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The 'Tortonian salinity crisis' of the eastern Betics (Spain)

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Abstract

The late Miocene depositional history of the Lorca and Fortuna basins, both occupying an internal position in the eastern Betics of Spain, is marked by a regressive sequence from open marine marls, via diatomites and evaporites, to continental sediments. Based on facies similarities, these evaporites have often been correlated to the well-known Mediterranean evaporites of the Messinian salinity crisis, although this correlation was never substantiated by reliable chronological data. In this paper, we present an integrated stratigraphy of this regressive sequence which shows that the evaporites of the Lorca and Fortuna basins are entirely of late Tortonian age and as such have no relation with the Messinian salinity crisis. The main phase of basin restriction, resulting in deposition of diatomites and evaporites, took place at 7.8 Ma, while the last marine deposits (massive evaporites of the Lorca basin) are dated at 7.6 Ma. Consequently, this 'Tortonian salinity crisis' of the eastern Betics had a duration of approximately 200 kyr, while continental deposition prevailed throughout the entire Messinian as also revealed by the fossil mammal record. The 'Tortonian salinity crisis' of the eastern Betics is obviously related to a local phase of basin restriction caused by uplift of the metamorphic complexes at the basin margins, probably in concert with strike-slip activity along SW–NE trending fault systems. The development of a submarine sill is of crucial importance for the increase in salinity because it allows marine waters to continuously enter the basin at the surface while it restricts or prevents the outflow of dense saline waters at depth. Furthermore, we show that evaporite and diatomite cyclicity in these restricted basins is predominantly related to precession controlled circum-Mediterranean climate changes and that glacio-eustatic sea level changes only play a minor role. It is remarkable that the lithological sequence of the Tortonian salinity crisis mimics in many aspects that of the Messinian salinity crisis. This suggests that the diatomaceous facies is an essential part of the lithological sequence associated with basin restriction.

Keywords: stratigraphy; evaporites; Miocene; Mediterranean region; Spain

1. Introduction

The geodynamic evolution of the Miocene basins that straddle the European–African collision zone was largely controlled by vertical motions

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that transformed the area into a mosaic of rapidly subsiding and emerging blocks. The semi-enclosed configuration of the Mediterranean and the deterioration of water exchange with the Indian and Atlantic Ocean repeatedly favoured deposition of evaporites in strongly restricted basins. Prime examples are the middle to late Miocene evaporites of the Red Sea basin, the middle Miocene (Badenian) salt deposits of the Carpathian foredeep, and the Messinian evaporites of the Mediterranean. The formation of these evaporites was heavily discussed over the last century, but critical factors – such as a reliable chronology, basin and gateway configuration, influence of tectonics and climate – are, in many cases, still poorly constrained.

The Mediterranean Messinian salinity crisis is one of the most impressive examples of evaporite formation in Neogene history [1]. It was suggested to be the result of a complex combination of tectonic and glacio-eustatic processes in the Gibraltar area which progressively restricted and finally isolated the entire Mediterranean Sea from the open ocean [2,3]. Typical Mediterranean Messinian sequences consist of a succession of open marine marls, diatomite-rich sediments, thick evaporites (carbonates, gypsum and halite), and finally continental deposits. Astronomical calibration only recently provided an accurate and high-resolution time frame for the Messinian and showed that the onset of the Messinian salinity crisis was a perfectly synchronous event in all studied basins of the western and eastern Mediterranean [4,5]. Therefore, evaporite deposition during the Messinian salinity crisis must have taken place independent of local paleogeographic and paleoenvironmental conditions.

