Astronomical tuning as the basis for high resolution chronostratigraphy: the intricate history of the Messinian Salinity Crisis

Frits Hilgen[1], Klaudia Kuiper[2,3], Wout Krijgsman[2], Erik Snel[1] and Erwin van der Laan[1]
[1]*Stratigraphy/Paleontology, Faculty of Geosciences, Utrecht University,*
Budapestlaan 4, 3584 CD Utrecht, The Netherlands
[2]*Paleomagnetic Laboratory Fort Hoofddijk, Faculty of Geosciences, Utrecht University,*
Budapestlaan 17, 3584 CD Utrecht, The Netherlands
[3]*Isotope Geochemistry, Faculty of Earth and Life Sciences, Free University,*
De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
email: fhilgen@geo.uu.nl

ABSTRACT: The Messinian Salinity Crisis (MSC) in the Mediterranean resulted from a complex interplay between tectonic gateway closure and climate evolution. The climate factor, in turn, can be separated into two components, one associated with dominantly precession controlled regional climate change and the other with dominantly obliquity related glacial cyclicity. The influence of these climate changes occurred superimposed on a long(er)-term tectonic trend. Discrimination into the various forcing factors only recently came within reach due to the development of an integrated high-resolution stratigraphy and astronomically tuned age models, both for the Messinian (pre-)evaporite successions in the Mediterranean and for benthic oxygen isotope records from the open ocean.

The application of these time scales in combination with a high-resolution integrated stratigraphic approach showed that 1) the onset of the MSC proper at 5.96 Ma is not related to glacio-eustatic sealevel lowering but its timing can best be attributed to the influence of the 400-kyr eccentricity cycle on regional climate superimposed on a tectonic trend, 2) the main desiccation phase between the Lower and Upper Evaporites coincides with the twin peak glacials TG12-14 suggesting a glacio-eustatic control, 3) the beginning of the Upper Evaporites and Lago Mare phase coincides with the onset of the major deglaciation following peak glacial TG 12, indicating that glacio-eustatic sealevel rise played a role, 4) the Pliocene flooding of the Mediterranean is not related to a glacioeustatic sealevel rise, and 5) the evaporite cycles are controlled by precession induced regional climate changes rather than by obliquity forced glacio-eustatic sealevel change.

Our astronomical age model for the Mediterranean Messinian is consistent with ^{40}Ar/^{39}Ar ages of ash layers intercalated in Messinian successions in the Mediterranean. However, the intercalibration between astronomical and ^{40}Ar/^{39}Ar dating has to be taken into account for a direct comparison of these ages.

INTRODUCTION

The Messinian Salinity Crisis is recognized as one of the key events in Earth history attracting a great deal of scientific interest and fuelling imagination with huge waterfalls during the basal Pliocene reflooding of the Mediterranean following desiccation (Hsü et al. 1973). During the crisis vast amounts of evaporites were deposited when the Mediterranean became progressively isolated from the world ocean (Fig. 1); these evaporites are locally sandwiched in between deep marine sediments of Tortonian and Zanclean (Pliocene) age. Scientific debate focused on whether the isolation of the Mediterranean was caused by a (dominant) tectonic or glacio-eustatic control (e.g. Ryan et al. 1973; Kastens 1992). Following the glacial scenario, basin isolation resulted from Antarctic ice growth rather than from tectonic closure of the gateways connecting the Mediterranean with the adjacent Atlantic Ocean. However, also the opposite causal relationship has been suggested with ice growth triggered by a reduction in ocean seawater salinity resulting from salt extraction (Ryan et al. 1973).

