).
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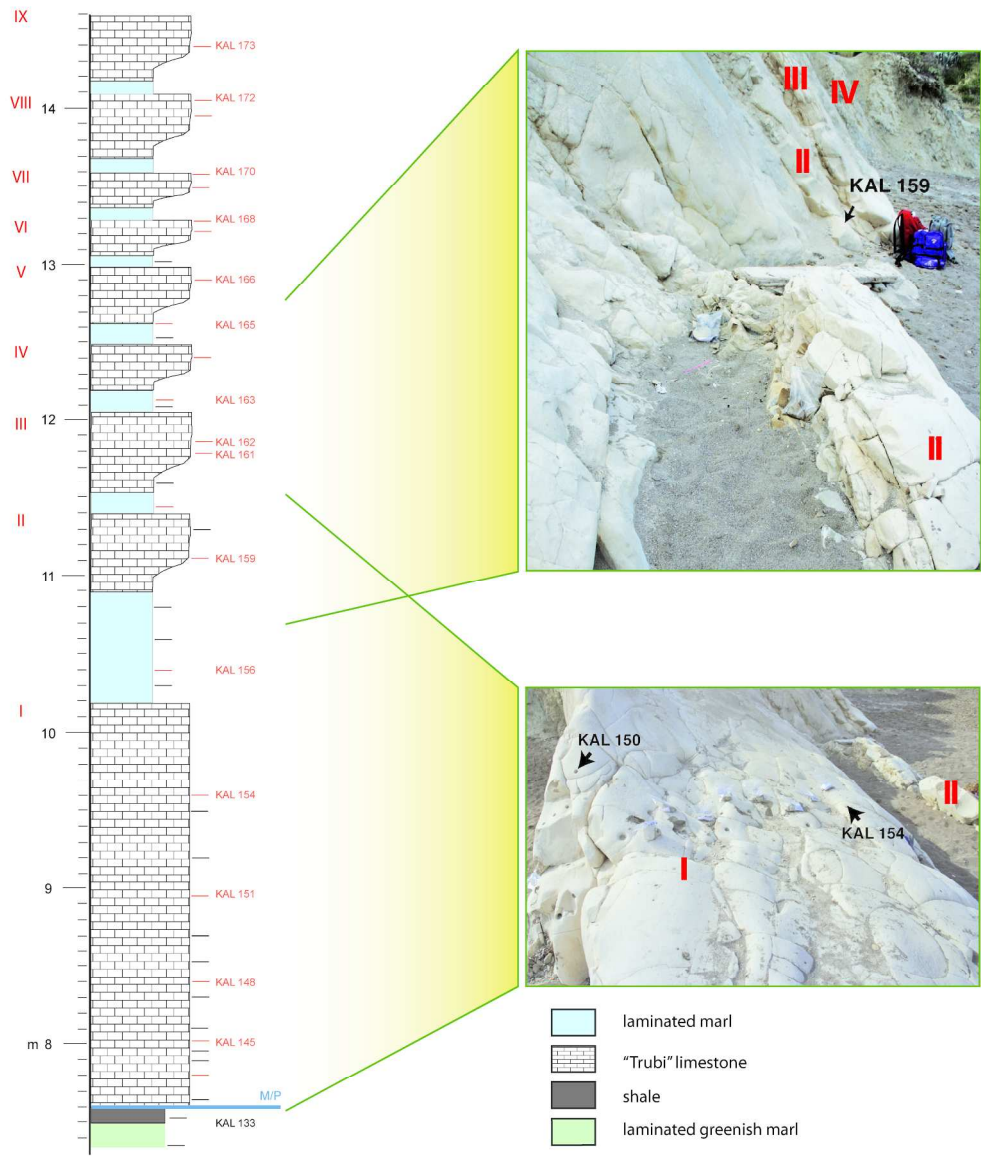