The synchroneity of the Messinian evaporites is challenged by Rouchy et al. [6] and Dinarés-Turrell et al. [7] who proposed that evaporite deposition in the Lorca and Fortuna basins (E Spain) started earlier than on Sicily and in the nearby Sorbas basin. Time constraints on the Lorca and Fortuna sequences, however, are extremely poor. In fact, it has not yet been proven that the evaporites of the Lorca and Fortuna basin are of Messinian age. To establish a reliable and accurate chronology for the salinity crisis of the Lorca and Fortuna basins, we decided to re-examine the sedimentary sequences by subjecting the most continuous sections to a detailed and high-resolution integrated stratigraphic study. These sequences form an excellent opportunity to compare the processes of evaporite deposition in relatively small areas, like the Lorca and Fortuna basins, with those with a large and complex area, like the Mediterranean. The results will provide useful information on the general processes of evaporite formation in the circum-Mediterranean area and on the mechanisms of basin evolution in the eastern Betics during the late Miocene.

2. Geological setting and sections

2.1. Lorca basin: the Serrata section

The quadrangularly shaped Lorca basin developed on the substratum of the Internal Units of the Betic Cordillera and is bound to the southeast and northwest by two major NE–SW oriented sinistral strike-slip faults (the Alhama de Murcia and the North Betic Fault, Fig. 1). The southwestern and northeastern limits were formed by NW–SE and N–S oriented normal faults which classify it as a 'pull-apart basin' or 'rhombgraben' [8]. The Lorca basin obtained its present fault-bound configuration during early Tortonian times, a period characterised by sedimentation of conglomerates, siliciclastics and carbonates [9]. A paleogeographic differentiation occurred during the middle-Tortonian resulting in sedimentation of coarse grained siliciclastics in the NW and a thick series of open-marine marls (Hondo Fm. [9]), diatomites and evaporites (Serrata Fm. [9]) in an elongated depocentre parallel to the SE margin [6,8]. The marine sequences are well-exposed along a SE–NW trending ridge (La Serrata) which yields several undisturbed continuous sections encompassing the entire stratigraphic sequence from marine marls to evaporites. These evaporites are in turn overlain by a sequence of continental reddish silts.

For our integrated stratigraphic study, we selected the Serrata section, 170 m thick and located 5 km to the north of the city of Lorca (Fig. 1). We

