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Title: Is Cyprideis agrigentina Decima a good palaeosalinometer for the Messinian Salinity Crisis? Morphometrical and geochemical analyses from the Eraclea Minoa section (Sicily)

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Keywords: Ostracoda; morphometrical analyses; geochemical analyses; palaeoenvironmental reconstruction; post-evaporitic Messinian; Sicily (Italy)

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Abstract: The living euryhaline species Cyprideis torosa (Jones) undergoes morphometric variations in size, noding and sieve-pore shape linked to the environmental salinity. In particular it is known that salinity values around 8-9 psu represent the osmoregulation threshold and also the turning point between smaller and greater valve dimensions and prevailingly noded against un-noded valves. The variation of the percentage of round-, elongate- and irregular-shaped sieve-pores on the valves has shown an empiric logarithmic correlation with the water salinity from 0 to 100 psu. Due to this ecologically cued polymorphism, C. torosa represents an invaluable palaeosalinometer for the Quaternary brackish basins.In this paper we attempt to verify whether the ecophenotypical behaviour of the post-evaporitic Messinian species Cyprideis agrigentina Decima was comparable with that of C. torosa. To reach this goal, three morphometric characters have been analysed: 1) size variability; 2) noding and ornamentation; 3) variability of the percentage of the sieve-pore shapes. The palaeoenvironmental interpretation was made using synecological and geochemical approaches [stable isotopes, trace elements, Sr-isotopes and natural radioactivity (NRD)]. For this study, the 250 m-thick Messinian Lago-Mare succession of Eraclea Minoa (Agrigento, Sicily) was chosen for the presence of monotypic assemblages made only by C. agrigentina for around 70 m of thickness. The results of the morphometric analyses showed that: 1) size variations are not related to the salinity changes recognized both from synecological and geochemical analyses; 2) no noded specimens have been recovered along the section; 3) the salinities calculated on the basis of the percentage of the sieve-pore shape are not correlated with the salinities inferred from the synecological and geochemical analyses. Thus, in this paper we conclude that C. agrigentina cannot be considered a palaeosalinometer for the Messinian Salinity Crisis.There is a correlation of the ▯13C with the percentages of sieve-pore shapes, linking them to the oxygen availability at the bottom of the basin.

ANSWERS TO REFEREE COMMENTS

**REFEREE #1 – NEVIO PUGLIESE**

GENERAL OPINION
Very good paper, well organized and , mainly, original work. Systematics correct. I appreciated the capability to combine different disciplines, mainly micropalaeontology and geochemistry.
Thus, I think the work is adequate for the magazine, and worthy of being published with minor corrections. Most of my suggestions are optional. It is not necessary that I revise the text again. My anonymity is not necessary.

INTRODUCTION
It is very clear; it properly presents the topic of the paper.
The aim of the work is very clear. However, it is included in the introduction.I suggest instead the Authors to better highlight the purpose of the work putting its sentences in a new paragraph. Basically the lines from 98 to 107 should become a new paragraph well separated from the previous text. The lines from 103 to 105 seem not clear. Are they maybe incomplete?
We have checked the sentence from line 103 to 105 and corrected the English language.
We have moved the lines from 98 to 107 to a new paragraph as suggested.

CHAPTER 2
Material and methods: very clear. However, I personally prefer the 0,062 mm-mesh, but I understand that for the purpose of the work the 0.126mm sieve used can be good too.
To analyze ostracods we generally use two sediment fractions (0.063 mm 0.125 mm) as suggested by the referee but in this case, being the work devoted only to the analysis of adult valves of C. agrigentina ( average sizes around 1 mm in length x....) we considered that the 0.125 mm mesh was more than enough. We have better specified this in the text.

CHAPTER 3
It is clear. There is a small mistake in the lines 238 to 240: the authors of the species not in italics: ***Livental….Olteanu*** become **Livental…Olteanu**.
All the author names have been written in plain text. Thanks to the referee to have signaled this editing mistake.

CHAPTER 4
No observations. It is very good. There is a small mistake in line 372: (**DeDeckker**…) becomes (**De Deckker**…).
We have corrected the misspelled name at line 364.

CHAPTER 5
I suggest to change a little the order of the paragraphs:
lines **434-439** concern the ornamentation; lines **440-449** concern the sizes; lines **450-464** concern the sieve-pore canals. Thus, following the aims of the introduction (lines **102-103**) I suggest to report the data in this order: sizes, ornamentation, pore canals.
As suggested, we changed the order of the paragraphs, starting with size followed with ornamentation and pore canals.

CHAPTER 6
The discussion is well organized and well articulated.

CHAPTER 7

The conclusions are clear and original, even if apparently negative. The authors well underline the role of C. agrigentina as in palaeoenvironmental research, excluding it as marker of palaeosalinity.

REFERENCES

Lines 734-735: Graham et al. (1982). I do not find it cited in the text.

We have deleted it

FIGURES

Fig. 2 : I suggest to indicate in the caption the meaning of the numbers 3,4,5,6 reported in the figure

We have better specified in the caption the meaning of numbers in Fig. 2 (now fig 3)

POSSIBLE OPTIONAL SUGGESTIONS

I suggest to insert a photo of *C. agrigentina*.

Done

**Referee #2 – Julio Rodriguez Lazaro**

I have read the ms and in my opinion it is a very good paper, perfectly planned and written, with several sets of data allowing to reach the important conclusions (though they are "negative" for the use of *C. agrigentina* as palaeosalinometer).

Only couple of comments in the text. In particular:

In Fig. 4, are mentioned levels A, B, E, but these haven't been so far described. In Fig. 5 they are included by the first time (and described in paragraph 4.5). Since they are very used through the text, the units A, B, C, D, E must be added to some other figures, in order to easy the reading.

Done. We have changed the order of Fig. 4 and 5 (now fig 5 and 6), mentioned in the paragraphs 4.1-4.4 the intervals and reported the intervals in Fig. 7 (now fig. 8).

Fig. 7 Interval B. The hydrological interpretation with: "High freshwater and detrital inputs. Possible low salinities that slightly increase again around 222-225 m." is in apparent contradiction with the salinity inferred by pores, in the left of figure. After the latter, there is the maximum of salinity in these levels.

Yes, fig. 7 (now 8) is thought to show the contradiction between the salinity inferred by geochemistry and the salinity inferred by sieve pores. To better clarify it, in Fig. 8 we added to "Palaeohydrology" the sentence "inferred from geochemical analyses". The lack of correspondence between the two dataset is widely discussed in chapter "Discussion" and is the core of the paper.

Intervals D, E. There are marked dysoxic levels coincident with the increase of Shannon diversity. In general, the increase of diversity is indicative of some stabilisation of the environment, which is the opposite of indicated. It must be another factor influencing (you mention the oxygen availability, at the end of discussion). (Please correct disoxyc in D, and hydrochemstry in E).

Yes, indeed Shannon-Wiener index and authigenic U curves are negatively correlated. We added a discussion on those results in the paragraph "Discussion" concluding that it is probable that at Eraclea Minoa the causes for the authigenic U accumulation were others than oxygen availability. We have corrected the misspelled words in Fig. 7 (now 8).

In this matter, a "Relatively stable hydrochemical conditions" are indicated in A, but the diversity is very low (monospecific), so some important environmental factor is acting to prevent the "natural trend" of increase of diversity. (oxygen availability, as well?) (have you any proxy for oxygen availability?).

You are right. Some important environmental factor is limiting the colonization by ostracods but....which one? In this paper we have tried to perform different geochemical analyses, but none of them explained us what happened in this close "Lago-Mare" basin after the acme of the Messinian Salinity Crisis. Data show that it was a high suitable environment for *C. agrigentina* alone, but which kind of environment?

Fortunately, the palaeoenviromental interpretation of the Eraclea Minoa succession wasn't the main aim of this paper, which is focussed to the possible use of *C. agrigentina* as palaeosalinometer. Anyway, in no other Lago-Mare section in which ostracod assemblages were studied there is such a long interval in which *C. agrigentina* is so abundant and alone in the assemblage. But Eraclea Minoa is also the only one section in which diagenetic gypsum cristalized from the groundwater, so....

Concerning the oxygen availability, we hoped that authigenic Uranium could be a good proxy to evaluate it. It seems that in the case of Eraclea Minoa it is not true. Anyway, another good proxy could be, as it has been discussed, the $\delta^{13}C$ and, indeed, it seems that the sieve-pore variability in C. agrigentina could correlate with it.

**COMMENTS BY EDITOR IN CHIEF**

As editor in chief, I will be glad to endorse the guest editor's decision to accept this ms for publication in our journal after one minor change. You have to realize that we have an international readership, therefore Figure 1 is not appropriate. Instead of just showing Italy (without even giving the name of the country), you need to provide a larger view of the Mediterranean, with proper country names (Rome and Florence are not needed on such a map).

We modified fig. 2 as requested.

Highlights

- We study in a palaeoenvironmental perspective a post-evaporitic ostracod assemblage.
- We perform morphometric and geochemical analyses on *Cyprideis agrigentina* valves.
- *C. agrigentina* sizes and ornamentation are not affected by salinity variations.
- Sieve-pore shapes in *C. agrigentina* seem linked to the bottom oxygen availability.
- *C. agrigentina* is not a palaeosalinometer for the Messinian Salinity Crisis.

# Is *Cyprideis agrigentina* Decima a good palaeosalinometer for the Messinian Salinity Crisis? Morphometrical and geochemical analyses from the Eraclea Minoa section (Sicily)

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ABSTRACT

The living euryhaline species *Cyprideis torosa* (Jones) undergoes morphometric variations in size, noding and sieve-pore shape linked to the environmental salinity. In particular it is known that salinity values around 8-9 psu represent the osmoregulation threshold and also the turning point between smaller and greater valve dimensions and prevailingly noded against un-noded valves. The variation of the percentage of round-, elongate- and irregular-shaped sieve-pores on the valves has shown an empiric logarithmic correlation with the water salinity from 0 to 100 psu. Due to this ecologically cued polymorphism, *C. torosa* represents an invaluable palaeosalinometer for the Quaternary brackish basins.

In this paper we attempt to verify whether the ecophenotypical behaviour of the post-evaporitic Messinian species *Cyprideis agrigentina* Decima was comparable with that of *C. torosa*. To reach this goal, three morphometric characters have been analysed: 1) size variability; 2) noding and ornamentation; 3) variability of the percentage of the sieve-pore shapes. The palaeoenvironmental interpretation was made using synecological and geochemical approaches [stable isotopes, trace elements, Sr-isotopes and natural radioactivity (NRD)]. For this study, the 250 m-thick Messinian Lago-Mare succession of Eraclea Minoa (Agrigento, Sicily) was chosen for the presence of monotypic assemblages made only by *C. agrigentina* for around 70 m of thickness.

The results of the morphometric analyses showed that: 1) size variations are not related to the salinity changes recognized both from synecological and geochemical analyses; 2) no noded specimens have been recovered along the section; 3) the salinities calculated on the basis of the percentage of the sieve-pore shape are not correlated with the salinities inferred from the synecological and geochemical analyses. Thus, in this paper we conclude that *C. agrigentina* cannot be considered a palaeosalinometer for the Messinian Salinity Crisis.

There is a correlation of the $\delta^{13}C$ ~~and NRD data~~ with the percentages of sieve-pore shapes, linking them to the behavior of the dissolved inorganic carbon (DIC) and to the oxygen availability at the bottom of the basin.

KEYWORDS

Ostracoda; morphometrical analyses; geochemical analyses; palaeoenvironmental reconstruction; post-evaporitic Messinian; Sicily (Italy).

## 1. Introduction

Since the pioneering studies by Schäfer (1953), Sandberg (1964), Vesper (1975) and Rosenfeld and Vesper (1977), it is known that the living anomalohaline species *Cyprideis torosa* (Jones) undergoes morphometrical variations in size, noding and sieve-pore shape linked to environmental physical and chemical parameters - especially salinity - showing a clear environmentally cued polymorphism. The species can withstand and thrive in a very wide range of salinity (0.4 to 150 psu according to Neale, 1988 and Griffiths and Holmes, 2000), thus it is commonly regarded as a valuable palaeosalinometer for the Quaternary marginal marine and athalassic brackish deposits (Marco-Barba, 2010; Pint et al., 2012 with references therein). Its low-Mg calcite shell represents also a source of biogenic carbonate for the geochemical analyses (trace elements, stable isotopes and $^{87}Sr/^{86}Sr$ ratios) to infer the chemical composition of past waterbodies, because of its high rate of valve calcification. In many studies, morphometrical variations were coupled with the geochemical approach to make more detailed palaeoenvironmental reconstructions of brackish environments (Barbieri et al., 1999; Anadón et al., 2002; Marco-Barba, 2010; Curry et al., 2013; Pint et al., 2013; Rossi et al., 2013).

Several studies (Carbonel, 1982; Aladin, 1993; van Harten, 1996; 2000; Keiser and Aladin, 2004; Keyser, 2005; Boomer and Frenzel, 2011; Frenzel et al., 2011; 2012 among others) showed that salinity values around 8-9 psu represent the osmoregulation threshold and also the turning point between smaller and greater valve dimensions and prevailingly noded against un-noded valves. Rosenfeld and Vesper (1977) showed an empiric logarithmic correlation between the variation of the percentage of round-, elongate- and irregular-shaped sieve-pores on the valves of *C. torosa* and the water salinity from 0 to 100 psu. This correlation has been confirmed by subsequent papers (Neale, 1988; Keating et al., 2007; Pint et al., 2012) and Frenzel et al. (2011) elaborated a transfer function based on the percentages of round sieve-pores.

In order to decipher the palaeosalinity changes during the end of the Messinian Salinity Crisis (Hsü et al., 1973; CIESM, 2008; Roveri et al., 2014a), Rosenfeld (1977) and Bonaduce and Sgarrella (1999) applied the counting of different sieve-pore shapes to the fossil species *Cyprideis* *agrigentina* Decima, supposing that also this species could morphologically react as *C. torosa*. In both cases they obtained hyperhaline values for the waters hosting *C. agrigentina* specimens (respectively 35-50 psu and 50-70 psu) considering ~~this~~ those values reliable for the evaporative palaeoenvironment that yielded the deposition of the gypsum.

*C. agrigentina* (Fig. 1) is one of the most widespread ostracod that lived in the Palaeomediterranean during the latest Messinian Lago-Mare event (5.53–5.33 Ma, CIESM, 2008; 5.55-5.33 Ma, Manzi et al., 2013; Roveri et al., 2014a). It seems to have been the first ostracod that colonized again the sterile bottoms of the Palaeomediterranean after the deposition of the Primary Lower Gypsum and the partially desiccation of the basin. ~~and i~~It has been recovered both in the Messinian sediments drilled on the Palaeomediterranean bottoms and in those cropping out along the peri-Mediterranean chains, from the most western area (Malaga Basin) to the easternmost Adana Basin (Benson, 1978; Iaccarino and Bossio, 1999; Bonaduce and Sgarrella, 1999; Grossi and Gennari, 2008; Guerra-Merchán et al., 2010; Cosentino et al., 2012; Faranda et al., 2013). In their study on the Messinian Lago-Mare palaeoenvironments inferred from the ostracod assemblages, Grossi et al. (2008) showed that *C. agrigentina* behaved as a very euryhaline species: it was associated a) with the benthic foraminifer *Ammonia tepida* ("*Cyprideis-Ammonia* assemblage") in very oligotypic assemblages supposed to be typical of high mesohaline environments; b) with *Loxoconcha muelleri* (Mehés) and *Loxoconcha eichwaldi* Livental ("*Cyprideis-Loxoconcha* assemblage") (low mesohaline environment); c) it was also a component, although not dominant, of the "pointed candonids-Leptocytheridae assemblage" and "pointed candonids assemblage", supposed to be characteristic of oligohaline to low mesohaline environments.

Anyway, despite its apparent capability to withstand different salinities, no noded specimens of *C. agrigentina* have been ever found (Ligios and Gliozzi, 2012) and this could arise some questions about the possible ecophenotypical reaction of *C. agrigentina* to the environment.

In this paper we attempt to verify whether the ecophenotypical behavior of *C. agrigentina* was comparable with that of *C. torosa*. To reach this goal, adult male and female valves of *C.*

*agrigentina* from the long section of Eraclea Minoa (Agrigento, Sicily) were investigated and three morphometrical characters have been analysed: 1) size variability; 2) noding and ornamentation; 3) variability of the percentage of the sieve-pore shapes. The palaeoenvironmental framework to which the ecophenotypical characters displayed by *C. agrigentina* will be compared has been built based on synecological analysis (assemblages taxonomic composition and diversity) (Chapter 3) and geochemical approaches [stable isotopes, trace elements, Sr-isotopes and natural radioactivity (NRD)] (Chapter 4).

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## 2. **Material and methods**

One hundred fifty-two samples have been soaked in a $H_2O_2$ $5\%_{vol}$ solution for 24 hours, sieved with 0.063 and 0.125 mm-mesh sieves and dried in oven at 40°C. Total manual picking has been carried out on the 0.125 mm dried sieved samples. When possible, up to 300 valves where hand-picked from each sample. Ostracods have been identified and their frequency counted; the obtained values have been normalized to 10 g in order to get comparable figures all along the section to perform a reliable palaeoenvironmental interpretation using the synecological approach proposed by Gliozzi and Grossi, 2008 and Grossi et al., 2008. Shannon-Wiener index has been calculated on the basis of the normalized matrix.

When possible, supplementary adult specimens of *C. agrigentina* were picked to increase the amount of material on which the morphometrical and geochemical analyses were performed. The morphometrical and geochemical analyses have been carried out on more than 3000 adult valves of *C. agrigentina*, and several thousand juvenile valves were added for Sr-analyses.

### *2.1 Morphometrical analyses*

All juvenile and adult valves of *C. agrigentina* were observed under the stereo-microscope to investigate the ornamentation and noding.

Over one thousand adult female and male valves of *C. agrigentina* from fifty-three selected samples were measured under the stereo-microscope, using the Leica Application Suite 2.5.0. Mean values were calculated for each sample.

Around 20 adult female and male valves of *C. agrigentina* from fifty-three samples, chosen on the basis of its high frequency, were observed under the Scanning Electron Microscope (LIME Laboratory, Roma Tre University). Following the methodology proposed by Rosenfeld and Vesper (1977), the rounded, elongated and irregular sieve-pores were counted and each percentage was calculated. To obtain the inferred salinity value, the following transfer function elaborated by Frenzel et al. (2011), based on the percentage of rounded sieve-pores was used:

$$S= e^{-0.06RS+4.7}$$

where S = salinity (psu) and RS = percentage of rounded sieve-pores.

*2.2 Geochemical analyses*

*2.2.1 Stable isotopes*

Carbon and oxygen stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) were performed on fifty-three ostracod samples each consisting of ~~8~~ eight *C. agrigentina* clean adult valves. Two splits of each sample (4 valves each) were reacted with anhydrous phosphoric acid at 76ºC ± 2ºC in a Finnigan MAT Kiel preparation device directly coupled to the inlet of a Finnigan MAT 251 triple collector isotope ratio mass spectrometer (Stable Isotope Laboratory, University of Michigan, Ann Arbor, MI, USA). The isotopic results of the mean of the two splits are reported in permil (‰) notation relative to the Pee Dee Belemnite (PDB) standard. The measured precision for the analyses was 0.04 for $\delta^{13}C$ and 0.07 for $\delta^{18}O$.

*2.2.2 Trace elements*

Trace and minor element analyses together with Ca on fifty-three ostracod samples, consisting each in 6 to 10 clean adult valves of *C. agrigentina*, were performed by inductively coupled plasma atomic emission spectrometry (ICP-AES). The ostracod valves were dissolved in 3 ml of ultrapure $HNO_3$ acid (3%). The solutions were analysed for Ca (317.9 nm), Mg (285.2 nm), Na (589.5 nm) and Sr (215.2 nm) in the ICP-AES Thermo Jarrell IRIS Advantage Radial device of the Institute of Environmental Assessment and Water Research (IDAEA-CSIC, Barcelona, Spain). The limits of detection were 0.05 ppm for Ca and Mg, 0.01 ppm for Na and 0.005 ppm for Sr. All the analyses were run against multielemental standards prepared from Johnson Mattey™ stock solutions. The obtained results are expressed as metal/calcium ratios of the valves ($Me/Ca_v$).

*2.2.3 Sr isotope analyses*

Strontium isotope measurements were obtained from 26 suitable samples of hand-picked valves of *C. agrigentina*, perfectly preserved. About 10 mg of each sample was subjected to the following procedure: ultrasonic cleaning in double distilled water to remove impurities; gentle crushing and re-washing in double-distilled water; fast dissolution in 4.0 N ultrapure HCl; centrifugation; loading onto standard BIO-RAD AG50-X12cation exchange resin. The total procedure blank was 0.5 ng. Sr was collected in 2.9 and 6.3 N HCl and evaporated.

Isotopic analyses were carried out at IGAG-CNR c/o Department of Earth Sciences, University of Rome —- La Sapienza using a FINNIGAN MAT 262RPQ multicollector mass spectrometer with Re double filaments in static mode. The internal precision (within-run precision) of the single analytical value is given as two standard error of the mean. The $^{87}Sr/^{86}Sr$ ratios of the samples were normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194. The internal precision (‘‘within-run’’ precision) of a single analytical result is reported as 2 standard errors of the mean (2SE) and is obtained as the mean of more than 800–1000 ratios collected in each sample with a stable beam of > 2.0 V. Repeated analyses of NIST-987 during the period of the analyses gave a mean value $^{87}Sr/^{86}Sr = 0.710251 \pm 15$ ($2\sigma$, n = 15).

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*2.2.4 Natural Radioactivity (NRD)*

Natural Radioactivity (NRD) was measured on 27 bulk sediment samples. Uranium, thorium and potassium were determined by high resolution gamma spectrometry using a low background (GEM-EG&G ORTEC) HPGe coaxial detector in a PopTop capsule including detector element, preamplifier and high voltage filter at the Institute of Environmental Geology and Geoengineering (IGAG, CNR, Rome - Italy). The multichannel buffer (16,384 channels, Ethernim-ORTEC 919E), including ADC with extended live time correction, was connected into an Ethernet environment under Windows XP and its control and spectral display was achieved by the use of MAESTRO application software. In particular, $^{232}$Th and K were estimated from 583 keV ($^{208}$Tl) and 1461 keV ($^{40}$K) peaks, while $^{238}$U was estimated ~~-~~by the weighted average of U1 and U2, ~~-~~where U1 is the product of the known $^{238}$U/$^{235}$U natural activity ratio by the $^{235}$U activity (calculated by the 186 keV peak corrected by the $^{226}$Ra contribution) and U2 is the $^{238}$U activity ~~-~~estimated by the 352 keV peak ($^{214}$Pb) assuming full equilibrium in the $^{238}$U radioactive series.

Capo di Bove leucitite (Voltaggio et al., 2004) was used as standard, while counting time and amount of each sample were, respectively, 86,400 sec and 150 grams.

*2.3 Statistical analyses*

A raw matrix of data ~~has been~~was constructed taking into account those samples that ~~have~~ provided all the results for the considered types of analyses (9 variables): stratigraphic position, ~~lithology,~~ $\delta^{13}$C, $\delta^{18}$O, Mg/Ca$_v$, Sr/Ca$_v$, Na/Ca$_v$, Th/U, assumed salinity after the sieve-pore analysis and the $^{87}$Sr/$^{86}$Sr ratio. The statistical software used was STATISTICA 7.0. From the raw matrix, with 9 variables and 20 cases (samples), a correlation matrix was obtained. Moreover from the raw matrix, a set of multivariate analysis techniques, as cluster and principal-component analysis (PCA) was applied. Cluster analysis defines groups of more or less related variables and the corresponding dendrogram (tree clustering) corresponds to the graphic display of the groups. PCA defines

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eigenvectors showing the position of the variables in the factor plane and revealing the underlying structure of the data set.From the raw matrix, with 8 variables and 26 cases (samples), a correlation matrix is obtained. Moreover from the raw matrix, a set of multivariate analysis techniques, as cluster and principal-component analysis (PCA) have been applied. Cluster analysis defines groups of more or less related variables and the corresponding dendrogram (tree clustering) corresponds to the graphic display of the groups. PCA defines eigenvectors showing the position of the variables in the factor plane and revealing the underlying structure of the data set. An additional analysis with 9 variables, the 8 ones mentioned above and the Th/U ratio, has been performed. In this case the number of suitable samples is reduced to 10.

**3. The Eraclea Minoa section and its palaeoenvironments inferred from ostracod assemblages**

The ca. 266 m-thick Messinian Lago-Mare succession of Eraclea Minoa crops out along the south-western coast of Sicily (lat. 37˚23'30"N, long. 13˚16'50"E) along the cliff which borders the village (Fig. 12). The section has been extensively studied since 1971 (Decima and Wezel, 1971) because it is one of the most complete Messinian Lago-Mare section of the Palaeomediterranean where several gypsum levels referred to the Upper Gypsum Unit crop out (among the most recent papers: Schreiber, 1997; Caruso and Rouchy, 2006; Van der Laan et al., 2006; Manzi et al., 2009 with references therein), and because it represents the GSSP of the Messinian/Zanclean boundary (Van Couvering et al., 2000 with references therein) (Fig. 23).

The succession is made of a rhythmic alternation of clays and marls interbedded with sandy and fine grained carbonates and seven gypsum bodies made by multiple strata of finely-laminated gypsum and gypsarenites/selenites (Fig. 34). The astrochronological tuning of the Eraclea Minoa section is different according to several authors. As stated by Caruso and Rouchy (2006), six sedimentary cycles covered by the Arenazzolo Fm. up to the Messinian/Zanclean boundary are recognizable, with a possible seventh basal cycle represented by an intensively deformed gypsum deposit located along the fault contact at the base of the succession. Van der Laan et al. (2006)

consider the presence of seven cycles and a half, including the Arenazzolo Fm. They are linked to the precessional cyclicity and date the deposition of the Eraclea Minoa succession between 5.508 Ma to 5.332 Ma. Finally, Manzi et al. (2009; 2012) hypothesize the presence of nine to ten sedimentary cycles, including the Arenazzolo Fm., bracketing the depositional age between 5.53 and 5.33 Ma.