Fig. 5. Kalamaki-Argassi Primary Lower Gypsum unit correlation.
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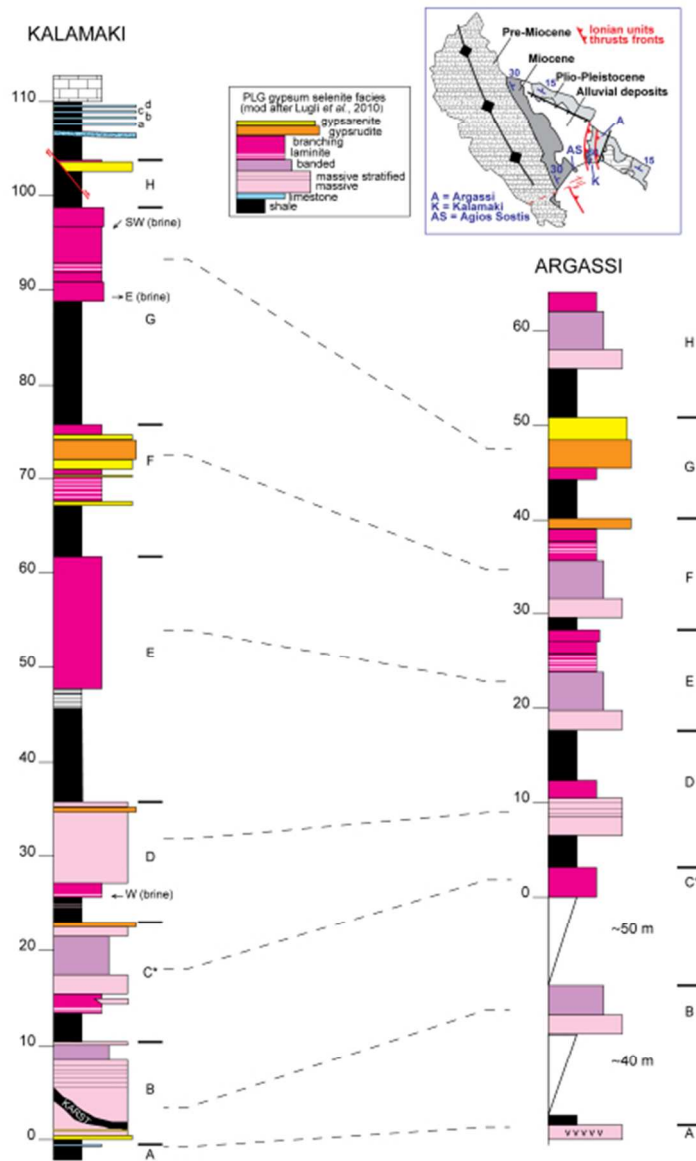


Fig. 6. Trubi Formation facies. Based on lithology, nine cycles (I to IX) of marly limestones alternating with marls are observed.
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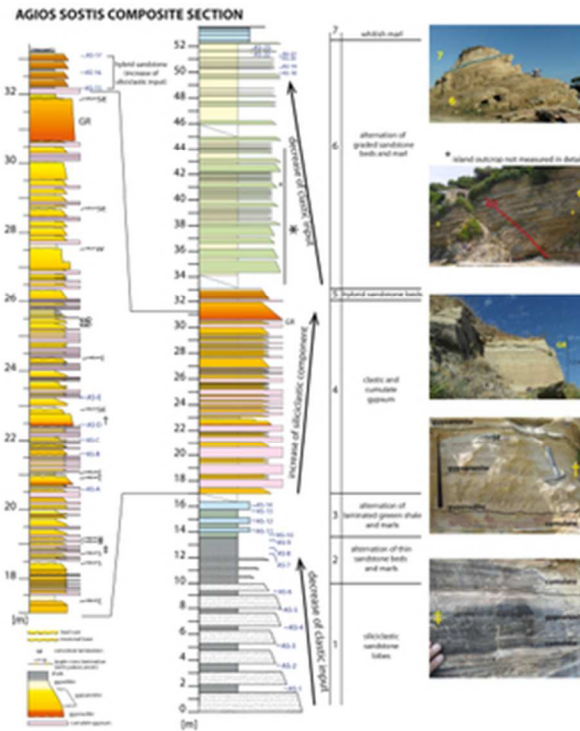