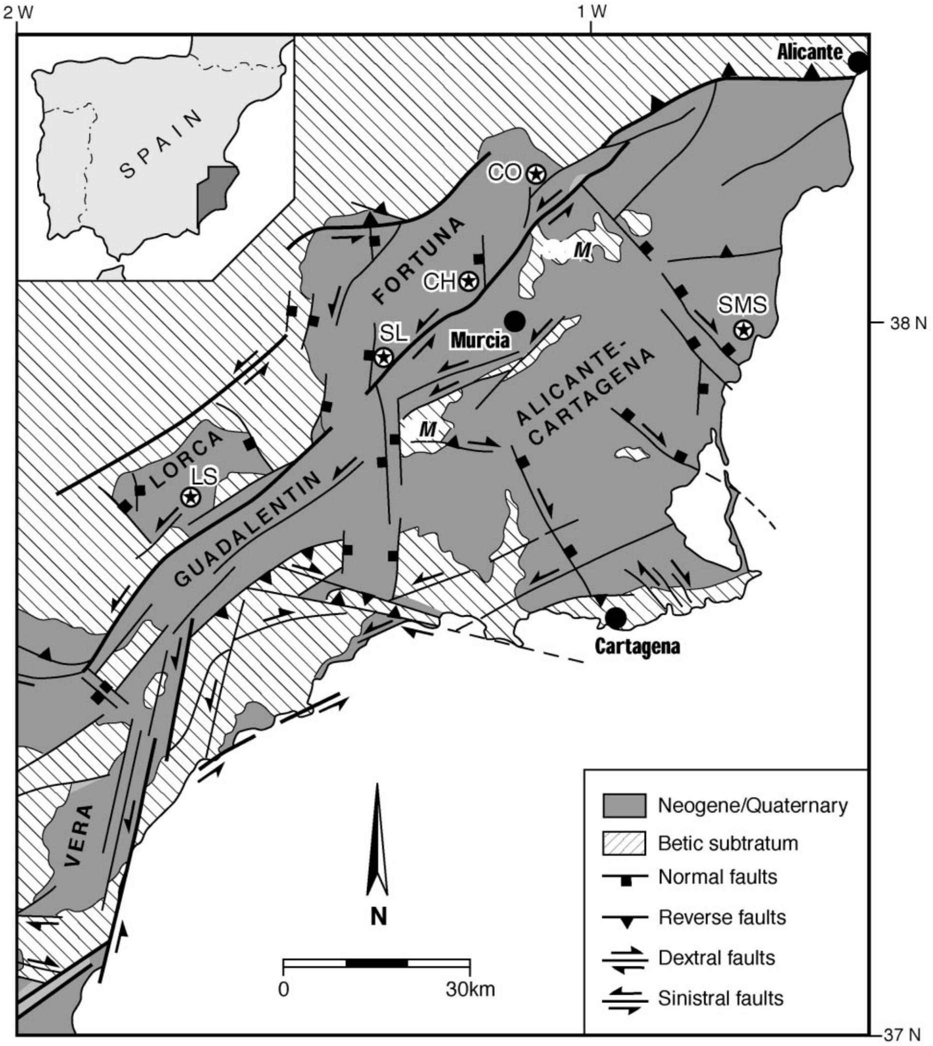

Fig. 1. Geological sketch map of the Neogene basins of SE Spain (modified after [15]). LS, Lorca Serrata section; SL, Sifón de Librilla section; CH, Chorrico section; CO, Chicamo section; SMS, San Miguel de Salinas. Major faults: NBF, North Betic Fault; CF, Crevillente Fault; AMF, Alhama de Murcia Fault. OCM, Orihuela-Callosa Massif; CM, Carrascoy Massif.

have sampled the lower part of the section along the transect of Section 3 of [6], the central and upper part in the Minas Volcán gypsum quarry (Section 4 of [6]) where the entire diatomite succession, including the transition to massive gypsum, is clearly exposed. The base of the Serrata section is formed by sediments of the Hondo Fm., consisting of cyclic alternations of grey homogeneous marls and white Opal CT-rich dolomitic layers (Fig. 2). This sedimentary cyclicity is similar to that of the 'Lower Abad' marls of the Sorbas basin, which was proven to be related to astronomical precession [10,11]. Four sedimentary cycles could be recognised up to the first prominent diatomite bed, which marks the transition to the Serrata Fm. This latter formation mainly consists of alternations of marine diatomites and silty marls, with interbedded sandstones and fine grained limestones or dolostones [9]. The Serrata Fm. contains seven intercalations of precursor evaporitic layers (Fig. 2), which laterally grade into seven gypsum beds at the basin margin (Cor-