Ostracods are discontinuously present at the base of the section, in the marls intercalated between the lowest six gypsum bodies and become abundant in the upper portion, below and above the seventh gypsum level. Assemblages show variable richness from 1 species (monotypic assemblages made only by *C. agrigentina*) up to 13 species mainly made by the typical Lago-Mare ostracod assemblages of Paratethyan origin.

In the lowest portion from 88 (sample EM 3-3) to 144 m (sample EM 6-7), *C. agrigentina* is scarce and the assemblages, made by *Loxoconcha muelleri* (Méhes), *L. kocki* Méhes, *L. eichwaldi* Livental, *Loxocorniculina djafarovi* (Schneider), *Loxocauda limata* (Schneider), *Camptocypria* sp. 1, *Tyrrhenocythere pontica* (Livental), *Euxinocythere* (*Maeotocythere*) *praebaquana* (Livental), *Amnicythere propinqua* (Livental), *A. subcaspia* (Livental), *A. multituberculata* (Livental) and *A. accicularia* Olteanu, are rather diversified. These assemblages can be referred to the "*Cyprideis*-Loxoconchidae assemblage" (*sensu* Grossi et al., 2008), suggesting low mesohaline and shallow waterbodies (supposed salinities <10 psu).

Monotypic assemblages have been recovered in the central portion of the Eraclea Minoa section, from 153 m (sample EM 6'-1) to 227 m (sample EM 7-12) and the collected valves are abundant and well preserved. In this long interval, *C. agrigentina* is the only species present in the samples or is accompanied by the euryhaline benthic foraminifer *Ammonia tepida* (Cushman). Grossi and Gennari (2008) defined the "*Cyprideis-Ammonia* assemblage" for some ostracod and forams associations recovered in the Lago-Mare borehole of Montepetra (northern Apennines, Italy) in which, together with *C. agrigentina* and *A. tepida*, also other ~~two~~ benthic foraminifers, *Florilus boueanum* (d'Orbigny) and *Elphidium* spp. were seldom present or *A. tepida* was the dominant species of the assemblage. The authors related such "*Cyprideis*-*Ammonia* assemblage" to high mesohaline to hyperhaline shallow waterbody. At Eraclea Minoa no other brackish benthic foraminifers have been recovered except *A. tepida*. Moreover, this latter species is not always present and generally ~~it~~ is far subordinated to *C. agrigentina*. Thus, the palaeoenvironmental interpretation of the interval from 153 to 227 m at Eraclea Minoa could be slightly different. At the moment, we can suppose for this new "*Cyprideis* assemblage" a relatively high salinity waterbody and/or a dysoxic bottom, based on the capability of the living species *C. torosa* and *Ammonia* spp. to withstand low oxygen contents (Jahn et al., 1996; Bernhard and Sen Gupta, 2002). Different assemblages, made only by scarce *C. agrigentina* and accompanying *Loxoconcha muelleri* were recovered in the Lago-Mare succession of Colle di Votta (Majella Mt., central Italy) (unpublished data), in oxygen-depleted sediments (Sampalmieri et al., 2010).

In this central portion of the succession there are only five scattered samples in which the dominant *C. agrigentina* is associated with few other species: with *L. djafarovi* (at 182 m, sample EM 6'-29a), pointing to a low mesohaline environment; with *Ilyocypris* sp. (at 198.5 and 201.0 m, respectively samples EM 6"-8 and 6"-11), suggesting two short oligohaline episodes; with *Fabaeformiscandona* sp. (at 213 m, EM 6"-19) pointing to a further oligohaline episode; with *A. accicularia* (at 220.6 m, EM 7-4) indicating a low mesohaline short interval.

Finally, in the uppermost part of the section [from 228 m (sample EM 7-13) to 265.5 m (sample EM 8-20)], *C. agrigentina* is again accompanied by the Paratethyan assemblage in which Loxoconchidae are slightly less abundant and two more leptocytherid species are included, even if with scarce frequency: *Amnicythere litica* (Livental) and *A. costata* (Olteanu). On the whole, this topmost interval seems again to be referable to the "*Cyprideis*-Loxoconchidae assemblage" (Grossi et al., 2008), pointing to shallow waterbodies with supposed salinities <10 psu~~)~~. Within this uppermost interval, it is possible to identify three horizons ~~(~~[from 228 m (sample EM 7-13) to 232 m (sample EM 7-19), at 234 m (sample EM 7-21) and from 235 m (sample EM 7-25) to 238 m (sample EM 7-28~~))~~ )] in which *C. agrigentina* shares its dominance only with two candonids species, *Fabaeformiscandona* sp. and *Cypria* sp., testifying an oligohaline and shallow environment, and two short levels [at 252.8 m (sample EM 8-3) and 257.8 m (sample EM 8-7)] in which *C. agrigentina* is again the only ostracod species of the assemblage.

## 4. Geochemical analyses ~~on *Cyprideis agrigentina* from Eraclea Minoa~~ and inferred palaeoenvironmental features

### *4.1 Stable isotopes*

~~*Ostracod*~~ *C. agrigentina* calcite valve~~ue~~s display a wide range of stable isotopic values. $\delta^{13}C$ ranges from –6.40 to 1.91‰; $\delta^{18}O$ ranges from -4.08 to 7.95‰ (Tab. 1; Figs. ~~4~~5, ~~5~~6). The $\delta^{13}C$ values of the ostracod valves show a slight increase from 153-189 m (interval A) to 198-225 m (interval B). Significant, rapid variations are shown around 198-204 m and in the upper portion of the section ~~(~~around 253-260 m~~).~~ (interval E).

The $\delta^{18}O$ values of the ostracod valves show a slight increase from 153 to 189 m (interval A), a rapid variation around 198-204 m (lower interval B), and ~~lowering in $\delta^{18}O$ values~~decrease from ~~198-~~204 to 225 m (upper interval B). In the upper portion of the section, from 257.8 to 258.5 m (interval E), a significant decrease in $\delta^{18}O$ values, from 8‰ to -1.4‰ is observed.

The $\delta^{13}C$ and $\delta^{18}O$ values from 153 to 189 m (interval A) display small fluctuations, suggesting minor variations in the palaeohydrological conditions. On the contrary, the valves from 198-204 m (interval B) and 253-260 m (interval E) display significant oscillations, both in $\delta^{13}C$ and $\delta^{18}O$ values, suggesting instabilities in the palaeohydrological conditions related to these intervals. In both cases the larger instabilities (major $\delta^{13}C$ and $\delta^{18}O$ oscillations) may be linked to significant detrital and freshwater inputs as reflected by the coarse-grained detrital beds at 199 m and 256-264.5 m.

The distribution in a X-Y plot (Fig. ~~4~~6) shows that the isotopic values from 153 to 216 m (interval A and lower B) display a negative covariant trend with a significant correlation (R=-0.894). This is mainly due to the negative correlation of the interval ~~from~~ 198-216 m (lower B, R=-0.903) and the almost invariant values in the interval 153-189 m (interval A).

*4.2 Trace elements*

For ~~*ostracod*~~ *C. agrigentina* calcite valves, the Mg, Sr and Na content expressed as $Mg/Ca_v$, $Sr/Ca_v$ and $Na/Ca_v$ molar ratios are listed in Tab~~.~~le 1 and represented in Fig. ~~5~~5. The $Mg/Ca_v$ values range from 0.0052 to 0.0158, the $Sr/Ca_v$ ~~values~~ range from 0.0022 to 0.0054 and the $Na/Ca_v$ ~~values range~~ from 0.0032 to 0.0046.

The $Mg/Ca_v$ values ~~from *C. agrigentina* valves~~ show a significant drop from 189~~-~~ to 198.2 m (intervals A and B boundary) towards the upper portion of the succession, with a rapid variation around 153-156 m (lower interval A). An overall increase trend in $Mg/Ca_v$ is recorded in the interval 198.2-225 m (interval B) and a significant increase ~~in $Mg/Ca_v$~~ is observed also in the upper part of the section (interval E). This is parallelized with a similar increase in the $\delta^{13}C$ values.

The $Na/Ca_v$ values ~~from *C. agrigentina*~~ show a slight decrease from 153-189 m (interval A) to 198-216 m (interval B), with a rapid variation around 198.2~~–~~-201 m. A significant decrease of $Na/Ca_v$ is observed in the upper portion of the section (interval B). This is parallelized with the decrease in Sr/Ca and $\delta^{18}O$ values.

*4.3 Sr isotopes*

Differently from the ratios of cation concentrations and oxygen isotopes, no Sr isotope fractionation occurs during chemical and biological processes within the marginal basin (Faure and Powell, 1972). Considering that Ostracoda are good monitors of the composition of the aquatic environment (De Deckker et al., 1988), the Sr isotopic composition~~s~~ of ostracod shells allow us to evaluate the connectivity of the basin with the open ocean and the paleoclimatic conditions and hydrography.

The Eraclea Minoa section shows that the $^{87}Sr/^{86}Sr$ values from the *C. agrigentina* valves are comprised between 0.708510 and 0.708729 (Tab~~.~~le 1). The range of values is high in the lower analysed interval (153-189 m - interval A) and decreases in the portion comprised between 198 to 225 m (interval B), reaching the minimum values (0.708510 and 0.708511) in the interval 204.2-210 m (low interval B), in correspondence of low $\delta^{18}O$, $Sr/Ca_v$ and $Na/Ca_v$ values. In the upper portion of the section (253-260 m - interval E) the $^{87}Sr/^{86}Sr$ values rise again, with a maximum (0.708704) at 253 m (Fig. ~~5~~5). Sr isotopic data of *C. agrigentina* are markedly different with respect to coeval global ocean values (Henderson et al., 1994; McArthur et al., 2001) being significantly lower than the marine waters at that time, but this is a common feature for ~~-~~latest Miocene–earliest Pliocene strontium values of the ~~Mediterranean~~ Palaeomediterranean Basin carbonates.

*4.4 Natural Radioactivity*

$^{232}Th$ and K measured in bulk sediment samples are highly correlated (~~r~~ R=~~-~~0.94) suggesting that $^{232}Th$ is mainly contained in the detrital fraction. Detrital uranium, in turns, was calculated by the product of measured $^{232}Th$ and the average $^{238}U/^{232}Th$ weight ratio of pelagic sediments, considered close to 0.25 (Mangini et al., 2001). Finally, authigenic uranium, ~~–~~$^{238}U_a$, ~~–~~was estimated by subtracting the detrital $^{238}U$ from measured $^{238}U$ (Tab~~.~~le 2). Authigenic uranium as well as the Th/U ratio was proposed by Wignall and Myers (1988) as an index of bottom-water oxygenation~~,~~; the $U_a$ values trend~~ing~~ to increase in a reducing environment, where uranium is immobile as tetravalent ion. According to Wignall (1994) $U_a$ values comprised between 2 and 10 are indicative of dysoxic environments; similarly for Th/U values, Th/U<<1 indicate anoxic conditions, Th/U>>1 indicate oxic conditions, while values in the range 1<Th/U>1 point to dysoxic conditions. Even if the use of authigenic uranium as proxy for reducing conditions ~~-~~is common in the chemiography of marine sediments (Pattan and Pearce, 2009), several authors have questioned the real preservation of the authigenic

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uranium signal by different processes as burn down, fast change of sedimentation rate and oxygen ventilation or bioturbation (Zheng et al., 2002). Therefore any indication of oxigen depletion suggested by the authigenic uranium has to be regarded in a wider fitting context.

$U_a$ from the bulk sediment display values from 0.3 to 9.5 ppm (Table 2). The lowest values are attained in intervals A, B and lower C, with figures generally below 2. In the upper part of interval C, $U_a$ increases and maintains high values in interval D and E, where some fluctuations occur, similarly to what observed for the stable isotopes and trace elements ratios (Fig. 5). A similar trend is observed for the Th/U ratios, which show values greater than 1 in intervals A, B and C, and values mainly around 1 in intervals D and E (Table 2).

*4.5 Palaeoenvironmental episodes inferred from the geochemical proxies*

The geochemical analyses performed on the valves of *C. agrigentina* and bulk sediment samples collected from the 96.5-260 m portion of the post-evaporitic Messinian succession of Eraclea Minoa confirm the frame of a Palaeomediterranean waterbody discontinuous and isolated, characterised by diluted waters after the evaporative phase of the Lower Gypsum Unit, the closure of the Atlantic-Palaeomediterranean connection and the subsequent global humid climate phase (Griffin, 2002; CIESM, 2008; Grossi et al., 2008). In fact, notwithstanding the ~~clear~~ well known saline character of the Palaeomediterranean waters, testified by the presence of brackish ostracod assemblages, all the geochemical indicators point to a clear differentiation with the Messinian oceanic seawater. On the other hand, the stable isotopes values reported in Figs. ~~4~~5, 6 do~~es~~ not show the overall covariant trend that would correspond to a marginal marine environment or a closed waterbody (Talbot, 1990; Utrilla et al., 1998; Ligios et al., 2012), and also trace elements behave in a different manner. The $Mg/Ca_v$ values from *C. agrigentina* (~~$Mg/Ca_v$=~~0.0052-0.0152) are similar to most of the analyses from *Cyprideis* shells for the Messinian Lago-Mare horizons from DSDP sites (De Deckker et al., 1988). For these $Mg/Ca_v$ values, De Deckker et al. (1988) consider the host water had Mg/Ca values lesser than that of Messinian seawater, and in some cases similar

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to most of the Mg/Ca shown by freshwaters (Mg/Ca=1). The Sr/$Ca_v$ values from *C. agrigentina* at 153-189 m (~~Sr/$Ca_v$=~~0.0025-0.0030) are similar to most of the analyses from *Cyprideis* shells from the Messinian Lago-Mare horizons from DSDP sites (De Deckker et al., 1988). For these Sr/$Ca_v$ values, these authors consider the host water had Sr/Ca values lesser than that of Messinian oceanic seawater. On the contrary, the Sr/$Ca_v$ values for most of the samples from 198-225 m and 252.8-257.8 m (~~Sr/$Ca_v$=~~0.0038-0.0054) indicate that the host water frequently had Sr/Ca values greater than that of Messinian oceanic seawater. The values of Sr/$Ca_v$ and Mg/$Ca_v$ indicate that the waters where the Eraclea Minoa ostracods lived were very different than the Messinian seawater and there is no indication of connection with oceanic seawater. Furthermore, the $^{87}$Sr/$^{86}$Sr range of values obtained from the analyses of *C. agrigentina* valves ~~from Eraclea Minoa~~ is consistent with the isotopic values of the Upper Gypsum Unit from Sicily and other localities of the Palaeomediterranean (Müller and Mueller, 1991; Keogh and Butler, 1999; Flecker and Ellam, 2006; Roveri et al., 2014b). This range is also similar to the range (0.708600-0.70875) reported from most ostracod valves (*Cyprideis*) from Messinian Lago-Mare deposits from several DSDP sites of the Palaeomediterranean studied by McCullock and De Deckker (1989). On the other hand, the Sr isotopic values from Eraclea Minoa are quite different from the value of the average ocean water during the deposition of the Upper Evaporite: 0.709012 (Howarth and McArthur, 1997; Flecker et al., 2002). The $^{87}$Sr/$^{86}$Sr values of the Eraclea Minoa *C. agrigentina*, as is the case of materials from other post-evaporitic Messinian localities, confirm to be the result of a large influence of freshwater on the Sr isotopic composition of the desiccating subbasins of the Palaeomediterranean (Müller et al., 1990). Finally, it is noteworthy that isotopic ratios anomalously low could result from reworking of older marine evaporites, or diagenetic overprinting. However, according to Keogh and Butler (1999), the reworking of Sr from the older marine evaporites implies mixing in different proportion between Sr deriving from continental run-off and coming from ground water circulating inside the buried ~~-~~evaporites. Such a process likely produces high variability in both salinity and $^{87}$Sr/$^{86}$Sr ratios.

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Based on the geochemical signature of *C. agrigentina* valves and bulk sediment samples, five main palaeoenvironmental intervals may be differentiated along the studied portion of the Eraclea Minoa succession (Fig. 5):

Interval A (153-189 m), characterised by high $\delta^{18}O$, $Na/Ca_v$, $Mg/Ca_v$ and $^{87}Sr/^{86}Sr$ values, and low $\delta^{13}C$, and $Sr/Ca_v$, and $U_a$. This interval records relatively stable hydrochemical conditions as suggested by the small variation of each geochemical indicator, isotopically concentrated waters and high $Na/Ca_v$ and $Mg/Ca_v$ ratios that were attained after the deposition of the 6th gypsum level. An overall evaporative environment (Fig. 45) with moderate salinity could be inferred for this interval. The high amount of Th and detrital U, the low content of authigenic uranium and the rather high Th/U ratios (Table 2) record possible well oxygenated bottoms.

Interval B (198 - to 225 m), characterised by low $\delta^{18}O$, $Na/Ca_v$, $Mg/Ca_v$, and $^{87}Sr/^{86}Sr$, and $U_a$ values, and high $\delta^{13}C$ and $Sr/Ca_v$. A major change is recorded at the base of this interval (198 m, sample EM 6"-8) where large shifts in all the geochemical indicators appear. A possible explanation for these features is to consider the noticeable detrital and freshwater inputs that increase the Ca dissolution, recorded both by the coarser lithologies, the high values of Th and detrital U and the low $^{87}Sr/^{86}Sr$ values for most samples. Those inputs may explain the lowering of $\delta^{18}O$ in the valves, the increase of $Sr/Ca_v$ (recording Sr inputs from the $CaSO_4$-rich subsurface waters) and the lowering in $Mg/Ca_v$ because of the high increase in Ca in the waterbody. The increase in $\delta^{13}C$ values could be produced by an increase in the productivity, linked to the detrital and nutrient inputs and a trend to re-equilibration with the atmospheric $CO_2$ (Fig. 45). As in the previous interval, NRD results (Table 2) testify for possible The high amount of Th and detrital U and the low content of authigenic uranium (Tab. 2) record well oxygenated bottoms.

Interval C (225-240 m). In this interval, only NRD analyses have been performed due to the low frequency of *C. agrigentina* in the ostracod assemblages, that prevented the possibility to reach the suitable amount of biogenic carbonate for the analyses. The content of authigenic uranium in the

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upper part of this interval, higher than in the previous one, (Table 2, Fig. 5) points to possibly progressively less oxygenated bottoms.

Interval D (240-242 m). This short interval is characterised by the highest values of authigenic U and low values of the Th/U ratios, suggesting possble dysoxic conditions at the bottom.

Interval E (252.8-259.1 m). In this interval two portions may be differentiated and a main change is recorded from the lower samples to the upper ones. The lower samples are characterised by high $\delta^{18}O$, $Sr/Ca_v$, $Na/Ca_v$, and $^{87}Sr/^{86}Sr$ values, and low $\delta^{13}C$ and $Mg/Ca_v$ values. The low content of authigenic uranium indicates possibly oxygenated bottoms. The upper samples are characterised by the opposite trend. The geochemical features of the ostracod valves from the lower part may be explained by the evaporitic concentration of the waterbody (Figs. 5, 6) leading to high $\delta^{18}O$, $Sr/Ca_v$ and $Na/Ca_v$ values. A subsequent large input of freshwater produced the lowering of $\delta^{18}O$, $Sr/Ca_v$ and $Na/Ca_v$. At present, we have no explanation for the variations of the $Mg/Ca_v$ values in this interval. It is worth to note the high content of authigenic uranium that reaches in one sample the value of 9.5 ppm, possibly indicating dysoxic conditions at the bottom.

## 5. Morphometrical analyses on *Cyprideis agrigentina* valves

Length and height of one thousand-sixty valves of adult males and females were measured. The obtained values fall within the variability field typical of the species (Decima, 1964; Ligios et al., 2012). The mean values of the length of the female left valve (the most numerous in the measured samples) have been compared. Generally the mean values of the length vary from 0.96 to 1.00 mm, but in few samples the mean values are rather small: at 185 m (sample EM 6"-3, mean value 0.90 mm), 201 m (EM 6"-11, mean value 0.89 mm), 222 m (EM 7-6, mean value 0.85 mm), and 223.5 m (EM 7-8, mean value 0.88 mm) (Fig. 7). Only in four samples the mean values of the length result significantly high: at 165 m (sample EM 6'-12 mean value 1.05 mm), 176.2 m

(~~sample~~ EM 6'-24, mean value 1.06 mm), 180 m (EM 6'-27, mean value 1.04 mm), and 210 m (EM 6"-17, mean value 1.14 mm).

The several thousands specimens of *C. agrigentina* investigated for the ornamentation and noding, showed rather homogeneous ornamentation: no noded specimens have been observed all along the section among both juveniles and adults; almost all valves were smooth (at least some of them showed few small pits in the posterior surface); only two samples (EM 6"-7 at 189.0 m and EM 6"-20 at 216.0 m) showed, respectively, the 54.2% and 54.6% of valves pitted on the entire surface (Fig. ~~6~~7).

The analysis of the percentage of the sieve-pore shape was carried out on fifty-three samples from the middle and upper portion of the section, where *C. agrigentina* was more abundant, making both monospecific and diversified assemblages. On average, more than 500 sieve-pores were observed for each sample and counted on the basis of their shape: rounded, elongated, irregular, following the indications by Rosenfeld and Vesper (1977). The results are reported in Fig. ~~6~~7. In most cases, the percentages of the rounded sieve-pores are comprised between 40 and 50%; in twelve scattered samples they are higher, reaching the maximum value of 65% at 96.5 m (sample EM 4-7) and only in a short interval from 198.5 m (sample EM 6"-8) to 216 m (sample EM 6"-20) they are lower, comprised between 19 and 30%, reaching their minimum values (19-21%) in the interval 204.5-216 m. Applying the transfer function elaborated by Frenzel et al. (2011) for *C. torosa*, the resulting salinities expressed in psu shows values included in the mesohaline range (5-18 psu, Venice Symposium, 1958) for most samples. Only few scattered samples in the lower and upper portions of the section point to the oligohaline range (0.5-5 psu), while higher salinities (polyhaline to euhaline ranges, 18-40 psu) are recorded only in a limited portion of the section, from 198.5 to 216 m (Fig. ~~7~~8).

## 6. Discussion

As explained in the introduction, the living species *C. torosa* is considered to be one of the most valuable tools to detect past salinities in the marginal marine environments, owing to its environmentally cued polymorphism that induces variations in size, noding and sieve-pore shapes depending on salinity. Large sizes, presence of nodes and high percentages (around 40-45%) of rounded sieve-pores point to salinity less than 8-9 psu that is considered an important osmoregulation threshold for the species (Keiser and Aladin, 2004; Keyser, 2005).

It is not clear when *Cyprideis torosa* appeared for the first time, owing to the difficulty to identify the species. Often in the Neogene sediments *Cyprideis* remains have been recorded as *Cyprideis* gr. *torosa* or *Cyprideis* sp. (Bossio et al., 1993; 1996; Testa, 1995). According to Decima (1964) and Ligios and Gliozzi (2012) the species is the only survivor of a stem that started in the Palaeomediterranean area with *Cyprideis ruggierii* Decima (late Tortonian-early Messinian), including *Cyprideis agrigentina* Decima (post-evaporitic Messinian) and *Cyprideis crotonensis* Decima (post-evaporitic Messinian-Late Pliocene). The great morphological similarity of the species of the stem lead some authors to suppose that the same environmentally cued polymorphism displayed by *C. torosa* could affect also its relatives (Neale, 1988), notwithstanding no noded specimens of the other species had never been recorded. Thus, Rosenfeld (1977) and Bonaduce and Sgarrella (1999) inferred hyperhaline post-evaporitic Messinian environments respectively for the Mavqi'im Formation (Israel) and at Eraclea Minoa, applying on *C. agrigentina* valves the empirical methods of the percentage of the rounded sieve-pores elaborated by Rosenfeld and Vesper (1977) on *C. torosa*.

As a first step to investigate whether *C. agrigentina* shared with *C. torosa* the same ecophenotypical behavior, we have analyzed size, ornamentation and sieve-pore shapes on some thousand of specimens from the post-evaporitic Messinian section of Eraclea Minoa. The expected results, in case of a comparable behavior, is a positive correlation between large size, noding (or strongly pitted valve surface), and high percentages of rounded sieve-pores. Fig. ~~6~~ 7 shows that this correlation lacks: the largest sizes (thus the supposed lowest salinities, below 8-9 psu) are attained by specimens recovered in samples bearing smooth valves (supposed high salinities) and percentages of rounded sieve-pores less than 40% (above the 8-9 psu threshold). In particular, in sample EM 6”-17 (at 210 m) the largest *C. agrigentina* valves matches with one of the lowest percentages of rounded sieve-pores (22,7%); the smallest sizes (supposed high salinities) correlates with smooth valve surfaces (supposed high salinities) but to percentages of rounded sieve-pores greater than 40% except in one case (sample EM 6”-11 at 201 m) in which the percentage is low (23.1%); the only two samples in which *C. agrigentina* valves are densely pitted (supposed low salinities), corresponds, on average, to intermediate dimensions and high percentage values.

From those comparisons it is possible to conclude that size and ornamentation/noding in *C. agrigentina* are not correlated. In particular, pitted ornamentation and noding seem to be, respectively, very rare and totally absent in *C. agrigentina*, despite the species seems to be strongly euryhaline as it is its living relative (Ligios and Gliozzi, 2012). Thus, it seems that those characters do not display in *C. agrigentina* the same salinity-dependant polymorphism of *C. torosa*.

A further question is to investigate whether the percentage variations of the sieve-pore shapes are correlated with salinity variations as in *C. torosa*. To test this hypothesis we have based the comparisons of the salinity curve obtained applying the transfer function elaborated by Frenzel et al. (2011) with the salinity inferred by the synecological analysis and with the palaeohydrological variations inferred by the geochemical analyses (Figs. ~~7~~8, ~~8~~9, ~~9~~10).