Fig. 7. Agios Sostis composite section: lithology, samples location, and facies characteristics of the different stratigraphic levels.
12x15mm (600 x 600 DPI)



Fig. 8. Sedimentary facies details of the PLG and RLG units. Argassi area: a. selenite, b. branching selenite. Agios Sostis area: c. pre-evaporitic sequence and MES boundary with the overlying RLG unit, d. gypsum turbidites, e: convolute lamination, f: alternations of primary cumulate gypsum (CU) and clastic gypsarenite (AR) and gypsrudite (GR).
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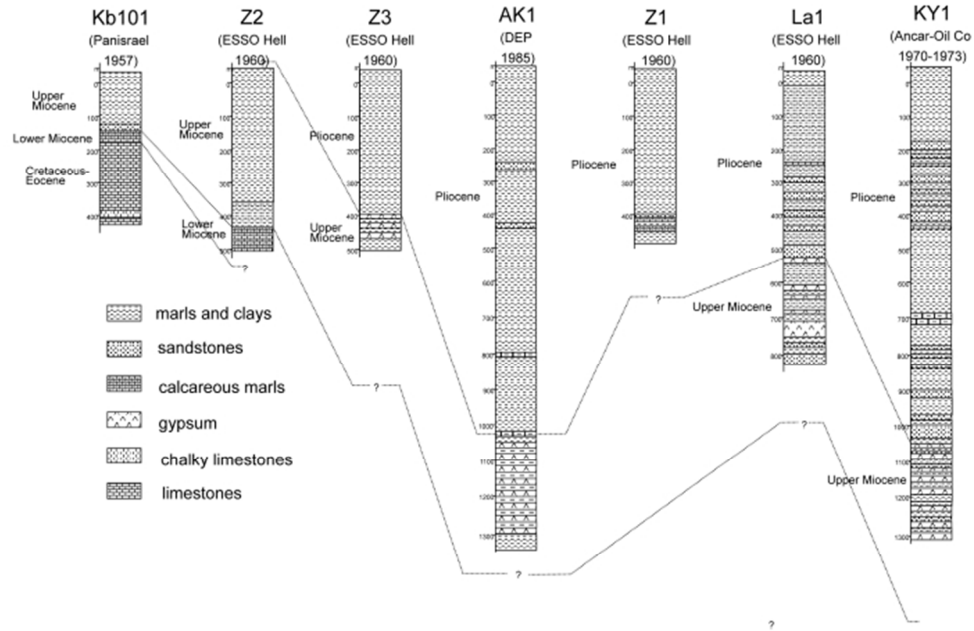


Fig. 9. Zakynthos (Alkanas) basin wells positioned in a west-to-east direction (the wells' locations are indicated in fig. 1). Correlation of the borehole logs shows that the Neogene deposits (gypsum included) increase their thickness eastward. Agios Kyrikos-1 well (AK-1) revealed indirect indices of halite accumulation in the Messinian gypsum stratigraphic level.
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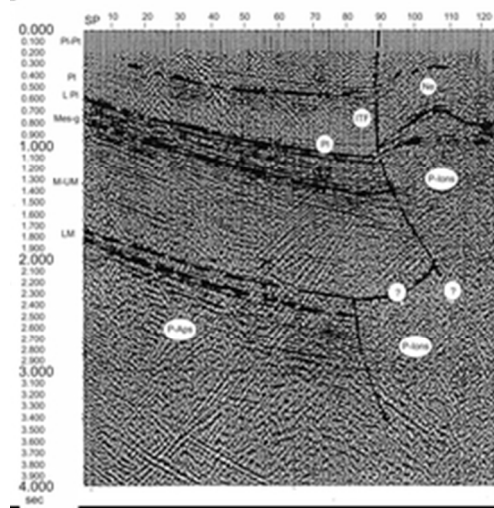