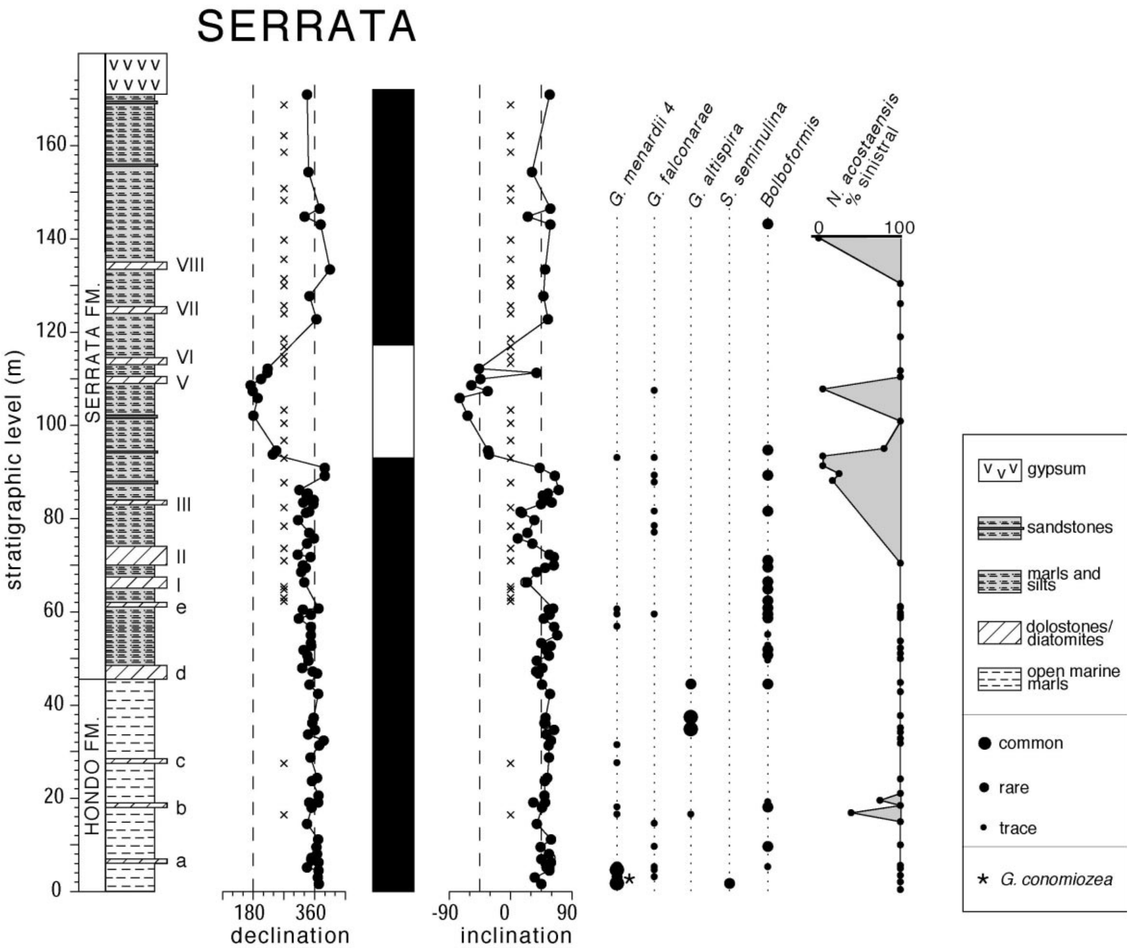

Fig. 2. Lithology, magnetostratigraphy and planktonic foraminiferal biostratigraphy of the Serrata section of the Lorca basin. The Hondo/Serrata transition marks the onset of more restricted conditions in the basin. The diatomaceous/opal-rich beds are labelled a–e. The roman numbering is after [6] and corresponds to precursor evaporitic layers which laterally grade into gypsum beds at the basin margin. The uppermost massif gypsum unit is overlain by continental deposits of the laminated pelite member sensu [9]. In the magnetostratigraphy column solid dots denote reliable directions, crosses denote unreliable results.

tijada del Pozuelo section), indicating that the Lorca basin was already periodically restricted and reflooded by marine waters [6]. The top of the Serrata Fm. consists of silty marls with intercalated sandstone beds, capped by a massive gypsum unit of approximately 50 m thick that is mainly composed of laminated, detrital and nodular gypsum [6,9,12–14].

2.2. *Fortuna basin: the Chicamo and Chorrico sections*

The Fortuna basin lies on the contact between the external and internal Betics and is also bound by two major NE–SW shear zones (the Alhama de Murcia and the Crevillente Fault, Fig. 1). The basin developed since the early Tortonian and its configuration was largely controlled by sets of both (sinistral) strike-slip and normal faults under an overall compressional regime resulting from Africa–Europe plate collision [15–17]. The sedimentary infill of the Fortuna basin shows a regressive sequence from marine marls (Los Baños Fm. [18]) to diatomites and evaporites (Rio Chicamo Fm. [18]) and continental deposits (Rambla Salada Fm. [18]).

