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Age refinement of the Messinian salinity crisis onset in the Mediterranean

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ABSTRACT

We propose a revised age calibration of the Messinian salinity crisis onset in the Mediterranean at 5.971 Ma based on the recognition of an extra gypsum cycle in the transitional interval of the Perales section (Sorbas basin, Spain) and the revision of the magnetostratigraphy of the Monticino section (Vena del Gesso basin, Italy). This age re-calibration allows to state more accurately that: (i) the interval encompassing the MSC-onset is continuous, thus ruling out any erosional feature or stratigraphic hiatus related to a major sea-level fall affecting the Mediterranean; (ii) the first gypsum was deposited during the summer insolation peak at 5.969 Ma associated with an eccentricity minimum and roughly coincident with glacial stage TG32; (iii) the MSC-onset was preconditioned by the tectonically-driven reduction of the hydrological exchanges with the Atlantic Ocean and finally triggered by glacial conditions in the northern hemisphere and by arid conditions in northern Africa.

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Introduction

The Messinian salinity crisis (MSC) onset has been dated at 5.96 ± 0.02 Ma (Krijgsman *et al.*, 1999a), based on the high-resolution cyclostratigraphic framework reconstructed for the pre-MSC Mediterranean successions, with sedimentary cycles controlled by astronomical forcing (Krijgsman *et al.*, 1995, 2004; Hilgen and Krijgsman, 1999; Sierro *et al.*, 2001). This stratigraphic framework could be only tentatively extended into the MSC interval due to the absence of clear biomagnetostratigraphic events (Krijgsman *et al.*, 2001). Recently, detailed sedimentologic and stratigraphic studies on the Messinian evaporites as well as in continuous open-marine sections in the Atlantic margin of Morocco, led to the reconstruction of a robust high-resolution stratigraphic framework for the evaporite-bearing successions (van der Laan *et al.*, 2006; Hilgen *et al.*, 2007; Manzi *et al.*, 2009; Lugli *et al.*, 2010).

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The recentmost MSC chronostratigraphic framework (Fig. 1) is mainly based on a thorough revision of the "Lower Evaporites" (LE) and their time-equivalent deposits (CIESM – Commission Internationale pour

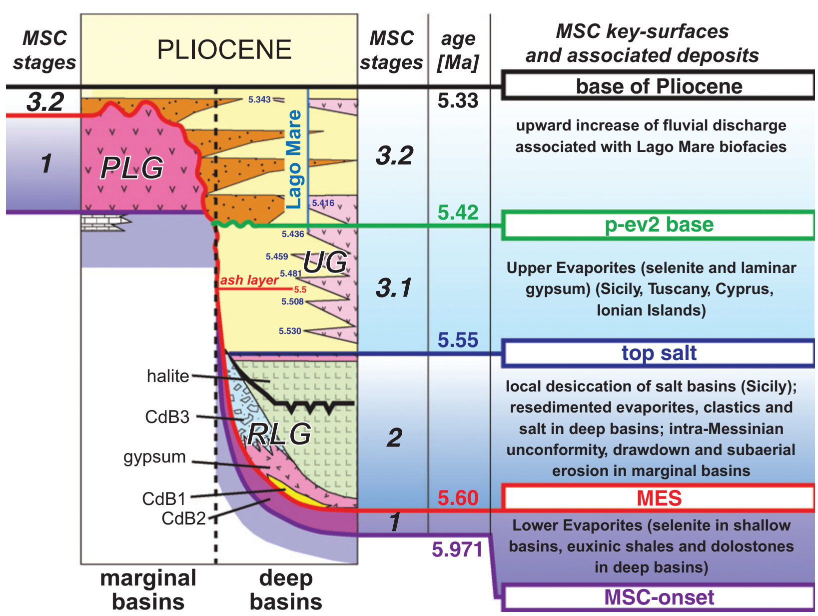

Fig. 1 The CIESM - Commission Internationale pour l'Exploration Scientifique de la mer Méditerranée (2008) Messinian salinity crisis stratigraphic framework (modified after; Roveri *et al.*, 2008a,b; Manzi *et al.*, 2011) showing the 5 key-surfaces used in the definition of the MSC stages. PLG, Primary Lower Gypsum; RLG, Resedimented Lower Gypsum; UG, Upper Gypsum; CdB1, CdB2, CdB3, Calcare di base types (Manzi *et al.*, 2011); MSC-onset, onset of the Messinian salinity crisis; MES, Messinian erosional surface (Lofi *et al.*, 2005); age of the base of Pliocene after Van Couvering *et al.*, 2000.