Based on the synecological analysis and the Shannon-Wiener diversity curve, it is possible to observe that the “*Cyprideis* assemblage”, correlatable with the minimum diversity values (monotypic ostracod assemblages) corresponds to different inferred salinities: oligo-low mesohaline in the intervals 153-171, 218-225 and 253-257.8 m; high mesohaline from 174 to 189 m; polyhaline-euhaline from 198.5 to 216.5 m. Moreover, it is worth to note that the two oligohaline levels with *Cyprideis* and *Ilyocypris*, included in the “*Cyprideis*” long interval at 198.5 and 201 m, according to the salinity curve based on sieve-pore percentage should have deposited in polyhaline/euhaline waters. We should conclude that there is no correspondence between the salinities inferred by the method of the sieve-pore percentages and the synecological palaeoenvironmental interpretation. This conclusion contradicts the statement by Bonaduce and Sgarrella (1999) who, on the basis of the percentage of sieve-pore shapes, inferred for the Eraclea Minoa portion of succession with monospecific *Cyprideis* assemblage hyperhaline environments (50-70 psu). Probably their conclusions are affected by the very few analyzed samples along the succession (only two) and the scarcity of counted sieve-pores for each sample (respectively 74 and 161).

The calculation of past salinities from the results of the geochemical analyses on the valves of *C. agrigentina* is difficult to assess. Although $Na/Ca_v$ could be tentatively perceived as a proxy of the salinity (assuming salinity dominated by NaCl solute), the obtained data must be considered with caution because of the poor knowledge of the Na uptake in the ostracod calcite shell (Holmes and De Deckker, 2012). However, recent attempts to use Na/Ca ratios from ostracod valves for palaeoenvironmental reconstructions must be taken into account (Gouramanis et al., 2010; Devriendt, 2011). On the other hand, Sr/Ca and Mg/Ca from ostracod valves just may inform about the Sr/Ca and Mg/Ca of the waters (De Deckker et al., 1999; Dettman and Dwyer, 2012; Holmes and De Deckker, 2012~~; Dettman and Dwyer, 2012~~), and only in some cases (i.e. some estuarine environments) these ratios could correlate with the salinity of the waters. On the other hand, $\delta^{18}O$ variations in closed non-marine environments are linked usually to evaporation/precipitation processes (Talbot, 1990), that in some cases are associated to salinity variations. Anyway, the decreasing $Na/Ca_v$ ratios from Interval A to Interval B (Fig. 5) is consistent with the interpretation of more diluted waters in this latter interval, as pointed by the low $\delta^{18}O$ values in B. However, this is in contradiction with the higher salinity assumed for interval B than for interval A based on the sieve-pore analysis of *C. agrigentina* (Fig. ~~7~~8).

We have tried to test the correlation between the geochemical results and the salinities assumed from the analysis of the sieve-pore percentages using a multivariate approach. The correlation matrix obtained for ~~eight~~ nine variables is shown in Tab~~.~~le 3. Significant correlations

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(p<0.01) are displayed only by the pairs $\delta^{18}O$ and Na/Ca$_v$, Na/Ca$_v$ and Mg/Ca$_v$, Sr/Ca$_v$ and stratigraphic position. Significant negative correlations are shown by $\delta^{13}C$ and Na/Ca$_v$, $\delta^{13}C$ and $\delta^{18}O$, $\delta^{13}C$ and Mg/Ca$_v$, Mg/Ca$_v$ and Sr/Ca$_v$. In fact salinity assumed from sieve-pore analysis (N pores), and Sr isotopic ratios of the valves do not show significant correlation with any of the other considered variables.

Principal Component Analysis (PCA) delineates similar patterns. About 34.92~~43.09~~% of the total variance is explained by the first eigenvector (Fig. ~~8~~9), which is tied to concentration-evaporation processes, indicated by the relations among $\delta^{18}O$, Na/Ca$_v$, Mg/Ca$_v$, Th/U and $^{87}Sr/^{86}Sr$ in the positive field. This factor is related to the precipitation/evaporation balance and residence time and probably to the resedimentation of evaporites. Inputs of oxygenated, $SO_4$-rich solutions would lead to lowering of $\delta^{18}O$, Na/Ca$_v$, Mg/Ca$_v$ and $^{87}Sr/^{86}Sr$. On the negative field, the variables are ~~$\delta^{13}C$,~~ Sr/Ca$_v$, the stratigraphic position and the percentages of rounded sieve-pores that are linked to DIC (Dissolved Inorganic Carbon) changes.~~probably are linked to the productivity-nutrient inputs, OM decomposition and at the end DIC (Dissolved Inorganic Carbon) changes and the environmental evolution.~~ On the other hand, factor 2 that accounts for 20.~~68~~72% of the variance, in the positive area contains a group formed by $\delta^{18}O$, Sr/Ca$_v$, stratigraphic position and NaCa$_v$, whereas in the negative area a group formed by N pores, $\delta^{13}C$, Th/U and Mg/Ca$_v$ exists. Factor 2 probably is linked to detrital, freshwater and nutrient inputs related to the environmental evolution~~climate~~.

Results from the cluster analysis reveal several groups (Fig. ~~9~~10). One of the groups shown by the dendrogram reflects the relationship between $\delta^{18}O$ and Na/Ca$_v$ revealing the control of the Na/Ca$_v$ exerted by the P/E balance ($\delta^{18}O$). They are associated with Mg/Ca$_v$, Th/U, and Sr isotopic ratios in the ostracod valve that, into a lesser extent, seem also to be influenced by the P/E balance. The pair Sr/Ca$_v$–position of the sample is associated to the pair $\delta^{13}C$–percentage of rounded sieve-pores. This pair reveals the link between DIC changes and the changes in sieve-pore shapes.

If we add the Th/U ratios in the sediments to the other variables in order to perform a new statistical analysis (9 variables), the number of available samples for this analysis is reduced to 10. In this new examination, the percentages of rounded sieve-pores is associated to Th/U and this pair is linked to $\delta^{13}C$. The links among these 3 variables reflect the relationship between the number of rounded sieve-pores in *C. agrigentina* and the environmental changes in the bottom of the basin in relation with the cycling of carbon (OM decomposition), oxygen availability and redox conditions. Nevertheless, for this analysis the correlations are low and weak. We need additional data to fully confirm these links with Th/U in the sediments. It is worth to note that, although some authors consider both the $U_a$ and Th/U values as good proxies to detect past oxic/dysoxic conditions (Adams and Weawer, 1958; Wignall and Myers, 1988 ; Wignall, 1994; Jones and Manning, 1994), Wignall and Meyers (1988) suggest to couple the $U_a$ results with the Shannon-Weaver dominance-diversity index (H) since, under low-oxygen conditions, assemblages are dominated by a few eurytopic forms, and values of H are typically low. If we compare the H-index curve (Fig. 8) with the oxygen availability at the bottom derived from the $U_a$ curve of Fig. 5, we notice that they are contradictory: when $U_a$ values are high (comprised between 2 and 10 and indicate possible dysoxic bottoms) the H-index values are high (rather well diversified assemblages). This negative correlation suggest, as supposed by Zheng et al. (2002) that the accumulation of $U_a$ in sediments could due also to physico-chemical variables other than the oxygen availability.

The results of the statistical analyses underline that there is no significant relationship between the salinity assumed from the sieve-pore analyses on the valves of *C. agrigentina* and the variables linked to the hydrochemical changes ($\delta^{18}O$, $Na/Ca_v$ and $Mg/Ca_v$, i.e. the salinity changes). On the other hand, the number of rounded sieve pores in C. *agrigentina* seems to be mainly linked to $\delta^{13}C$ (OM decomposition, DIC-cycling of C), oxygen availability and redox condition in the bottom.

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In conclusion, this puzzly set of data does not confirm that the percentages variation of the sieve-pore shapes in *C. agrigentina* is a reliable salinity indicator for the Lago-Mare episode of the Messinian Salinity Crisis. On the other hand, the complexity of the hydrochemical evolution due to the ~~deposition~~ re-sedimentation of the Upper Gypsum Unit and scattered inputs of detrital materials and meteoric waters accounts for a complex palaeohydrological and palaeohydrochemical scenario in which it seems that the factor~~s~~ responsible for the changes in the shape of the pores in the valves of *C. agrigentina* could be the behaviour of the DIC and the oxygen availability.

On the other hand, the geochemical data give a negative response to the hypothesis that the "*Cyprideis* assemblage" could be related to dysoxia at the bottom. Data from the percentage of the authigenic U, Th/U ratios indicate that some ~~episodes of oxygen depletion~~accumulation of U occurred at the bottom of the Eraclea Minoa waterbody, but it seems that they were not so important to affect the benthic ostracod assemblages.

Although it is beyond the aim of this paper, in order to try to understand the palaeoenvironmental meaning of the "*Cyprideis* assemblage" we have tried to extend our investigations comparing other Lago-Mare successions of the Mediterranean area that included monotypic *C. agrigentina* assemblages. In the first case, such assemblage, represented by very scarce specimens, has been recovered in the lower portion of the Lago-Mare succession of the Adana Basin (Turkey) during the deposition of resedimented evaporites and marls, where a very high sedimentation rate was recorded (Faranda et al., 2013). The authors linked the low diversity and the scattered distribution of the ostracod assemblage of the Adana Basin to the high siliciclastic input connected with the high subsidence rate that affected the Adana Basin during the Lago-Mare phase. At Eraclea Minoa the "*Cyprideis* assemblage" is present with high frequencies and continuously recovered along the entire interval, but it is rather confined to the thick marly-sandy succession included between gypsum bodies 6 and 7. If we hypothesize that this portion of succession represents one precessional cycle, as supposed by Van der Laan et al. (2006), high sedimentation rates affected both Adana (12.5 mm/yr) (Radeff et al., submitted) and Eraclea Minoa

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(4~~,~~.3 mm/yr) successions. Similar stratigraphical, sedimentological and paleontological conditions have been found also in the lower portion of the Lago-Mare succession cropping out in the Iraklion Basin (central Crete) (unpublished data). Unfortunately, not everywhere high sedimentation rates and siliciclastic inputs support only the "*Cyprideis* assemblage": in the Mondragone 1 well (Garigliano Plain, Campania, southern Italy) around one-thousand meters of sediments deposited within the short temporal frame of the *Loxocorniculina djafarovi* zone (5.40-5.33 Ma), thus a very high sedimentation rate above 13 mm/yr was calculated, but the recovered Lago-Mare ostracod assemblages were highly diversified (Cosentino et al., 2006).

In conclusion, at the moment no plausible hypothesis can be arised on the palaeoenvironmental meaning of the "*Cyprideis* assemblage", once again stressing the peculiar and complex geological and palaeoenvironmental history of the Eraclea Minoa succession.

## 7. Conclusion

The ostracod assemblages of the post-evaporitic Messinian section of Eraclea Minoa (Sicily) have been studied in a palaeoenvironmental perspective to decipher the environmental changes verified during the deposition of the Upper Gypsum Unit. Rich and diversified assemblages made mainly by Paratethyan species, have been recovered in the lower and upper portion of the succession, pointing to shallow and low mesohaline waterbodies. In the central portion of the succession, very abundant monospecific assemblages made only by *C. agrigentina*~~,~~ were recognized, suggesting high mesohaline to hyperhaline shallow waterbody with low oxygen content. To test this latter interpretation, morphometric and geochemical analyses (stable~~,~~ isotopes, trace elements, $^{87}Sr/^{86}Sr$, and NRD)~~,~~ have been performed on ~~*C. agrigentina*~~ostracod valves and bulk sediment samples in order to verify if ~~*its*~~ *C. agrigentina* ecophenotypical behavior was comparable with that of the living species *C. torosa*.

The results have shown that:

1) *C. agrigentina* sizes and ornamentations are not affected by salinity variations;

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2) The percentages of sieve-pore shapes do not depend from the water salinity, as in *C. torosa*, but seem linked to the behavior of the DIC and the oxygen availability at the bottom.

Thus, it is possible to conclude that *C. agrigentina* cannot be considered as a palaeosalinometer for the Messinian Salinity Crisis.

Furthermore, the geochemical analyses have shown that the deposition of the Eraclea Minoa succession occurred in a complex palaeohydrological and palaeohydrochemical scenario.

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## REFERENCES

Adams J.A. & Weaver C.E., 1958. Thorium-uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies. Bulletin American Association of Petroleum Geologists 42(2), 387-430.

Aladin, N.V., 1993. Salinity tolerance, morphology and physiology of the osmoregulation organs in Ostracoda with special reference to Ostracoda from the Aral Sea. In Jones, P. and McKenzie K. (Eds.), Ostracoda in Earth and Life Sciences, A.A. Balkema, Rotterdam, 387-404.

Anadón, P., Gliozzi, E., Mazzini, I., 2002. Paleoenvironmental reconstruction of marginal marine environments from combined paleoecological and geochemical analyses on Ostracods. In:

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Holmes, J., Chivas, A. (Eds), The Ostracoda: Applications in Quaternary Research, Geophysical Monograph 131, 227–247.

Barbieri, M., Carrara, C., Castorina, F., Dai Pra, G., Esu, D., Gliozzi, E., Paganin, G., Sadori, L., 1999. Multidisciplinary study of Middle-Upper Pleistocene deposits in a core from the Piana Pontina (central Italy). Giornale di Geologia 61, 47–73.

Benson, R.H., 1978. The paleoecology of the ostracodes of DSDP Leg 42A. In: Initial Reports of the Deep Sea Drilling Project 42, 777–787, U.S. Government Printing Office, Washington, D.C.

Bernhard, J.M, Sen Gupta, B.K., 2002. Foraminifera of oxygen-depleted environment. In: Sen Gupta, B.K. (Ed.), Modern Foraminifera. Kluwer Academic Publishers, 201-216.

Bonaduce, G., Sgarrella, F., 1999. Paleoecological interpretation of the latest Messinian sediments from southern Sicily (Italy). Memorie della Società Geologica Italiana 54, 83–91.

Boomer, I., Frenzel, P., 2011. Possible environmental and biological controls on carapace size in *Cyprideis torosa* (Jones, 1850). Joannea Geologie und Paläontologie 11, 26–27.

Bossio, A., Costantini, A., Lazzarotto, A., Liotta, D., Mazzanti, R., Mazzei, R., Salvatorini, G., Sandrelli, F., 1993. Rassegna delle conoscenze sulla stratigrafia del Neoautoctono toscano. Memorie della Società Geologica Italiana 49, 17–98.

Bossio, A., Cerri, R., Mazzei, R., Salvatorini, G., Sandrelli, F., 1996. Geologia dell'area Spicchiaiola-Pignano (Settore orientale del Bacino di Volterra). Bollettino della Società Geologica Italiana 115, 393-422.

Carbonel, P., 1982. Les Ostracodes, traceurs des variations hydrologiques dans des systèmes de transition eaux douces-eaux salées. Mémoirs de la Societé géologique de France 8(144), 117–128.

Caruso, A., Rouchy, J.-M., 2006. The Upper Gypsum Unit. In: Roveri, M., Manzi, V., Lugli, S., Schreiber, B.C., Caruso, A., Rouchy, J.-M., Iaccarino, S.M., Gennari, R., Vitale, F.P., Ricci

Lucchi, F. (Eds.), Clastic vs. primary precipitated evaporites in the Messinian Sicilian basins. Acta Naturalia de “L’Ateneo Parmense” 42(4), 157-159.

CIESM (Commission Internationale pour l’Exploration de la Mer Méditerranée~~Mediterranee~~, Monaco), 2008. The Messinian Salinity Crisis from Mega-Deposits to Microbiology: A Consensus Report. CIESM Workshop Monograph 33, 1-168.

Cosentino, D., Bertini, A., Cipollari, P., Florindo, F., Gliozzi, E., Grossi, F., Lo Mastro, S., Sprovieri, M., 2012. Orbitally-forced palaeoenvironmental and palaeoclimate changes in the late post-evaporitic Messinian stage of the central Mediterranean Basin. Geological Society of America Bulletin 124(3-4), 499-516.

Cosentino, D., Federici, I., Cipollari, P., Gliozzi, E., 2006. Environments and tectonic instability in central Italy (Garigliano Basin) during the late Messinian *Lago-Mare* episode: New data from the onshore Mondragone well (Garigliano Plain, central Italy). Sedimentary Geology 188-189, 293-317.

Curry, B., Mesquita-Joanes, F., Fanta, S., Sterner, D., Calò, C., Tinner, W., 2013. Two coastal sinkhole lakes in SW Sicily (Italy) reveal low-salinity excursion during Greek and Roman occupation. Naturalista Siciliano 4, 37(1), 93-95.

De Deckker, P., Chivas, A.R., Shelley, J.M.G., 1988. Paleoenvironment of the Messinian Mediterranean “Lago Mare” from strontium and magnesium in ostracode shells. Palaios, 3, 352-358.

De Deckker, P., Chivas, A.R., Shelley, J.M.G., 1999. Uptake of Mg and Sr in the euryhaline ostracod *Cyprideis* determined from in vitro experiments. Palaeogeography, Palaeoclimatology, Palaeoecology 148, 105–116.

Decima, A., 1964. Ostracodi del genere *Cyprideis* Jones del Neogene e del Quaternario italiani. Palaeontographia Italica, 57(1962), 81-133.

Decima, A., Wezel, F.C., 1971. Osservazioni sulle evaporiti messiniane della Sicilia centro-meridionale. Rivista mineraria siciliana 130-132, 172-187.

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Dettman, D.L., Dwyer, G.S., 2012. Biological and environmental controls on ostracod shell trace-element chemistry. In: D. J. Horne, J. Holmes, J. Rodriguez-Lazaro and F. Viehberg (Eds.). Ostracoda as proxies for Quaternary climate change. Developments in Quaternary Sciences. Elsevier, v. 17, -145-163.

Devriendt, L.S.J., 2011. Late Quaternary environment of paleolake Carpentaria inferred from the chemistry of ostracod valves. Master of Sciences Research Thesis, University of Wollongong, Australia, 175 pp. http://ro.uow.edu.au/theses/3319/

Faranda, C., Gliozzi, E., Cipollari, P., Grossi, F., Darbaş, G., Gürbüz, K., Nazik, A., Gennari, R., Cosentino, D., 2013. Messinian paleoenvironmental changes in the easternmost Mediterranean Basin: Adana Basin, southern Turkey. Turkish J Earth Sci 22, 839-863.

Faure, G., Powell, J.L., 1972. Strontium Isotope Geology. Springer-Verlag, Berlin, 1-188.

Flecker, R., de Villiers, S., Ellam, R.M., 2002. Modelling the effect of evaporation on the salinity–$^{87}Sr/^{86}Sr$ relationship in modern and ancient marginal–marine systems: the Mediterranean Messinian Salinity Crisis. Earth Planet. Sci. Lett. 203 (1), 221– 233.

Flecker, R., Ellam, R.M., 2006. Identifying Late Miocene episodes of connection and isolation in the Mediterranean–Paratethyan realm using Sr isotopes. Sediment. Geol. 188–189, 189–203.

Frenzel, P., Schulze, I., Pint, A., 2011. Salinity dependant morphological variation in *Cyprideis torosa*. Joannea Geologie und Paläontologie 11, 59–61.

Frenzel, P., Schulze, I., Pint, A., 2012. Noding of *Cyprideis torosa* valves (Ostracoda) – a proxy for salinity? New data from field observations and a long-term microcosm experiment. International Review of Hydrobiology 97(4), 314–329.

Gliozzi, E., Grossi, F., 2008. Late Messinian Lago-mare ostracod palaeoecology: a correspondence analysis approach. Palaeogeography, Palaeoclimatology, Palaeoecology 264, 288-295.

Gouramanis, C., Wilkins, D., De Deckker, P., 2010. 6000 years of environmental changes recorded in Blue Lake, South Australia, based on ostracod ecology and valve chemistry. Palaeogeography, Palaeoecology, Palaeoclimatology 297, 223-237.

Graham, D.W., Bender, M.L., Williams, D.F.,Keigwin, L.D., 1982. Strontium-calcium ratios in the Cenozoic planktonic foraminifera. Geochim. Cosmochim. Acta 46, 1281-1292.

Griffin, D.L., 2002. Aridity and humidity: Two aspects of the late Miocene climate of North Africa and the Mediterranean. Palaeogeography, Palaeoclimatology, Palaeoecology 182, 65–-91.

Griffiths, H.I., Holmes, J.A., 2000. Non-marine ostracods & Quaternary palaeoenvironments. Quaternary Research Association, Technical Guide 8, 1-179.

Grossi, F., Gennari, R., 2008. Palaeoenvironmental reconstruction across the Messinian/Zanclean boundary by means of ostracods and foraminifers: the Montepetra borehole (Northern Apennine, Italy). Atti del Museo Civico di Storia Naturale di Trieste 53(suppl), 67-88.

Grossi, F., Cosentino, D., Gliozzi, E., 2008. Palaeoenvironmental reconstruction of the late Messinian lago-mare successions in central and eastern Mediterranean using ostracod assemblages. Bollettino della Società Paleontologica Italiana 47(2), 131–146.

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

Henderson, G. M., Martel, D. J., O'Nions, R. K., Shackleton, N. J., 1994. Evolution of seawater $^{87}Sr/^{86}Sr$ over the last 400 ka: the absence of glacial/interglacial cycles. Earth Planetary Sciences and Letetrs 128, 643–651.

Holmes, J., De Deckker, P., 2012. Introduction to ostracod shell chemistry and its application to Quaternary palaeoclimate studies. In: D. J. Horne, J. Holmes, J. Rodriguez-Lazaro and F. Viehberg (Eds.). Ostracoda as proxies for Quaternary climate change. Developments in Quaternary Sciences. Elsevier, v. 17, 131-144.

Howarth, R., McArthur, J.M., 1997. Statistics for Strontium Isotope Stratigraphy: a robust LOWESS fit to the marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. J. Geol. 105, 441–456.

Hsü, K.J., Ryan, W.F.B., Cita, M.B., 1973. Late Miocene desiccation of the Mediterranean. Nature 242, 240–244.

Iaccarino, S., Bossio, A., 1999. Paleoenvironment of uppermost Messinian sequences in the Western Mediterranean (sites 974, 975 and 978). In: Zahn, R., Comas, M.C., Klaus, A., et al. (Eds.), Proceedings of Ocean Drilling Program, Scientific Results 161, 529–541, College Station, Texas.

Jahn, A., Gamenick, I., Theede, H., 1996. Physiological adaptations of *Cyprideis torosa* (Crustacea, Ostracoda) to hydrogen sulphide. Marine Ecology Progress Series 142, 215–223.

Jones, B. and Manning, D.A.C., 1994. Comparison of geochemical indices used for the interpretation of paleoredox conditions in ancient mudstones. Chemical Geology 111, 111–129.

Keating, K.W., Hawkes, I., Holmes, J.A., Flower, R.J., Leng, M.J., Abu-Zied, R.H., Lord, A.R., 2007. Evaluation of ostracod-based palaeoenvironmental reconstruction with instrumental data from the arid Faiyum Depression. Egyptian Journal of Paleolimnology 38, 261–283.

Keogh, S.M., Butler, R.W.H., 1999. The Mediterranean water body in the late Messinian: interpreting the record from marginal basins on Sicily. J. Geol. Soc. (Lond.) 156, 837– 846.

Keyser, D., 2005. Histological peculiarities of the noding process in *Cyprideis torosa* (Jones) (Crustacea, Ostracoda). Hydrobiologia 538, 95–106.

Keyser, D., Aladin, N., 2004. Noding in *Cyprideis torosa* and its causes. Studia Quaternaria 2, 19–24.

Ligios, S., Anadón, P., Castorina, F., D'Amico, C., Esu, D., Gliozzi, E., Gramigna, P., Mola, M., Monegato, G., 2012. Ostracoda and Mollusca biodiversity and hydrochemical features of Late Miocene brackish basins of Italy. Geobios 45, 351-367.

Ligios, S., Gliozzi, E., 2012. The genus *Cyprideis* Jones, 1857 (Crustacea, Ostracoda) in the Neogene of Italy: A geometric morphometric approach. Revue de micropaléontologie 55, 171–207.

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**Formatted:** English (U.K.)

Mangini, A., Jung, M., Laukenmann, S., 2001. What do we learn from peaks of uranium and of manganese in deep sea sediments? Marine Geology 177(1), 63-78.

Manzi, V., Lugli, S., Roveri, M., Schreiber, C., 2009. A new facies model for the Upper Gypsum of Sicily (Italy): chronological and palaeoenvironmental constraints for the Messinian salinity crisis in the Mediterranean. Sedimentology 56, 1937-1960.

Manzi, V., Gennari, R., Lugli, S., Roveri, M., Scafetta, N., Schreiber, B.C., 2012. High-frequency cyclicity in the Mediterranean Messinian evaporites: evidence for solar–lunar climate forcing. Journal of Sedimentary Research. 82, 991–1005.

Manzi, V., Gennari, R., Hilgen, F., Krijgsman, W., Lugli, S., Roveri, M., Sierro F.J., 2013. Age refinement of the Messinian salinity crisis onset in the Mediterranean. Terra Nova, doi: 10.1111/ter.12038

Marco-Barba, J., 2010. Freshwater ostracods ecology and geochemistry as paleoenvironmental indicators in marginal marine ecosystems: a case of study the Albufera of Valencia. Ph. D. thesis, Univ. of Valencia.

McArthur, J.M., Howarth, R.J., Bailey T.R., 2001. Strontium isotope stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. Journal of Geology 109, 155–170.

McCulloch, M.T., De Deckker, P., 1989. Sr-isotope constraints on the Mediterranean environment at the end of the Messinian salinity crisis. Nature 342, 63– 65.

Müller, D.W., Mueller, P.A., 1991. Origin and age of the Mediterranean Messinian evaporites: implications from Sr isotopes. Earth Planet. Sci. Lett. 107, 1 –12.

Müller, D.W., Mueller, P.A., McKenzie, J.A., 1990. Strontium isotopic ratios as fluid tracers in Messinian evaporites of the Tyrrhenian sea (western Mediterranean sea). Proc. ODP Sci. Res. 107, 603–614.

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Neale, J.V., 1988. Ostracods and paleosalinity reconstruction. In: De Deckker, P., Colin, J.-P., Peypouquet, J.-P. (Eds.), Ostracoda in the Earth Sciences. Elsevier, Amsterdam, pp. 125–155.

Pattan, J.N., Pearce, N.J.G., 2009. Bottom water oxygenation history in southeastern Arabian Sea during the past 140 ka: Results from redox-sensitive elements. Palaeogeography, Palaeoclimatology, Palaeoecology 280(3-4), 396-405.

