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Research paper

# *Globorotalia truncatulinoides* in Central - Western Mediterranean Sea during the Little Ice Age

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## ABSTRACT

*Globorotalia truncatulinoides* oscillations have been recorded from different marine sediment cores collected in the central and western Mediterranean Sea. The abundances of this species over the last 500 yrs. demonstrates its potential value as bio-indicator of particular oceanographic condition during the Maunder Minimum (MM) event of the Little Ice Age (LIA). The comparison between the *G. truncatulinoides* abundance patterns of the Balearic Basin, central and south Tyrrhenian Sea and central and eastern Sicily Channel allows to highlight a similar response of this species during the MM event in the central-western Mediterranean Sea. The ecological meanings of this species and its peculiar high abundance percentages in the total assemblages suggest the development of enhanced vertical mixing conditions during MM winter season with a strong advection of nutrients from the nutrient-rich deeper layers and enhances the productivity levels in the mixed layer. The intensified vertical mixing could be linked to persistence of an atmospheric blocking event recorded by several authors during the MM.

## 1. Introduction

The study of the climate changes of the last centuries allows comparison of data from historical documents, instrumental and paleodata records with multi-decadal variability arising from external forcing and internal climate variability (IPCC, 2013). During this time interval, several climate oscillations played an important role in Europe social reorganization, as the Little Ice Age (LIA, 1250–1850 CE). The LIA is characterized by a widespread cooling approximately 0.5–1.0 °C and a lowering of the equilibrium line altitude of mountain glaciers around the world of about 100 m (e.g. Broecker, 2001; Luterbacher et al., 2004, 2006). In the Mediterranean region, four climatic oscillations related to solar activity minima can be identified: Wolf, Spörer, Maunder and Dalton cold events (Lirer et al., 2013, 2014; Margaritelli et al., 2016, 2018; Incarbona et al., 2019). The Maunder Minimum (MM, ca. 1645–1715 CE) delineates the coldest phase of the LIA (Wanner et al., 2000; Luterbacher et al., 2001), with an increase in climatic variability over wide parts of Europe. This period is characterized by high concentration in atmospheric $\Delta^{14}C$ (Stuiver and Braziunas, 1993), volcanic eruptions (Briffa et al., 1998) and a reduced solar activity (Spörer, 1887; Maunder, 1922; Eddy, 1976; Lean et al., 1995; Luterbacher et al., 2001). In fact, solar activity during the MM was near its lowest levels of the past 8000 years (Lean and Rind, 1999; Luterbacher et al., 2001).

Presently, the Mediterranean is considered one of the most responsive regions to global climate change (Giorgi, 2006) and due to its latitudinal position between North Africa, situated within the arid zone of the subtropical high, and Central and Northern Europe, affected by the westerly air flows (e.g. Lionello et al., 2006; and references therein) and semi-enclosed configuration (Giorgi and Lionello, 2008), it is a key area to investigate paleoclimatic changes at decadal scale (e.g., Cacho et al., 1999; Rohling et al., 2001; Oldfield et al., 2003; Martrat et al., 2004; Frigola et al., 2007; Combourieu-Nebout et al., 2009; Taricco et al., 2009, 2015; Nieto-Moreno et al., 2011; Luterbacher et al., 2012; Moreno et al., 2012; Cisneros et al., 2016; Margaritelli et al., 2020).

Planktonic foraminifera represent an often applied tool for paleoceanographic, paleoecological and sea-surface temperature reconstructions, thanks to the properties of their fossil assemblages or their geochemical signals (e.g. Sbaffi et al., 2004; Kucera, 2007; Piva et al., 2008; Grauel et al., 2013; Lirer et al., 2013, 2014; Goudeau et al., 2015; Kontakiotis, 2016; Incarbona et al., 2019; Antonarakou et al., 2015, 2018, 2019; Giamali et al., 2019). However, the distribution data of recent planktonic foraminifera in the

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Mediterranean area are limited (e.g. De Castro Coppa et al., 1980; Hemleben et al., 1989; Pujol and Vergnaud Grazzini, 1995; Bàrcena et al., 2004; Schiebel and Hemleben, 2005; Rigual-Hernández et al., 2012; Kontakiotis et al., 2017; Mallo et al., 2017).

This paper focuses on the planktonic foraminifer *Globorotalia truncatulinoides* oscillations in the central and western Mediterranean Sea (Balearic Sea, central and southern Tyrrhenian Sea, central and eastern Sicily Channel - Fig. 1) over the last 500 yrs., demonstrating its potential value as indicator of particular climate condition over the MM event during the LIA and its connection with Atmospheric blocking events.

Atmospheric blocking events are midlatitude weather situations where a Northeast Atlantic high-pressure system modifies the flow of the westerly winds by blocking or diverting their pathway (Moffa Sánchez et al., 2014). Blocking is accompanied by cold winter temperatures in Western Europe and the climatological maximum in winter blocking days is located over Western Europe, with a secondary maximum over Greenland (Häkkinen et al., 2011).