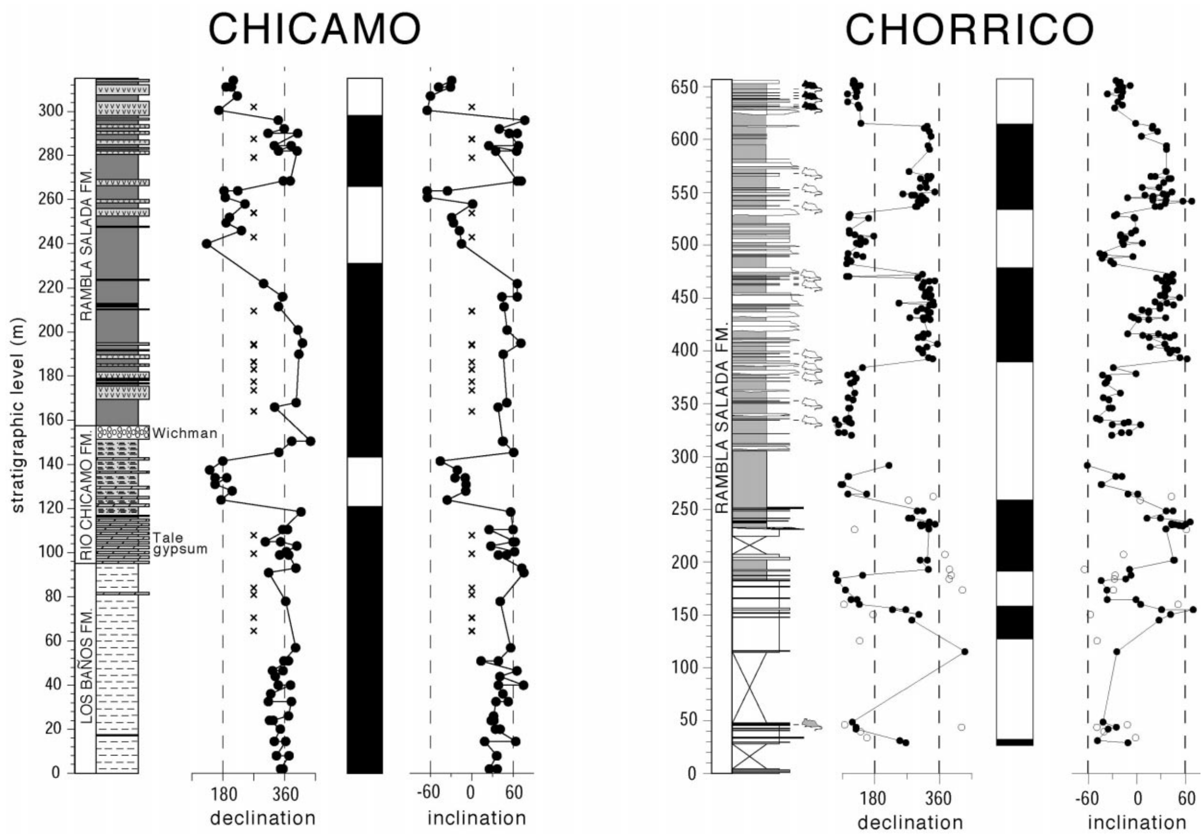

Fig. 3. Lithology, magnetostratigraphy and fossil mammal sites of the Chicamo and Chorrico sections of the Fortuna basin. The Los Baños/Rio Chicamo transition marks the onset of more restricted conditions in the basin. The Rio Chicamo Fm. reveals a distinct sedimentary cyclicity of evaporites/diatomites and laminated marls. The Rio Chicamo/Rambla Salada transition marks the onset of continental sedimentation. Mice denote fossil mammal sites: grey mouse indicates MN12 site, white mice MN13 and black mice MN13 with the additional presence of *Paraethomys* (see also [21] and legend to Fig. 2).

The Chicamo section, 320 m thick and situated along the Rio Chicamo river, 4 km to the south of the village of Abanilla, comprises the uppermost part of the Los Baños Fm., the entire Rio Chicamo Fm. and the lowermost part of the Rambla Salada Fm. [7,19,20]. The basal part is perfectly exposed along the river – as well as in a neighbouring gully complex – and consists of marine, bluish coloured, homogeneous marls of the Los Baños Fm. (Fig. 3). Occasionally, very thin turbidites are intercalated. Upward, these marls show a sudden transition to a well laminated, 15 m thick, gypsum unit, informally named Tale Gypsum [18]. Above the Tale Gypsum, an alternation of six sedimentary cycles, consisting of diatomitic marls and evaporites, characterises the restricted environment of the Fortuna basin during sedimentation of the Rio Chicamo Fm. The uppermost evaporite cycle is overlain by a conglomerate unit with the informal name 'Wichman bed' [19]. The sediments of the upper part (Rambla Salada Fm.) are all of continental origin and consist of marls, clays, sands and occasionally gypsum. This part is well-exposed in two relatively fresh outcrops along the main road from Abanilla to Santomera.