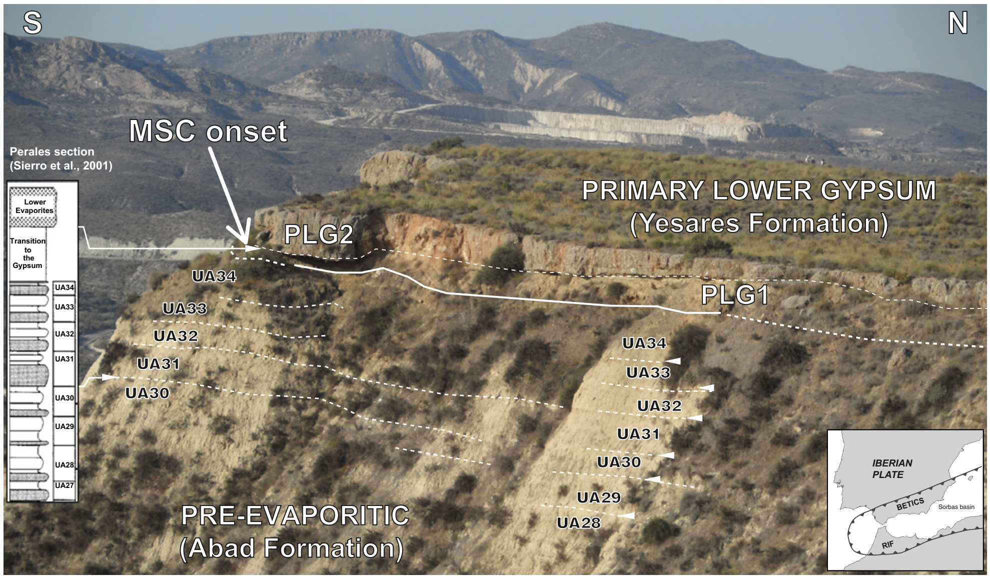

Fig. 2 Panoramic view of the MSC-onset in the Perales section (Sorbas basin, Betic Cordillera, Spain).