It became increasingly clear that only a high-resolution age model based on astronomical tuning would provide the necessary means to unravel the intricate and fascinating history of the Messinian Salinity Crisis and, in particular, to discriminate between the role of tectonics and climate. However the Messinian was not incorporated in the astronomical time scale initially developed for the Mediterranean late Neogene because the characteristic diatomaceous and evaporitic sediments of the Messinian were considered less suitable for establishing a reliable magnetostratigraphy and astronomical tuning. Only after most of the Tortonian had been tuned, attention focused again on the Messinian. The first preliminary attempts were based on simple cycle counts in the successive lithostratigraphic units of the Mediterranean Messinian (Hilgen et al. 1995; Vai 1997). The tuning of the complete pre-evaporite Messinian resulted in an age of 7.25 Ma for the base of the Messinian and of 5.96 Ma for the onset of evaporite formation and, hence, the salinity crisis proper (Hilgen and Krijgsman 1999; Krijgsman et al. 1999); these ages are now generally accepted. More problematical, however, proved the tuning of the evaporites themselves, even though these evaporites are arranged in a cyclic fashion as well. This tuning, which is based on cycle counts rather than on cycle patterns, hinted at the presence of a hiatus of ~90 kyr in marginal basins between the Lower and Upper Evaporites, covering an interval when sealevel was significantly lowered in the Mediterranean (Krijgsman et al. 1999; Krijgsman et al. 2001).

In this paper we will briefly review the progress made in dating the classical Messinian, present the current state of the astronomical tuning, compare it in detail with isotope records from the open ocean and discuss the implications.

DEFINITION OF THE MESSINIAN

The Messinian Stage, named after the town of Messina on the island of Sicily off the coast of Italy, was introduced by Mayer-Eymar in 1867 and more precisely defined in 1868 to fill up the gap between the Tortonian and the now obsolete Astian (sensu lato, equivalent to the present Lower and Middle Pliocene stages of the Zanclean and Piacenzian). Mayer-Eymar (1878) explicitly stated that the middle Messinian is represented by gypsum and associated limestones throughout the Apennines. In the lower Messinian, he included "gelbliche bis schwärzliche Schiefertone" which represent the equivalent of the Tripoli diatomite Formation of Sicily. The upper Messinian contains continental deposits, which indicate a regressive phase prior to the (basal) Pliocene transgression. More recently, Selli (1960) defined the Messinian as the *"intervallo di tempo compreso fra il Tortoniano (strati di Tortona) e il Pliocene (strati di Tabiano), caratterizzato in tutto il Mediterraneo da una crisi di salinità e in Italia essenzialmente da un ambiente iperalino e da sedimenti evaporitici"*.

Selli (1960) argued that the Tortonian/Messinian (T/M) boundary should be placed 25 meter below the local base of the Tripoli diatomite formation in the neostratotype section of the Messinian at Pasquasia-Capodarso on central Sicily, at the level that coincides with the first marked environmental change indicated by dystrophic faunal elements, which he interpreted as the actual beginning of the Messinian salinity crisis. This paleo-environmental criterion made it difficult to export the boundary to the extra-Mediterranean realm lacking the clear expression of the salinity crisis itself. However calcareous plankton biostratigraphy was successfully employed for correlating this level with the adjacent Atlantic (d'Onofrio et al. 1975) and the First Occurrence of *Globorotalia conomiozea* became the new guiding criterion for recognizing the boundary (Colalongo et al. 1979). The Messinian GSSP or base of the Messinian is now formally defined at the base of the reddish layer of color cycle no. 15 in the Oued Akrech section located in the Bou Regreg area on the Atlantic side of Morocco (Hilgen et al. 2000). This level closely coincides with the first common occurrence of the *Globorotalia miotomida* group (Sierro et al. 1993; *G. conomiozea* group of Hilgen et al. 1995), falls within the interval of reversed polarity that corresponds to Chron C3Br.1r, and has an astronomical age of 7.25 Ma (Hilgen et al. 2000).

The Messinian-Zanclean (Miocene-Pliocene) boundary also underwent drastic changes in definition in addition to changes in its chronostratigraphic position (e.g. Van Couvering et al. 2000). Cita (1975), following the discovery of the Pliocene flooding event in deep-sea cores of the successful DSDP Leg 13 in the Mediterranean proposed to define the Miocene-Pliocene boundary at the base of the deep marine Trubi marls in the Zanclean neostratotype section (Cita and Gartner 1973) at Capo Rosello on southern Sicily. Despite several opposing views, the proposal to keep the Miocene-Pliocene boundary coincident with the base of the Trubi marls and Zanclean Stage, as defined in the Mediterranean at Eraclea Minoa (25 km NW of Capo Rosello) received overwhelming support and was formally accepted (Van Couvering et al. 2000).