*Globorotalia truncatulinoides* originated at 2.82 Ma in Southwest Pacific (Lazarus et al., 1995; Spencer-Cervato and Thierstein, 1997; Lourens et al., 2004), later appears in the Atlantic Ocean at 2.544–2.525 Ma (Sexton and Norris, 2008) and finally invaded other ocean basin ~2.0 Ma ago (Spencer-Cervato and Thierstein, 1997; Sexton and Norris, 2008). More recently, it became adapted to colder environments in the Southern Ocean, colonizing subpolar waters in two successive phases of expansion at 300 and 200 kyr (Pharr and Williams, 1987; Kennett, 1970). According to Cita (1973), *G. truncatulinoides* appeared in the Mediterranean much later than in the major ocean basins. Biostratigraphic studies in the Mediterranean Sea have shown that this species is common only after 2.0 Ma ago (Ruggieri and Sprovieri, 1977; Rio et al., 1984; Caruso et al., 2009; Lirer et al., 2019a). This may be due to the mechanism that *G. truncatulinoides* enter marginal basins, like the Mediterranean and the Caribbean Seas through shallow and narrow passages (e.g., Schmuker and Schiebel, 2002). In the Mediterranean area, and in particular over the last 5 millennia, *G. truncatulinoides* is recorded only in the central-western basin: i) Sicily Channel (Sprovieri et al., 2003; Rouis-Zargouni et al., 2010; Incarbona et al., 2019); ii) Tyrrhenian Sea (Buccheri et al., 2002; Amore et al., 2004; Sbaffi et al., 2004; Budillon et al., 2009; Lirer et al., 2013; Di Bella et al., 2014; Morabito et al., 2014; Margaritelli et al., 2016) and iii) Balearic Sea (Margaritelli et al., 2018). Conversely, it has been absent in the Adriatic, Ionian and eastern Mediterranean Sea. This marked difference in the geographical distribution of *G. truncatulinoides* confirms the onset of the modern day hydrographic conditions in the western Mediterranean Sea, strongly characterized by the development of deep vertical mixing. Concerning the late Quaternary interval, in the Mediterranean area, *G. truncatulinoides* is mainly associated with the climate phases of the Bølling/Allerød (B/A), between the end of Younger Dryas (YD) and the onset of Sapropel S1 (Sprovieri et al., 2003; Budillon et al., 2009; Siani et al., 2010; Geraga et al., 2008, 2010; Lirer et al., 2013; Di Donato et al., 2019; Morabito et al., 2014), the YD (Mojtahid et al., 2015), the interstadials (Piva et al., 2008) and interglacial/glacial transition (Capotondi et al., 2016). In addition, Ivanova et al. (2003) in the Arabian Sea record documented this species also during the glacial stages and at glacial/interglacial transition (over the last 130 kyr BP), possibly related to transport from Southern Indian Ocean.

On that note, the main aim of this paper is the understanding of the hydrographic changes and the climate forcing that have allowed the proliferation of *G. truncatulinoides* over the MM.

## 2. Present-day oceanography of the study area

The Mediterranean is an elongated, enclosed sea with an anti-estuarine circulation, forced by the negative hydrological balance and salinity difference with the Atlantic Ocean (Robinson and Golnaraghi, 1994). The oceanic surface water enters from the Atlantic Ocean through the Gibraltar Strait, and spreads eastward into the Mediterranean Sea, occupying the upper 100–200 m of the water column (the depth range changes regionally). This Atlantic Water (AW) is exposed to a positive Evaporation-Precipitation (E-P) regime and mixes with resident waters along its path. These two processes lead to a progressive modification of its salinity (eastward positive gradient), ranging from ~36.5 at Gibraltar, 38.0–38.5 in the western Mediterranean, up to >39 in the easternmost part of the basin (POEM Group, 1992; Millot, 1999). The AW flows along the Algerian coast (Algerian Current), as a rather coherent flow, from which baroclinic instabilities may induce separation of a number of eddies and mesoscale meanders (Pinardi and Masetti, 2000; Hamad et al., 2005; Malanotte-Rizzoli et al., 2014). Off the western coast of Sicily, the vein of AW divides in two, of which one flows south of Sicily (across a well-known upwelling area; Robinson et al., 1999; Lermusiaux and Robinson, 2001; Béranger et al., 2004) towards the deep Ionian Sea and the Eastern Mediterranean, while the other enters the Tyrrhenian Sea, along the northern coast of Sicily, where it continues its way cycloni-

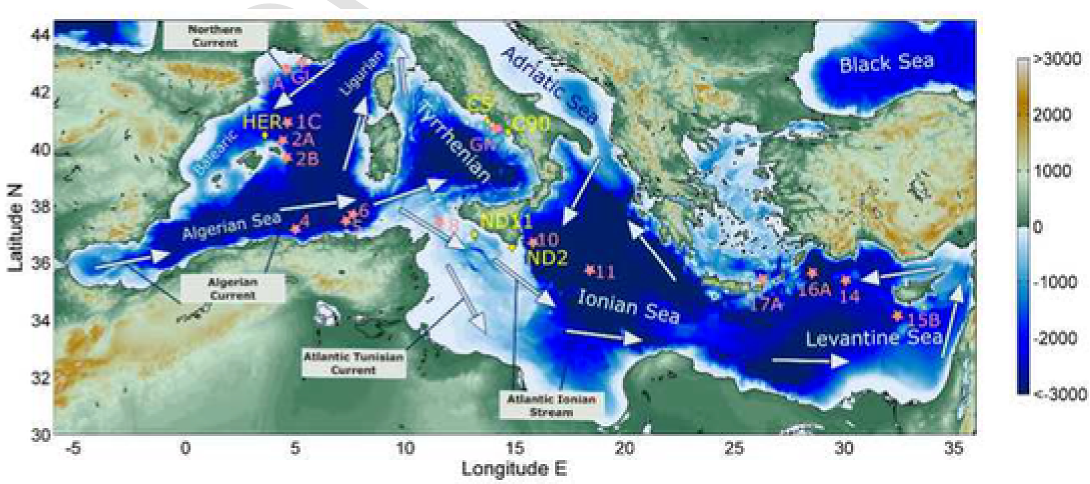


**Fig. 1.** Map of the Mediterranean Sea with the sampling points of the study cores (yellow diamonds), where: HER = HER-MC-MR3.3/3.1, ND11 = ND11-SW104, ND2 = ND2-SW104. Stations shown in Fig. 5 are indicated by red stars. The bathymetry and the main current systems of the Atlantic Water (AW) are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cally around the basin. Within the Sicily Channel itself, AW is again split in two veins (Béranger et al., 2004), called the Atlantic Tunisian Current (that reaches the African coast and then flows eastward along it) and the Atlantic Ionian Stream (that transports the bulk of the fresh AW in the eastern Mediterranean). The central part of the Tyrrhenian is characterized by high water depths, multiple mesoscale features such as anticyclonic and cyclonic eddies (Vetrano et al., 2010) and generally by an oligotrophic character (D'Ortenzio and Ribera d'Alcalà, 2009). Surface and intermediate waters are able to exit the Tyrrhenian Sea through the relatively shallow Corsica Channel. The current that forms along the Ligurian coast is called the Northern Current (NC), which is observed to circulate along the whole northern boundary of the Western Mediterranean Sea, up to the Balearic Sea and the Ibiza Channel.

For this paper climatological values of Mixed Layer Depth (MLD) have been used (Houpert et al., 2015a). For more details about the data and the methods used see Houpert et al. (2015b).