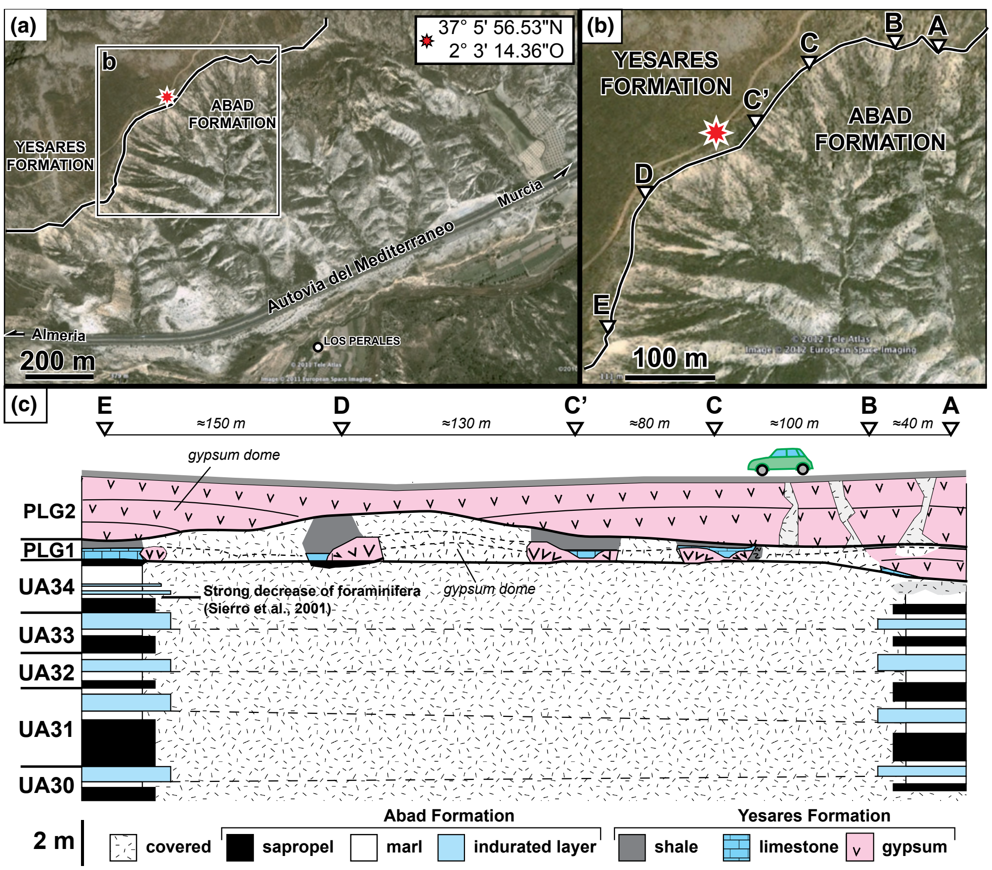

Fig. 3 Perales section (Sorbas basin, Betic Cordillera, Spain), reconstruction of the lateral facies changes in the interval encompassing the Messinian salinity crisis onset. The lowermost gypsum bed shows rapid lateral transitions: from a 20 cm-thick limestone layer (section E) to small, isolated gypsum cauliflowers (section D) or domes (sections C and C′) and to a 1 m-thick gypsum bed separated from the overlying one by a few cm-thick shale interval (from section B to section A).

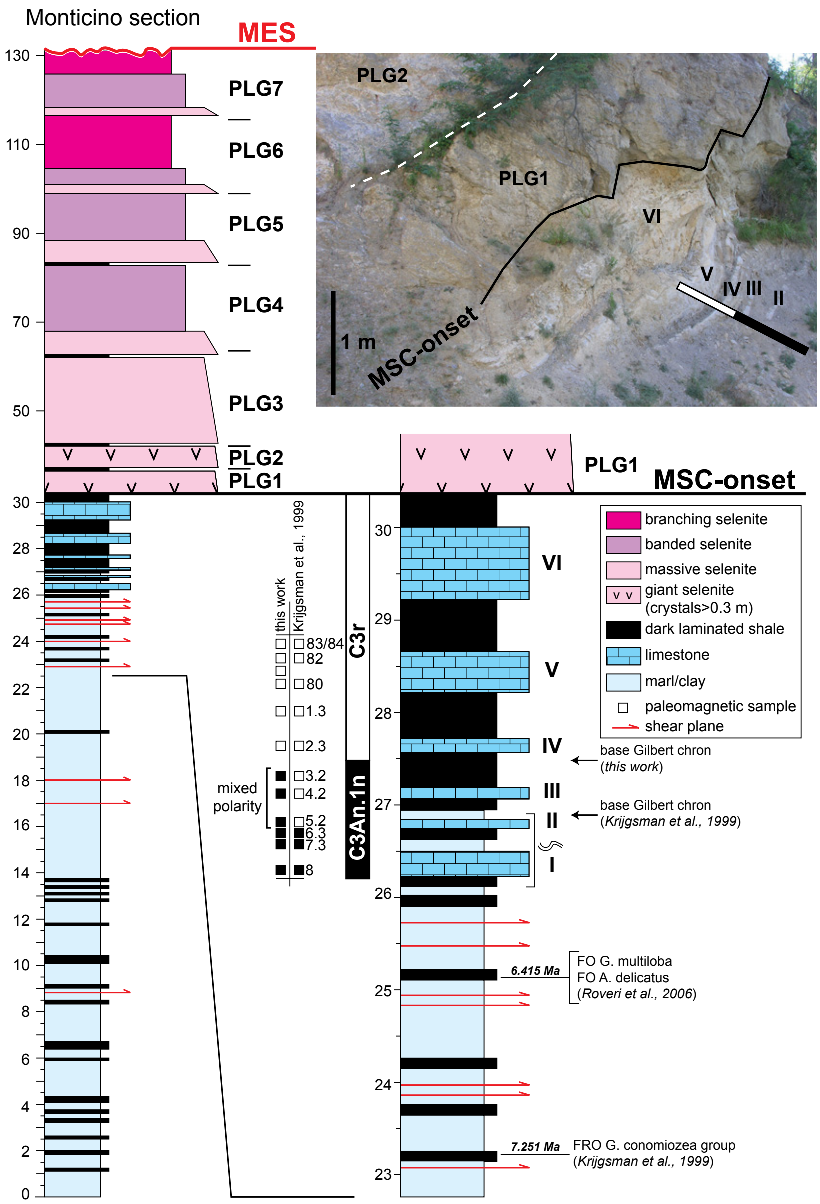

Fig. 4 The Monticino section (Vena del Gesso basin, Northern Apennines Italy). PLG1-PLG7, cycle of the Primary Lower Gypsum unit. I, II, III, IV, V, VI, limestone bed (Calcare di base *sensu* Vai, 1988).