AN ASTROCHRONOLOGY FOR THE MESSINIAN IN THE MEDITERRANEAN BASIN

The classic Messinian sequence in the Mediterranean as described from Sicily (Decima and Wezel 1971) starts with cyclic alternations of open marine marls and sapropels, passes via diatomites into the Lower Evaporites (gypsum, evaporitic limestone and halite), and ends, above an erosional surface and sometimes angular unconformity, with the Upper Evaporites (gypsum, marls) and fresh to brackish water deposits of Lago Mare facies. Here we define the MSC as the interval of evaporite deposition and Lago Mare sedimentation in the Mediterranean starting at 5.96 Ma and ending with the Pliocene reflooding at 5.33 Ma.

Messinian pre-evaporite sequences

Continuous pre-evaporite sequences from all over the Mediterranean were subjected to integrated high-resolution stratigraphic studies in order to construct a cyclostratigraphic framework and develop an astronomical age model that would allow accurate dating of the onset of the MSC. Cyclostratigraphic correlations between the Mediterranean sections are rather straightforward and were confirmed by high-resolution planktonic foraminiferal biostratigraphy. Astronomical tuning of Messinian pre-evaporite cycles to successive insolation peaks generally shows a good to excellent fit between the characteristic sedimentary cycle patterns and the astronomical target curve, including precession/obliquity interference patterns in insolation (Hilgen and Krijgsman 1999; Sierro et al. 2001; see also Fig. 2). Alternating thick/thin beds correlate in a consistent way with high/low amplitude variations in insolation, proving that no sedimentary cycles are missing and that alternative correlations can be excluded. Additional paleoclimatic studies confirmed that the sedimentary cycles of the Messinian pre-evaporites reflect — precession induced — changes in (circum) Mediterranean climate (Nijenhuis et al. 1996; Sierro et al. 1999).

The "Lower Evaporite" units

The resultant astrochronology shows that the transition to the evaporites occurs at exactly the same sedimentary cycle in sections located in the Western, Central and Eastern Mediterranean (Hilgen and Krijgsman 1999; Krijgsman et al. 1999, 2002). It proves that the MSC is a synchronous event over the entire Mediterranean, the onset of which is dated astronomically at 5.96 ± 0.02 Ma. The pre-evaporitic marl-sapropel cycles are replaced by gypsum-marl cycles of the Lower Evaporites (LE), indicating that the evaporite cycles are related to precession controlled oscillations in (circum) Mediterranean climate as well. As a consequence, gypsum beds correspond to precession maxima (insolation minima) and relatively dry climate (Krijgsman et al. 2001). The total amount of cycles in the Lower and Upper Evaporites also excludes an obliquity control; hence glacio-eustatic sealevel changes are not responsible for the evaporite cycles (Krijgsman et al. 1999).

The total number of evaporite (gypsum) cycles in the Lower Evaporites of Spain (17 cycles) and Italy (16 cycles) is in good agreement and implies a total duration of approximately 350-370 kyr for the LE (Vai and Ricci Lucchi 1976; Krijgsman et al. 2001; Fig. 2). Deposition of the Lower Evaporites is thus independent of the paleogeographic and geodynamic setting of the individual basins. Moreover these evaporites are marine requiring, thereby excluding a relative sea level fall that exceeds the paleodepth of the marginal basins (i.e. < 200m). This scenario favours a deep water model instead of a shallow water (re-