## 3. Material and methods

This study focuses on the distribution patterns of *G. truncatulinoides* between five different marine cores in the central and western part of the Mediterranean as follow: Balearic Sea (core HER-MC-MR3.1A/3.3, 40°29′N, 3°37′E - Margaritelli et al., 2018), central (core C5, 40°58′24,993"N, 13°47′03,040"E – Margaritelli et al., 2016) and southern Tyrrhenian Sea (core C90, 40°35,76′00"N, 14°42,48′00″E - Lirer et al., 2013), western (core SW104 -ND11, 37°01′57"N, 13°10′54″E - this study) and eastern Sicily Channel (core SW104-ND2, 36°33′52"N, 14°52′59″E – this study) (Fig. 1). The sampling resolution in each sediment core is 1 cm. The age models of the compared cores are based on radionuclides and AMS$^{14}$C datings. In Fig. 2 we compared the age-depth profiles of the five marine cores with the related tie-points and the identified study time interval (core HER-MC-MR3.1A/3.3: mean Sed Rate 0,015 cm/yr; core C5: mean Sed Rate 0,43 cm/yr; C90: mean Sed Rate 0,20 cm/yr; core ND11-SW104: mean Sed Rate 0,07 cm/yr; core ND2-SWI04: mean Sed Rate 0,30 cm/yr). See for details about the chronologies as follows: Cisneros et al. (2016), for core HER-MC-MR3.1A/3.3; Margaritelli et al. (2016), for core C5; Lirer et al. (2013), for core C90; Margaritelli et al. (2016) and Margaritelli et al., 2020) for core ND11-SW104 and Dentici (2018), for core ND2-SWI04.

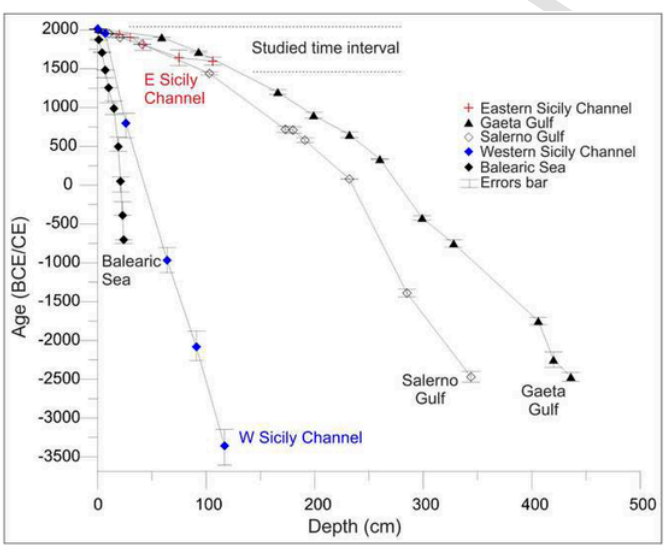


**Fig. 2.** Comparison of the age-depth profiles of the five study cores: Balearic Islands (Cisneros et al., 2016); Gaeta Gulf (Margaritelli et al., 2016); Salerno Gulf (Lirer et al., 2013); Western Sicily Channel (Margaritelli, 2016 and Margaritelli et al., 2020); Eastern Sicily Channel (Dentici, 2018).

### 3.1. Statistical analysis

All statistical analyses were performed on *G. truncatulinoides* left coiled abundance and Δ$^{14}$C signal (proxy for solar activity, Stuiver et al., 1998) over the Maunder event. As first step, we identified the measures of central tendency (mean, median, and mode) and of variability (standard deviation, variance, the minimum and maximum variables, and the kurtosis and skewness) to quantitatively describe our data (Table 1). In a second phase, since the probability distribution of the raw data of both biotic and abiotic fails the Kolmogorov-Smirnov test (Dodge, 2008) for normality, except for Balearic Sea and western Sicily Channel marine sediment cores, the Spearman correlation index (Dodge, 2008) was carried out by using IBM SPSS software (realize 22) was carried out for possible relationships between biotic and abiotic variables. The correlation matrix was calculated for *G. truncatulinoides* abundances measured for five marine sediment cores spanning from West to East the Mediterranean Sea (Table 2).

The descriptive analysis points out that in Gaeta and Salerno gulfs *G. truncatulinoides* has a wide range in variability with respect to Balearic Sea and eastern Sicily Channel. Conversely, in the western Sicily Channel, *G. truncatulinoides* signal shows a restricted range vary-

**Table 1**
Descriptive statistics of *Globorotalia truncatulinoides* abundances into five marine sediment cores covering the Mediterranean Sea. More than one modalities exist only the lowest values is reported.

| | | Balearic Sea | Gaeta Gulf | Salerno Gulf | western Sicily Cìhannel | eastern Sicily Cìhannel |
|---|---|---|---|---|---|---|
| Mean | | 15.593 | 10.47 | 9.45 | 12.979 | 7.215 |
| Median | | 15.721 | 9.43 | 8.88 | 13.000 | 7.239 |
| Mode | | 11.3 | 4.85 | 5.11 | 11.2 | 4.13 |
| Standard deviation | | 2.341 | 3.78 | 2.56 | 0.853 | 1.940 |
| Variance | | 5.482 | 14.34 | 6.56 | 0.728 | 3.765 |
| Asymmetry | | −0.156 | 0.21 | 0.40 | −0.185 | −0.129 |
| Standard error of asymmetry | | 0.240 | 0.24 | 0.24 | 0.240 | 0.240 |
| kurtosis | | −1.060 | −1.08 | −1.07 | −0.949 | −1.269 |
| Standard error of kurtosis | | 0.476 | 0.47 | 0.47 | 0.476 | 0.476 |
| Minimum | | 11.307 | 4.85 | 5.11 | 11.209 | 4.134 |
| Maximum | | 19.469 | 17.16 | 13.98 | 14.394 | 10.282 |
| Percentile | 25 | 13.705 | 7.87 | 7.26 | 12.307 | 5.182 |
| | 50 | 15.721 | 9.43 | 8.88 | 13.000 | 7.239 |
| | 75 | 17.600 | 13.60 | 12.09 | 13.709 | 9.110 |

**Table 2**
Correlation matrix (Spearman's rho) for the compared marine records and the Δ $^{14}$C signal (Stuiver et al., 1998). The double and single star indicate a correlation with a 0.01 and 0.05 p-value, respectively.