The Chorrico section, 750 m thick, is situated in the Molina de Segura suburbs, 6 km to the north of Murcia. It is the most suitable (longest and continuous) section to study the post-evaporitic continental Rambla Salada Fm. We had already sampled the upper 350 m of the section for a magnetostratigraphic study that focused on the Messinian evolution of the eastern Betics and the dating of late Miocene mammal events in Spain [21]. For our present study, we extended the Chorrico section downward by an additional 300 m (Fig. 3) until we reached the suburbs of Molina de Segura which are built on the evaporite units of the Fortuna basin. The downward extension of the section comprised predominantly continental marls, silts and sandstones.

3. Biostratigraphy

3.1. Planktonic foraminifera

Planktonic foraminiferal biostratigraphy is based on the stratigraphic distribution of four marker species plus the coiling ratio of *N. acostaensis* and is performed according to standard methods. The best datable part of the Serrata section is the lower part corresponding with the Hondo Fm. The joint presence of *Sphaeroidinellopsis seminulina* and *Globorotalia menardii 4* – including conical forms being indistinguishable from *Globorotalia miotumida* – in the basal part of this section (Fig. 2) allows a correlation with the Metochia (Crete) and Gibliscemi (Sicily) sections from which a similar association has been reported [22] with an age of 7.892 Ma [23]. Previous reports of *Globorotalia conomiozea* from the same level [6] are basically correct, but the associated faunal elements seem to indicate that these keeled and conical globorotaliids belong to an early (late Tortonian) influx of the *G. miotumida* group into the Mediterranean, which precedes the FRO of this group at the base of the Messinian by about 650 kyr.

Supporting biostratigraphic evidence for the correctness of this correlation is provided by the presence of *Globoquadrina altispira* in several samples from the Hondo Fm. (Fig. 2). This species is relatively frequent immediately above and below the late Tortonian influx of the *G. miotumida* group in Crete and Sicily and (almost) absent in younger Miocene deposits. Also the scattered occurrences of *Globorotaloides falconarae*[1] in the Hondo Fm. and the lower part of the overlying Serrata Fm. suggests a late Tortonian age for the base of the Serrata section because the LO of this species in the central and eastern Mediterranean is dated at 7.443–7.456 Ma [22,23]. The isolated occurrence of *S. seminulina* at the base of the Serrata section, however, is at variance with Crete and Sicily, where the interval above and below the late Tortonian influx of the *G. miotumida* group is characterised by scattered occurrences of this species. The dominant dextral coiling of *Neogloboquadrina acostaensis* 18 m above the base is also at odd with Crete and Sicily where sinistral coiling dominates between the early influx of the *G. miotumida* group and the LO of *G. falconarae* [22].

Representatives of *Bolboformis* are relatively common, particularly in the lower part of the Serrata Fm. and belong for the larger part to *Bolboformis intermedia*. This again is an indication that the Serrata section is of late Tortonian age, since in Crete and Sicily *Bolboformis* almost exclusively occurs in the Tortonian with *B. intermedia* being restricted to the late Tortonian [22]. The absence of *Bolboformis*, *G. menardii 4* and *G. falconarae* in the upper part of the Serrata Fm. may be related to increasingly stressed surface water conditions, which near the top of the section resulted in the flourishing of low-diverse faunas dominated by *Globigerina bulloides* and/or *Globigerina quinqueloba*.