Fig. 10. Alikanas basin seismic profile (modified from the initial representation by Marinescu; in Nikolaou, 1986). The seismic profile shows a) the position of the Ionian thrust, b) the eastward increase in the thickness of the Neogene deposits. The seismic line's location is indicated in Fig. 1. PL-PT: Pliocene-Pleistocene, PI: Pliocene, LPI: lower Pliocene, Mes-g: Messinian gypsum, M-UM: middle-upper Miocene, LM: lower Miocene, P-Aps: pre-Neogene sequence of the Pre-Apulia zone, P-Ions: pre-Neogene sequence of the Ionian zone (Triassic evaporites), ITF: Ionian thrust front, Ne: undifferentiated Neogene, SP: shot point, sec: time in seconds.
20x21mm (300 x 300 DPI)

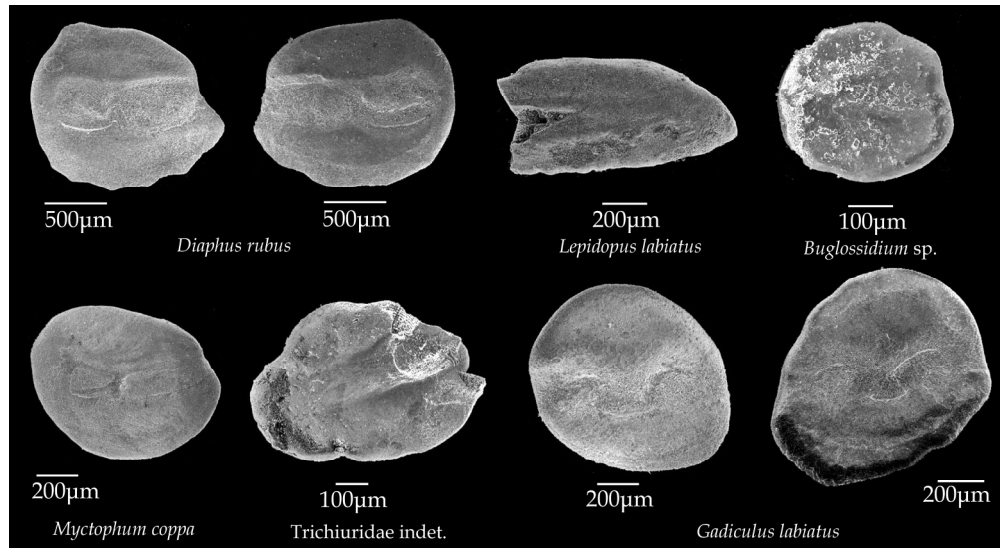


Fig. 11. Fish otoliths discovered in the pre-evaporitic sequence of Kalamaki section.
187x101mm (300 x 300 DPI)

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Fig. 12. A: plots of VGP latitude of the West and East Kalamaki subsections. B: plots of ChRM directions corrected for bed tilting, full and empty red and purple circles represent normal and reversed mean direction for Kalamaki West and east subsection, respectively. C: Zijderveld diagrams with demagnetization paths of selected samples from the Kalamaki west subsection.