| | Balearic Sea | Gaeta Gulf | Salerno Gulf | W Sicily Channel | E Sicily Channel | Δ $^{14}$C |
|---|---|---|---|---|---|---|
| Balearic Sea | 1000 | | | | | |
| Gaeta Gulf | 0.555 ** | 1000 | | | | |
| Salerno Gulf | 0.893 ** | 0.742 ** | 1000 | | | |
| W Sicily Channel | 0.943 ** | 0.753 ** | 0.953 ** | 1000 | | |
| E Sicily Channel | 0.949 ** | 0.302 ** | 0.772 ** | 0.828 ** | 1000 | |
| Δ $^{14}$C | 0.485 ** | 0.925 ** | 0.692 ** | 0.694 ** | 0.226 * | 1000 |

ing between 11% and 14% (Table 1). Moreover, the interquartile range is very narrow for western Sicily Channel, it indicates that 50% of data has an abundance varying between 12% and 13% (Table 1). This parameter is larger for the eastern Sicily Channel (5.18–9.11%) and Balearic Sea (13.7–17.6) and larger for Gaeta (7.87–13.6%) and Salerno (7.26–12.1%) records. The correlation matrix reveals a good correlation, with a *p*-value level at 0.01, between the abundance of *G. truncatulinoides* in all five marine sediment cores and between these latter and the $\Delta^{14}C$ data during the Maunder period (Table 2). Only core ND2-SWI04 (eastern Sicily Channel) shows lower correlation indexes with $\Delta^{14}C$ and core C5 (Gaeta Gulf) signals probably due to the chronologies and/or additional local factors that could have altered the *G. truncatulinoides* signal.

The core top data published in MARGO dataset (Kucera et al., 2005) was integrated with those retrieved during the NextData Project (http://nextdataproject.it) and recorded into Weather and Water Database (WDB, wdb-paleo database, Alberico et al., 2017) in order to illustrate, by using the algorithms available into a Geographic Information System, the geographical variation of *G. truncatulinoides* abundance over the whole Mediterranean Sea (Fig. 3).

### *3.2. Planktonic foraminifera*

The study of planktonic foraminiferal assemblages was made on samples washed over a 63 μm sieve to remove the clay and silt fractions. Quantitative planktonic foraminiferal analyses were carried out on the size fraction >125 μm, considering at least 300 specimens, a number statistically consistent to perform paleoecological and paleoclimatic reconstructions (Patterson and Fishbein, 1989). In this study, we considered only the distribution patterns of *G. truncatulinoides* left coiled (type II of Quillévéré et al., 2013) because of right coiled ones is scattered present (less 1%) over the last 500 years in the study sites (Sprovieri et al., 2003; Lirer et al., 2013). This micropaleontological feature shows similarities with that reported by Pujol and Vergnaud Grazzini (1995) in the modern assemblage (surface sediments and plankton tows) documenting very low abundance (less 1%) of *G. truncatulinoides* right coiled and in the sediment-trap record of Gulf of Lion (Rigual-Hernández et al., 2012).

*G. truncatulinodes* relative abundance data are as follows: Balearic Sea (Margaritelli et al., 2018); central and south Tyrrhenian Sea are from Margaritelli et al. (2018) and Lirer et al. (2013), respectively; western (Margaritelli, 2016; Margaritelli et al., 2020) and eastern Sicily Channel (Dentici, 2018) (Fig. 4).

## 4. Ecological features of *G. truncatulinoides*

*G. truncatulinoides* is a deep-dwelling planktonic foraminifer (Bé, 1960; Bé and Tolderlund, 1971; Emiliani, 1954; Le Grande et al., 2004) having a complex life cycle, which involves substantial vertical migration in the water column, likely related to reproduction (e.g., Bé and Ericson, 1963; Deuser and Ross, 1989; Lohomann and Schweitzer, 1990). Reproduction of the species is believed to occur once per year in late winter at depths where vertical mixing of the water column is required for the migration of juveniles to surface waters (Lohmann and Schweitzer., 1990; Schiebel et al., 2002; Spear et al., 2011).

*G. truncatulinoides* continues its life cycle by migrating down through the water column, adding an additional calcite layer (secondary crust) (Bè and Lott, 1964) at ~350 m depth when reaching cooler waters below the thermocline (Orr, 1967; Lohomann and Schweitzer, 1990; Mulitza et al., 1997; Wilke et al., 2009). Lohomann and Schweitzer (1990) showed that adults live and reproduce at different depths, possibly reflecting different water masses or thermocline depth. Geochemical assessments of calcification temperatures confirm that *G. truncatulinoides* records hydrographic properties down to the lower thermocline (Cléroux et al., 2009; Steph et al., 2009).

Peaks of relative and absolute abundance occur in deep winter mixed water layers, probably as a result of its life cycle (Schiebel and Hemleben, 2017). Some authors (Itou and Noriki, 2002; Salmon et al., 2015) suggested a relation between *G. truncatulinoides* flux increase, during winter and spring seasons, and food availability. In addition, in sediment-trap records in the Gulf of Lion, this species increases in abundance during winter-spring transition, when the Sea Surface Temperature (SST) is low in phase with the intense mixing occurring in this area (Rigual-Hernández et al., 2012).

It may be suggested that the winter mixing is in favour of reproductive strategy of the left coiled form (Pujol and Vergnaud Grazzini, 1995; Schiebel and Hemleben, 2017). The coiling direction of *G. truncatulinoides* has been considered to be indicative of different water masses (temperature and salinity) (e.g., Bé, 1960; Tolderlund and Bé , 1971) and depths (Lohmann, 1992). A specific study on coiling direction of *G. truncatulinoides* in the Mediterranean and a possible connection with change in environmental/oceanographic conditions is not present. However, the right coiled specimens (during the Middle and Late Holocene) occur just after the chronological interval of Sapropel