Pint, A., Frenzel, P., Fuhrmann, R., Scharf, B., Wennrich, V., 2012. Distribution of *Cyprideis torosa* (Ostracoda) in Quaternary athalassic sediments in Germany and its application for palaeoecological reconstructions. International Review of Hydrobiology 97(4), 330-335.

Pint, A., Melzer, S., Frenzel, P., Engel, M., Brückner, H., 2013. Monospecific occurrence of *Cyprideis torosa* associated with micro- and macrofauna of marine origin in sabkha sediments of the Northern Arabian Peninsula. Naturalista Siciliano 4, 37(1), 277-278.

Radeff, G., Schildgen, T.F., Cosentino, D., Strecker, M.R., Cipollari, P., Darbaş, G., Gürbüz, K., (submitted). Sedimentary evidence for late Miocene uplift of the SE margin of the central Anatolian Plateau: Adana Basin, Southern Turkey. Geological Society of America Bulletin.

Rosenfeld, A, Vesper, B., 1977. The variability of the sieve-pores in recent and fossil species of *Cyprideis torosa* (Jones, 1850) as an indicator for salinity and paleosalinity. In: Löffler, H., Danielopol, D. (Eds.), Aspects of ecology and zoogeography of recent and fossil Ostracoda. Junk Publishers, The Hague, 55–67.

Rosenfeld, A., 1977. The Sieve-pores of *Cyprideis torosa* (Jones, 1850) from the Messinian Mavqi'im Formation in the Coastal Plain and Continental Shelf of Israel as an Indicator of Paleoenvironment. Israel Journal of Earth-Sciences 26, 89-93.

Rossi, V., Amorosi, A., Sammartino, I., Sarti, G., 2013. Environmental changes in the lacustrine ancient harbour of Magdala (Kinneret Lake, Israel) inferred from ostracod, geochemical and sedimentological analyses. Naturalista Siciliano 4, 37(1), 331-332.

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

Roveri, M., Lugli, S., Manzi, V., Gennari, R., Schreiber, B.C., 2014b. High-resolution strontium isotope stratigraphy of the Messinian deep Mediterranean basins: Implications for marginal to central basins correlation, Marine Geology, doi: 10.1016/j.margeo.2014.01.002

Sampalmieri, G., Iadanza, A., Cipollari, P., Cosentino, D., Lo Mastro, S., 2010. Palaeoenvironments of the Mediterranean Basin at the Messinian hypersaline/hyposaline transition: evidence from natural radioactivity and microfacies of post-evaporitic successions of the Adriatic sub-basin. Terra Nova 22, 239-250.

Sandberg, P., 1964. The ostracod genus *Cyprideis* in the Americas. Stockholm Contributions in Geology 12, 1-178.

Schäfer, H.W., 1953. Über Meeres- und Brackwasserostracoden aus dem Deutschen Küstengebiet mit 2. Mitteilung über die Ostracodenfauna Griechenlands. Hydrobiologia 5(4), 351-389.

Schreiber, B.C., 1997. Field trip to Eraclea Minoa: Upper Messinian. "Neogene Mediterronean Paleoceanography". Excursion Guide Book Palermo-Caltanissetta Agrigento. Erice (Sicily), 24-27 September 1997, 72-80.

Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. Chemical Geology (Isot. Geosci. Sect.) 80, 261–279.

Testa, G., 1995. Upper Miocene extensional tectonics and synrift sedimentation in the western sector of the Volterra Basin (Tuscany, Italy). Studi Geologici Camerti vol. spec. 1, 617-630.

Utrilla, R., Vazquez, A., Anadón, P., 1998. Paleohydrology of the Upper Miocene Bicorb Lake (E Spain) as inferred from stable isotopic data from inorganic carbonates. Sedimentary Geology 121, 191-206.

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Van Couvering, J.A., Castradori, D., Cita, M.B., Hilgen, F.J., Rio, D., 2000. The base of the Zanclean Stage and of the Pliocene Series. Episodes 23(3), 179-187.

Van der Laan, E., Snel, E., de Kaenel, E., Hilgen, F.J., Krijgsman, W., 2006. No major deglaciation across the Miocene-Pliocene boundary: integrated stratigraphy and astronomical tuning of the Loulja sections (Bou Regreg area, NW Morocco). Paleoceanography 21, PA3011, doi:10.1029/2005PA001193.

Van Harten, D., 1996. *Cyprideis torosa* (Ostracoda) revisited. Of salinity, nodes and shell size. In: Keen, C. (Ed.), Proceedings of the second European Ostracodologists Meeting. British Micropalaeontological Society, London, pp. 191–194.

Van Harten, D., 2000. Variable noding in *Cyprideis torosa* (Ostracoda, Crustacea): an overview, experimental results and a model from Catastrophe Theory. Hydrobiologia 419, 131–139.

Venice Symposium on the Classification of Brackish Waters, Venice 8-14 April 1958 in Remane, A., Schlieper, C. (eds.), Die Biologie der Brackwassers. Schweizerbartsche Verlag, Stuttgart, 1-348.

Vesper, B., 1975. To the problem of noding on *Cyprideis torosa* (Jones, 1850). In: Swain, F., Kornicker, L.S., Lundin, R.F. (Eds.), Biology and Paleobiology of Ostracoda. Bulletin of American Paleontology 65(282), 205-216.

Voltaggio, M., Branca, M., Tedesco, D., Tuccimei, P., Di Pietro, L., 2004. $^{226}$Ra-excess during the 1631-1944 activity period of -Vesuvius (Italy): a model of alpha recoil enrichment in a metasomatized mantle and implications on the current state of the magmatic system. Geochimica et Cosmochimica Acta 68, 167-181.

Wignall, P.B., 1994. Black Shales. Claredon Press, Oxford, 127 pp.

Wignall, P.B., Myers, K.J., 1988. Interpreting benthic oxygen levels in mudrocks: anew approach. Geology 16, 452-455.

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Zheng, Y., Anderson, R.F.,Van Geen, A., Fleisher, M.Q., 2002. Remobilization of authigenic uranium in marine sediments by bioturbation. Geochimica et Cosmochimica Acta 66 (10), 1759–1772.

FIGURE CAPTIONS

Fig. 1 – SEM pictures of *Cyprideis agrigentina* Decima. a. male left valve, sample EM 8-3; b. male right valve, sample EM 7-2; c. female left valve, sample EM 7-2; d. female right valve, sample EM 8-3. White bar corresponds to 0.1 mm.

Fig. ~~1~~ 2 – Geographical location of the Eraclea Minoa section.

Fig. ~~2~~ 3 – Panoramic view of the Eraclea Minoa section. In evidence the gypsum levels of the Upper Gypsum Unit from gypsum body 3 to gypsum body 6 (marked by numbers) and the Messinian/Zanclean boundary.

Fig. ~~3~~ 4 – Simplified stratigraphic log of the Eraclea Minoa section (modified from Manzi et al., 2009). Legend: 1. sapropels; 2. clays; 3. sandstones/sandy levels; 4. microconglomerate levels; 5. marls; 6. gypsum bodies (Upper Gypsum Unit); 7. samples for paleontological analyses; 8. samples for morphometrical analyses (ornamentation, dimensions and percentage of sieve-pore shapes) on *C. agrigentina* valves; 9. samples for stable isotopes analyses on *C. agrigentina* valves; 10. samples for trace elements analyses on *C. agrigentina* valves; 11. samples for Sr-isotopes analyses on *C. agrigentina* valves; 12. samples for NRD analyses on marls.

Fig. 5 – Stable isotopes, trace and minor elements, $^{87}Sr/^{86}Sr$, and authigenic uranium curves plotted against the stratigraphic log of the Eraclea Minoa section. For the descriptions of the intervals, see the text.

Fig. ~~4~~ 6 - Stable isotopic composition ($\delta^{13}C$ and $\delta^{18}O$; PDB notation) of *Cyprideis agrigentina* calcite valves (Table 1). Note the negative correlation and regression line for samples from interval

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lower B. The larger variation of $\delta^{13}C$ and $\delta^{18}O$ along the regression line corresponds to samples EM 6"-8 (198.2 m) to 6"-20 (216 m) from lower interval B. E/P: Evaporation /Precipitation ratio; PP: Primary productivity; Eq-Atm: Atmospheric $CO_2$ equilibrium. See also Fig. ~~5~~4.

~~Fig. 5 – Stable isotopes, trace and minor elements, $^{87}Sr/^{86}Sr$, and authigenic uranium curves plotted against the stratigraphic log of the Eraclea Minoa section. For the descriptions of the intervals, see the text.~~

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Fig. ~~6~~ 7 – Results of the morphometrical analyses (mean lengths, percentages of sieve-pore shape and ornamentation/noding) performed on *Cyprideis agrigentina* adult valves, plotted against the stratigraphic log of the Eraclea Minoa section.

Fig. ~~7~~8 ~~–~~ - Comparisons among the palaeosalinity curve inferred by the analysis of the percentages of the sieve-pore shape on *Cyprideis agrigentina* and the palaeoenvironmental and palaeohydrochemistry changes inferred from synecological and Shannon-Wiener and geochemical proxies.

Fig. ~~8~~ 9 - Principal Component Analysis (PCA) plot of the scores of the eigenvectors for the variables listed in Table 3. Abbreviations: N pores: variability of percentage of sieve pores (rounded sieve pores assumed as a proxy of salinity), Position: stratigraphic position of the samples, Sr isot: $^{87}Sr/^{86}Sr$ values. See the text for discussion.

Fig. ~~9~~ 10 - Tree diagram for the considered variables defining the relationships between the groups of variables. Ward's method, 1-Pearson r. Abbreviations as in Fig. 8. See the text for discussion.

## TABLE CAPTIONS

Table 1 – Stratigraphic position and lithology of the samples, and geochemical analytical results from *C. agrigentina* valves: stable isotope data ($\delta^{13}C$ and $\delta^{18}O$; PDB notation), $Mg/Ca_v$, $Sr/Ca_v$, and $Na/Ca_v$ in molar ratios, and $^{87}Sr/^{86}Sr$ ratios.

Table 2 – Summary of natural radioactivity data, with the concentrations of U, Th and K (with relative errors), values of authigenic uranium expressed in ppm and percentage and Th/U ratios.

Table 3 – Correlation matrix for the data in Table 1 and Th/U ratios (9 variables, 20 samples). The correlation coefficient r between the diverse variables is shown in the upper part of each division. The p value is indicated in the lower part of each division. The r values are in bold when the correlation is significant $p<0.01$. Abbreviations: N pores: variability of percentage of sieve pores (rounded sieve pores assumed as a proxy of salinity), Position: stratigraphic position of the samples, Sr isot: $^{87}Sr/^{86}Sr$ values.

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# Is *Cyprideis agrigentina* Decima a good palaeosalinometer for the Messinian Salinity Crisis? Morphometrical and geochemical analyses from the Eraclea Minoa section (Sicily)

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## ABSTRACT

The living euryhaline species *Cyprideis torosa* (Jones) undergoes morphometric variations in size, noding and sieve-pore shape linked to the environmental salinity. In particular it is known that salinity values around 8-9 psu represent the osmoregulation threshold and also the turning point between smaller and greater valve dimensions and prevailingly noded against un-noded valves. The variation of the percentage of round-, elongate- and irregular-shaped sieve-pores on the valves has shown an empiric logarithmic correlation with the water salinity from 0 to 100 psu. Due to this ecologically cued polymorphism, *C. torosa* represents an invaluable palaeosalinometer for the Quaternary brackish basins.

In this paper we attempt to verify whether the ecophenotypical behaviour of the post-evaporitic Messinian species *Cyprideis agrigentina* Decima was comparable with that of *C. torosa*. To reach this goal, three morphometric characters have been analysed: 1) size variability; 2) noding and ornamentation; 3) variability of the percentage of the sieve-pore shapes. The palaeoenvironmental interpretation was made using synecological and geochemical approaches [stable isotopes, trace elements, Sr-isotopes and natural radioactivity (NRD)]. For this study, the 250 m-thick Messinian Lago-Mare succession of Eraclea Minoa (Agrigento, Sicily) was chosen for the presence of monotypic assemblages made only by *C. agrigentina* for around 70 m of thickness.

The results of the morphometric analyses showed that: 1) size variations are not related to the salinity changes recognized both from synecological and geochemical analyses; 2) no noded specimens have been recovered along the section; 3) the salinities calculated on the basis of the percentage of the sieve-pore shape are not correlated with the salinities inferred from the synecological and geochemical analyses. Thus, in this paper we conclude that *C. agrigentina* cannot be considered a palaeosalinometer for the Messinian Salinity Crisis.

There is a correlation of the $\delta^{13}C$ with the percentages of sieve-pore shapes, linking them to the behavior of the dissolved inorganic carbon (DIC) and to the oxygen availability at the bottom of the basin.

KEYWORDS

Ostracoda; morphometrical analyses; geochemical analyses; palaeoenvironmental reconstruction; post-evaporitic Messinian; Sicily (Italy).

## 1. Introduction

Since the pioneering studies by Schäfer (1953), Sandberg (1964), Vesper (1975) and Rosenfeld and Vesper (1977), it is known that the living anomalohaline species *Cyprideis torosa* (Jones) undergoes morphometrical variations in size, noding and sieve-pore shape linked to environmental physical and chemical parameters - especially salinity - showing a clear environmentally cued polymorphism. The species can withstand and thrive in a very wide range of salinity (0.4 to 150 psu according to Neale, 1988 and Griffiths and Holmes, 2000), thus it is commonly regarded as a valuable palaeosalinometer for the Quaternary marginal marine and athalassic brackish deposits (Marco-Barba, 2010; Pint et al., 2012 with references therein). Its low-Mg calcite shell represents also a source of biogenic carbonate for the geochemical analyses (trace elements, stable isotopes and $^{87}Sr/^{86}Sr$ ratios) to infer the chemical composition of past waterbodies, because of its high rate of valve calcification. In many studies, morphometrical variations were coupled with the geochemical approach to make more detailed palaeoenvironmental reconstructions of brackish environments (Barbieri et al., 1999; Anadón et al., 2002; Marco-Barba, 2010; Curry et al., 2013; Pint et al., 2013; Rossi et al., 2013).

Several studies (Carbonel, 1982; Aladin, 1993; van Harten, 1996; 2000; Keiser and Aladin, 2004; Keyser, 2005; Boomer and Frenzel, 2011; Frenzel et al., 2011; 2012 among others) showed that salinity values around 8-9 psu represent the osmoregulation threshold and also the turning point between smaller and greater valve dimensions and prevailingly noded against un-noded valves. Rosenfeld and Vesper (1977) showed an empiric logarithmic correlation between the variation of the percentage of round-, elongate- and irregular-shaped sieve-pores on the valves of *C. torosa* and the water salinity from 0 to 100 psu. This correlation has been confirmed by subsequent papers (Neale, 1988; Keating et al., 2007; Pint et al., 2012) and Frenzel et al. (2011) elaborated a transfer function based on the percentages of round sieve-pores.

In order to decipher the palaeosalinity changes during the end of the Messinian Salinity Crisis (Hsü et al., 1973; CIESM, 2008; Roveri et al., 2014a), Rosenfeld (1977) and Bonaduce and Sgarrella (1999) applied the counting of different sieve-pore shapes to the fossil species *Cyprideis* *agrigentina* Decima, supposing that also this species could morphologically react as *C. torosa*. In both cases they obtained hyperhaline values for the waters hosting *C. agrigentina* specimens (respectively 35-50 psu and 50-70 psu) considering those values reliable for the evaporative palaeoenvironment that yielded the deposition of the gypsum.

*C. agrigentina* (Fig. 1) is one of the most widespread ostracod that lived in the Palaeomediterranean during the latest Messinian Lago-Mare event (5.53–5.33 Ma, CIESM, 2008; 5.55-5.33 Ma, Manzi et al., 2013; Roveri et al., 2014a). It seems to have been the first ostracod that colonized again the sterile bottoms of the Palaeomediterranean after the deposition of the Primary Lower Gypsum and the partially desiccation of the basin. It has been recovered both in the Messinian sediments drilled on the Palaeomediterranean bottoms and in those cropping out along the peri-Mediterranean chains, from the most western area (Malaga Basin) to the easternmost Adana Basin (Benson, 1978; Iaccarino and Bossio, 1999; Bonaduce and Sgarrella, 1999; Grossi and Gennari, 2008; Guerra-Merchán et al., 2010; Cosentino et al., 2012; Faranda et al., 2013). In their study on the Messinian Lago-Mare palaeoenvironments inferred from the ostracod assemblages, Grossi et al. (2008) showed that *C. agrigentina* behaved as a very euryhaline species: it was associated a) with the benthic foraminifer *Ammonia tepida* ("*Cyprideis-Ammonia* assemblage") in very oligotypic assemblages supposed to be typical of high mesohaline environments; b) with *Loxoconcha muelleri* (Mehés) and *Loxoconcha eichwaldi* Livental ("*Cyprideis-Loxoconcha* assemblage") (low mesohaline environment); c) it was also a component, although not dominant, of the "pointed candonids-Leptocytheridae assemblage" and "pointed candonids assemblage", supposed to be characteristic of oligohaline to low mesohaline environments.

Anyway, despite its apparent capability to withstand different salinities, no noded specimens of *C. agrigentina* have been ever found (Ligios and Gliozzi, 2012) and this could arise some questions about the possible ecophenotypical reaction of *C. agrigentina* to the environment.

In this paper we attempt to verify whether the ecophenotypical behavior of *C. agrigentina* was comparable with that of *C. torosa*. To reach this goal, adult male and female valves of *C.*

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*agrigentina* from the long section of Eraclea Minoa (Agrigento, Sicily) were investigated and three morphometrical characters have been analysed: 1) size variability; 2) noding and ornamentation; 3) variability of the percentage of the sieve-pore shapes. The palaeoenvironmental framework to which the ecophenotypical characters displayed by *C. agrigentina* will be compared has been built based on synecological analysis (assemblages taxonomic composition and diversity) (Chapter 3) and geochemical approaches [stable isotopes, trace elements, Sr-isotopes and natural radioactivity (NRD)] (Chapter 4).

## 2. **Material and methods**

One hundred fifty-two samples have been soaked in a $H_2O_2$ 5%$_{vol}$ solution for 24 hours, sieved with 0.063 and 0.125 mm-mesh sieves and dried in oven at 40°C. Total manual picking has been carried out on the 0.125 mm dried sieved samples. When possible, up to 300 valves where hand-picked from each sample. Ostracods have been identified and their frequency counted; the obtained values have been normalized to 10 g in order to get comparable figures all along the section to perform a reliable palaeoenvironmental interpretation using the synecological approach proposed by Gliozzi and Grossi, 2008 and Grossi et al., 2008. Shannon-Wiener index has been calculated on the basis of the normalized matrix.

When possible, supplementary adult specimens of *C. agrigentina* were picked to increase the amount of material on which the morphometrical and geochemical analyses were performed. The morphometrical and geochemical analyses have been carried out on more than 3000 adult valves of *C. agrigentina*, and several thousand juvenile valves were added for Sr-analyses.

### *2.1 Morphometrical analyses*

All juvenile and adult valves of *C. agrigentina* were observed under the stereo-microscope to investigate the ornamentation and noding. Over one thousand adult female and male valves of *C.*

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*agrigentina* from fifty-three selected samples were measured under the stereo-microscope, using the Leica Application Suite 2.5.0. Mean values were calculated for each sample.

Around 20 adult female and male valves of *C. agrigentina* from fifty-three samples, chosen on the basis of its high frequency, were observed under the Scanning Electron Microscope (LIME Laboratory, Roma Tre University). Following the methodology proposed by Rosenfeld and Vesper (1977), the rounded, elongated and irregular sieve-pores were counted and each percentage was calculated. To obtain the inferred salinity value, the following transfer function elaborated by Frenzel et al. (2011), based on the percentage of rounded sieve-pores was used:

$$S= e^{-0.06RS+4.7}$$

where S = salinity (psu) and RS = percentage of rounded sieve-pores.

*2.2 Geochemical analyses*

*2.2.1 Stable isotopes*

Carbon and oxygen stable isotope analyses ($\delta^{13}C$ and $\delta^{18}O$) were performed on fifty-three ostracod samples each consisting of eight *C. agrigentina* clean adult valves. Two splits of each sample (4 valves each) were reacted with anhydrous phosphoric acid at 76ºC ± 2ºC in a Finnigan MAT Kiel preparation device directly coupled to the inlet of a Finnigan MAT 251 triple collector isotope ratio mass spectrometer (Stable Isotope Laboratory, University of Michigan, Ann Arbor, MI, USA). The isotopic results of the mean of the two splits are reported in permil (‰) notation relative to the Pee Dee Belemnite (PDB) standard. The measured precision for the analyses was 0.04 for $\delta^{13}C$ and 0.07 for $\delta^{18}O$.

*2.2.2 Trace elements*

Trace and minor element analyses together with Ca on fifty-three ostracod samples, consisting each in 6 to 10 clean adult valves of *C. agrigentina*, were performed by inductively coupled plasma atomic emission spectrometry (ICP-AES). The ostracod valves were dissolved in 3 ml of ultrapure $HNO_3$ acid (3%). The solutions were analysed for Ca (317.9 nm), Mg (285.2 nm), Na (589.5 nm) and Sr (215.2 nm) in the ICP-AES Thermo Jarrell IRIS Advantage Radial device of the Institute of Environmental Assessment and Water Research (IDAEA-CSIC, Barcelona, Spain). The limits of detection were 0.05 ppm for Ca and Mg, 0.01 ppm for Na and 0.005 ppm for Sr. All the analyses were run against multielemental standards prepared from Johnson Mattey™ stock solutions. The obtained results are expressed as metal/calcium ratios of the valves ($Me/Ca_v$).

*2.2.3 Sr isotope analyses*

Strontium isotope measurements were obtained from 26 suitable samples of hand-picked valves of *C. agrigentina*, perfectly preserved. About 10 mg of each sample was subjected to the following procedure: ultrasonic cleaning in double distilled water to remove impurities; gentle crushing and re-washing in double-distilled water; fast dissolution in 4.0 N ultrapure HCl; centrifugation; loading onto standard BIO-RAD AG50-X12cation exchange resin. The total procedure blank was 0.5 ng. Sr was collected in 2.9 and 6.3 N HCl and evaporated. Isotopic analyses were carried out at IGAG-CNR c/o Department of Earth Sciences, University of Rome - La Sapienza  using a FINNIGAN MAT 262RPQ multicollector mass spectrometer with Re double filaments in static mode. The internal precision (within-run precision) of the single analytical value is given as two standard error of the mean.  The $^{87}Sr/^{86}Sr$ ratios of the samples were normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194. The internal precision (within-run' precision) of a single analytical result is reported as 2 standard errors of the mean (2SE) and is obtained as the mean of more than 800–1000 ratios collected in each sample with a stable beam of > 2.0 V. Repeated analyses of NIST-987 during the period of the analyses gave a mean value $^{87}Sr/^{86}Sr = 0.710251 \pm 15$ ($2\sigma$, $n = 15$).

*2.2.4 Natural Radioactivity (NRD)*

Natural Radioactivity (NRD) was measured on 27 bulk sediment samples. Uranium, thorium and potassium were determined by high resolution gamma spectrometry using a low background (GEM-EG&G ORTEC) HPGe coaxial detector in a PopTop capsule including detector element, preamplifier and high voltage filter at the Institute of Environmental Geology and Geoengineering (IGAG, CNR, Rome - Italy). The multichannel buffer (16,384 channels, Ethernim-ORTEC 919E), including ADC with extended live time correction, was connected into an Ethernet environment under Windows XP and its control and spectral display was achieved by the use of MAESTRO application software. In particular, $^{232}$Th and K were estimated from 583 keV ($^{208}$Tl) and 1461 keV ($^{40}$K) peaks, while $^{238}$U was estimated by the weighted average of U1 and U2, where U1 is the product of the known $^{238}$U/$^{235}$U natural activity ratio by the $^{235}$U activity (calculated by the 186 keV peak corrected by the $^{226}$Ra contribution) and U2 is the $^{238}$U activity estimated by the 352 keV peak ($^{214}$Pb) assuming full equilibrium in the $^{238}$U radioactive series. Capo di Bove leucitite (Voltaggio et al., 2004) was used as standard, while counting time and amount of each sample were, respectively, 86,400 sec and 150 grams.

*2.3 Statistical analyses*

A raw matrix of data was constructed taking into account those samples that provided all the results for the considered types of analyses (9 variables): stratigraphic position, $\delta^{13}$C, $\delta^{18}$O, Mg/Ca$_v$, Sr/Ca$_v$, Na/Ca$_v$, Th/U, assumed salinity after the sieve-pore analysis and the $^{87}$Sr/$^{86}$Sr ratio. The statistical software used was STATISTICA 7.0. From the raw matrix, with 9 variables and 20 cases (samples), a correlation matrix was obtained. Moreover from the raw matrix, a set of multivariate analysis techniques, as cluster and principal-component analysis (PCA) was applied. Cluster analysis defines groups of more or less related variables and the corresponding dendrogram (tree clustering) corresponds to the graphic display of the groups. PCA defines eigenvectors showing the position of the variables in the factor plane and revealing the underlying structure of the data set.

## 3. The Eraclea Minoa section and its palaeoenvironments inferred from ostracod assemblages

The ca. 266 m-thick Messinian Lago-Mare succession of Eraclea Minoa crops out along the south-western coast of Sicily (lat. 37˚23'30"N, long. 13˚16'50"E) along the cliff which borders the village (Fig. 2). The section has been extensively studied since 1971 (Decima and Wezel, 1971) because it is one of the most complete Messinian Lago-Mare section of the Palaeomediterranean where several gypsum levels referred to the Upper Gypsum Unit crop out (among the most recent papers: Schreiber, 1997; Caruso and Rouchy, 2006; Van der Laan et al., 2006; Manzi et al., 2009 with references therein), and because it represents the GSSP of the Messinian/Zanclean boundary (Van Couvering et al., 2000 with references therein) (Fig. 3).