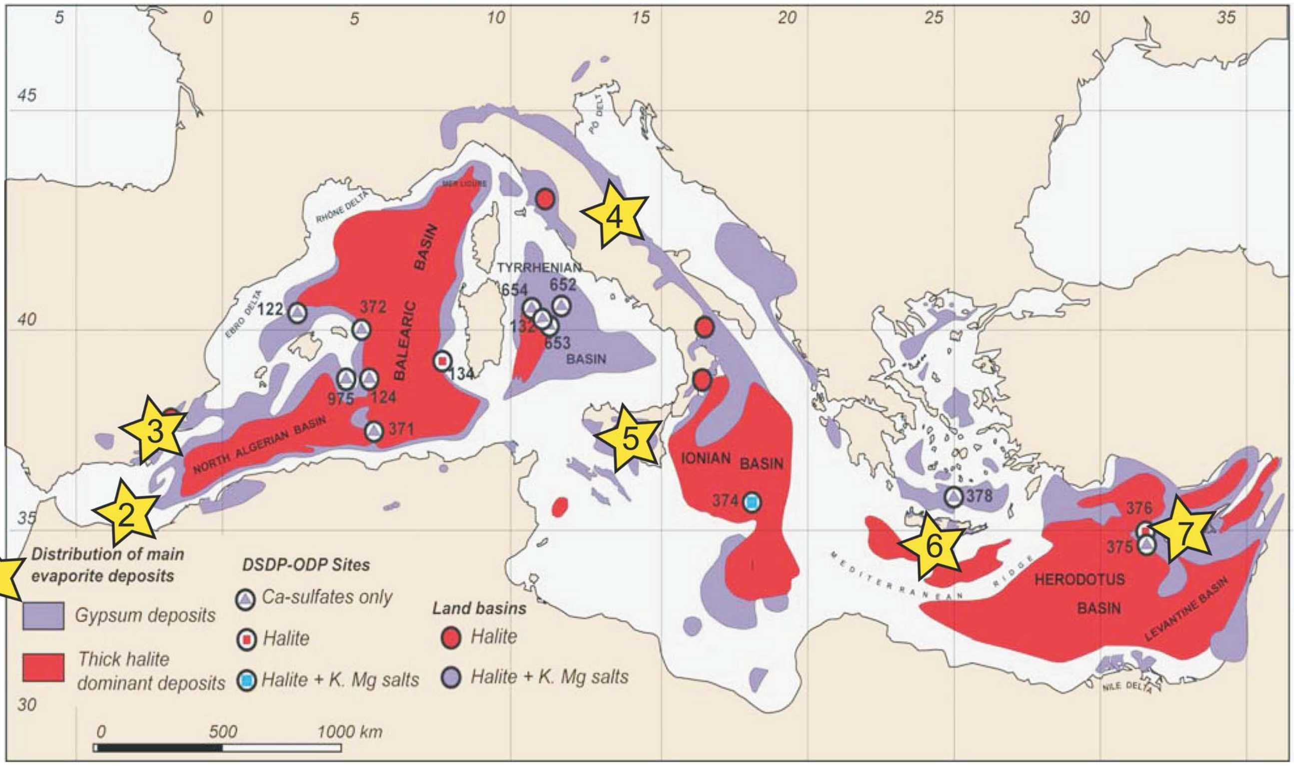

FIGURE 1
Map showing key locations used to construct the astrochronological framework for the Messinian: 1) Bou Regreg; 2) Melilla; 3) Sorbas/Nijar; 4) Northern Apennines; 5) Sicily; 6) Crete/Gavdos; 7) Cyprus. It also shows the distribution and extent of the Messinian evaporites in the Mediterranean with location of the DSDP-ODP sites that recovered evaporitic deposits (modified after Rouchy and Caruso 2006).

petitive process of desiccating and reflooding) model for the deep (>1000m) Mediterranean basins.

It should be noted here that all the information on the Lower Evaporite units comes from basins indicating a marginal setting during the Messinian. Researchers have traditionally assigned the "N" reflectors (below the salt) as the deep basin equivalents of the marginal Lower Evaporites, but there is thus far no direct evidence of repetitive gypsum/marl cycles in the very deep basins (Roveri and Manzi 2006; Ryan 2007).

The "Upper Evaporite" units

Complete isolation and possible desiccation were only established after deposition of the Lower Evaporites, when the Mediterranean water level dropped more than 1000 meters as evidenced by incised canyons of the Rhone, Ebro, Po and Nile rivers in the Mediterranean margins (e.g. Clauzon 1973; see also Ryan 2007 and references therein). Deposition of the Upper Evaporite (UE) unit, overlying erosional surfaces, took place in an essentially non-marine, deep Mediterranean basin forming a large Lago Mare (Ruggieri and Sprovieri 1976). The UE units and lateral equivalents of the Mediterranean latest Messinian also display a marked cyclicity, comprising in general seven to eight sedimentary cycles in the Upper Evaporites of Sicily (Decima and Wezel 1971), the so-called post-evaporitic deposits of Northern Italy (Vai 1997) and the Zorreras/Feos units of southeast Spain (Fortuin and Krijgsman 2003). The total number of sedimentary cycles is in good agreement with the total number of precession peaks (Fig. 2), whereas there is clearly not time enough for an obliquity control, thus excluding glacio-eustasy. As the average periodicity for precession in Neogene times is 21.7 kyr, the Upper Evaporite units were deposited in approximately 175 kyr.