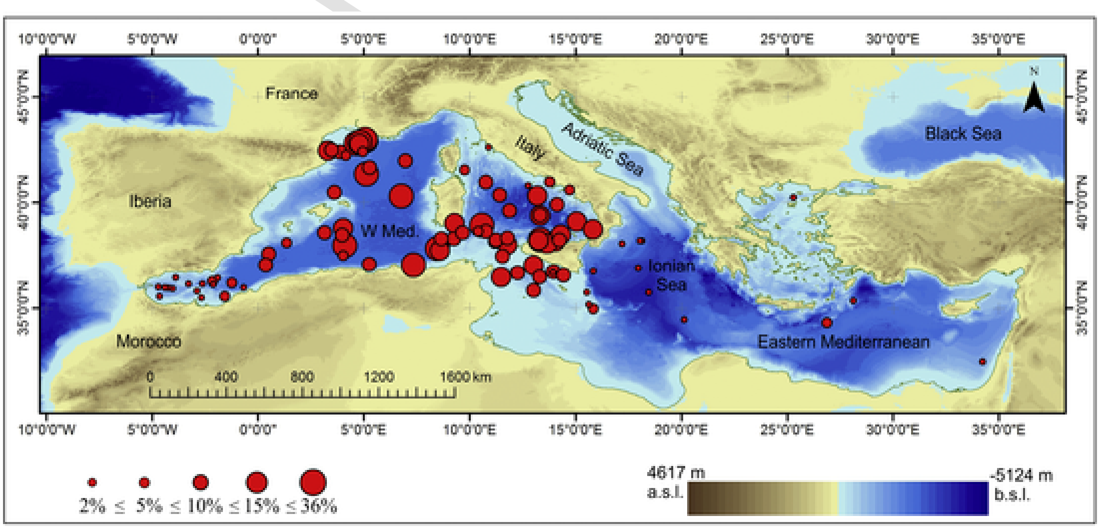


**Fig. 3.** Geographical distribution of *G. truncatulinoides* abundance % in core top samples of the Mediterranean Sea (Kallel et al., 1997; MARGO database Kucera et al., 2005 modified in this work with additional core top samples from Nextdata Project - http://www.nextdataproject.it).

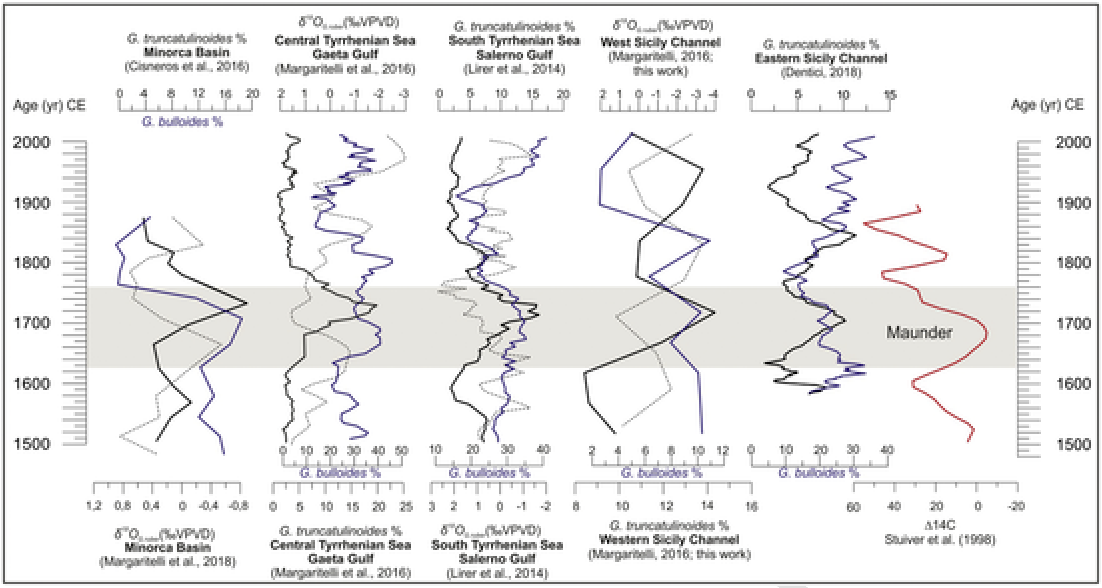


**Fig. 4.** Comparison in time domain of *G. truncatulinoides* left coiled abundance percentages (black line) between the marine records: Balearic Sea (Margaritelli et al., 2018) with $\delta^{18}O_{G.ruber}$ data from Margaritelli et al. (2018); central Tyrrhenian Sea (Margaritelli et al., 2016) with $\delta^{18}O_{G.ruber}$ data (Margaritelli et al., 2016); south Tyrrhenian Sea (Lirer et al., 2014) with $\delta^{18}O_{G.ruber}$ data (Lirer et al., 2013, 2014); western Sicily Channel (Margaritelli, 2016; this work) with $\delta^{18}O_{G.ruber}$ data (Margaritelli, 2016); eastern Sicily Channel (Dentici, 2018) and the $\Delta^{14}C$ (in red; Stuiver et al., 1998). In blue, the distribution pattern of *Globigerina bulloides* is shown for each site. The grey bar represents the Maunder Minimum event according to the $\Delta^{14}C$ signal (Stuiver et al., 1998). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

S1 deposition in the western Mediterranean (Sprovieri et al., 2003; Lirer et al., 2013) and virtually disappeared over the last 2 millennia. We could speculate a possible connection of right coiled specimens with still weak stratified water masses after the sapropel deposition occurring during the summer season.

The morphospecies *G. truncatulinoides* includes five genetic types (I, II, III, IV and V), as documented by phylogenetic analyses of partial SSU rDNA and internal transcribed spacer (ITS) sequences (de Vargas et al., 2001; Quillévéré et al., 2013). The genetic type II is present in the Mediterranean basin (de Vargas et al., 2001).

Studies focused on modern planktonic foraminiferal distribution (De Castro Coppa et al., 1980; Pujol and Vergnaud Grazzini, 1995) and sediment-trap records (Rigual-Hernández et al., 2012) in the Mediterranean Sea indicate that the abundance percentages of *G. truncatulinoides* are highest during the winter and very low during the summer season (Fig. 5). In addition, Vergnaud Grazzini, 1976 describe the maximum abundances of *G. truncatulinoides* from December to April.