The succession is made of a rhythmic alternation of clays and marls interbedded with sandy and fine grained carbonates and seven gypsum bodies made by multiple strata of finely-laminated gypsum and gypsarenites/selenites (Fig. 4). The astrochronological tuning of the Eraclea Minoa section is different according to several authors. As stated by Caruso and Rouchy (2006), six sedimentary cycles covered by the Arenazzolo Fm. up to the Messinian/Zanclean boundary are recognizable, with a possible seventh basal cycle represented by an intensively deformed gypsum deposit located along the fault contact at the base of the succession. Van der Laan et al. (2006) consider the presence of seven cycles and a half, including the Arenazzolo Fm. They are linked to the precessional cyclicity and date the deposition of the Eraclea Minoa succession between 5.508 Ma to 5.332 Ma. Finally, Manzi et al. (2009; 2012) hypothesize the presence of nine to ten sedimentary cycles, including the Arenazzolo Fm., bracketing the depositional age between 5.53 and 5.33 Ma.

Ostracods are discontinuously present at the base of the section, in the marls intercalated between the lowest six gypsum bodies and become abundant in the upper portion, below and above the seventh gypsum level. Assemblages show variable richness from 1 species (monotypic assemblages made only by *C. agrigentina*) up to 13 species mainly made by the typical Lago-Mare ostracod assemblages of Paratethyan origin.

In the lowest portion from 88 (sample EM 3-3) to 144 m (sample EM 6-7), *C. agrigentina* is scarce and the assemblages, made by *Loxoconcha muelleri* (Méhes), *L. kocki* Méhes, *L. eichwaldi* Livental, *Loxocorniculina djafarovi* (Schneider), *Loxocauda limata* (Schneider), *Camptocypria* sp. 1, *Tyrrhenocythere pontica* (Livental), *Euxinocythere* (*Maeotocythere*) *praebaquana* (Livental), *Amnicythere propinqua* (Livental), *A. subcaspia* (Livental), *A. multituberculata* (Livental) and *A. accicularia* Olteanu, are rather diversified. These assemblages can be referred to the "*Cyprideis*-Loxoconchidae assemblage" (*sensu* Grossi et al., 2008), suggesting low mesohaline and shallow waterbodies (supposed salinities <10 psu).

Monotypic assemblages have been recovered in the central portion of the Eraclea Minoa section, from 153 m (sample EM 6'-1) to 227 m (sample EM 7-12) and the collected valves are abundant and well preserved. In this long interval, *C. agrigentina* is the only species present in the samples or is accompanied by the euryhaline benthic foraminifer *Ammonia tepida* (Cushman). Grossi and Gennari (2008) defined the "*Cyprideis-Ammonia* assemblage" for some ostracod and forams associations recovered in the Lago-Mare borehole of Montepetra (northern Apennines, Italy) in which, together with *C. agrigentina* and *A. tepida,* also other benthic foraminifers, *Florilus boueanum* (d'Orbigny) and *Elphidium* spp. were seldom present or *A. tepida* was the dominant species of the assemblage. The authors related such "*Cyprideis-Ammonia* assemblage" to high mesohaline to hyperhaline shallow waterbody. At Eraclea Minoa no other brackish benthic foraminifers have been recovered except *A. tepida*. Moreover, this latter species is not always present and generally is far subordinated to *C. agrigentina*. Thus, the palaeoenvironmental interpretation of the interval from 153 to 227 m at Eraclea Minoa could be slightly different. At the moment, we can suppose for this new "*Cyprideis* assemblage" a relatively high salinity waterbody and/or a dysoxic bottom, based on the capability of the living species *C. torosa* and *Ammonia* spp. to withstand low oxygen contents (Jahn et al., 1996; Bernhard and Sen Gupta, 2002). Different assemblages, made only by scarce *C. agrigentina* and accompanying *Loxoconcha muelleri* were

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recovered in the Lago-Mare succession of Colle di Votta (Majella Mt., central Italy) (unpublished data), in oxygen-depleted sediments (Sampalmieri et al., 2010).

In this central portion of the succession there are only five scattered samples in which the dominant *C. agrigentina* is associated with few other species: with *L. djafarovi* (at 182 m, sample EM 6’-29a), pointing to a low mesohaline environment; with *Ilyocypris* sp. (at 198.5 and 201.0 m, respectively samples EM 6”-8 and 6”-11), suggesting two short oligohaline episodes; with *Fabaeformiscandona* sp. (at 213 m, EM 6”-19) pointing to a further oligohaline episode; with *A. accicularia* (at 220.6 m, EM 7-4) indicating a low mesohaline short interval.

Finally, in the uppermost part of the section [from 228 m (sample EM 7-13) to 265.5 m (sample EM 8-20)], *C. agrigentina* is again accompanied by the Paratethyan assemblage in which Loxoconchidae are slightly less abundant and two more leptocytherid species are included, even if with scarce frequency: *Amnicythere litica* (Livental) and *A. costata* (Olteanu). On the whole, this topmost interval seems again to be referable to the “*Cyprideis*-Loxoconchidae assemblage” (Grossi et al., 2008), pointing to shallow waterbodies with supposed salinities <10 psu. Within this uppermost interval, it is possible to identify three horizons [from 228 m (sample EM 7-13) to 232 m (sample EM 7-19), at 234 m (sample EM 7-21) and from 235 m (sample EM 7-25) to 238 m (sample EM 7-28)] in which *C. agrigentina* shares its dominance only with two candonids species, *Fabaeformiscandona* sp. and *Cypria* sp., testifying an oligohaline and shallow environment, and two short levels [at 252.8 m (sample EM 8-3) and 257.8 m (sample EM 8-7)] in which *C. agrigentina* is again the only ostracod species of the assemblage.

## 4. Geochemical analyses and inferred palaeoenvironmental features

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### *4.1 Stable isotopes*

*C. agrigentina* calcite valves display a wide range of stable isotopic values. $\delta^{13}$C ranges from –6.40 to 1.91‰; $\delta^{18}$O ranges from -4.08 to 7.95‰ (Tab. 1; Figs. 5, 6). The $\delta^{13}$C values of the ostracod valves show a slight increase from 153-189 m (interval A) to 198-225 m (interval B). Significant, rapid variations are shown around 198-204 m and in the upper portion of the section around 253-260 m (interval E).

The $\delta^{18}$O values of the ostracod valves show a slight increase from 153 to 189 m (interval A), a rapid variation around 198-204 m (lower interval B), and decrease from 204 to 225 m (upper interval B). In the upper portion of the section, from 257.8 to 258.5 m (interval E), a significant decrease in $\delta^{18}$O values, from 8‰ to -1.4‰ is observed.

The $\delta^{13}$C and $\delta^{18}$O values from 153 to 189 m (interval A) display small fluctuations, suggesting minor variations in the palaeohydrological conditions. On the contrary, the valves from 198-204 m (interval B) and 253-260 m (interval E) display significant oscillations, both in $\delta^{13}$C and $\delta^{18}$O values, suggesting instabilities in the palaeohydrological conditions related to these intervals. In both cases the larger instabilities (major $\delta^{13}$C and $\delta^{18}$O oscillations) may be linked to significant detrital and freshwater inputs as reflected by the coarse-grained detrital beds at 199 m and 256-264.5 m.

The distribution in a X-Y plot (Fig. 6) shows that the isotopic values from 153 to 216 m (interval A and lower B) display a negative covariant trend with a significant correlation (R=-0.894). This is mainly due to the negative correlation of the interval 198-216 m (lower B, R=-0.903) and the almost invariant values in the interval 153-189 m (interval A).

*4.2 Trace elements*

For *C. agrigentina* calcite valves, the Mg, Sr and Na content expressed as $Mg/Ca_v$, $Sr/Ca_v$ and $Na/Ca_v$ molar ratios are listed in Table 1 and represented in Fig. 5. The $Mg/Ca_v$ values range from 0.0052 to 0.0158, the $Sr/Ca_v$ range from 0.0022 to 0.0054 and the $Na/Ca_v$ from 0.0032 to 0.0046.

The Mg/Ca$_v$ values show a significant drop from 189 to 198.2 m (intervals A and B boundary) towards the upper portion of the succession, with a rapid variation around 153-156 m (lower interval A). An overall increase trend in Mg/Ca$_v$ is recorded in the interval 198.2-225 m (interval B) and a significant increase is observed also in the upper part of the section (interval E). This is parallelized with a similar increase in the $\delta^{13}C$ values.

The Na/Ca$_v$ values show a slight decrease from 153-189 m (interval A) to 198-216 m (interval B), with a rapid variation around 198.2-201 m. A significant decrease of Na/Ca$_v$ is observed in the upper portion of the section (interval B). This is parallelized with the decrease in Sr/Ca and $\delta^{18}O$ values.

*4.3 Sr isotopes*

Differently from the ratios of cation concentrations and oxygen isotopes, no Sr isotope fractionation occurs during chemical and biological processes within the marginal basin (Faure and Powell, 1972). Considering that Ostracoda are good monitors of the composition of the aquatic environment (De Deckker et al., 1988), the Sr isotopic composition of ostracod shells allow us to evaluate the connectivity of the basin with the open ocean and the paleoclimatic conditions and hydrography.

The Eraclea Minoa section shows that the $^{87}Sr/^{86}Sr$ values from the *C. agrigentina* valves are comprised between 0.708510 and 0.708729 (Table 1). The range of values is high in the lower analysed interval (153-189 m - interval A) and decreases in the portion comprised between 198 to 225 m (interval B), reaching the minimum values (0.708510 and 0.708511) in the interval 204.2-210 m (low interval B), in correspondence of low $\delta^{18}O$, Sr/Ca$_v$ and Na/Ca$_v$ values. In the upper portion of the section (253-260 m - interval E) the $^{87}Sr/^{86}Sr$ values rise again, with a maximum (0.708704) at 253 m (Fig. 5). Sr isotopic data of *C. agrigentina* are markedly different with respect to coeval global ocean values (Henderson et al., 1994; McArthur et al., 2001) being significantly lower than the marine waters at that time, but this is a common feature for latest Miocene–earliest Pliocene strontium values of the Palaeomediterranean Basin carbonates.

*4.4 Natural Radioactivity*

$^{232}$Th and K measured in bulk sediment samples are highly correlated (R=0.94) suggesting that $^{232}$Th is mainly contained in the detrital fraction. Detrital uranium, in turns, was calculated by the product of measured $^{232}$Th and the average $^{238}$U/$^{232}$Th weight ratio of pelagic sediments, considered close to 0.25 (Mangini et al., 2001). Finally, authigenic uranium, $^{238}U_a$, was estimated by subtracting the detrital $^{238}$U from measured $^{238}$U (Table 2). Authigenic uranium as well as the Th/U ratio was proposed by Wignall and Myers (1988) as an index of bottom-water oxygenation; the $U_a$ values trend to increase in a reducing environment, where uranium is immobile as tetravalent ion. According to Wignall (1994) $U_a$ values comprised between 2 and 10 are indicative of dysoxic environments; similarly for Th/U values, Th/U<<1 indicate anoxic conditions, Th/U>>1 indicate oxic conditions, while values in the range 1<Th/U>1 point to dysoxic conditions. Even if the use of authigenic uranium as proxy for reducing conditions is common in the chemiography of marine sediments (Pattan and Pearce, 2009), several authors have questioned the real preservation of the authigenic uranium signal by different processes as burn down, fast change of sedimentation rate and oxygen ventilation or bioturbation (Zheng et al., 2002). Therefore any indication of oxigen depletion suggested by the authigenic uranium has to be regarded in a wider fitting context.

$U_a$ from the bulk sediment display values from 0.3 to 9.5 ppm (Table 2). The lowest values are attained in intervals A, B and lower C, with figures generally below 2. In the upper part of interval C, $U_a$ increases and maintains high values in interval D and E, where some fluctuations occur, similarly to what observed for the stable isotopes and trace elements ratios (Fig. 5). A similar trend is observed for the Th/U ratios, which show values greater than 1 in intervals A, B and C, and values mainly around 1 in intervals D and E (Table 2).

*4.5 Palaeoenvironmental episodes inferred from the geochemical proxies*

The geochemical analyses performed on the valves of *C. agrigentina* and bulk sediment samples collected from the 96.5-260 m portion of the post-evaporitic Messinian succession of Eraclea Minoa confirm the frame of a Palaeomediterranean waterbody discontinuous and isolated, characterised by diluted waters after the evaporative phase of the Lower Gypsum Unit, the closure of the Atlantic-Palaeomediterranean connection and the subsequent global humid climate phase (Griffin, 2002; CIESM, 2008; Grossi et al., 2008). In fact, notwithstanding the well known saline character of the Palaeomediterranean waters, testified by the presence of brackish ostracod assemblages, all the geochemical indicators point to a clear differentiation with the Messinian oceanic seawater. On the other hand, the stable isotopes values reported in Figs. 5, 6 do not show the overall covariant trend that would correspond to a marginal marine environment or a closed waterbody (Talbot, 1990; Utrilla et al., 1998; Ligios et al., 2012), and also trace elements behave in a different manner. The Mg/$Ca_v$ values from *C. agrigentina* (0.0052-0.0152) are similar to most of the analyses from *Cyprideis* shells for the Messinian Lago-Mare horizons from DSDP sites (De Deckker et al., 1988). For these Mg/$Ca_v$ values, De Deckker et al. (1988) consider the host water had Mg/Ca values lesser than that of Messinian seawater, and in some cases similar to most of the Mg/Ca shown by freshwaters (Mg/Ca=1). The Sr/$Ca_v$ values from *C. agrigentina* at 153-189 m (0.0025-0.0030) are similar to most of the analyses from *Cyprideis* shells from the Messinian Lago-Mare horizons from DSDP sites (De Deckker et al., 1988). For these Sr/$Ca_v$ values, these authors consider the host water had Sr/Ca values lesser than that of Messinian oceanic seawater. On the contrary, the Sr/$Ca_v$ values for most of the samples from 198-225 m and 252.8-257.8 m (0.0038-0.0054) indicate that the host water frequently had Sr/Ca values greater than that of Messinian oceanic seawater. The values of Sr/$Ca_v$ and Mg/$Ca_v$ indicate that the waters where the Eraclea Minoa ostracods lived were very different than the Messinian seawater and there is no indication of connection with oceanic seawater. Furthermore, the $^{87}Sr/^{86}Sr$ range of values obtained from the analyses of *C. agrigentina* valves is consistent with the isotopic values of the Upper Gypsum Unit

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from Sicily and other localities of the Palaeomediterranean (Müller and Mueller, 1991; Keogh and Butler, 1999; Flecker and Ellam, 2006; Roveri et al., 2014b). This range is also similar to the range (0.708600-0.70875) reported from most ostracod valves (*Cyprideis*) from Messinian Lago-Mare deposits from several DSDP sites of the Palaeomediterranean studied by McCullock and De Deckker (1989). On the other hand, the Sr isotopic values from Eraclea Minoa are quite different from the value of the average ocean water during the deposition of the Upper Evaporite: 0.709012 (Howarth and McArthur, 1997; Flecker et al., 2002). The $^{87}Sr/^{86}Sr$ values of the Eraclea Minoa *C. agrigentina*, as is the case of materials from other post-evaporitic Messinian localities, confirm to be the result of a large influence of freshwater on the Sr isotopic composition of the desiccating subbasins of the Palaeomediterranean (Müller et al., 1990). Finally, it is noteworthy that isotopic ratios anomalously low could result from reworking of older marine evaporites, or diagenetic overprinting. However, according to Keogh and Butler (1999), the reworking of Sr from the older marine evaporites implies mixing in different proportion between Sr deriving from continental run-off and coming from ground water circulating inside the buried evaporites. Such a process likely produces high variability in both salinity and $^{87}Sr/^{86}Sr$ ratios.

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Based on the geochemical signature of *C. agrigentina* valves and bulk sediment samples, five main palaeoenvironmental intervals may be differentiated along the studied portion of the Eraclea Minoa succession (Fig. 5):

Interval A (153-189 m), characterised by high $\delta^{18}O$, $Na/Ca_v$, $Mg/Ca_v$ and $^{87}Sr/^{86}Sr$ values, and low $\delta^{13}C$, $Sr/Ca_v$, and $U_a$. This interval records relatively stable hydrochemical conditions as suggested by the small variation of each geochemical indicator, isotopically concentrated waters and high $Na/Ca_v$ and $Mg/Ca_v$ ratios that were attained after the deposition of the 6$^{th}$ gypsum level. An overall evaporative environment (Fig. 5) with moderate salinity could be inferred for this interval. The high amount of Th and detrital U, the low content of authigenic uranium and the rather high Th/U ratios (Table 2) record possible well oxygenated bottoms.

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Interval B (198-225 m), characterised by low $\delta^{18}O$, Na/Ca$_v$, Mg/Ca$_v$, $^{87}Sr/^{86}Sr$, and $U_a$ values, and high $\delta^{13}C$ and Sr/Ca$_v$. A major change is recorded at the base of this interval (198 m, sample EM 6”-8) where large shifts in all the geochemical indicators appear. A possible explanation for these features is to consider the noticeable detrital and freshwater inputs that increase the Ca dissolution, recorded both by the coarser lithologies, the high values of Th and detrital U and the low $^{87}Sr/^{86}Sr$ values for most samples. Those inputs may explain the lowering of $\delta^{18}O$ in the valves, the increase of Sr/Ca$_v$ (recording Sr inputs from the $CaSO_4$-rich subsurface waters) and the lowering in Mg/Ca$_v$ because of the high increase in Ca in the waterbody. The increase in $\delta^{13}C$ values could be produced by an increase in the productivity, linked to the detrital and nutrient inputs and a trend to re-equilibration with the atmospheric $CO_2$ (Fig. 5). As in the previous interval, NRD results (Table 2) testify for possible well oxygenated bottoms.

Interval C (225-240 m). In this interval, only NRD analyses have been performed due to the low frequency of *C. agrigentina* in the ostracod assemblages that prevented the possibility to reach the suitable amount of biogenic carbonate for the analyses. The content of authigenic uranium in the upper part of this interval, higher than in the previous one, (Table 2, Fig. 5) points to possibly progressively less oxygenated bottoms.

Interval D (240-242 m). This short interval is characterised by the highest values of authigenic U and low values of the Th/U ratios, suggesting possble dysoxic conditions at the bottom.

Interval E (252.8-259.1 m). In this interval two portions may be differentiated and a main change is recorded from the lower samples to the upper ones. The lower samples are characterised by high $\delta^{18}O$, Sr/Ca$_v$, Na/Ca$_v$, and $^{87}Sr/^{86}Sr$ values, and low $\delta^{13}C$ and Mg/Ca$_v$ values. The low content of authigenic uranium indicates possibly oxygenated bottoms. The upper samples are characterised by the opposite trend. The geochemical features of the ostracod valves from the lower part may be explained by the evaporitic concentration of the waterbody (Figs. 5, 6) leading to high

$\delta^{18}O$, $Sr/Ca_v$ and $Na/Ca_v$ values. A subsequent large input of freshwater produced the lowering of $\delta^{18}O$, $Sr/Ca_v$ and $Na/Ca_v$. At present, we have no explanation for the variations of the $Mg/Ca_v$ values in this interval. It is worth to note the high content of authigenic uranium that reaches in one sample the value of 9.5 ppm, possibly indicating dysoxic conditions at the bottom.

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**5. Morphometrical analyses on *Cyprideis agrigentina* valves**

Length and height of one thousand-sixty valves of adult males and females were measured. The obtained values fall within the variability field typical of the species (Decima, 1964; Ligios et al., 2012). The mean values of the length of the female left valve (the most numerous in the measured samples) have been compared. Generally the mean values of the length vary from 0.96 to 1.00 mm, but in few samples the mean values are rather small: at 185 m (sample EM 6”-3, mean value 0.90 mm), 201 m (EM 6”-11, mean value 0.89 mm), 222 m (EM 7-6, mean value 0.85 mm), and 223.5 m (EM 7-8, mean value 0.88 mm) (Fig. 7). Only in four samples the mean values of the length result significantly high: at 165 m (sample EM 6’-12 mean value 1.05 mm), 176.2 m (EM 6’-24, mean value 1.06 mm), 180 m (EM 6’-27, mean value 1.04 mm), and 210 m (EM 6”-17, mean value 1.14 mm).

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The several thousands specimens of *C. agrigentina* investigated for the ornamentation and noding, showed rather homogeneous ornamentation: no noded specimens have been observed all along the section among both juveniles and adults; almost all valves were smooth (at least some of them showed few small pits in the posterior surface); only two samples (EM 6”-7 at 189.0 m and EM 6”-20 at 216.0 m) showed, respectively, the 54.2% and 54.6% of valves pitted on the entire surface (Fig. 7).

The analysis of the percentage of the sieve-pore shape was carried out on fifty-three samples from the middle and upper portion of the section, where *C. agrigentina* was more abundant, making both monospecific and diversified assemblages. On average, more than 500 sieve-pores were observed for each sample and counted on the basis of their shape: rounded, elongated, irregular, following the indications by Rosenfeld and Vesper (1977). The results are reported in Fig. 7. In most cases, the percentages of the rounded sieve-pores are comprised between 40 and 50%; in twelve scattered samples they are higher, reaching the maximum value of 65% at 96.5 m (sample EM 4-7) and only in a short interval from 198.5 m (sample EM 6”-8) to 216 m (sample EM 6”-20) they are lower, comprised between 19 and 30%, reaching their minimum values (19-21%) in the interval 204.5-216 m. Applying the transfer function elaborated by Frenzel et al. (2011) for *C. torosa,* the resulting salinities expressed in psu shows values included in the mesohaline range (5-18 psu, Venice Symposium, 1958) for most samples. Only few scattered samples in the lower and upper portions of the section point to the oligohaline range (0.5-5 psu), while higher salinities (polyhaline to euhaline ranges, 18-40 psu) are recorded only in a limited portion of the section, from 198.5 to 216 m (Fig. 8).

## 6. Discussion

As explained in the introduction, the living species *C. torosa* is considered to be one of the most valuable tools to detect past salinities in the marginal marine environments, owing to its environmentally cued polymorphism that induces variations in size, noding and sieve-pore shapes depending on salinity. Large sizes, presence of nodes and high percentages (around 40-45%) of rounded sieve-pores point to salinity less than 8-9 psu that is considered an important osmoregulation threshold for the species (Keiser and Aladin, 2004; Keyser, 2005).

It is not clear when *Cyprideis torosa* appeared for the first time, owing to the difficulty to identify the species. Often in the Neogene sediments *Cyprideis* remains have been recorded as *Cyprideis* gr. *torosa* or *Cyprideis* sp. (Bossio et al., 1993; 1996; Testa, 1995). According to Decima (1964) and Ligios and Gliozzi (2012) the species is the only survivor of a stem that started in the Palaeomediterranean area with *Cyprideis ruggierii* Decima (late Tortonian-early Messinian), including *Cyprideis agrigentina* Decima (post-evaporitic Messinian) and *Cyprideis crotonensis* Decima (post-evaporitic Messinian-Late Pliocene). The great morphological similarity of the species of the stem lead some authors to suppose that the same environmentally cued polymorphism displayed by *C. torosa* could affect also its relatives (Neale, 1988), notwithstanding no noded specimens of the other species had never been recorded. Thus, Rosenfeld (1977) and Bonaduce and Sgarrella (1999) inferred hyperhaline post-evaporitic Messinian environments respectively for the Mavqi'im Formation (Israel) and at Eraclea Minoa, applying on *C. agrigentina* valves the empirical methods of the percentage of the rounded sieve-pores elaborated by Rosenfeld and Vesper (1977) on *C. torosa*.

As a first step to investigate whether *C. agrigentina* shared with *C. torosa* the same ecophenotypical behavior, we have analyzed size, ornamentation and sieve-pore shapes on some thousand of specimens from the post-evaporitic Messinian section of Eraclea Minoa. The expected results, in case of a comparable behavior, is a positive correlation between large size, noding (or strongly pitted valve surface), and high percentages of rounded sieve-pores. Fig. 7 shows that this correlation lacks: the largest sizes (thus the supposed lowest salinities, below 8-9 psu) are attained by specimens recovered in samples bearing smooth valves (supposed high salinities) and percentages of rounded sieve-pores less than 40% (above the 8-9 psu threshold). In particular, in sample EM 6"-17 (at 210 m) the largest *C. agrigentina* valves matches with one of the lowest percentages of rounded sieve-pores (22,7%); the smallest sizes (supposed high salinities) correlates with smooth valve surfaces (supposed high salinities) but to percentages of rounded sieve-pores greater than 40% except in one case (sample EM 6"-11 at 201 m) in which the percentage is low (23.1%); the only two samples in which *C. agrigentina* valves are densely pitted (supposed low salinities), corresponds, on average, to intermediate dimensions and high percentage values.

From those comparisons it is possible to conclude that size and ornamentation/noding in *C. agrigentina* are not correlated. In particular, pitted ornamentation and noding seem to be, respectively, very rare and totally absent in *C. agrigentina*, despite the species seems to be strongly euryhaline as it is its living relative (Ligios and Gliozzi, 2012). Thus, it seems that those characters do not display in *C. agrigentina* the same salinity-dependant polymorphism of *C. torosa*.

A further question is to investigate whether the percentage variations of the sieve-pore shapes are correlated with salinity variations as in *C. torosa*. To test this hypothesis we have based the comparisons of the salinity curve obtained applying the transfer function elaborated by Frenzel et al. (2011) with the salinity inferred by the synecological analysis and with the palaeohydrological variations inferred by the geochemical analyses (Figs. 8, 9, 10).

Based on the synecological analysis and the Shannon-Wiener diversity curve, it is possible to observe that the "*Cyprideis* assemblage", correlatable with the minimum diversity values (monotypic ostracod assemblages) corresponds to different inferred salinities: oligo-low mesohaline in the intervals 153-171, 218-225 and 253-257.8 m; high mesohaline from 174 to 189 m; polyhaline-euhaline from 198.5 to 216.5 m. Moreover, it is worth to note that the two oligohaline levels with *Cyprideis* and *Ilyocypris*, included in the "*Cyprideis*" long interval at 198.5 and 201 m, according to the salinity curve based on sieve-pore percentage should have deposited in polyhaline/euhaline waters. We should conclude that there is no correspondence between the salinities inferred by the method of the sieve-pore percentages and the synecological palaeoenvironmental interpretation. This conclusion contradicts the statement by Bonaduce and Sgarrella (1999) who, on the basis of the percentage of sieve-pore shapes, inferred for the Eraclea Minoa portion of succession with monospecific *Cyprideis* assemblage hyperhaline environments (50-70 psu). Probably their conclusions are affected by the very few analyzed samples along the succession (only two) and the scarcity of counted sieve-pores for each sample (respectively 74 and 161).