Unfortunately, the tuning of the UE is not fully certain because it is based on counting and tuning the number of supposedly precession related UE cycles from the Miocene-Pliocene boundary downward which itself is well tuned. Only the UE at Eraclea Minoa reveal a pattern that can be recognized in the astronomical target curve (Fig. 2). Tentatively calibrating the post-evaporite cycles to the insolation curve leaves only a small "Messinian gap" (between 5.59 and 5.50 Ma) during which the desiccation of the Mediterranean, deposition of halite, and the accompanying isostatic rebound processes (tectonic tilting and erosion) must have occurred.

Recent studies in northern Italy indicate that the Colombacci Formation with its characteristic limestone beds that were initially listed as being the full equivalent of the Upper Evaporites, covers a significantly reduced time span. It is now suggested that it corresponds to the younger part of the Upper Evaporites only (Roveri and Manzi 2006). The older part of the UE is contained in part by the underlying Formazione di Tetto. This unit has been deposited in a deep basin equivalent of the marginal rimmed basins in which the LE were deposited. The older part of the Formazione di Tetto consists of reworked evaporites and supposedly covers the so-called Messinian gap (see above) inferred from marginal basins, suggesting that the deep basins in Northern Italy did not experience any desiccation event (Roveri and Manzi 2006).

CORRELATION TO THE BENTHIC OXYGEN ISOTOPE RECORD FROM THE OPEN OCEAN

Benthic oxygen isotope records are instrumental to test the glacio-eustatic hypothesis for the MSC by unraveling potential linkages between ice volume and evaporite deposition. Clearly these isotope records had to come from outside the Mediterranean, the Messinian in the Mediterranean itself being totally unsuitable for constructing such a record due to aberrant environmental conditions and the (partial) absence of (benthic) foraminiferal faunas. The first high-resolution isotope record covering the interval of the evaporitic Messinian was published by Keigwin (1987) from single hole DSDP Site 522 in the North Atlantic. The Lower and Upper Evaporites were correlated to two successive glacial episodes around 5.2 and 4.8 Ma. Other detailed but better dated isotope records followed and were used to decipher the succession of glacials in the latest Miocene (Hodell et al. 1994, 2001; Shackleton et al. 1995; Shackleton and Hall 1997; Vidal et al. 2002; Van der Laan et al. 2005). A nomenclature for late Miocene isotope stages was introduced by Shackleton et al. (1995) who numbered distinctly positive isotope peaks from young to old and assigned them to specific magnetic chrons. This numbering scheme was extended by Hodell et al. (1994). The initial tuning of the isotope records has been modified to some extend over the last years and the tuning seems now well established (van der Laan et al. 2005; 2006; Fig. 2). Although it is difficult to separate the bottom water temperature from the ice volume signal in benthic $\delta^{18}O$, amplitudes for glacio-eustatic sealevel lowerings associated with late Messinian obliquity controlled glacials have been estimated on the order of ~50-60m for peak glacials (Kastens 1992; Shackleton et al. 1995). Note that such amplitudes in the glacial-interglacial signal are comparable with those reached during the late Pliocene and early Pleistocene.