l'Exploration Scientifique de la mer Méditerranée, 2008; Roveri *et al.*, 2008a; Manzi *et al.*, 2009, 2011). It envisages a two-step/three stages progression of the MSC, inspired and substantially modified after Clauzon *et al.* (1996). During stage 1, thick primary shallow-water evaporites (Primary Lower Gypsum, PLG; Roveri *et al.*, 2008a) accumulated in semi-enclosed marginal basins, whereas in the deep settings only euxinic shale and dolostone accumulated (Manzi *et al.*, 2007, 2011; DeLange and Krijgsman, 2010; Dela Pierre *et al.*, 2011). Since 5.60 Ma (stage 2) an acceleration of tectonic activity, likely coupled with glacial conditions (TG12 and TG14), caused the large-scale erosion of the PLG and their en-mass resedimentation in basin lows to form the RLG unit (Resedimented Lower Gypsum; 2008b) which also includes huge volumes of primary halite and records the MSC acme.

During stage 3 the Mediterranean was characterized by a peculiar palaeoceanographic setting with a diluted superficial water-mass hosting hypohaline Paratethyan faunal assemblages; the local and periodic gypsum precipitation ("Upper Evaporites"; UE) suggests the maintenance of marine connections, albeit reduced, with the global ocean (Manzi *et al.*, 2009).

The 5.96 $\pm$ 0.02 Ma age for the MSC-onset is based on the lithological transition from pre-evaporitic sapropel-marl-diatomite successions to the base of the LE (Krijgsman *et al.*, 1999a, 2004; Sierro *et al.*, 2001). This transition takes place at the same sedimentary cycle at the Molinos/Perales (Spain), Falconara (Sicily) and Metochia (Greece) (Krijgsman *et al.*, 1999a). However, detailed investigations on the LE showed that this transition is more complex than commonly thought, and strongly differs between deep and marginal settings (Roveri *et al.*, 2008a; Manzi *et al.*, 2009, 2011). Molinos/Perales is the only section clearly showing the PLG base; the other two sections grade into evaporitic carbonates/dolostones that cannot be easily correlated to time-equivalent PLG gypsum beds.

Monticino (Vena del Gesso basin, Italy) is another well-studied MSC section where a complete integrated-stratigraphic study of the transition interval to the PLG unit was performed (Marabini and Poluzzi, 1977; Marabini and Vai, 1988; Krijgsman *et al.*, 1999b).

Following the recent revisitation of the PLG evaporites (Lugli *et al.*, 2008, 2010), we propose here a new stratigraphic calibration of the MSC-onset, improving the pioneering studies of Sierro *et al.* (2001). Based on new detailed observations of the transition interval between the pre-evaporites and the PLG in the Perales and Monticino sections, we present a more precise calibration of the interval preceding the MSC to the astronomical target curves that: (i) reduces stratigraphic and chronologic uncertainties in the position of the MSC-onset; (ii) helps understanding the global processes (climatic trend, glaciations, global sea-level fluctuations) associated with the deposition of the gypsum beds and their stacking pattern.