The distribution of this species concentrates in the central-western part of the Mediterranean Sea, in areas of intense water mixing during winter (Pujol and Vergnaud Grazzini, 1995), decreasing until it disappears going towards east (Fig. 5), probably due to an increasing pattern of the water column temperatures going eastward (Iona et al., 2018) and the disability to cope with the ultra-oligotrophy of the easternmost part of the Mediterranean compared to other regions during winter and spring (Avnaim-Katav et al., 2020). The geographic distribution pattern of *G. truncatulinoides* is well documented also core-top data of Kallel et al. (1997) and in the Margo dataset (Kucera at el.,

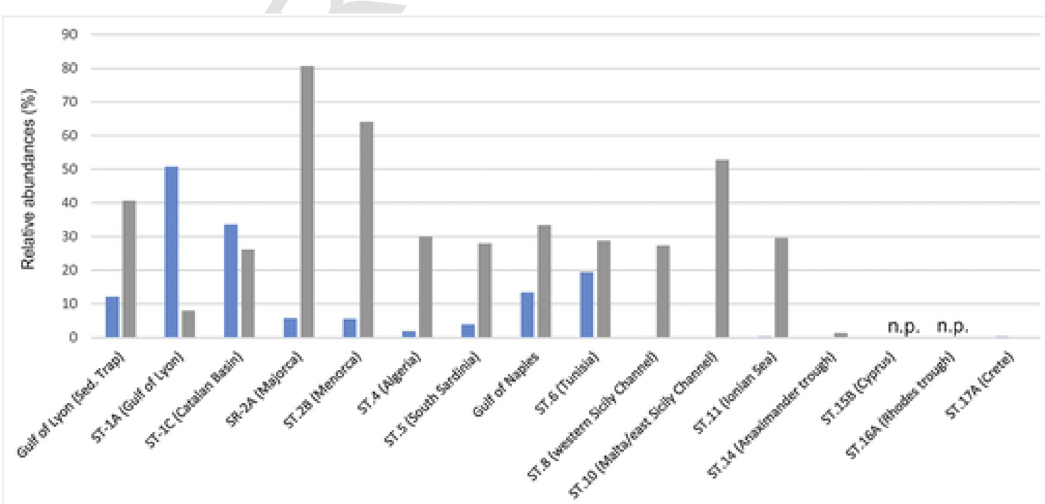


**Fig. 5.** Histogram of the relative abundances (%) of living *G. truncatulinoides* in the Mediterranean Sea. Sediment trap data from Gulf of Lion (GL) refer to Rigual-Hernández et al. (2012). Living *G. truncatulinoides* from Gulf of Naples (GN) refers to De Castro Coppa et al. (1980), while all other data refer to Pujol and Vergnaud Grazzini (1995). Grey bars represent the winter signal and blue bars the summer-autumn season. The acronym "n.p." means "not present". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2005) (Fig. 3). In particular, high abundance values of this species concentrates from Minorca basin to Sicily Channel, while it is absent from the Adriatic Sea and it shows low abundance values in the Alboran Sea and in scattered sites of the Ionian Sea and in the Eastern Mediterranean (Fig. 3). In addition, in recent studies on fossil planktonic foraminiferal assemblages, over the last ca. four millennia, display the absence of this species from the Ionian Sea (Geraga et al., 2008), Adriatic Sea (Siani et al., 2010), Aegean Sea (Triantaphyllou et al., 2009; Kontakiotis et al., 2013; Kontakiotis, 2016; Giamali et al., 2019) and in the Levantine Sea (Rohling et al., 1993; Avnaim-Katav et al., 2020).

## 5. Results and discussions

The LIA starts at ca. 1250 CE and is characterized by three climatic oscillations: Wolf, Spörer and Maunder cold events (Stuiver et al., 1998). The MM is characterized by persistent extremely cold winters in Europe (Barriopedro et al., 2008) and, according to regional time series, winters of that period were characterized by a higher frequency of severe climatic conditions than those of the twentieth century (Luterbacher et al., 2001).

The comparison between the *G. truncatulinoides* left coiled relative abundance of the Balearic Sea (Margaritelli et al., 2018), central (Margaritelli et al., 2016) and south Tyrrhenian Sea (Lirer et al., 2013), western (Margaritelli, 2016; Margaritelli et al., 2020) and eastern Sicily Channel (Dentici, 2018) allows to highlight a reaction of this species to the MM events in the central-western Mediterranean Sea (Fig. 4).

Despite relatively low time-resolution and the spatial heterogeneity of the compared marine sites, it is possible to observe a good correspondence of the increase in abundance of *G. truncatulinoides* from 1650 CE to 1760 CE, with maximum interval of ca. 50 years of highest abundance, during the Late MM event (Barriopedro et al., 2008). In terms of amplitude signal, the relative abundance of *G. truncatulinoides* in the sites located in western Mediterranean Sea (Gaeta and Salerno Gulfs and in Balearic Sea) are quite similar (reaching the maxima abundance values between 16% and 20%) while in the two sites in the Sicily Channel reaches the maxima abundance values between 10% in the east and 14% in the west (Fig. 4). This framework is also visible in the score plot analysis pointing out a general progressive decreasing trend from west to east in *G. truncatulinoides* abundance patterns (Fig. 6).

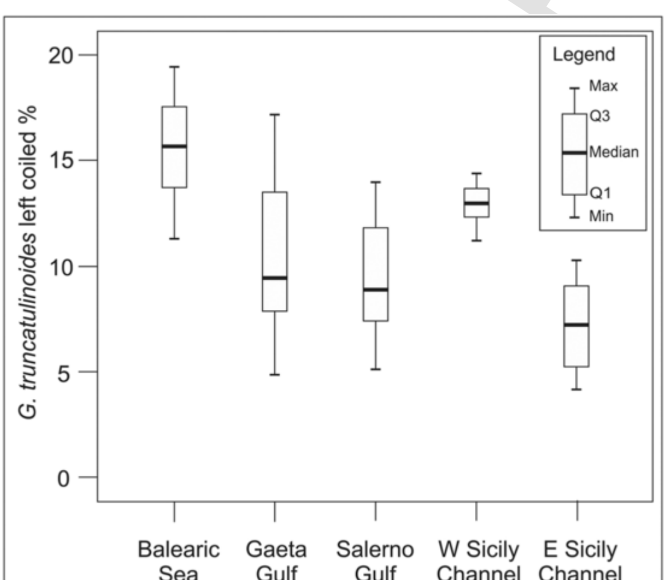


**Fig. 6.** Boxplot display the distribution of *G. truncatulinoides* left coiled by using five numbers: minimum, first quartile (Q1), median, third quartile (Q3), and maximum.