No glacio-eustatic control for the onset of the MSC

Although it was initially tempting to link the onset of evaporite formation to peak glacial stages TG20 and 22 as suggested by Hodell et al. (1994), improved age control showed that this is not the case (Hodell et al. 2001; Fig. 2). In fact the onset of the MSC evaporites at 5.96 Ma coincides with the glacio-eustatic sealevel rise following glacial stage TG32 and can best be explained by the influence of the 400-kyr eccentricity cycle on regional climate and, hence, Mediterranean water budget, which occurs superimposed on the ongoing trend in tectonic isolation of the basin (Krijgsman et al. 1999). The oxygen isotope records in particular portrayed a late Messinian glacial interval ranging from ~6.3 tot 5.5 Ma marked by heavier values and high-frequency fluctuations, the latter reflecting dominantly obliquity controlled glacial cycles. This interval is particularly evident at ODP Site 982 but is somewhat less obviously expressed in other sites as well. This glacial series contains two prominent peak glacials TG20 and 22 in the lower reversed Gilbert Chron, with astronomical ages of 5.75 and 5.79 Ma (Fig. 2); these glacials correspond to the *Globorotalia margaritae* acme in the Bou Regreg area (Benson and Rakic-el Bied 1996; Krijgsman et al. 2004). The whole glacial interval ends with two other conspicuous obliquity controlled glacials TG12 and 14 (with astronomical ages of 5.548 and 5.582 Ma), followed by a marked stepwise deglaciation from TG12 to TG9 (5.445 Ma) recognized in all oceanic basins (e.g., Shackleton and Hall 1997; Vidal et al. 2002) (Fig. 2). This deglaciation is associated with a distinct marked glacio-eustatic sealevel rise and is marked by invasions of the warm water planktonic foraminiferal species *Globorotalia menardii* and *Neogloboquadrina dutertrei* in the Bou Regreg area on the Atlantic side of Morocco that denote this key event in Messinian paleoceanographic history (van der Laan et al. 2006).

A glacio-eustatic cause for the Mediterranean desiccation phase

The much improved age control suggests that the base of the Upper Evaporites is intimately linked to the beginning of the major stepwise deglaciation between TG12 and TG9 from 5.55 to 5.45 Ma, or more correctly with the first step of the deglaciation between 5.55 and 5.52 Ma (van der Laan et al. 2006). This leaves the option that the hiatus, or so-called Messinian gap, between the LE and UE observed in marginal basins corresponds with the last two peak glacials TG12-14 of the Messinian glacial interval. The reason why glacio-eustatic sealevel lowering associated with twinned glacials TG14-12 resulted in the final desiccation of the Mediterranean rather than the even more prominent peak glacials TG22-20 is explained by the additional influence of the ongoing trend in tectonic isolation of the basin. This scenario suggests a strong link between Messinian glacial history and associated glacio-eustatic sealevel change and the final desiccation/drawdown of the Mediterranean and the subsequent refill at the base of the Upper Evaporites and Lago Mare. If this correlation holds, it may explain why repetitive (marginally) marine influences are reported from the Upper Evaporites/Lago Mare (Carnevale et al. 2006) although indications exist that the dominant environmental conditions were not fully marine but dominantly hyposaline. In this way it may even be argued that the “Pliocene” flooding already started at the base of the UE.

End of the MSC: Pliocene flooding of the Mediterranean

The Messinian glacial history and the final phases of the MSC made it tempting to link the Pliocene reflooding of the Mediterranean to a significant sea-level rise resulting from deglaciation. Hodell et al. (1994) incorrectly linked the main flooding event to the TG12-9 transition through linear extrapolation of the sedimentation rate in the Salé drill hole. However, improved time constraints revealed that the M/P boundary was significantly younger. Suc et al. (1997) therefore attributed the Pliocene flooding to the abrupt deglaciation associated with TG5 which occurs in the M/P boundary interval and is particularly evident in the record from ODP site 846 (Shackleton et al. 1995). Close inspection of the benthic isotope record of the Loulja section (Bou Regreg area) tuned to precession revealed that the M/P boundary (as currently formally defined in the Mediteranean) does not coincide with any major deglaciation (van der Laan et al. 2006) (Fig. 2). This outcome renders credibility to alternative scenarios such as the headward erosion of fluvial incisions in the Gibraltar area (Blanc 2002; Loget et al. 2005).

INDEPENDENT CONFIRMATION: ^{40}AR/^{39}AR DATING

Independent confirmation of our astronomical age model for the Messinian, and the MSC in particular, comes from $^{40}Ar/^{39}Ar$ dating of ash layers intercalated in tuned cyclic evaporite successions or their (carbonate) equivalents in marginal settings. Absolute age uncertainties must be taken into account when $^{40}Ar/^{39}Ar$ and astronomical ages are compared. For $^{40}Ar/^{39}Ar$ ages the absolute uncertainty is in excess of 2.5% due to uncertainties in the decay constants and ages of the primary dating standards; this error is in sharp contrast with the generally published much smaller analytical errors. However, intercalibration with the astronomical dating method significantly reduces the absolute uncertainties in $^{40}Ar/^{39}Ar$ dating (Kuiper et al. 2004) and has the advantage that a direct comparison can be made be-