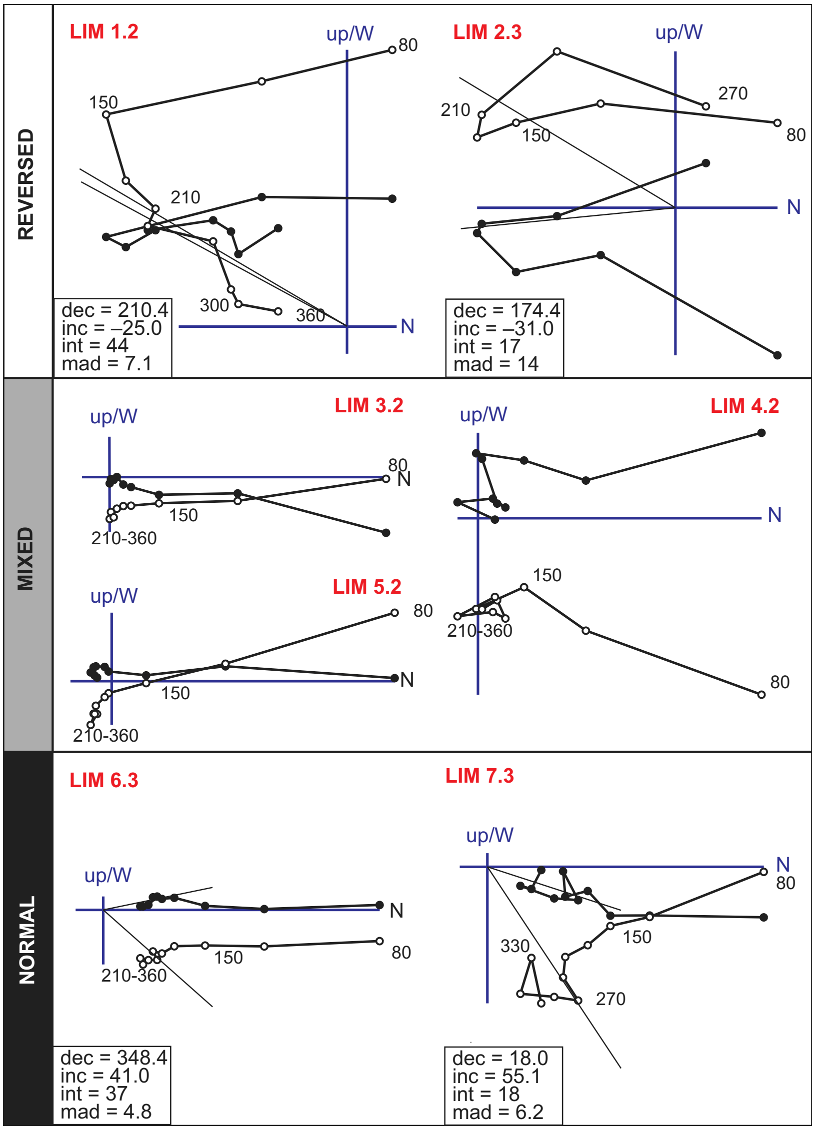

Fig. 5 Zijderveld diagrams of the samples used in this work for the refining of the position of the base of the gilbert chron, see location of samples in fig. 4.

Perales section, Sorbas basin (Betic Cordillera, Spain)

The Perales section (Fig. 2), located in the central portion of the Sorbas basin (SB), includes up to 55 lithological cycles in the Abad Formation, recorded by the rhythmic deposition of homogeneous marls, more indurated opal-rich carbonatic layers, sapropels and diatomites, between the Tortonian-Messinian boundary (7.251 Ma; Hilgen *et al.*, 2000) and the base of the Yesares Fm corresponding with the MSC-onset (5.96 ± 0.02; Krijgsman *et al.*, 1999a). A high-resolution integrated stratigraphic study resulted in the recognition of 18 planktonic foraminifera bioevents, which were shown to be synchronous throughout the Mediterranean by means of cyclostratigraphic bed-to-bed correlations (Sierro *et al.*, 2001). Paleomagnetic investigations revealed the presence of three components of magnetic remanence, a low-temperature (100–240 °C) normally directed component, an intermediate (240–420 °C) dual polarity component, and a high-temperature (>420 °C) normally directed component. The intermediate component was interpreted as the primary component, although reliable directions were difficult to obtain because of partial overprints probably caused by delayed acquisition. Polarities were generally more straightforward and the N/R reversal boundary corresponding to the base of the Gilbert Chron (C3r(y)) could be located between the homogeneous marls of cycle UA31 and the sapropel of UA32, i.e. three precessional cycles below the transitional interval to the Yesares Fm (Krijgsman *et al.*, 1999a; Sierro *et al.*, 2001).

In the badlands facing Los Perales, an additional, highly discontinuous gypsum bed has been observed within the "transitional interval" at the Abad-Yesares boundary (Sierro *et al.*, 2001), below the lowermost continuous gypsum bed, usually considered as the first PLG cycle (Fig. 2). This bed shows rapid lateral facies and thickness transitions (Fig. 3) related to the distribution of hyper-saturated and oxygenated conditions within the basin controlling where gypsum may form (DeLange and Krijgsman, 2010; Lugli *et al.*, 2010).

Thus, in agreement with the stratigraphic correlation proposed between "Los Molinos" and "Los Yesos" sections (Roveri *et al.*, 2009; Lugli *et al.*, 2010), the stratigraphic framework of Sierro *et al.* (2001) can be improved as follows: the "transitional to gypsum" interval contains the "true" 1st PLG cycle whereas the formerly considered "first evaporitic layer" actually corresponds to the 2nd PLG cycle.