The calculation of past salinities from the results of the geochemical analyses on the valves of *C. agrigentina* is difficult to assess. Although $Na/Ca_v$ could be tentatively perceived as a proxy of the salinity (assuming salinity dominated by NaCl solute), the obtained data must be considered with caution because of the poor knowledge of the Na uptake in the ostracod calcite shell (Holmes and De Deckker, 2012). However, recent attempts to use Na/Ca ratios from ostracod valves for palaeoenvironmental reconstructions must be taken into account (Gouramanis et al., 2010;

Devriendt, 2011). On the other hand, Sr/Ca and Mg/Ca from ostracod valves just may inform about the Sr/Ca and Mg/Ca of the waters (De Deckker et al., 1999; Dettman and Dwyer, 2012; Holmes and De Deckker, 2012), and only in some cases (i.e. some estuarine environments) these ratios could correlate with the salinity of the waters. On the other hand, $\delta^{18}O$ variations in closed non-marine environments are linked usually to evaporation/precipitation processes (Talbot, 1990), that in some cases are associated to salinity variations. Anyway, the decreasing $Na/Ca_v$ ratios from Interval A to Interval B (Fig. 5) is consistent with the interpretation of more diluted waters in this latter interval, as pointed by the low $\delta^{18}O$ values in B. However, this is in contradiction with the higher salinity assumed for interval B than for interval A based on the sieve-pore analysis of *C. agrigentina* (Fig. 8).

We have tried to test the correlation between the geochemical results and the salinities assumed from the analysis of the sieve-pore percentages using a multivariate approach. The correlation matrix obtained for nine variables is shown in Table 3. Significant correlations ($p<0.01$) are displayed only by the pairs $\delta^{18}O$ and $Na/Ca_v$, $Na/Ca_v$ and $Mg/Ca_v$, $Sr/Ca_v$ and stratigraphic position. Significant negative correlations are shown by $\delta^{13}C$ and $Na/Ca_v$, $\delta^{13}C$ and $\delta^{18}O$, $\delta^{13}C$ and $Mg/Ca_v$, $Mg/Ca_v$ and $Sr/Ca_v$. In fact salinity assumed from sieve-pore analysis (N pores), and Sr isotopic ratios of the valves do not show significant correlation with any of the other considered variables.

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Principal Component Analysis (PCA) delineates similar patterns. About 34.92% of the total variance is explained by the first eigenvector (Fig. 9), which is tied to concentration-evaporation processes, indicated by the relations among $\delta^{18}O$, $Na/Ca_v$, $Mg/Ca_v$, Th/U and $^{87}Sr/^{86}Sr$ in the positive field. This factor is related to the precipitation/evaporation balance and residence time and probably to the resedimentation of evaporites. Inputs of oxygenated, $SO_4$-rich solutions would lead to lowering of $\delta^{18}O$, $Na/Ca_v$, $Mg/Ca_v$ and $^{87}Sr/^{86}Sr$. On the negative field, the variables are $Sr/Ca_v$, the stratigraphic position and the percentages of rounded sieve-pores that are linked to DIC

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(Dissolved Inorganic Carbon) changes. On the other hand, factor 2 that accounts for 20.72% of the variance, in the positive area contains a group formed by $\delta^{18}O$, $Sr/Ca_v$, stratigraphic position and $NaCa_v$, whereas in the negative area a group formed by N pores, $\delta^{13}C$, Th/U and $Mg/Ca_v$ exists. Factor 2 probably is linked to detrital, freshwater and nutrient inputs related to the environmental evolution.

Results from the cluster analysis reveal several groups (Fig. 10). One of the groups shown by the dendrogram reflects the relationship between $\delta^{18}O$ and $Na/Ca_v$ revealing the control of the $Na/Ca_v$ exerted by the P/E balance ($\delta^{18}O$). They are associated with $Mg/Ca_v$, Th/U, and Sr isotopic ratios in the ostracod valve that, into a lesser extent, seem also to be influenced by the P/E balance. The pair $Sr/Ca_v$-position of the sample is associated to the pair $\delta^{13}C$-percentage of rounded sieve-pores. This pair reveals the link between DIC changes and the changes in sieve-pore shapes.

It is worth to note that, although some authors consider both the $U_a$ and Th/U values as good proxies to detect past oxic/dysoxic conditions (Adams and Weawer, 1958; Wignall and Myers, 1988 ; Wignall, 1994; Jones and Manning, 1994), Wignall and Meyers (1988) suggest to couple the $U_a$ results with the Shannon-Weaver dominance-diversity index (H) since, under low-oxygen conditions, assemblages are dominated by a few eurytopic forms, and values of H are typically low. If we compare the H-index curve (Fig. 8) with the oxygen availability at the bottom derived from the $U_a$ curve of Fig. 5, we notice that they are contradictory: when $U_a$ values are high (comprised between 2 and 10 and indicate possible dysoxic bottoms) the H-index values are high (rather well diversified assemblages). This negative correlation suggest, as supposed by Zheng et al. (2002) that the accumulation of $U_a$ in sediments could due also to physico-chemical variables other than the oxygen availability.

The results of the statistical analyses underline that there is no significant relationship between the salinity assumed from the sieve-pore analyses on the valves of *C. agrigentina* and the variables linked to the hydrochemical changes ($\delta^{18}O$, $Na/Ca_v$ and $Mg/Ca_v$, i.e. the salinity changes).

On the other hand, the number of rounded sieve pores in C. *agrigentina* seems to be mainly linked to $\delta^{13}C$ (DIC-cycling of C).

In conclusion, this puzzly set of data does not confirm that the percentages variation of the sieve-pore shapes in *C. agrigentina* is a reliable salinity indicator for the Lago-Mare episode of the Messinian Salinity Crisis. On the other hand, the complexity of the hydrochemical evolution due to the re-sedimentation of the Upper Gypsum Unit and scattered inputs of detrital materials and meteoric waters accounts for a complex palaeohydrological and palaeohydrochemical scenario in which it seems that the factor responsible for the changes in the shape of the pores in the valves of *C. agrigentina* could be the behaviour of the DIC and the oxygen availability.

On the other hand, the geochemical data give a negative response to the hypothesis that the "*Cyprideis* assemblage" could be related to dysoxia at the bottom. Data from the percentage of the authigenic U, Th/U ratios indicate that some accumulation of $U_a$ occurred at the bottom of the Eraclea Minoa waterbody, but it seems that they were not so important to affect the benthic ostracod assemblages.

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Although it is beyond the aim of this paper, in order to try to understand the palaeoenvironmental meaning of the "*Cyprideis* assemblage" we have tried to extend our investigations comparing other Lago-Mare successions of the Mediterranean area that included monotypic *C. agrigentina* assemblages. In the first case, such assemblage, represented by very scarce specimens, has been recovered in the lower portion of the Lago-Mare succession of the Adana Basin (Turkey) during the deposition of resedimented evaporites and marls, where a very high sedimentation rate was recorded (Faranda et al., 2013). The authors linked the low diversity and the scattered distribution of the ostracod assemblage of the Adana Basin to the high siliciclastic input connected with the high subsidence rate that affected the Adana Basin during the Lago-Mare phase. At Eraclea Minoa the "*Cyprideis* assemblage" is present with high frequencies and continuously recovered along the entire interval, but it is rather confined to the thick marly-sandy succession included between gypsum bodies 6 and 7. If we hypothesize that this portion of succession represents one precessional cycle, as supposed by Van der Laan et al. (2006), high sedimentation rates affected both Adana (12.5 mm/yr) (Radeff et al., submitted) and Eraclea Minoa (4.3 mm/yr) successions. Similar stratigraphical, sedimentological and paleontological conditions have been found also in the lower portion of the Lago-Mare succession cropping out in the Iraklion Basin (central Crete) (unpublished data). Unfortunately, not everywhere high sedimentation rates and siliciclastic inputs support only the "*Cyprideis* assemblage": in the Mondragone 1 well (Garigliano Plain, Campania, southern Italy) around one-thousand meters of sediments deposited within the short temporal frame of the *Loxocorniculina djafarovi* zone (5.40-5.33 Ma), thus a very high sedimentation rate above 13 mm/yr was calculated, but the recovered Lago-Mare ostracod assemblages were highly diversified (Cosentino et al., 2006).

In conclusion, at the moment no plausible hypothesis can be arised on the palaeoenvironmental meaning of the "*Cyprideis* assemblage", once again stressing the peculiar and complex geological and palaeoenvironmental history of the Eraclea Minoa succession.

## 7. Conclusion

The ostracod assemblages of the post-evaporitic Messinian section of Eraclea Minoa (Sicily) have been studied in a palaeoenvironmental perspective to decipher the environmental changes verified during the deposition of the Upper Gypsum Unit. Rich and diversified assemblages made mainly by Paratethyan species, have been recovered in the lower and upper portion of the succession, pointing to shallow and low mesohaline waterbodies. In the central portion of the succession, very abundant monospecific assemblages made only by *C. agrigentina* were recognized, suggesting high mesohaline to hyperhaline shallow waterbody with low oxygen content. To test this latter interpretation, morphometric and geochemical analyses (stable isotopes, trace elements, $^{87}Sr/^{86}Sr$, and NRD) have been performed on ostracod valves and bulk sediment samples in order to verify if *C. agrigentina* ecophenotypical behavior was comparable with that of the living species *C. torosa*.

The results have shown that:

1) *C. agrigentina* sizes and ornamentations are not affected by salinity variations;
2) The percentages of sieve-pore shapes do not depend from the water salinity, as in *C. torosa*, but seem linked to the behavior of the DIC and the oxygen availability at the bottom.

Thus, it is possible to conclude that *C. agrigentina* cannot be considered as a palaeosalinometer for the Messinian Salinity Crisis.

Furthermore, the geochemical analyses have shown that the deposition of the Eraclea Minoa succession occurred in a complex palaeohydrological and palaeohydrochemical scenario.

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REFERENCES

Adams J.A. & Weaver C.E., 1958. Thorium-uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies. Bulletin American Association of Petroleum Geologists 42(2), 387-430.

Aladin, N.V., 1993. Salinity tolerance, morphology and physiology of the osmoregulation organs in Ostracoda with special reference to Ostracoda from the Aral Sea. In Jones, P. and McKenzie K. (Eds.), Ostracoda in Earth and Life Sciences, A.A. Balkema, Rotterdam, 387-404.

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Anadón, P., Gliozzi, E., Mazzini, I., 2002. Paleoenvironmental reconstruction of marginal marine environments from combined paleoecological and geochemical analyses on Ostracods. In: Holmes, J., Chivas, A. (Eds), The Ostracoda: Applications in Quaternary Research, Geophysical Monograph 131, 227–247.

Barbieri, M., Carrara, C., Castorina, F., Dai Pra, G., Esu, D., Gliozzi, E., Paganin, G., Sadori, L., 1999. Multidisciplinary study of Middle-Upper Pleistocene deposits in a core from the Piana Pontina (central Italy). Giornale di Geologia 61, 47–73.

Benson, R.H., 1978. The paleoecology of the ostracodes of DSDP Leg 42A. In: Initial Reports of the Deep Sea Drilling Project 42, 777–787, U.S. Government Printing Office, Washington, D.C.

Bernhard, J.M, Sen Gupta, B.K., 2002. Foraminifera of oxygen-depleted environment. In: Sen Gupta, B.K. (Ed.), Modern Foraminifera. Kluwer Academic Publishers, 201-216.

Bonaduce, G., Sgarrella, F., 1999. Paleoecological interpretation of the latest Messinian sediments from southern Sicily (Italy). Memorie della Società Geologica Italiana 54, 83–91.

Boomer, I., Frenzel, P., 2011. Possible environmental and biological controls on carapace size in *Cyprideis torosa* (Jones, 1850). Joannea Geologie und Paläontologie 11, 26–27.

Bossio, A., Costantini, A., Lazzarotto, A., Liotta, D., Mazzanti, R., Mazzei, R., Salvatorini, G., Sandrelli, F., 1993. Rassegna delle conoscenze sulla stratigrafia del Neoautoctono toscano. Memorie della Società Geologica Italiana 49, 17–98.

Bossio, A., Cerri, R., Mazzei, R., Salvatorini, G., Sandrelli, F., 1996. Geologia dell'area Spicchiaiola-Pignano (Settore orientale del Bacino di Volterra). Bollettino della Società Geologica Italiana 115, 393-422.

Carbonel, P., 1982. Les Ostracodes, traceurs des variations hydrologiques dans des systèmes de transition eaux douces-eaux salées. Mémoirs de la Societé géologique de France 8(144), 117–128.

Caruso, A., Rouchy, J.-M., 2006. The Upper Gypsum Unit. In: Roveri, M., Manzi, V., Lugli, S., Schreiber, B.C., Caruso, A., Rouchy, J.-M., Iaccarino, S.M., Gennari, R., Vitale, F.P., Ricci Lucchi, F. (Eds.), Clastic vs. primary precipitated evaporites in the Messinian Sicilian basins. Acta Naturalia de "L'Ateneo Parmense" 42(4), 157-159.

CIESM (Commission Internationale pour l'Exploration de la Mer Méditerranée, Monaco), 2008. The Messinian Salinity Crisis from Mega-Deposits to Microbiology: A Consensus Report. CIESM Workshop Monograph 33, 1-168.

Cosentino, D., Bertini, A., Cipollari, P., Florindo, F., Gliozzi, E., Grossi, F., Lo Mastro, S., Sprovieri, M., 2012. Orbitally-forced palaeoenvironmental and palaeoclimate changes in the late post-evaporitic Messinian stage of the central Mediterranean Basin. Geological Society of America Bulletin 124(3-4), 499-516.

Cosentino, D., Federici, I., Cipollari, P., Gliozzi, E., 2006. Environments and tectonic instability in central Italy (Garigliano Basin) during the late Messinian *Lago-Mare* episode: New data from the onshore Mondragone well (Garigliano Plain, central Italy). Sedimentary Geology 188-189, 293-317.

Curry, B., Mesquita-Joanes, F., Fanta, S., Sterner, D., Calò, C., Tinner, W., 2013. Two coastal sinkhole lakes in SW Sicily (Italy) reveal low-salinity excursion during Greek and Roman occupation. Naturalista Siciliano 4, 37(1), 93-95.

De Deckker, P., Chivas, A.R., Shelley, J.M.G., 1988. Paleoenvironment of the Messinian Mediterranean "Lago Mare" from strontium and magnesium in ostracode shells. Palaios, 3, 352-358.

De Deckker, P., Chivas, A.R., Shelley, J.M.G., 1999. Uptake of Mg and Sr in the euryhaline ostracod *Cyprideis* determined from in vitro experiments. Palaeogeography, Palaeoclimatology, Palaeoecology 148, 105–116.

Decima, A., 1964. Ostracodi del genere *Cyprideis* Jones del Neogene e del Quaternario italiani. Palaeontographia Italica, 57(1962), 81-133.

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Decima, A., Wezel, F.C., 1971. Osservazioni sulle evaporiti messiniane della Sicilia centro-meridionale. Rivista mineraria siciliana 130-132, 172-187.

Dettman, D.L., Dwyer, G.S., 2012. Biological and environmental controls on ostracod shell trace-element chemistry. In: D. J. Horne, J. Holmes, J. Rodriguez-Lazaro and F. Viehberg (Eds.). Ostracoda as proxies for Quaternary climate change. Developments in Quaternary Sciences. Elsevier, v. 17, 145-163.

Devriendt, L.S.J., 2011. Late Quaternary environment of paleolake Carpentaria inferred from the chemistry of ostracod valves. Master of Sciences Research Thesis, University of Wollongong, Australia, 175 pp. http://ro.uow.edu.au/theses/3319/

Faranda, C., Gliozzi, E., Cipollari, P., Grossi, F., Darbaş, G., Gürbüz, K., Nazik, A., Gennari, R., Cosentino, D., 2013. Messinian paleoenvironmental changes in the easternmost Mediterranean Basin: Adana Basin, southern Turkey. Turkish J Earth Sci 22, 839-863.

Faure, G., Powell, J.L., 1972. Strontium Isotope Geology. Springer-Verlag, Berlin, 1-188.

Flecker, R., de Villiers, S., Ellam, R.M., 2002. Modelling the effect of evaporation on the salinity–$^{87}Sr/^{86}Sr$ relationship in modern and ancient marginal–marine systems: the Mediterranean Messinian Salinity Crisis. Earth Planet. Sci. Lett. 203 (1), 221– 233.

Flecker, R., Ellam, R.M., 2006. Identifying Late Miocene episodes of connection and isolation in the Mediterranean–Paratethyan realm using Sr isotopes. Sediment. Geol. 188–189, 189–203.

Frenzel, P., Schulze, I., Pint, A., 2011. Salinity dependant morphological variation in *Cyprideis torosa*. Joannea Geologie und Paläontologie 11, 59–61.

Frenzel, P., Schulze, I., Pint, A., 2012. Noding of *Cyprideis torosa* valves (Ostracoda) – a proxy for salinity? New data from field observations and a long-term microcosm experiment. International Review of Hydrobiology 97(4), 314–329.

Gliozzi, E., Grossi, F., 2008. Late Messinian Lago-mare ostracod palaeoecology: a correspondence analysis approach. Palaeogeography, Palaeoclimatology, Palaeoecology 264, 288-295.

**Field Code Changed**

Gouramanis, C., Wilkins, D., De Deckker, P., 2010. 6000 years of environmental changes recorded in Blue Lake, South Australia, based on ostracod ecology and valve chemistry. Palaeogeography, Palaeoecology, Palaeoclimatology 297, 223-237.

Griffin, D.L., 2002. Aridity and humidity: Two aspects of the late Miocene climate of North Africa and the Mediterranean. Palaeogeography, Palaeoclimatology, Palaeoecology 182, 65-91.

Griffiths, H.I., Holmes, J.A., 2000. Non-marine ostracods & Quaternary palaeoenvironments. Quaternary Research Association, Technical Guide 8, 1-179.

Grossi, F., Gennari, R., 2008. Palaeoenvironmental reconstruction across the Messinian/Zanclean boundary by means of ostracods and foraminifers: the Montepetra borehole (Northern Apennine, Italy). Atti del Museo Civico di Storia Naturale di Trieste 53(suppl), 67-88.

Grossi, F., Cosentino, D., Gliozzi, E., 2008. Palaeoenvironmental reconstruction of the late Messinian lago-mare successions in central and eastern Mediterranean using ostracod assemblages. Bollettino della Società Paleontologica Italiana 47(2), 131–146.

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

Henderson, G. M., Martel, D. J., O'Nions, R. K., Shackleton, N. J., 1994. Evolution of seawater $^{87}Sr/^{86}Sr$ over the last 400 ka: the absence of glacial/interglacial cycles. Earth Planetary Sciences and Letetrs 128, 643–651.

Holmes, J., De Deckker, P., 2012. Introduction to ostracod shell chemistry and its application to Quaternary palaeoclimate studies. In: D. J. Horne, J. Holmes, J. Rodriguez-Lazaro and F. Viehberg (Eds.). Ostracoda as proxies for Quaternary climate change. Developments in Quaternary Sciences. Elsevier, v. 17, 131-144.

Howarth, R., McArthur, J.M., 1997. Statistics for Strontium Isotope Stratigraphy: a robust LOWESS fit to the marine Sr-isotope curve for 0 to 206 Ma, with look-up table for derivation of numeric age. J. Geol. 105, 441–456.

**Formatted:** Not Highlight

Hsü, K.J., Ryan, W.F.B., Cita, M.B., 1973. Late Miocene desiccation of the Mediterranean. Nature 242, 240–244.

Iaccarino, S., Bossio, A., 1999. Paleoenvironment of uppermost Messinian sequences in the Western Mediterranean (sites 974, 975 and 978). In: Zahn, R., Comas, M.C., Klaus, A., et al. (Eds.), Proceedings of Ocean Drilling Program, Scientific Results 161, 529–541, College Station, Texas.

Jahn, A., Gamenick, I., Theede, H., 1996. Physiological adaptations of *Cyprideis torosa* (Crustacea, Ostracoda) to hydrogen sulphide. Marine Ecology Progress Series 142, 215–223.

Jones, B. and Manning, D.A.C., 1994. Comparison of geochemical indices used for the interpretation of paleoredox conditions in ancient mudstones. Chemical Geology 111, 111–129.

Keating, K.W., Hawkes, I., Holmes, J.A., Flower, R.J., Leng, M.J., Abu-Zied, R.H., Lord, A.R., 2007. Evaluation of ostracod-based palaeoenvironmental reconstruction with instrumental data from the arid Faiyum Depression. Egyptian Journal of Paleolimnology 38, 261–283.

Keogh, S.M., Butler, R.W.H., 1999. The Mediterranean water body in the late Messinian: interpreting the record from marginal basins on Sicily. J. Geol. Soc. (Lond.) 156, 837– 846.

Keyser, D., 2005. Histological peculiarities of the noding process in *Cyprideis torosa* (Jones) (Crustacea, Ostracoda). Hydrobiologia 538, 95–106.

Keyser, D., Aladin, N., 2004. Noding in *Cyprideis torosa* and its causes. Studia Quaternaria 2, 19–24.

Ligios, S., Anadón, P., Castorina, F., D’Amico, C., Esu, D., Gliozzi, E., Gramigna, P., Mola, M., Monegato, G., 2012. Ostracoda and Mollusca biodiversity and hydrochemical features of Late Miocene brackish basins of Italy. Geobios 45, 351-367.

Ligios, S., Gliozzi, E., 2012. The genus *Cyprideis* Jones, 1857 (Crustacea, Ostracoda) in the Neogene of Italy: A geometric morphometric approach. Revue de micropaléontologie 55, 171–207.



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Mangini, A., Jung, M., Laukenmann, S., 2001. What do we learn from peaks of uranium and of manganese in deep sea sediments? Marine Geology 177(1), 63-78.

Manzi, V., Lugli, S., Roveri, M., Schreiber, C., 2009. A new facies model for the Upper Gypsum of Sicily (Italy): chronological and palaeoenvironmental constraints for the Messinian salinity crisis in the Mediterranean. Sedimentology 56, 1937-1960.

Manzi, V., Gennari, R., Lugli, S., Roveri, M., Scafetta, N., Schreiber, B.C., 2012. High-frequency cyclicity in the Mediterranean Messinian evaporites: evidence for solar–lunar climate forcing. Journal of Sedimentary Research 82, 991–1005.

Manzi, V., Gennari, R., Hilgen, F., Krijgsman, W., Lugli, S., Roveri, M., Sierro F.J., 2013. Age refinement of the Messinian salinity crisis onset in the Mediterranean. Terra Nova, doi: 10.1111/ter.12038

Marco-Barba, J., 2010. Freshwater ostracods ecology and geochemistry as paleoenvironmental indicators in marginal marine ecosystems: a case of study the Albufera of Valencia. Ph. D. thesis, Univ. of Valencia.

McArthur, J.M., Howarth, R.J., Bailey T.R., 2001. Strontium isotope stratigraphy: LOWESS version 3: Best fit to the marine Sr-isotope curve for 0–509 Ma and accompanying look-up table for deriving numerical age. Journal of Geology 109, 155–170.

McCulloch, M.T., De Deckker, P., 1989. Sr-isotope constraints on the Mediterranean environment at the end of the Messinian salinity crisis. Nature 342, 63– 65.

Müller, D.W., Mueller, P.A., 1991. Origin and age of the Mediterranean Messinian evaporites: implications from Sr isotopes. Earth Planet. Sci. Lett. 107, 1 –12.

Müller, D.W., Mueller, P.A., McKenzie, J.A., 1990. Strontium isotopic ratios as fluid tracers in Messinian evaporites of the Tyrrhenian sea (western Mediterranean sea). Proc. ODP Sci. Res. 107, 603–614.

Neale, J.V., 1988. Ostracods and paleosalinity reconstruction. In: De Deckker, P., Colin, J.-P., Peypouquet, J.-P. (Eds.), Ostracoda in the Earth Sciences. Elsevier, Amsterdam, pp. 125–155.

Pattan, J.N., Pearce, N.J.G., 2009. Bottom water oxygenation history in southeastern Arabian Sea during the past 140 ka: Results from redox-sensitive elements. Palaeogeography, Palaeoclimatology, Palaeoecology 280(3-4), 396-405.

Pint, A., Frenzel, P., Fuhrmann, R., Scharf, B., Wennrich, V., 2012. Distribution of *Cyprideis torosa* (Ostracoda) in Quaternary athalassic sediments in Germany and its application for palaeoecological reconstructions. International Review of Hydrobiology 97(4), 330-335.

Pint, A., Melzer, S., Frenzel, P., Engel, M., Brückner, H., 2013. Monospecific occurrence of *Cyprideis torosa* associated with micro- and macrofauna of marine origin in sabkha sediments of the Northern Arabian Peninsula. Naturalista Siciliano 4, 37(1), 277-278.

Radeff, G., Schildgen, T.F., Cosentino, D., Strecker, M.R., Cipollari, P., Darbaş, G., Gürbüz, K., (submitted). Sedimentary evidence for late Miocene uplift of the SE margin of the central Anatolian Plateau: Adana Basin, Southern Turkey. Geological Society of America Bulletin.

Rosenfeld, A, Vesper, B., 1977. The variability of the sieve-pores in recent and fossil species of *Cyprideis torosa* (Jones, 1850) as an indicator for salinity and paleosalinity. In: Löffler, H., Danielopol, D. (Eds.), Aspects of ecology and zoogeography of recent and fossil Ostracoda. Junk Publishers, The Hague, 55–67.

Rosenfeld, A., 1977. The Sieve-pores of *Cyprideis torosa* (Jones, 1850) from the Messinian Mavqi'im Formation in the Coastal Plain and Continental Shelf of Israel as an Indicator of Paleoenvironment. Israel Journal of Earth-Sciences 26, 89-93.

Rossi, V., Amorosi, A., Sammartino, I., Sarti, G., 2013. Environmental changes in the lacustrine ancient harbour of Magdala (Kinneret Lake, Israel) inferred from ostracod, geochemical and sedimentological analyses. Naturalista Siciliano 4, 37(1), 331-332.