This difference seems to reflect the core top (Fig. 3) and the present day (Fig. 5) distributions of this species highlighting a decreasing trend from west to east through the Sicily Channel. In addition, the *G. truncatulinoides* highest abundance intervals occur when the $\delta^{18}O_{G.\ ruber}$ values are heavier suggesting cold climate condition (Fig. 4). Recently, Margaritelli et al. (2018) and Lirer et al., 2019b) proposed a Mediterranean $\delta^{18}O_{G.\ ruber}$ west-east correlation documenting a trend vs heavier values during the MM, suggesting regional cold climate condition. Mg/Ca SST reconstructions for the Balearic Sea ($Mg/Ca_{G.\ bulloides}$, Cisneros et al., 2016) and from western Sicily Channel ($Mg/Ca_{G.ruber}$ SST, Margaritelli et al., 2020) confirm the cooling during MM in correspondence of *G. truncatulinoides* maxima. This cooling is also well documented in continental temperature reconstructions in Europe (Luterbacher et al., 2016). The onset of the MM characterized by a strong increase in abundance of *G. truncatulinoides* (Fig. 4) suggesting enhanced vertical mixing during winter (Margaritelli et al., 2016, 2018). The intensification of vertical mixing could be linked to atmospheric blocking (blocking events occur when long-lasting high-pressure systems are able to "block" or redirect migratory cyclones) (Barriopedro et al., 2008; Moffa Sánchez et al., 2011; Häkkinen et al., 2011). In fact, Barriopedro et al. (2008) suggest that cold conditions in Europe during the MM may be linked to an eastward shift of long-lasting blockings, and not to an increase in frequency of blocking episodes. The authors showed that cold European events were more likely to occur under low solar activity blocking regimes. Also, Rîmbu and Czymzik (2015) showed that the appearance of extremely cold winters from eastern and central Europe were associated with the intensification of the blocking circulation over the Scandinavian Peninsula and the British Isles.

Barriopedro et al. (2008) found evidences of a connection between northern hemisphere winter blocking events and the solar cycle. They underlined that during periods of low solar activity, in particular during the MM, blocking events were of greater duration, more intense and had high percentages of December–March 'blocking' days that were associated with extremely cold temperatures. The anticyclonic circulation of the blocking affects temperatures especially on the eastern and southern flanks by advection of cold air from the north and east (e.g., Trigo et al., 2004; Bieli et al., 2015). The persistence of the atmospheric blocking events, diverted the normal flow of westerly winds across the Europe (Degroot, 2018). In addition, Raible et al. (2007), comparing the MM cyclone simulations with the 1990 cyclone control simulation, suggesting that the extreme wind speed events were intensified in winter and summer as the mean cyclone density during the MM event (Raible et al., 2007).

The atmospheric blocking events could have triggered an intense phenomenon of mixing water producing ideal ecological conditions for *G. truncatulinoides* proliferation. In fact, the break - down of the thermocline during winter and the intensification of vertical mixing could have facilitated the ascent of *G. truncatulinoides* to the euphotic zone, where it proliferates due to strong advection of nutrients from the nutrient-rich deeper layers and consequently high primary productivity (Hemleben et al., 1985; Renaud and Schmidt, 2003; Schiebel and Hemleben, 2005; Schiebel et al., 2002).

This interpretation is also supported by the increase in abundance of the nutrient rich species *Globigerina bulloides* (maxima values between 20% to 40% of the total planktonic foraminiferal fauna) at the study sites (Fig. 4), indicating enhanced primary production during the onset of Maunder event. The mixed layer depth (MLD) is one of the most important seasonal oceanic features, which variability has a key influence on the upper ocean physics, chemistry and biology. Major biogeochemical processes occur here, having a pivotal influence on Earth's climate (Falkowski et al., 1998). The ML is typically tens of meters deep, and due to the fact that it is well mixed, temperature, salinity and water density of the ML are rather uniform. Its base is defined by regions with rapidly changing conditions (enhanced vertical gradients), called thermocline, halocline and pycnocline. Wind is the main mixing agent that drives the formation and the deepening of the ML, homogenizing its temperature and salinity. Generally, the ML is nutrient-poor, and it is the mixing at its base that allows the injection of nutrients from the nutrient-rich deeper layers and enhances the productivity levels (Schiebel et al., 2001).

The Mediterranean circulation is characterized by the presence of a number of sub-basin gyres, intense mesoscale activity and a strong seasonal variability, which in turn is due to the highly variable atmospheric forcing (Millot, 1999). The upper layer and especially the ML reflect this variability in time and space. According to D'Ortenzio et al. (2005), the Mediterranean MLD seasonal variability is today characterized by a basin scale deepening from November to February–March and increasing stratification in April. Stratification is maintained throughout the summer and early fall. The maximum values of MLD are observed in February-March in the Gulf of Lion and the southern Adriatic Sea (D'Ortenzio et al., 2005), which are regions of dense water formation (Schroeder et al., 2012).

In exceptionally cold and windy winters, the dense water formation, and hence the area with maximum MLD, may extend to include also the Ligurian Sea (Schroeder et al., 2008) and the Balearic basin (Smith et al., 2008), where the deepest sampling point is located. The occurrence of a blocking activity during the MM might have increased the wind intensity in winter in the area, extending the region where deep convection may occur. Strong north-westerly winds (Mistral-like) have a major impact on the Balearic Sea-Provencal Basin-Ligurian Sea, but also the Sicily Channel is located on their path and is frequently hit by the same wind events, where they cause Ekman upwelling (Jouini et al., 2016). Present climatological MLD in winter (JFM) for the five sampling stations are comprised between 40 m and 75 m (Fig. 7). It is very likely that these average values, especially the winter ones, were significantly higher during the MM, given the lower solar heating of the sea surface and the increased intensity of winterly winds, due to the blocking episodes.

We suggest that the impact of blocking activity might have reinforced the deep vertical mixing in the study sites (central-western Mediterranean), with a strong advection of nutrients from the nutrient-rich deeper layers and enhanced productivity levels in the mixed layer, as supported by the increase in abundance of opportunistic species such as *G. bulloides* during the MM. These condition during cold winter seasons of MM, could have generated a new favourable ecological niche for *G. truncatulinoides* during this short time interval.