Monticino section, Vena del Gesso basin (Northern Apennines, Italy)

The Monticino section was first studied by Marabini and Poluzzi (1977) who described the presence of up to six carbonate beds, named "Calcare di Base", at the transition between the pre-MSC euxinic shales and the selenite beds of the Gessoso-solfifera Formation. The Monticino and the Rio Albonello sections (Marabini and Poluzzi, 1977) are actually the only sections of the Vena del Gesso basin (VDGB) showing the stratigraphic interval encompassing the MSC-onset. Afterwards, the studies mainly focused on the Messinian vertebrate assemblages recovered from sedimentary fillings of some paleok-

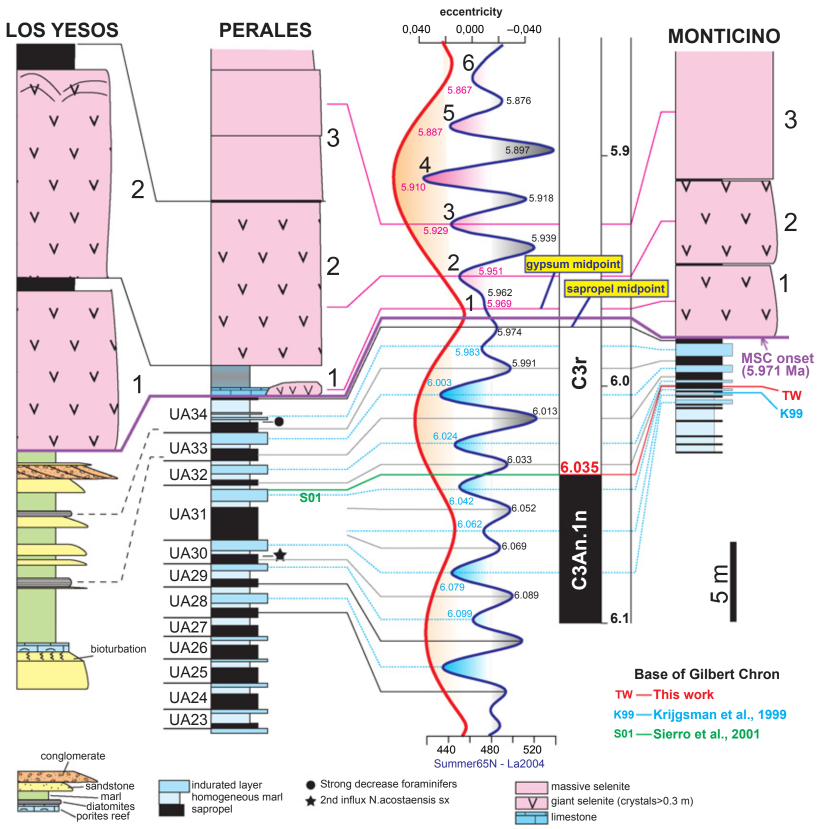

Fig. 6 Calibration of the Messinian salinity crisis onset and stratigraphic correlation between the two k-sections Perales and Monticino

arst cavities formed during the phase of tectonic activity responsible for the emersion of this area and the formation of the so called intra-Messinian unconformity at the acme of the MSC (Vai, 1988). This important erosional surface, separating MSC stage 1 and 2 and corresponding to the Messinian erosional surface (MES, also equivalent to the Marginal erosional surface of Lofi *et al.*, 2011), is associated with an important phase of erosion and dismantlement of the PLG in the VDGB and to its subsequent resedimentation in the adjacent deeper basins (Roveri *et al.*, 2001, 2003; Manzi *et al.*, 2005).

The Monticino section was also studied for integrated stratigraphic purposes (Krijgsman *et al.*, 1999b; Roveri *et al.*, 2006), although major tectonic complications (*e.g.* shear-planes) in the pre-evaporitic succession hampered a detailed correlation to the astronomical target curve. Based on the analysis of 11 paleomagnetic samples from the uppermost pre-evaporitic succession (in the 4 m below the base of the PLG unit; Fig. 4) Krijgsman *et al.* (1999b) placed the N/R base of the Gilbert chron between the 2nd and the 4th limestone beds (Calcare di Base; Vai, 1988).

The natural remanent magnetization (NRM) of the Monticino samples is composed of two different components: a low-temperature (100–240 °C) normal polarity component, interpreted as a subrecent viscous overprint, and a high temperature component of dual polarity, gradually removed up to 360 °C. Further heating created new magnetic minerals and resulted in random directions. The high-temperature component was considered as the (near-) primary component ChRM component (Krijgsman *et al.*, 1999b).