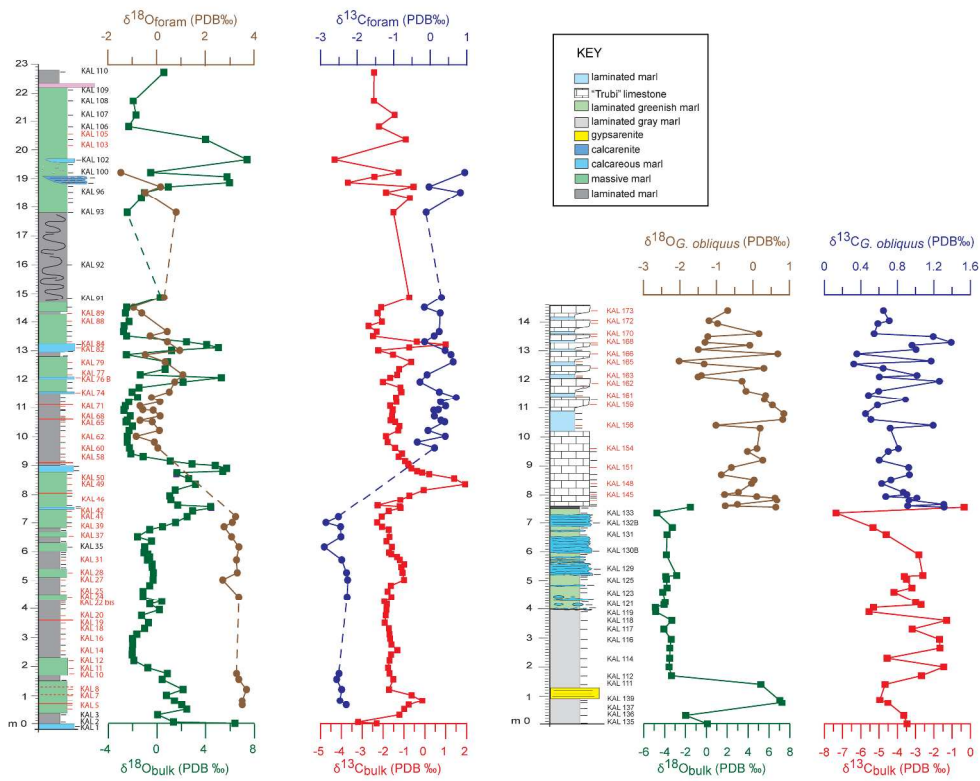


Fig. 13. Pre-evaporitic sequence, Lago-Mare, and Trubi Formation carbon and oxygen stable isotopes. 278x223mm (300 x 300 DPI)

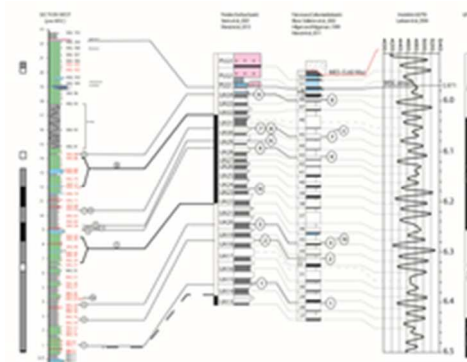


Fig. 14. Chronostratigraphic framework of Kalamaki section's pre-evaporitic sequence and correlation with Perales section (Sorbas basin) (modified after Sierro et al., 2001; Manzi et al., 2013) and Falconara section (Caltanissetta basin) (modified after Blanc-Valleron et al., 2002; Hilgen & Krijgsman, 1999; Manzi et al., 2011) via the astronomical Insolation summer curve of Laskar et al. 2004 and GPTS of Lourens et al., 2004.

Bio-magnetostratigraphic events are: 1) FAO *T. multiloba*; 2) FAO dextral *N. acostaensis*; 3) *G. scitula* influx; 4) *N. acostaensis* dominance sinistral; 5) *T. multiloba* influx; 6) *G. scitula* influx; 7) dominance *N. acostaensis* sinistral; 8) Last abundant influx *T. multiloba*; 9) HO planktonic Foraminifera; I) top C3An.1n; II) boundary C3An.2n/C3r.