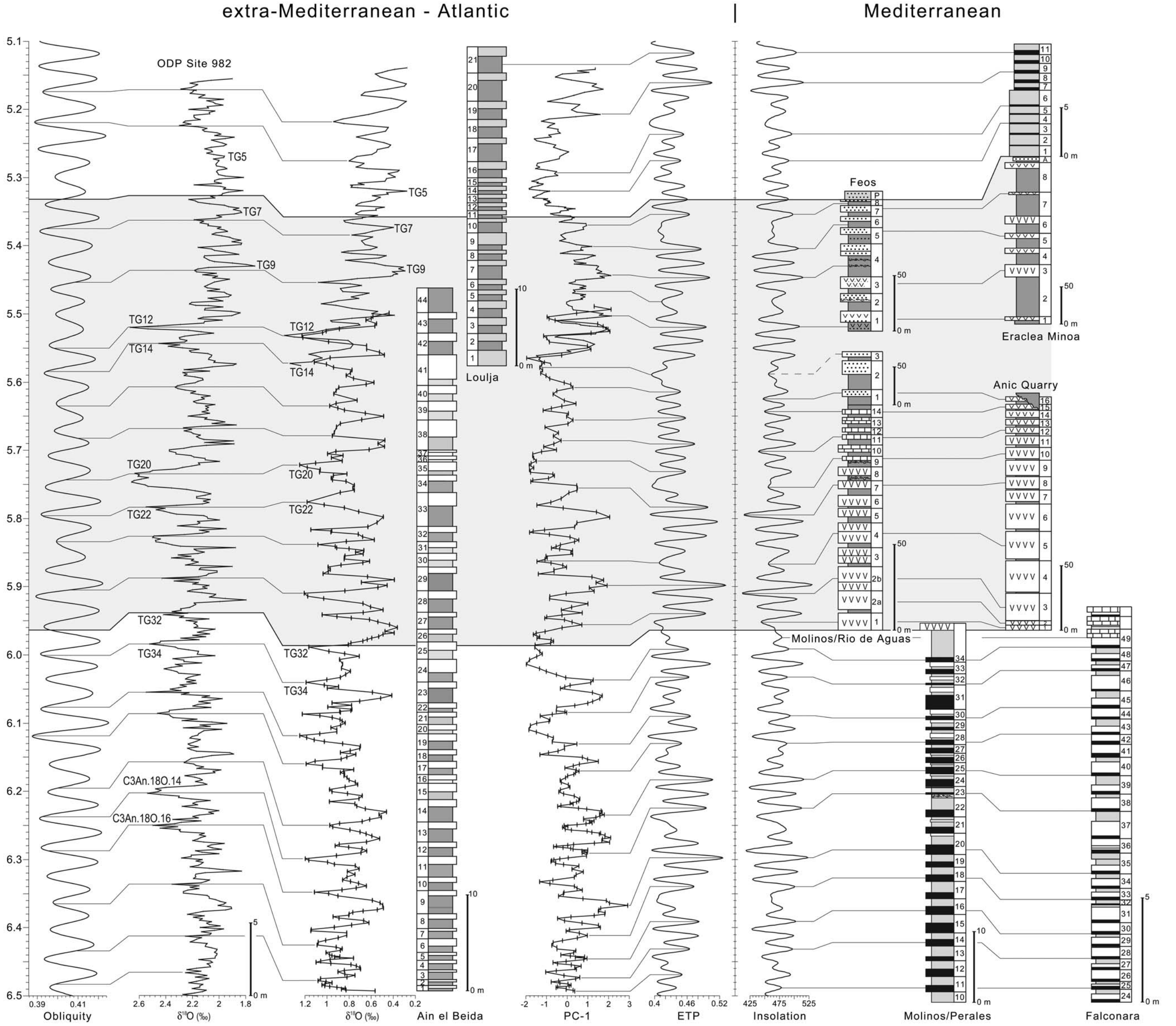

FIGURE 2
Astronomical tuning of Messinian key sections located in the Mediterranean or in the adjacent Atlantic (after Lourens et al. 1996; Fortuin and Krijgsman 2003; Hilgen and Krijgsman 1999; Sierro et al. 2001; Krijgsman et al. 2001; Van der Laan et al. 2005, 2006; Hodell et al. 2001; see Figure 1 for locations). Also shown is the astrochronology of benthic oxygen isotope and geochemical records of Ain el Beida, Loulja and ODP site 982. The first Principal Component of the geochemical element data (ICP) of Ain el Beida and Loulja shows a striking similarity with the precession dominated colour cycles used for the tuning, while the oxygen isotope records are dominated by obliquity. Marked glacial and interglacial stages have been indicated in the isotope records. Shading marks the interval of the Messinian Salinity Crisis.

tween both dating methods for samples/sections other than the ones used for the intercalibration.