The presence of dominant dextral *N. acostaensis* in several samples from the Serrata Fm. (Fig. 2) is puzzling because no dominant dextral *N. acostaensis* has been observed in time-equivalent sediments from Crete, Sicily, and Morocco [22,25]. One explanation is that these dextral populations reflect special (but unspecified) local surface water conditions. An alternative explanation is that they have been derived by erosion from lower Tortonian marine sediments, which in the central and eastern Mediterranean are characterised by dextral coiling of *N. acostaensis* [22,26]. Four samples from the Serrata Fm. contain reworked Cretaceous and Eocene planktonic fora-

[1] Note that the label *Catapsydrax parvulus* in [22] has been replaced by *Globorotaloides falconarae* (see discussion in [24]).

minifera, one of which with dextral *N. acostaensis*. Another two samples containing dextral *N. acostaensis* include a few large-sized *G. falconarae* and one specimen of *Globoquadrina dehiscens*. Both these taxa may have been reworked from older Tortonian sediments. All other samples from the Serrata Fm. lack clear evidence for reworking. The only sample from the Hondo Fm. containing reworked Cretaceous and Eocene species is just the one containing dominant dextral *N. acostaensis*.

Reworking does thus occur, but whether or not the deviating coiling pattern in *N. acostaensis* should be entirely attributed to the process of redeposition remains unresolved. The problem of reworking also plays in the nearby Fortuna basin. The marls of the Los Baños Fm. in the Chicamo section contain fluctuating numbers of poorly preserved planktonic foraminifera. The neogloboquadrinids compare best with *N. acostaensis* from the lower Tortonian on Sicily because of their dominant dextral coiling and the presence of specimens resembling small-sized *Neogloboquadrina atlantica* (see [26]). This interpretation is supported by the presence of specimens resembling *Globorotalia partimlabiata* and of *G. dehiscens* (in one sample). The lack of clear in-situ microfaunas suggests adverse environmental conditions and occasionally massive reworking during the deposition of these marls. Clear evidence of substantial reworking in the marls of the Los Baños Fm recommends caution with regard to the biostratigraphic interpretation of the time-equivalent Hondo Fm. The few samples from the Rio Chicamo Fm. (being time-equivalent with the Serrata Fm. in the Lorca basin) seems to contain an in-situ planktonic foraminiferal fauna dominated by *G. quinqueloba* and/or *G. bulloides* and a few sinistral *N. acostaensis*. The absence of dextral *N. acostaensis* might provide a hint that the dextral *N. acostaensis* in the Lorca basin has been reworked.

The planktonic foraminiferal data presented above leaves little doubt that reworking is a serious problem in the Lorca and Fortuna basins which prevents any straightforward biostratigraphic interpretation. If we weigh all the similarities and inconsistencies between the Spanish data and those from Crete, Sicily, and Morocco, then the scale is tipped to a late Tortonian age for the Serrata section in the Lorca basin.