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

Roveri, M., Lugli, S., Manzi, V., Gennari, R., Schreiber, B.C., 2014b. High-resolution strontium isotope stratigraphy of the Messinian deep Mediterranean basins: Implications for marginal to central basins correlation, Marine Geology, doi: 10.1016/j.margeo.2014.01.002

Sampalmieri, G., Iadanza, A., Cipollari, P., Cosentino, D., Lo Mastro, S., 2010. Palaeoenvironments of the Mediterranean Basin at the Messinian hypersaline/hyposaline transition: evidence from natural radioactivity and microfacies of post-evaporitic successions of the Adriatic sub-basin. Terra Nova 22, 239-250.

Sandberg, P., 1964. The ostracod genus *Cyprideis* in the Americas. Stockholm Contributions in Geology 12, 1-178.

Schäfer, H.W., 1953. Über Meeres- und Brackwasserostracoden aus dem Deutschen Küstengebiet mit 2. Mitteilung über die Ostracodenfauna Griechenlands. Hydrobiologia 5(4), 351-389.

Schreiber, B.C., 1997. Field trip to Eraclea Minoa: Upper Messinian. "Neogene Mediterronean Paleoceanography". Excursion Guide Book Palermo-Caltanissetta Agrigento. Erice (Sicily), 24-27 September 1997, 72-80.

Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. Chemical Geology (Isot. Geosci. Sect.) 80, 261–279.

Testa, G., 1995. Upper Miocene extensional tectonics and synrift sedimentation in the western sector of the Volterra Basin (Tuscany, Italy). Studi Geologici Camerti vol. spec. 1, 617-630.

Utrilla, R., Vazquez, A., Anadón, P., 1998. Paleohydrology of the Upper Miocene Bicorb Lake (E Spain) as inferred from stable isotopic data from inorganic carbonates. Sedimentary Geology 121, 191-206.

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Van Couvering, J.A., Castradori, D., Cita, M.B., Hilgen, F.J., Rio, D., 2000. The base of the Zanclean Stage and of the Pliocene Series. Episodes 23(3), 179-187.

Van der Laan, E., Snel, E., de Kaenel, E., Hilgen, F.J., Krijgsman, W., 2006. No major deglaciation across the Miocene-Pliocene boundary: integrated stratigraphy and astronomical tuning of the Loulja sections (Bou Regreg area, NW Morocco). Paleoceanography 21, PA3011, doi:10.1029/2005PA001193.

Van Harten, D., 1996. *Cyprideis torosa* (Ostracoda) revisited. Of salinity, nodes and shell size. In: Keen, C. (Ed.), Proceedings of the second European Ostracodologists Meeting. British Micropalaeontological Society, London, pp. 191–194.

Van Harten, D., 2000. Variable noding in *Cyprideis torosa* (Ostracoda, Crustacea): an overview, experimental results and a model from Catastrophe Theory. Hydrobiologia 419, 131–139.

Venice Symposium on the Classification of Brackish Waters, Venice 8-14 April 1958 in Remane, A., Schlieper, C. (eds.), Die Biologie der Brackwassers. Schweizerbartsche Verlag, Stuttgart, 1-348.

Vesper, B., 1975. To the problem of noding on *Cyprideis torosa* (Jones, 1850). In: Swain, F., Kornicker, L.S., Lundin, R.F. (Eds.), Biology and Paleobiology of Ostracoda. Bulletin of American Paleontology 65(282), 205-216.

Voltaggio, M., Branca, M., Tedesco, D., Tuccimei, P., Di Pietro, L., 2004. $^{226}$Ra-excess during the 1631-1944 activity period of Vesuvius (Italy): a model of alpha recoil enrichment in a metasomatized mantle and implications on the current state of the magmatic system. Geochimica et Cosmochimica Acta 68, 167-181.

Wignall, P.B., 1994. Black Shales. Claredon Press, Oxford, 127 pp.

Wignall, P.B., Myers, K.J., 1988. Interpreting benthic oxygen levels in mudrocks: anew approach. Geology 16, 452-455.

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Zheng, Y., Anderson, R.F.,Van Geen, A., Fleisher, M.Q., 2002. Remobilization of authigenic uranium in marine sediments by bioturbation. Geochimica et Cosmochimica Acta 66 (10), 1759–1772.

## FIGURE CAPTIONS

Fig. 1 – SEM pictures of *Cyprideis agrigentina* Decima. a. male left valve, sample EM 8-3; b. male right valve, sample EM 7-2; c. female left valve, sample EM 7-2; d. female right valve, sample EM 8-3. White bar corresponds to 0.1 mm.

Fig. 2 – Geographical location of the Eraclea Minoa section.

Fig. 3 – Panoramic view of the Eraclea Minoa section. In evidence the gypsum levels of the Upper Gypsum Unit from gypsum body 3 to gypsum body 6 (marked by numbers) and the Messinian/Zanclean boundary.

Fig. 4 – Simplified stratigraphic log of the Eraclea Minoa section (modified from Manzi et al., 2009). Legend: 1. sapropels; 2. clays; 3. sandstones/sandy levels; 4. microconglomerate levels; 5. marls; 6. gypsum bodies (Upper Gypsum Unit); 7. samples for paleontological analyses; 8. samples for morphometrical analyses (ornamentation, dimensions and percentage of sieve-pore shapes) on *C. agrigentina* valves; 9. samples for stable isotopes analyses on *C. agrigentina* valves; 10. samples for trace elements analyses on *C. agrigentina* valves; 11. samples for Sr-isotopes analyses on *C. agrigentina* valves; 12. samples for NRD analyses on marls.

Fig. 5 – Stable isotopes, trace and minor elements, $^{87}Sr/^{86}Sr$, and authigenic uranium curves plotted against the stratigraphic log of the Eraclea Minoa section. For the descriptions of the intervals, see the text.

Fig. 6 - Stable isotopic composition ($\delta^{13}C$ and $\delta^{18}O$; PDB notation) of *Cyprideis agrigentina* calcite valves (Table 1). Note the negative correlation and regression line for samples from interval lower

B. The larger variation of $\delta^{13}C$ and $\delta^{18}O$ along the regression line corresponds to samples EM 6"-8 (198.2 m) to 6"-20 (216 m) from lower interval B. E/P: Evaporation /Precipitation ratio; PP: Primary productivity; Eq-Atm: Atmospheric $CO_2$ equilibrium. See also Fig. 4.

Fig. 7 – Results of the morphometrical analyses (mean lengths, percentages of sieve-pore shape and ornamentation/noding) performed on *Cyprideis agrigentina* adult valves, plotted against the stratigraphic log of the Eraclea Minoa section.

Fig. 8 - Comparisons among the palaeosalinity curve inferred by the analysis of the percentages of the sieve-pore shape on *Cyprideis agrigentina* and the palaeoenvironmental and palaeohydrochemistry changes inferred from synecological and Shannon-Wiener and geochemical proxies.

Fig. 9 - Principal Component Analysis (PCA) plot of the scores of the eigenvectors for the variables listed in Table 3. Abbreviations: N pores: variability of percentage of sieve pores (rounded sieve pores assumed as a proxy of salinity), Position: stratigraphic position of the samples, Sr isot: $^{87}Sr/^{86}Sr$ values. See the text for discussion.

Fig. 10 - Tree diagram for the considered variables defining the relationships between the groups of variables. Ward's method, 1-Pearson r. Abbreviations as in Fig. 8. See the text for discussion.

TABLE CAPTIONS

Table 1 – Stratigraphic position and lithology of the samples, and geochemical analytical results from *C. agrigentina* valves: stable isotope data ($\delta^{13}C$ and $\delta^{18}O$; PDB notation), $Mg/Ca_v$, $Sr/Ca_v$, and $Na/Ca_v$ in molar ratios, and $^{87}Sr/^{86}Sr$ ratios.

Table 2 – Summary of natural radioactivity data, with the concentrations of U, Th and K (with relative errors), values of authigenic uranium expressed in ppm and percentage and Th/U ratios.

Table 3 – Correlation matrix for the data in Table 1 and Th/U ratios (9 variables, 20 samples). The correlation coefficient r between the diverse variables is shown in the upper part of each division. The p value is indicated in the lower part of each division. The r values are in bold when the correlation is significant $p<0.01$. Abbreviations: N pores: variability of percentage of sieve pores (rounded sieve pores assumed as a proxy of salinity), Position: stratigraphic position of the samples, Sr isot: $^{87}Sr/^{86}Sr$ values.

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Figure 1
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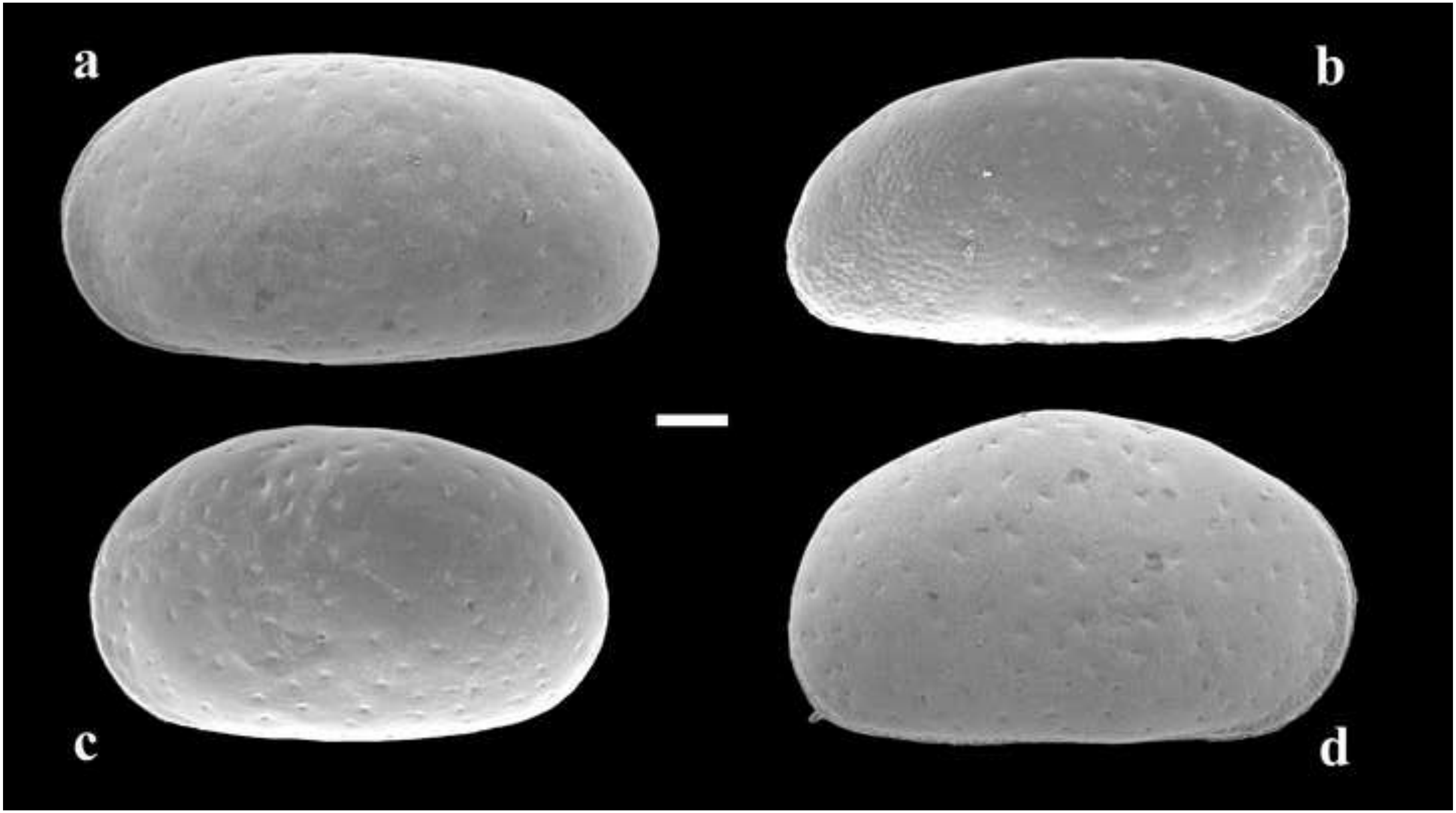

Figure 2

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Figure 3
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Figure 4

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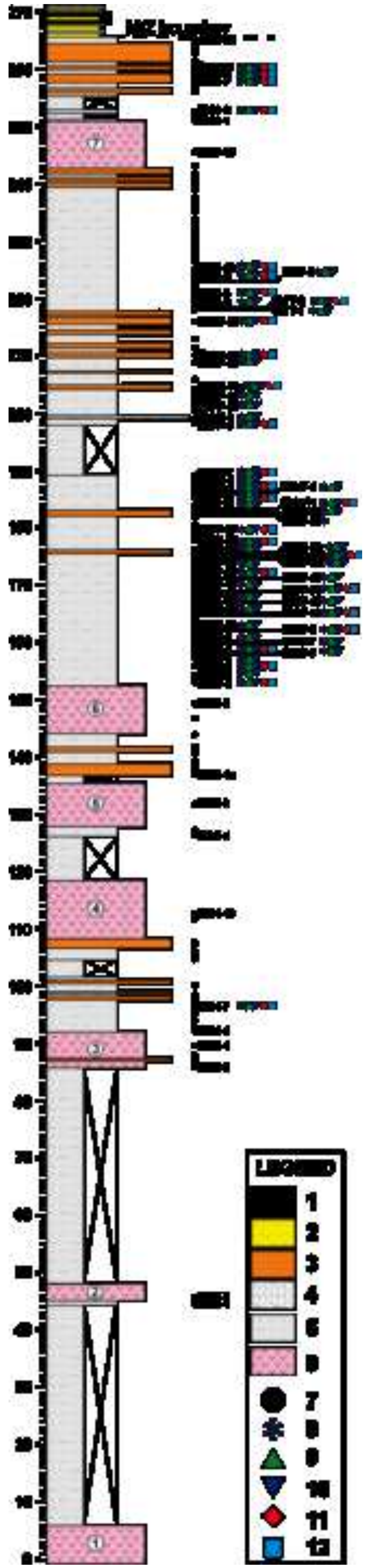

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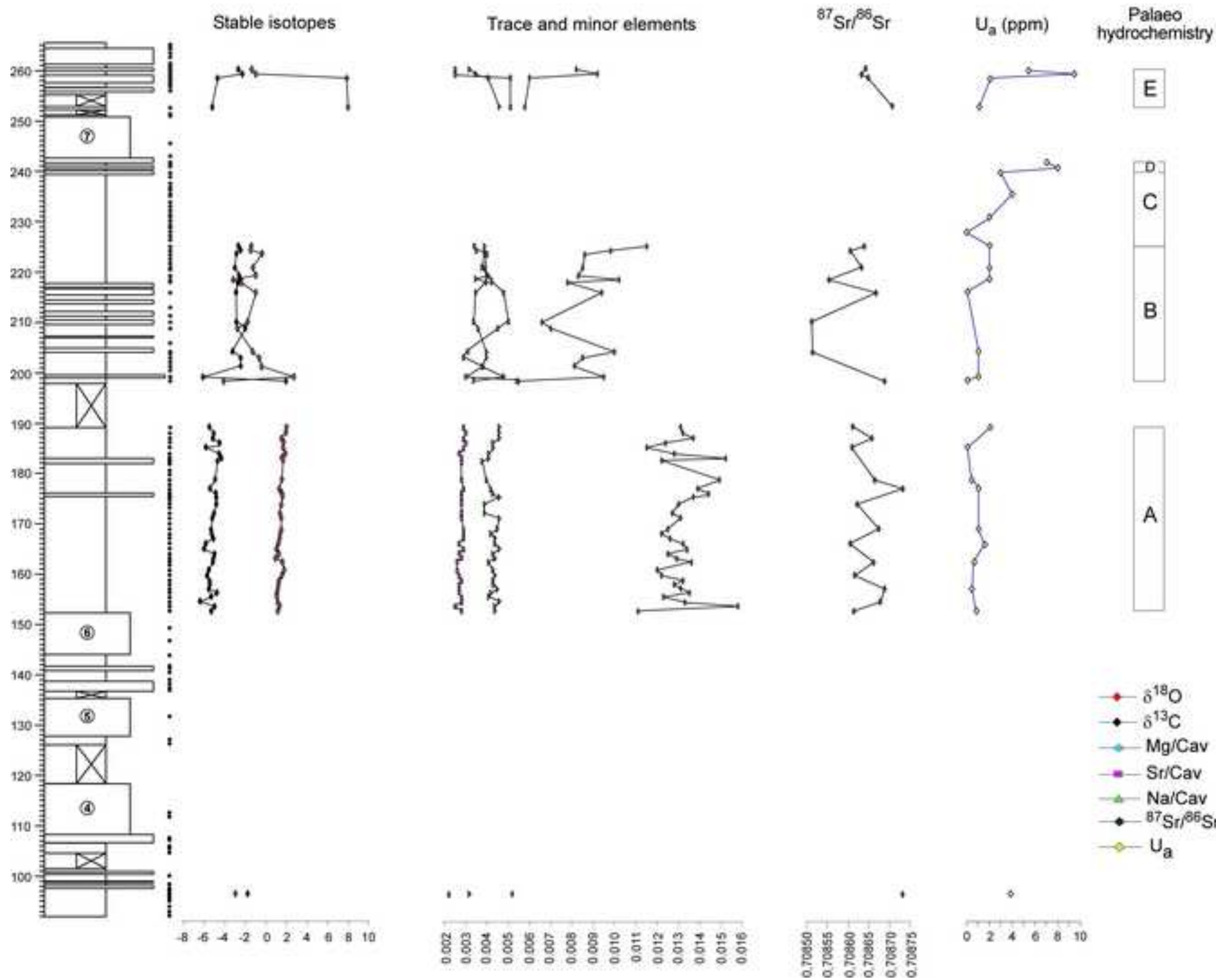

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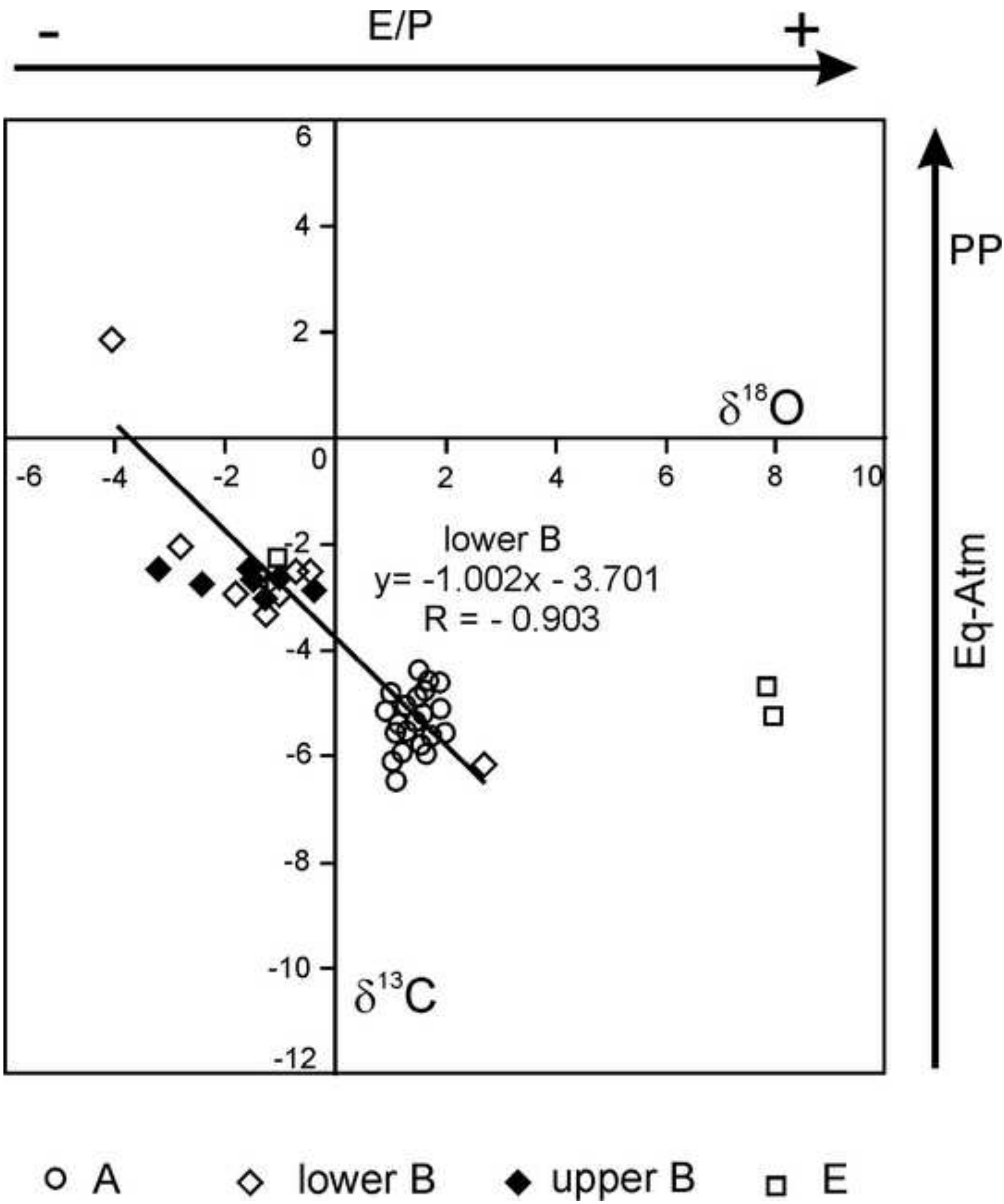

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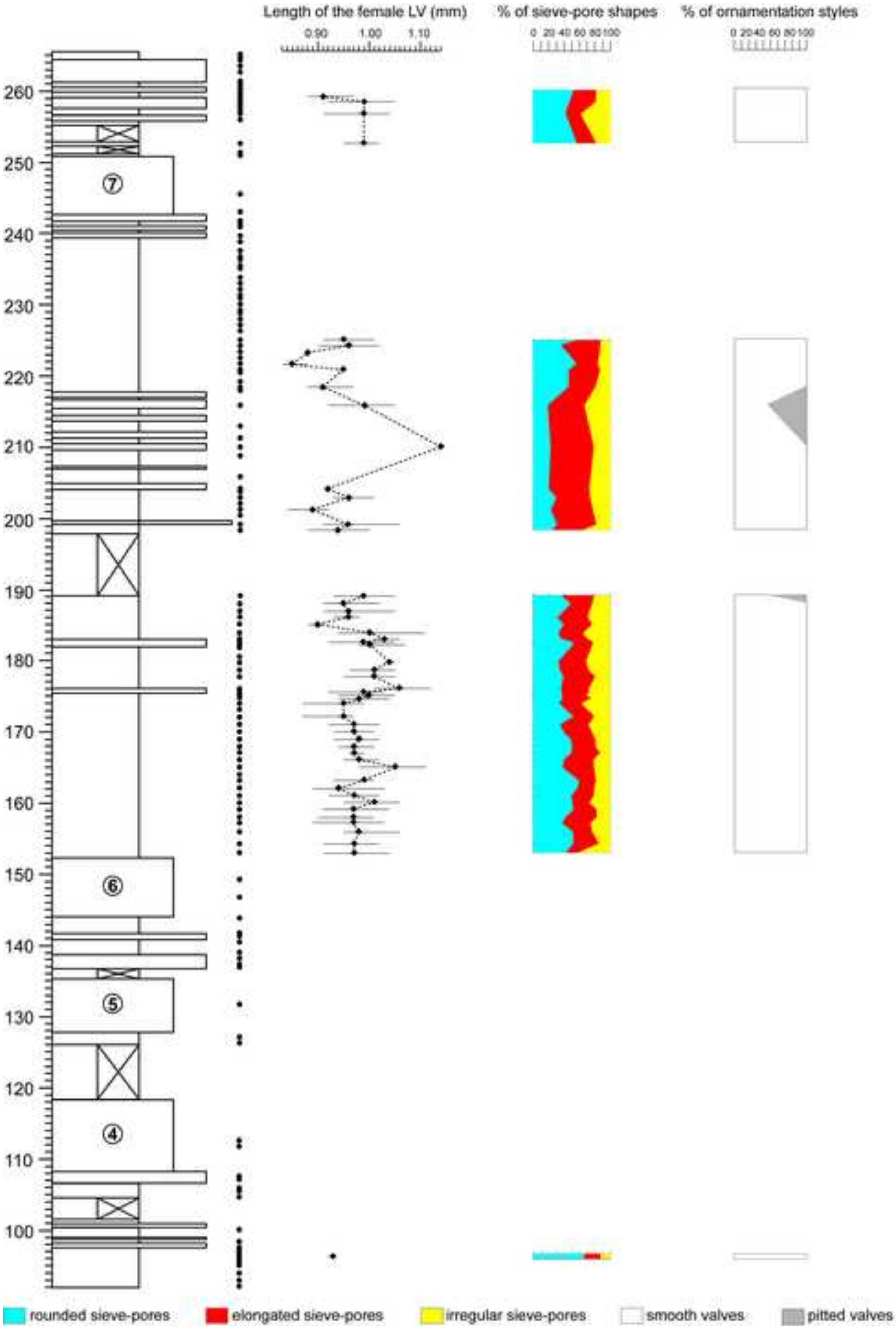