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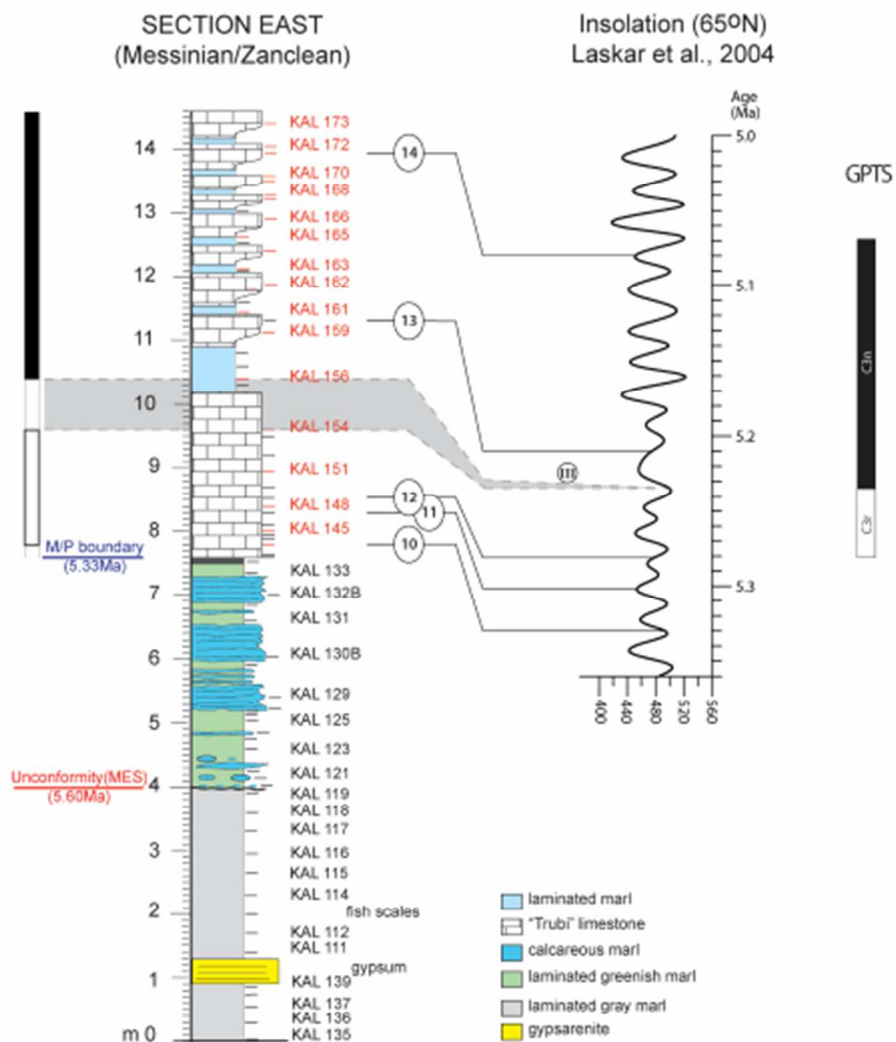


Fig. 15. Kalamaki section age model of the PLG top portion, Lago-Mare, and Trubi Formation, correlated with insolation curve (based on Laskar et al., 2004).
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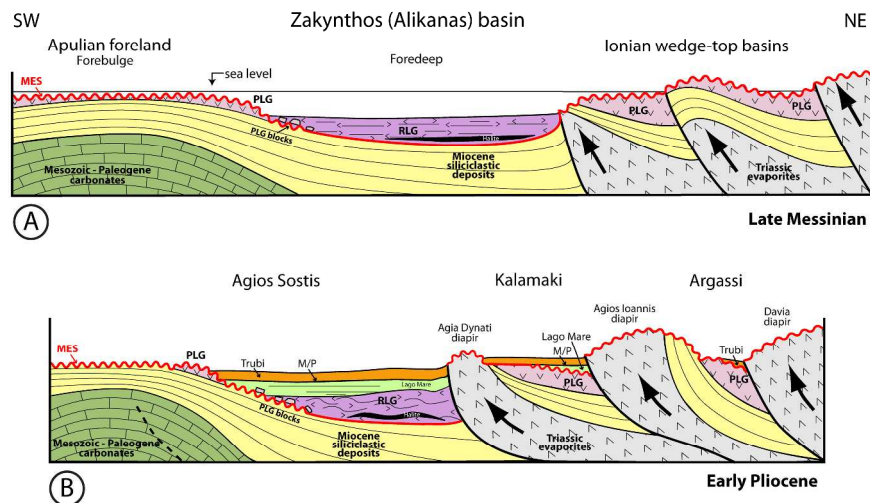


Fig. 16. Paleogeographic reconstruction.