A detailed re-investigation of the earlier palaeomagnetic analyses comprising the transitional interval of the "Calcare di Base" unit shows that cycles I and II are of normal polarity and that cycles IV, V of reversed polarity (Figs. 4 and 5). The intermediate interval between cycles II and IV (see samples LIM 3.2. 4.2 and 5.2 in Fig. 5) can best be qualified of "mixed polarity", probably related to a significant overlap of a reversed and normal component. Krijgsman *et al.* (1999b) placed the N/R base of the Gilbert chron between the 2nd and the 4th limestone beds (Calcare di Base; Vai, 1988), based on the assumption that the mixed polarity was the result of a secondary normal overprint in combination with a primary reversed signal. In the mixed polarity interval, the high-temperature component is, however, not clearly resolved. Similarly to what have been observed in many other polarity transitions, mixed polarities can also result from delayed acquisition processes resetting part of the paleomagnetic signal (Vasiliev *et al.*, 2008). In that case, the reversed component is of later origin, and the mixed polarity interval contributes to the normal chron C3An.1n. The base of the PLG in the VDGB is then also located roughly three precessional cycles above the base of the Gilbert Chron.

Discussion

The recognition of an additional PLG cycle in the SB together with the re-interpretation of the paleomagnetic data of the Monticino section indicates that the onset of the MSC is located three precessional cycles above the base of the Gilbert Chron in both western (SE Spain) and central (N Italy) Mediterranean (Fig. 6).

Lugli *et al.* (2010) reconstructed a robust stratigraphic framework of the PLG unit, allowing bed-by-bed correlation of each gypsum-shale cycle. The proposed tuning with the astronomical curves highlights a strong climatic control at the precessional and eccentricity scale in the facies distribution, bed thickness and stacking pattern.

Accordingly, the Perales and Monticino sections can be precisely correlated and constrained into this cyclostratigraphic framework (Fig. 7).

According to earlier integrated stratigraphic studies of the pre-MSC

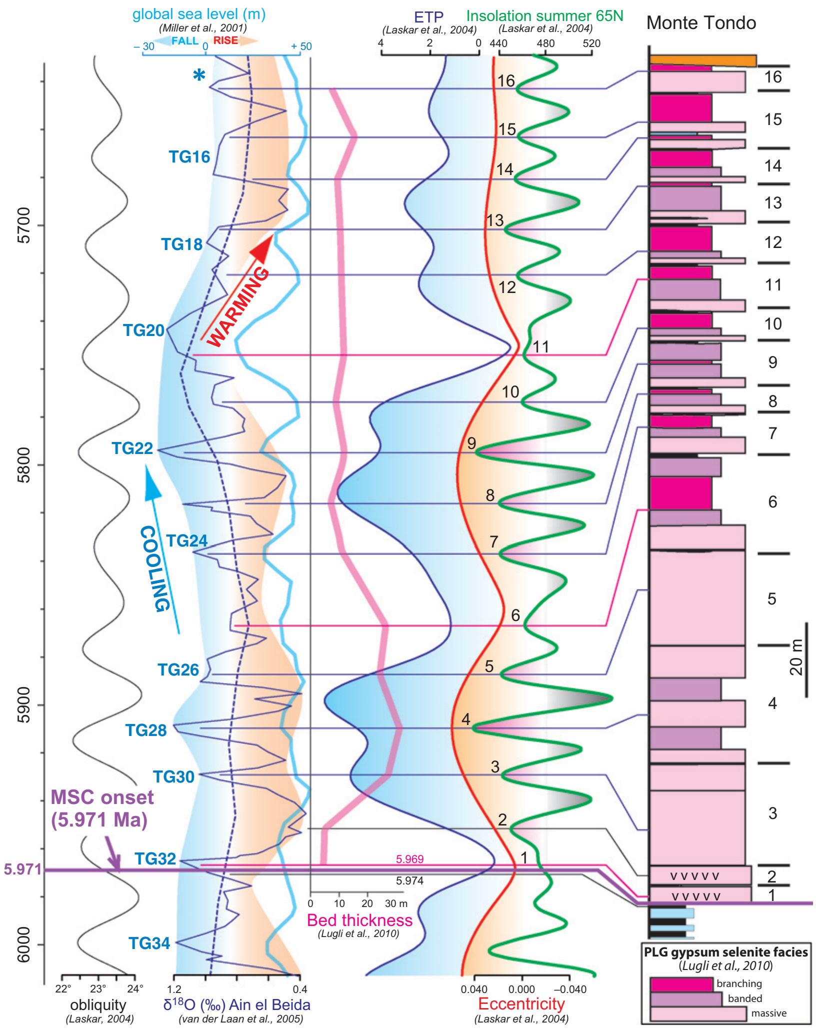

Fig. 7 Tuning of the Primary Lower Gypsum unit. According to the sedimentologic and sequence stratigraphic interpretation suggested for the Primary Lower Gypsum deposits (Roveri *et al.*, 2008b; Lugli *et al.*, 2010) the boundary between the banded selenite and the branching selenite facies represents the aridity peak within each single gypsum beds. Thus, it has been correlated with insolation minima.