Figure 8

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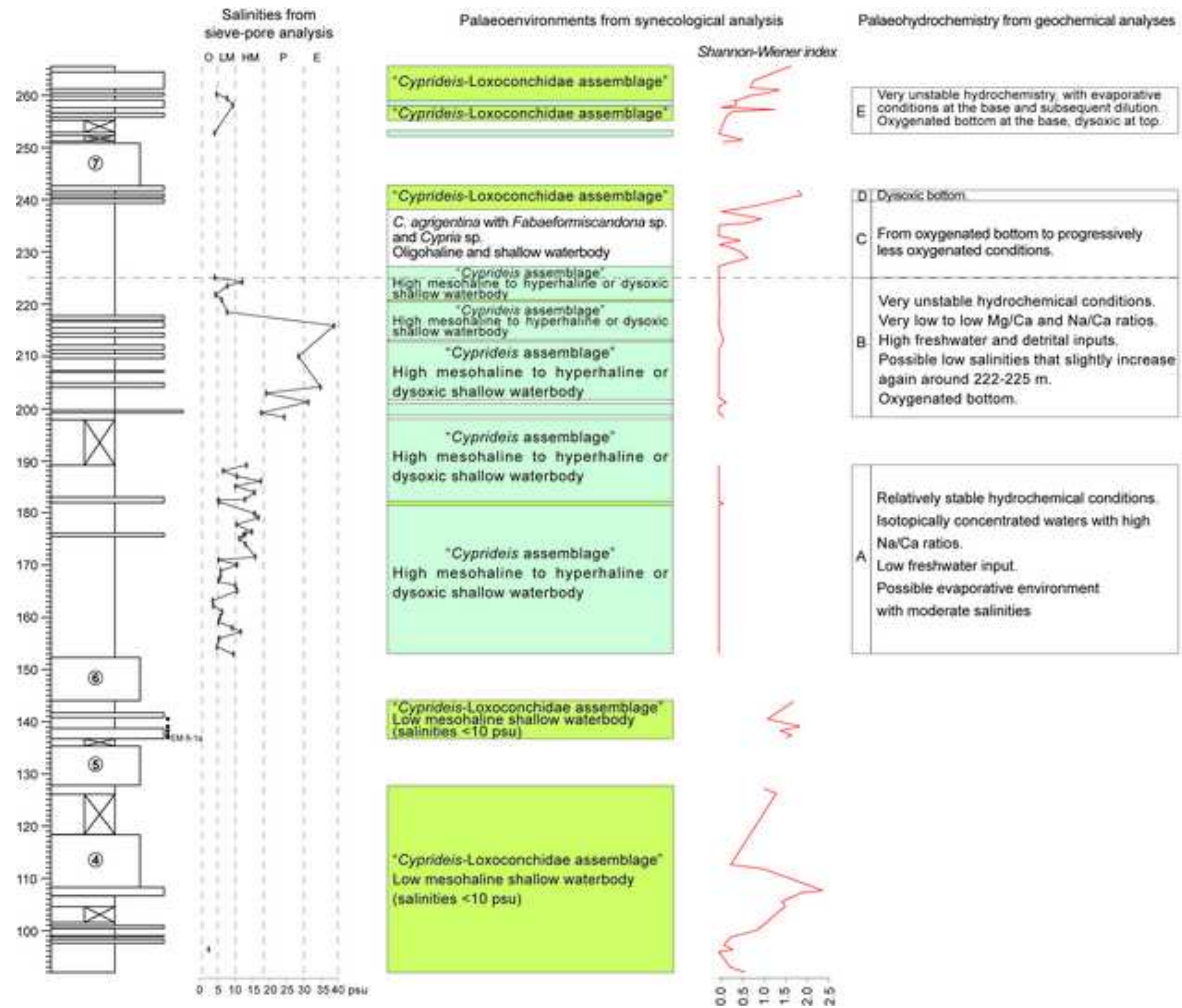

Figure 9
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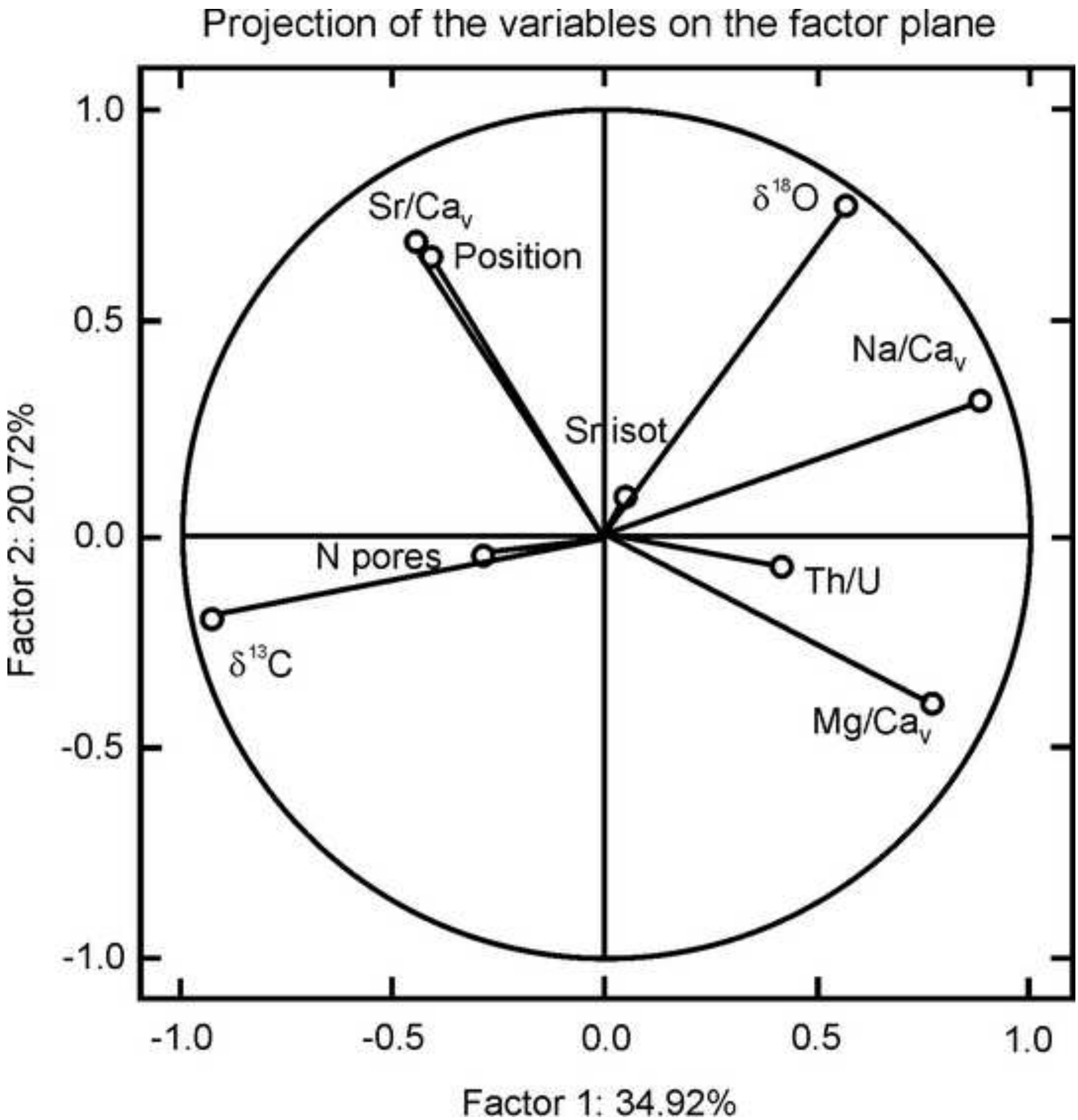

Figure 10
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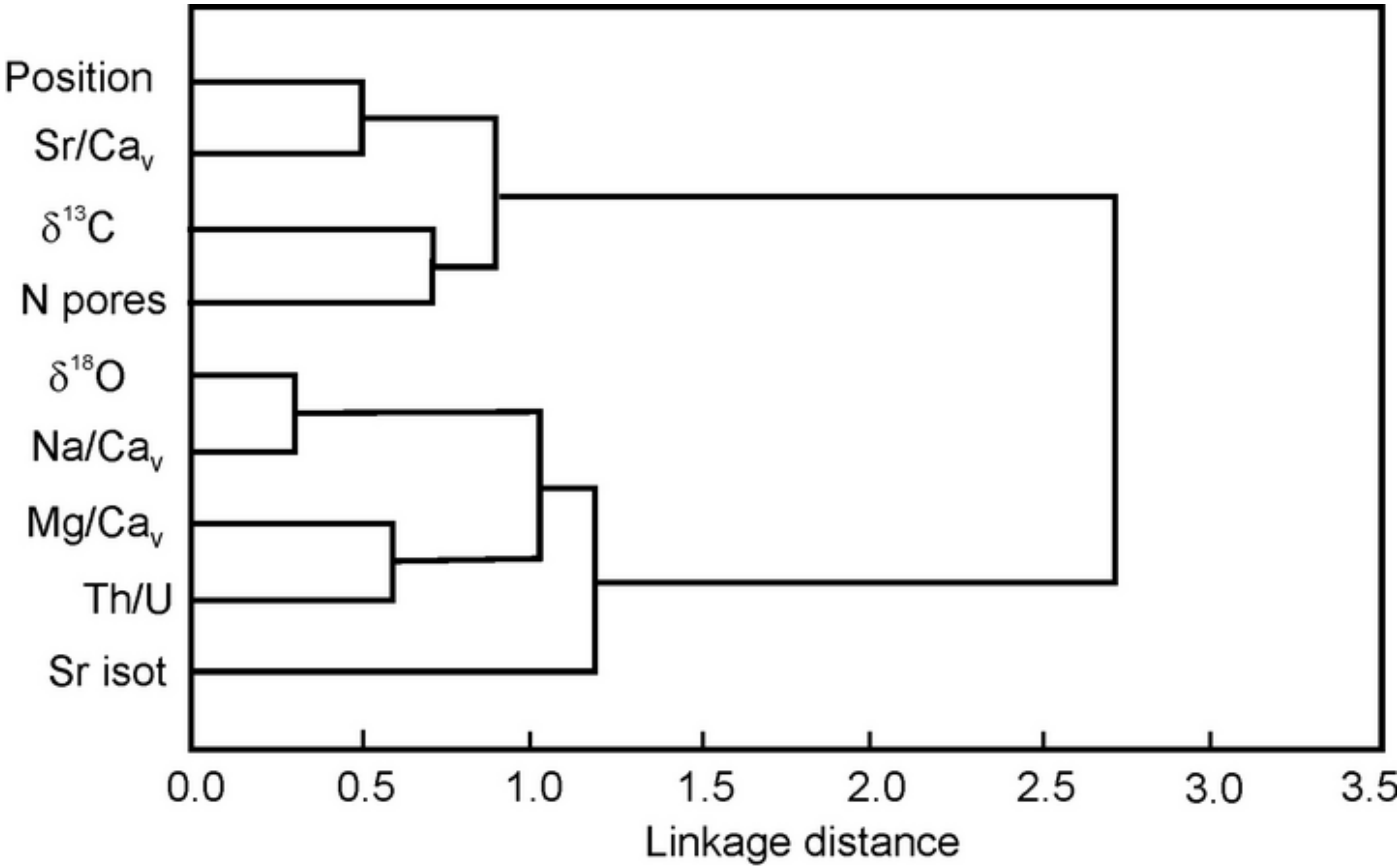

**Table 1**
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## Table 1

| Height (m) | Sample | Lithology | Stable Isotopes (n. of valves) | $d^{13}C$ (VPDB) | $d^{18}O$ (VPDB) | Trace elements (n. of valves) | Me/Ca molar | | | 87Sr/86Sr ±se* | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Mg/Cav | Sr/Cav | Na/Cav | | |
| 259.1 | EM 8-11 | sandstone | 8 | -2.68 | -1.37 | 10 | 0.0082 | 0.0025 | 0.0032 | 0.708640 | ±6 |
| 258.5 | EM 8-9 | marl | 8 | -2.29 | -1.02 | 10 | 0.0092 | 0.0025 | 0.0035 | 0.708630 | ±8 |
| 257.8 | EM 8-7 | sandstone | 8 | -4.70 | 7.83 | 10 | 0.0060 | 0.0051 | 0.0041 | 0.708647 | ±10 |
| 252.8 | EM 8-3 | marl | 8 | -5.24 | 7.95 | 10 | 0.0058 | 0.0051 | 0.0046 | 0.708704 | ±7 |
| 225.0 | EM 7-10 | marl | 8 | -2.67 | -1.44 | 10 | 0.0115 | 0.0034 | 0.0039 | 0.708637 | ±11 |
| 224.3 | EM 7-9 | marl | 8 | -2.47 | -1.52 | 10 | 0.0098 | 0.0035 | 0.0039 | 0.708602 | ±2 |
| 223.5 | EM 7-8 | marl | 8 | -2.87 | -0.37 | 8 | 0.0086 | 0.0040 | 0.0039 | | |
| 220.9 | EM 7-5 | marl | 8 | -3.01 | -1.27 | 9 | 0.0085 | 0.0039 | 0.0038 | 0.708629 | ±7 |
| 219.1 | EM 7-3 | marl | 8 | -2.63 | -0.98 | 9 | 0.0083 | 0.0040 | 0.0041 | | |
| 218.5 | EM 7-2 | marl | 8 | -2.46 | -3.20 | 10 | 0.0102 | 0.0042 | 0.0035 | 0.708552 | ±9 |
| 218.0 | EM 7-1 | marl | 8 | -2.76 | -2.40 | 9 | 0.0078 | 0.0042 | 0.0040 | | |
| 216.0 | EM 6"-20 | sandstone | 8 | -2.92 | -1.01 | 8 | 0.0094 | 0.0048 | 0.0035 | 0.708666 | ±10 |
| 210.0 | EM 6"-17 | sandstone | 8 | -2.88 | -1.79 | 7 | 0.0066 | 0.0050 | 0.0034 | 0.708510 | ±7 |
| 208.9 | EM 6"-16 | marl | 8 | -2.00 | -2.81 | 8 | 0.0070 | 0.0045 | 0.0036 | | |
| 204.2 | EM 6"-14a | marl | 8 | -3.27 | -1.26 | 8 | 0.0100 | 0.0031 | 0.0040 | 0.708511 | ±6 |
| 203.0 | EM 6"-13 | marl | 8 | -2.46 | -0.69 | 8 | 0.0085 | 0.0029 | 0.0040 | | |
| 201.1 | EM 6"-11 | marl | 8 | -2.48 | -0.43 | 8 | 0.0081 | 0.0038 | 0.0038 | | |
| 199.2 | EM 6"-9 | gravel | 8 | -6.14 | 2.72 | 10 | 0.0095 | 0.0030 | 0.0048 | | |
| 198.2 | EM 6"-8 | marl | 8 | 1.91 | -4.08 | 10 | 0.0055 | 0.0054 | 0.0034 | 0.708685 | ±11 |
| 189.0 | EM 6"-7 | marl | 8 | -5.53 | 1.99 | 8 | 0.0131 | 0.0029 | 0.0046 | 0.708609 | ±7 |
| 188.0 | EM 6"-6 | marl | 8 | -5.08 | 1.93 | 8 | 0.0132 | 0.0030 | 0.0046 | | |
| 187.0 | EM 6"-5 | marl | 8 | -5.20 | 1.46 | 8 | 0.0137 | 0.0029 | 0.0046 | 0.708654 | ±9 |
| 186.0 | EM 6"-4 | marl | 8 | -4.56 | 1.69 | 9 | 0.0124 | 0.0030 | 0.0043 | | |
| 185.0 | EM 6"-3 | marl | 8 | -5.88 | 1.65 | 8 | 0.0115 | 0.0029 | 0.0043 | 0.708608 | ±9 |
| 183.9 | EM 6"-2 | marl | 8 | -4.57 | 1.90 | 8 | 0.0128 | 0.0027 | 0.0041 | | |
| 183.1 | EM 6"-1 | marl | 8 | -4.35 | 1.52 | 6 | 0.0152 | 0.0028 | 0.0041 | | |
| 182.8 | EM 6'-31 | sandstone | 8 | -4.74 | 1.63 | 8 | 0.0122 | 0.0028 | 0.0038 | | |
| 180.0 | EM 6'-27 | marl | 8 | -4.93 | 1.55 | 9 | 0.0149 | 0.0028 | 0.0040 | 0.708663 | ±7 |
| 177.8 | EM 6'-25 | marl | 8 | -5.44 | 1.33 | 10 | 0.0139 | 0.0029 | 0.0042 | 0.708729 | ±10 |
| 176.0 | EM 6'-24 | marl | 8 | -4.89 | 1.55 | 8 | 0.0144 | 0.0028 | 0.0043 | | |
| 175.5 | EM 6'-23 | sandstone | 8 | -4.82 | 1.58 | 7 | 0.0137 | 0.0028 | 0.0046 | | |
| 175.1 | EM 6'-22b | sandstone | 8 | -4.83 | 1.49 | 8 | 0.0130 | 0.0028 | 0.0039 | 0.708619 | ±6 |
| 174.6 | EM 6'-22 | marl | 8 | -5.08 | 1.38 | 8 | 0.0127 | 0.0028 | 0.0039 | | |
| 173.9 | EM 6'-21 | marl | 8 | -5.25 | 1.46 | 7 | 0.0131 | 0.0028 | 0.0046 | | |
| 172.0 | EM 6'-19 | marl | 8 | -5.35 | 1.50 | 7 | 0.0125 | 0.0029 | 0.0045 | 0.708671 | ±6 |
| 171.0 | EM 6'-18 | marl | 8 | -5.27 | 1.39 | 7 | 0.0122 | 0.0029 | 0.0042 | | |
| 169.9 | EM 6'-17 | marl | 8 | -5.15 | 1.29 | 9 | 0.0126 | 0.0029 | 0.0044 | | |
| 169.0 | EM 6'-16 | marl | 8 | -5.87 | 1.21 | 8 | 0.0132 | 0.0027 | 0.0044 | 0.708602 | ±7 |
| 168.0 | EM 6'-15 | marl | 8 | -6.05 | 1.05 | 8 | 0.0134 | 0.0029 | 0.0046 | | |
| 167.0 | EM 6'-14 | marl | 8 | -5.02 | 1.28 | 8 | 0.0125 | 0.0027 | 0.0043 | | |
| 166.0 | EM 6'-13 | marl | 8 | -5.13 | 0.94 | 8 | 0.0129 | 0.0028 | 0.0044 | | |
| 165.0 | EM 6'-12 | marl | 8 | -5.17 | 1.57 | 8 | 0.0136 | 0.0026 | 0.0041 | 0.708658 | ±9 |
| 163.0 | EM 6'-10 | marl | 8 | -5.60 | 1.76 | 8 | 0.0120 | 0.0026 | 0.0043 | | |
| 162.0 | EM 6'-9 | marl | 8 | -5.74 | 1.56 | 8 | 0.0122 | 0.0027 | 0.0044 | 0.708614 | ±6 |
| 161.0 | EM 6'-8 | marl | 8 | -5.52 | 1.28 | 9 | 0.0132 | 0.0028 | 0.0043 | | |
| 160.0 | EM 6'-7 | marl | 8 | -5.48 | 1.17 | 7 | 0.0128 | 0.0027 | 0.0043 | | |
| 159.1 | EM 6'-6 | marl | 8 | -5.55 | 1.12 | 8 | 0.0131 | 0.0027 | 0.0045 | 0.708685 | ±5 |
| 158.0 | EM 6'-5 | marl | 8 | -4.80 | 1.02 | 8 | 0.0135 | 0.0027 | 0.0042 | | |
| 157.1 | EM 6'-4 | marl | 8 | -5.35 | 1.07 | 9 | 0.0123 | 0.0028 | 0.0041 | | |
| 156.0 | EM 6'-3 | marl | 8 | -6.40 | 1.12 | 8 | 0.0133 | 0.0028 | 0.0046 | 0.708675 | ±10 |
| 154.3 | EM 6'-2 | marl | 8 | -5.00 | 1.30 | 7 | 0.0158 | 0.0025 | 0.0044 | | |
| 153.0 | EM 6'-1 | marl | 8 | -5.34 | 1.14 | 6 | 0.0111 | 0.0028 | 0.0044 | 0.708612 | ±11 |
| 96.2 | EM 4-7 | marl | 8 | -1.81 | -3.00 | 7 | 0.0052 | 0.0022 | 0.0032 | 0.708729 | ±10 |

**Table 2**
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## Table 2

| Height (m) | Sample | U (mean) (ppm) | Th | | K | | $U_{aut}$ (ppm) | $U_{aut}$ (%) | Th/U |
|---|---|---|---|---|---|---|---|---|---|
| | | | (ppm) | error (%) | % | error (%) | | | |
| 260.4 | EM 8-11 | 6.7 | 5.3 | 0.1 | 0.96 | 0.03 | 5.4 | 81 | 0.8 |
| 259 | EM 8-9 | 11.7 | 8.7 | 0.1 | 1.76 | 0.03 | 9.5 | 81 | 0.7 |
| 257.8 | EM 8-7 | 4.7 | 9.0 | 0.1 | 1.88 | 0.03 | 2.5 | 53 | 1.9 |
| 252.8 | EM 8-3 | 4.0 | 9.0 | 0.1 | 1.99 | 0.03 | 1.8 | 45 | 2.3 |
| 241.8 | EM 7-33 | 8.5 | 4.4 | 0.1 | 0.76 | 0.02 | 7.4 | 87 | 0.5 |
| 240.9 | EM 7-31 | 10.1 | 7.8 | 0.1 | 1.56 | 0.03 | 8.2 | 81 | 0.8 |
| 239.8 | EM 7-28 | 5.0 | 7.9 | 0.1 | 1.66 | 0.03 | 3.0 | 61 | 1.6 |
| 236.2 | EM7-24 | 5.7 | 6.8 | 0.1 | 1.47 | 0.03 | 4.0 | 70 | 1.2 |
| 230.9 | EM 7-17 | 4.4 | 9.3 | 0.1 | 1.91 | 0.03 | 2.1 | 48 | 2.1 |
| 228 | EM7-13 | 2.8 | 10.1 | 0.1 | 1.90 | 0.03 | 0.3 | 11 | 3.6 |
| 225 | EM 7-10 | 4.6 | 10.0 | 0.1 | 2.00 | 0.03 | 2.1 | 46 | 2.2 |
| 220.9 | EM 7-5 | 4.7 | 10.3 | 0.1 | 2.11 | 0.04 | 2.1 | 45 | 2.2 |
| 218.5 | EM 7-2 | 4.5 | 9.8 | 0.1 | 1.80 | 0.03 | 2.0 | 44 | 2.2 |
| 216 | EM 6''-20 | 3.1 | 9.5 | 0.1 | 2.02 | 0.03 | 0.7 | 23 | 3.1 |
| 204.5 | EM 6''-14a | 3.4 | 8.8 | 0.1 | 1.83 | 0.03 | 1.2 | 35 | 2.6 |
| 199.0 | EM 6''-9 | 2.7 | 5.8 | 0.1 | 0.81 | 0.03 | 1.3 | 48 | 2.1 |
| 198.5 | EM 6''-8 | 3.1 | 10.2 | 0.1 | 1.93 | 0.03 | 0.6 | 19 | 3.3 |
| 189.0 | EM 6''-7 | 4.5 | 8.3 | 0.1 | 1.60 | 0.03 | 2.5 | 56 | 1.8 |
| 185 | EM 6''-3 | 3.1 | 9.7 | 0.1 | 1.83 | 0.03 | 0.7 | 22 | 3.1 |
| 180 | EM 6'-27 | 2.4 | 8.0 | 0.1 | 1.92 | 0.03 | 0.4 | 17 | 3.3 |
| 178 | EM 6'-25 | 3.2 | 8.6 | 0.1 | 2.05 | 0.03 | 1.1 | 34 | 2.7 |
| 172 | EM 6'-19 | 3.3 | 9.0 | 0.1 | 1.89 | 0.03 | 1.1 | 33 | 2.7 |
| 169 | EM 6'-16 | 3.9 | 9.3 | 0.1 | 2.03 | 0.03 | 1.6 | 41 | 2.4 |
| 165 | EM 6'-12 | 2.9 | 9.1 | 0.1 | 2.18 | 0.04 | 0.6 | 22 | 3.1 |
| 159 | EM 6'-6 | 2.9 | 9.7 | 0.1 | 2.02 | 0.03 | 0.5 | 17 | 3.4 |
| 153 | EM 6'-1 | 3.1 | 9.1 | 0.1 | 1.91 | 0.03 | 0.8 | 26 | 2.9 |
| 96.5 | EM 4-7 | 5.9 | 8.0 | 0.1 | 1.62 | 0.03 | 3.9 | 66 | 1.4 |

**Table 3**

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| | Position | $\delta^{13}C$ | $\delta^{18}O$ | $Mg/Ca_v$ | $Sr/Ca_v$ | $Na/Ca_v$ | N pores | Sr isot | Th/U |
|---|---|---|---|---|---|---|---|---|---|
| Position | 1.000 | | | | | | | | |
| *p* | | | | | | | | | |
| $\delta^{13}C$ | 0.192 | 1.000 | | | | | | | |
| *p* | p=0.418 | | | | | | | | |
| $\delta^{18}O$ | 0.238 | **-0.690** | 1.000 | | | | | | |
| *p* | p=0.311 | **p=0.001** | | | | | | | |
| $Mg/Ca_v$ | -0.331 | **-0.628** | 0.039 | 1.000 | | | | | |
| *p* | p=0.154 | **p=0.003** | p=0.872 | | | | | | |
| $Sr/Ca_v$ | **0.506** | 0.376 | 0.216 | **-0.562** | 1.000 | | | | |
| *p* | **p=0.023** | p=0.102 | p=0.360 | **p=0.010** | | | | | |
| $Na/Ca_v$ | -0.173 | **-0.823** | **0.693** | **0.516** | -0.095 | 1.000 | | | |
| *p* | p=0.466 | **p=0.000** | **p=0.001** | **p=0.020** | p=0.692 | | | | |
| N pores | 0.078 | 0.286 | -0.231 | -0.030 | 0.349 | -0.188 | 1.000 | | |
| *p* | p=0.743 | p=0.221 | p=0.328 | p=0.901 | p=0.131 | p=0.428 | | | |
| Sr isot | -0.244 | 0.035 | 0.192 | -0.166 | 0.068 | -0.035 | 0.275 | 1.000 | |
| *p* | p=0.299 | p=0.882 | p=0.418 | p=0.484 | p=0.777 | p=0.884 | p=0.240 | | |
| Th/U | -0.403 | -0.219 | 0.080 | 0.410 | 0.211 | 0.420 | 0.392 | 0.084 | 1.000 |
| *p* | p=0.079 | p=0.353 | p=0.738 | p=0.072 | p=0.372 | p=0.065 | p=0.087 | p=0.725 | |