In addition, caused by the water exchange between Mediterranean and Atlantic (Garret et al., 1990; Sannino et al., 2009; Rogerson et al., 2012), the inflow through the Strait of Gibraltar could have slightly changed in the past, but not as a response to intensified current systems in the Atlantic. It only could have become slightly higher than now, as a response to a more active dense water formation within the Mediterranean Sea, which cold period such as the MM. However, the mass transport values of the inflow are so small (<1 Sv) that a variation can barely been taken in consideration as a cause of the observed peaks in *G. truncatulinoides* occurrences. According to this oceanographic framework and with the available quantitative data for this study we suggest that *G. truncatulinoides* left coiled (genetic type II, de Vargas et al., 2001) increases within the Mediterranean basin due to a strong intensification of deep vertical mixing associated with a blocking event.

Moreover, in the sediment trap data from Gulf of Lion, Rigual-Hernández et al. (2012) suggested that the elevated abundances of *G. truncatulinoides*, during the winter–spring transition, may indicate an affinity of *G. truncatulinoides* with the increase mixing conditions and nutrient availability in the Gulf of Lions (Fig. 5). In the north-western basin, the modern assemblages of planktonic foraminifera show highest percentages of *G. truncatulinoides* (Fig. 3), probably associated with Western Mediterranean Deep Water formation (Hayes and Broggy, 2019), which provide the means for this species to complete its life cycle.

## 6. Conclusions

*G. truncatulinoides* represents a deep dwelling winter species in the Mediterranean Sea and its life-cycle is characterized by a vertical migration in the water column.

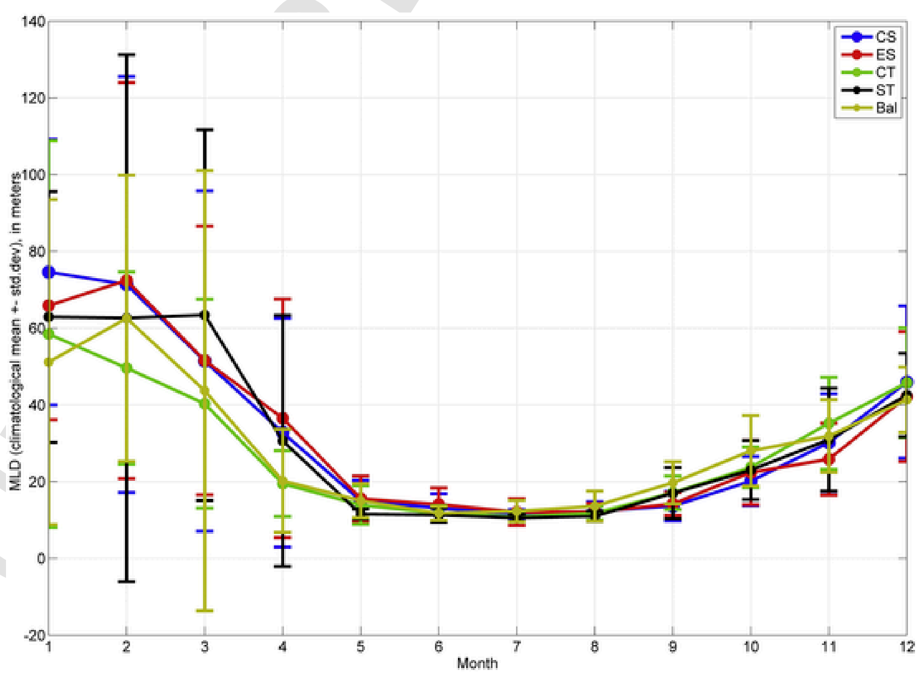


**Fig. 7.** Monthly climatological values of Mixed Layer Depth (MLD) under present climatic conditions. ST = southern Tyrrhenian, CT = central Tyrrhenian, ES = eastern Sicily; CS = central Sicily; Bal = Balearic Sea.

In this paper we present a comparison of *G. truncatulinoides* oscillations in the central and western Mediterranean Sea (Balearic Sea, central and southern Tyrrhenian Sea, central and eastern Sicily Channel) over the last 500 yrs. with a particular attention to the MM, the coldest phase of the LIA, characterized by an increase in climatic variability all over Europe.

*G. truncatulinoides*, in all of the records presented here, shows a significant increase in abundance during the MM. This time-interval is characterized by an atmospheric blocking event. These particular climatic conditions could be responsible of intense deep vertical mixing phenomenon during the winter season with enhances of the productivity in the mixed layer, producing the ideal ecological conditions for *G. truncatulinoides* proliferation. In addition, we suggest that maximum abundance of *G. truncatulinoides* left coiled is a response to more active dense water formation within the Mediterranean Sea during a cold time-period such as the MM. This suggests that *G. truncatulinoides* can be considered an excellent bioindicator of surface water mixing and nutrient availability in the central and western Mediterranean Sea (Balearic Sea, central and southern Tyrrhenian Sea, central and eastern Sicily Channel).

## Authors statement

Dr. Giulia Margaritelli: carried out foraminiferal and geochemical analysis on cores from Minorca basin, central Tyrrhenian Sea and west Sicily Channel; developed the interpretative framework of the work and wrote the manuscript. Participated to the oceanographic cruises focused to recover the cores from central Tyrrhenian Sea and western and eastern Sicily Channel.

Dr. Fabrizio Lirer: developed the interpretative framework of the work and wrote the manuscript. Participated to the oceanographic cruises focused to recover the cores from central and south Tyrrhenian Sea and western and eastern Sicily Channel.

Dr. Katrin Schroeder: supported oceanographic discussions and wrote part of the manuscript.

Dr. Alberico Ines: carried out statistical analysis and wrote part of the manuscript.

Dr. Maria Paola Dentici: carried out foraminiferal analysis on core from eastern Sicily Channel. Participated to the oceanographic cruise focused to recover the cores from western and eastern Sicily Channel.

Prof. Antonio Caruso: supported the discussion on ecology of *Globorotalia truncatulinoides* in the Sicily Channel.

## Uncited reference

Itou and Noriki, 2002

## Declaration of Competing Interest

None.

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