unit, the base of the Gilbert chron falls in the upper part of cycle UA31 of the Perales section and is unambiguously correlated to the astronomical curves (Krijgsman *et al.*, 1999a,b, 2004; Sierro *et al.*, 2001). The base of the 1st PLG cycle, being located three precessional cycles higher, at the top of cycle UA34 (Fig. 6). Using the most recent astronomical solution (Laskar *et al.*, 2004) an age of 5.969 Ma and 5.974 Ma can be assigned respectively to the midpoint of the 1st PLG cycle and to the midpoint of the underlying dark organic-rich shale interval. The beginning of the MSC in the Mediterranean thus has an age of 5.971 Ma.

Our new calibration leads to interesting speculations about the climate events accompanying the MSC-onset based on the comparison with the sedimentary record from the Atlantic side. The Ain El Beida section (AEB; Krijgsman *et al.*, 2004) provides a continuous deep marine record of the 6.5–5.5 Ma interval that has been studied in detail following an integrated stratigraphy approach (biostratigraphy, magnetostratigraphy, stable isotope) and astronomically tuned.

The calibration of the PLG cycles to the AEB $\delta^{18}O$ curve (Van der Laan *et al.*, 2005) and to the global sea level record (Miller *et al.*, 2011) is shown in Fig. 7. The Monte Tondo section, located in the nearby of Monticino, is the reference section for the PLG (Lugli *et al.*, 2010). It shows that the PLG cycles 3-4-5, characterized by the maximum thickness in all the Mediterranean (Lugli *et al.*, 2010), are related to: i) a phase of strong climate variability related to a maximum of eccentricity and associated greater amplitude of boreal summer insolation, and ii) a phase of global sea level high-stand related to long-term obliquity cycles. Starting at around 5.870 Ma (PLG cycle 6) the onset of a cooling phase and global sea level fall could be responsible for the progressive reduction of the gypsum bed thickness and the development of the branching selenite facies, whose presence suggests shallower water depth in the evaporitic basins (Lugli *et al.*, 2010). Thus, the thickness of the PLG cycles during a phase of reduced tectonic activity could have been modulated by global sea level variations.

It is worth noting that the first gypsum was deposited at times of: (i) an eccentricity minimum roughly coincident with glacial stage TG32 (Van der Laan *et al.*, 2005); (ii) a strong peak in the Ti/Al ratio in cycle AEB25 (van der Laan *et al.*, 2012).

This suggests that the MSC-onset occurred during a time interval characterized by glacial conditions in the northern hemisphere and by arid climate in the gateway area (Northwest Africa) in agreement with the pollen record of southern Mediterranean (Fauquette *et al.*, 2006). These events superimposed to the longer-term tectonic restriction of the gateway started since the Tortonian, were likely responsible for triggering evaporative conditions in the marginal basins of the Mediterranean Sea.

Our results indicate that: (i) the interval encompassing MSC-onset is devoid of erosional features or stratigraphic hiatus related to major sea-level drop in the Mediterranean; (ii) in agreement to the evaporite facies and stacking pattern (Lugli *et al.*, 2010), the Yesares Formation of Sorbas was deposited during the first stage of the MSC. This allow to rule out previous hypothesis (Riding *et al.*, 1999; Braga *et al.*, 2006) claiming that the Yesares Fm. was deposited after the complete desiccation of the Mediterranean and the development of a major unconformity in the marginal basins.

Conclusions

A detailed sedimentological, stratigraphic and paleomagnetic revision of two key-sections, Perales (Sorbas basin) and Monticino (Vena del Gesso basin), recording the transition toward evaporative conditions in marginal shallow-water settings results in a refined age calibration of the MSC-onset in the Mediterranean at around 5.971 Ma and the removal of uncertainties that prevented a more accurate positioning of the MSC-onset in marginal and deep basins.

This age refinement also suggests that the MSC-onset was preconditioned by the tectonically-driven reduction of the hydrological exchanges with the Atlantic ocean and was finally triggered by glacial conditions in the northern hemisphere and by arid conditions in northern Africa. In this oceanographic setting the deposition of gypsum beds in marginal basins was controlled by sea level and insolation oscillations modulated by eccentricity.

Acknowledgments

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