A. During the Messinian, the Zakynthos (Alikanas) foreland basin was formed in front of the Ionian thrust. The Neogene formations deposited over the Pre-Apulian domain corresponded to the foredeep and the flank between foredeep and forebulge, whereas those overlying the Ionian zone corresponded to the wedge-top, which was uplifted due to the diapiric movements of the Ionian Triassic evaporites. In the 1st MSC stage, PLG was deposited on both forebulge and wedge-top. In the 2nd MSC stage, PLG was totally or partially eroded (creating the Messinian Erosional Surface; MES) and redeposited with correlative conformity mainly as gypsum turbidites (RLG unit) in the depocenter of the foreland basin.

B. During the end of the Messinian, in Kalamaki-Argassi wedge-top area the Lago-Mare sediments were unconformably overlying the Primary Lower Gypsum above the MES, while in the depocenter of the foreland basin they were conformably deposited over the Resedimented Lower Gypsum. The Zanclean flood was recorded on both areas by the conformable deposition of the Trubi Formation.

With red ruffled and continuous line the unconformity and the correlative conformity of the MES, respectively.

316x189mm (300 x 300 DPI)

Family	Genus/Species	Ecology	References
Gonostomatidae	indet.	-	-
Sternoptychidae	<i>Maurolicus muelleri</i> (Gmelin, 1789)	0-1524 m, usually 300-400 m; SP-Tr; marine, bathypelagic	Mauchline, 1988; Wheeler, 1992
Phosichthyidae	<i>Vinciguerria poweriae</i> (Cocco, 1838)	50-1000 m, usually 300-600 m; ST-Tr; marine, bathypelagic	Mundy, 2005
Myctophidae	<i>Ceratoscopelus maderensis</i> (Lowe, 1839)	51-1082 m; Te; marine, bathypelagic	Hulley, 1990; Mytilineou <i>et al.</i> , 2005
	<i>Diaphus cavallonis</i> Brzobohaty and Nolf, 2000 *	-	-
	<i>Diaphus cf. pedemontanus</i> Robba, 1970 *	-	-
	<i>Diaphus rafinesquii</i> (Cocco, 1838)	40-1200 m; Te; marine, bathypelagic	Hulley, 1990
	<i>Diaphus rubus</i> Girone <i>et al.</i> , 2010 *	-	-
	<i>Diaphus taaningi</i> Norman, 1930	40-475 m; Tr; marine, bathypelagic	Hulley, 1990
	<i>Myctophum coppa</i> Girone <i>et al.</i> , 2010 *	-	-
Moridae	<i>Physiculus</i> aff. <i>huloti</i> Polli, 1953	92-320 m; Tr; marine, benthopelag.	OBIS, 2006
Gadidae	<i>Gadiculus argenteus</i> Guichenot, 1850	100-1000 m; Te-ST; marine, pelagic- oceanic	Muus & Nielsen, 1999
	<i>Gadiculus labiatus</i> (Schubert, 1905) *	-	-
Gobiidae	indet.	-	-
Trichiuridae	<i>Lepidopus caudatus</i> (Euphrasen, 1788)	42-620 m, usually 100-300 m; ST-Te	Mytilineou <i>et al.</i> , 2005
Soleidae	<i>Buglossidium</i> sp.	5-450 m, usually 10- 40 m; ST	Muus & Nielsen, 1999