Kuiper et al. (2004) obtained single crystal and multiple fusion ^{40}Ar/^{39}Ar sanidine ages from ash layers in astronomically tuned sections of the pre-evaporite Messinian. The resultant ^{40}Ar/^{39}Ar ages are in good agreement with previously published ^{40}Ar/^{39}Ar ages of the same ash layers but proved to be systematically younger than the astronomical ages by ~0.7-0.8 % if the widely used age of 28.02 ± 0.28 Ma for the Fish Canyon (Tuff) sanidine dating standard (FCs; Renne et al. 1998) was used to calculate the ^{40}Ar/^{39}Ar ages of the ash layers. Importantly, the systematic bias does not result from errors in the tuning but from uncertainties in the ^{40}Ar/^{39}Ar dating method mentioned before. Assuming that the astronomical ages are reliable, an intercalibrated astronomical age of 28.20 ± 0.01 Ma could be derived for the FCs standard (Kuiper et al. 2004, in prep). This intercalibration is critical if one aims to directly compare astronomical and ^{40}Ar/^{39}Ar ages.

More or less synchronously with the development of an astronomical time scale for the Messinian, the first ^{40}Ar/^{39}Ar biotite ages for the Tortonian/Messinian (T/M) boundary interval were published from northern Italy. The boundary was first dated at 7.23 Ma (Vai et al. 1993) and later bracketed between 7.08 and 7.16 Ma (Laurenzi et al. 1997), both studies using an age of

27.55 Ma for the FCT-3 biotite dating standard. The T/M boundary ages would increase by ~170 kyr if recalculated against the astronomically calibrated age of 28.20 Ma for the FCs (or even >200 kyr when the intercalibration between FC sanidine and biotite is also taken into account; Dazé et al. 2003). The recalculated ages of Laurenzi et al. (1997) are very close to the astronomical tuned age of 7.25 Ma for the T/M boundary (Hilgen et al. 2000) despite the fact that biotite is considered less suitable for $^{40}Ar/^{39}Ar$ dating than sanidine (e.g., due to recoil problems) and no single crystal dates were obtained.

Some of the ash layers from the basinal succession in the Melilla Basin used for the intercalibration of astronomical and $^{40}Ar/^{39}Ar$ time have also been dated in nearby exposed shallow marine successions from the basin margin (Roger et al. 2000, Münch et al. 2006); these ages are consistent with the results from the basinal succession (Kuiper 2003; Kuiper et al. in prep). However also some younger ash layers from the Terminal Carbonate Complex (TCC) in the Melilla Basin have been dated; this TCC is considered to be the lateral equivalent of the Lower Evaporites. The recalculated ages of these ash layers are consistent with the astronomical age model of Krijgsman et al. (2001), but incompatible with the age model of Riding et al. (1998). The latter age model starts from a major erosional unconformity that marks a significant hiatus spanning hundreds of thousands of years between the pre-evaporite Abad marls and the Yesares gypsum in the Sorbas and Nijar basins in SE Spain.

Finally, Odin et al. (1997) obtained a $^{40}Ar/^{39}Ar$ plateau age of 5.51 ± 0.04 Ma and a total gas age of 5.50 ± 0.04 (analytical error) Ma for biotites from an ash layer intercalated in the Formazione di Tetto directly above the erosional unconformity that developed on top of the LE in northern Italy. The biotite HD-B1 with a K/Ar age of 24.21 Ma was used as monitor dating standard. Well-documented intercalibration studies for HD-B1 and FCs have not been published and recalibration to an astronomically calibrated standard is therefore difficult. Summarizing our astronomical age model is consistent with and thus confirmed by $^{40}Ar/^{39}Ar$ ages presently available for the Mediterranean Messinian.

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