3.2. Calcareous nannofossils

Biostratigraphic information obtained by the study of calcareous nannofossils in samples from the Serrata section also show a strong influence of reworking. Moreover, the peculiar environmental conditions which characterised the sedimentation in the Lorca basin affected the composition of the nannofossil assemblages as well. This resulted in assemblages characterised by the dominance of reworked (Cretaceous, Paleogene and lower Miocene) forms over the autochtonous ones in most of the studied samples. Eleven out of 87 samples were completely barren of any nannofossil. Reworking is particularly strong in the interval from 78 to 125 m, where assemblages completely barren of in situ nannofossils were observed in most of the samples. Samples with a consistent presence of autochtonous nannofossils are those corresponding to the lower part of the section (Hondo Fm.) and sparse samples from the Serrata Fm, but these assemblages have mainly long-ranging species and lack of biostratigraphic markers. Differently to what reported by Rouchy et al. [6], we did not find any evidence of Messinian nannofossil markers. The nannofossil species belonging to the genus *Amaurolithus*, typically associated with the *G. miotumida* group at the Tortonian/Messinian transition in the Mediterranean, are completely missing. Moreover, from the same level where earlier *G. conomiozea* has been reported [6], we did not find any evidence of the presence of *Reticulofenestra rotaria*, a species considered by several authors (e.g. [27,28]) a good marker for the Messinian in the Mediterranean (it has a scattered distribution from C3Br.2r to C3Ar- [28]). We focused on other lines of evidence in an attempt to provide a biostratigraphic 'meaning' to the poor data obtained. The absence of *Reticulofenestra pseudoumbilicus* (>7 μm) in all the observed in-situ assemblages helped to tentatively interpret what has been observed. This long-range species, which appeared in the middle Miocene (at about 14.5 Ma) and became extinct in the Pliocene (at 3.7 Ma), temporarily disappeared from the stratigraphic record in the interval from 8.8 to 7.1 Ma [29], defining a *R. pseudoumbilicus* paracme [30]. This late Miocene interval lacking *R. pseudoumbilicus* was observed in various ocean basins (see [29], for references). Some diachrony was evidenced for the re-entrance of this species, which seems to occur at the top of the interval corresponding to C3Ar. This indicates that *R. pseudoumbilicus* should have occurred (due to its re-entrance) in the Serrata section, to conform to a Messinian age as inferred by Rouchy et al. [6], but this is not the case. On the contrary, the nannofossil assemblages observed both in Hondo and Serrata Fms have the peculiar 'atypical character' of the upper Tortonian nannofossil assemblages in the Mediterranean. They lack of the biostratigraphic markers known in the oceanic sediments (e.g. discosterids of the *D. berggrenii–quinqueramus* group) and show the effects of the environmental conditions (restricted environment and increased reworking of older sediments). Particularly, in the samples from Serrata Fm low-diversity assemblages were observed, with some of the few autochtonous species showing unusual abundances. Bloom of *Coccolithus pelagicus* and peaks in abundance of helicoliths were recorded, generally in correspondence with the opal-rich beds, indicating the environmental control on the nannofossil distributions.

3.3. Mammals

In the Fortuna basin, middle Turolian (MN 12) fossil mammal assemblages have been found in the locality of Casa del Acero, located approximately 70–80 m above the marine evaporites [31–33], at the base of the Choricco section, and in the Barranco de la Parra section near Librilla. Biozone MN12 is definitely older than 6.8 Ma because younger levels in the Fortuna basin reveal MN13 fauna [21]. A late Turolian age (MN13) is given to the Librilla, Chorrico and Salinas (near Molina de Segura) sections [21].

4. Magnetostratigraphy

Paleomagnetic samples have been thermally demagnetised according to standard procedures. The mean NRM intensity in the Serrata section is around 0.1 mA/m. Thermal demagnetisation of the NRM reveals the presence of an initial component of normal polarity consistent with a present-day field direction. A characteristic dual polarity component of magnetisation was obtained in 66% of the specimens in the temperature range between 200 and 390°C (Fig. 4). Further heating above 400°C only revealed viscous random directions, caused by the oxidation of pyrite into magnetite. In 33% of the specimens the characteristic component could not be isolated with confidence. Declinations and inclinations were calculated for each characteristic component stable endpoint direction after correction for bedding tilt. Magnetostratigraphic results of the Serrata section reveal three polarity zones. The lower part (0–95 m) consists of normal polarities[2], a small reversed zone is found between 95 and 120 m, and the top part (120–175 m) is of normal polarity again (Fig. 2).

NRM intensities in the Chicamo section range from 0.04 to 10 mA/m, although most of the samples show values around 0.1 mA/m. After removal of a weathering induced overprint ($T < 240$°C) a characteristic dual polarity component (Fig. 4) is removed between temperatures of 240 and 400 or 680°C (depending on lithology) indicating that iron oxides, such as hematite and magnetite, are carriers of the ChRM. Removal of the secondary overprint often results in a very weak ChRM component. We generally refrained from interpreting the Zijderveld diagrams when the ChRM intensity at 240°C is less than 0.02 mA/m. The

[2] Rouchy et al. [6] found two single levels with reversed polarity in the lower part of their Serrata section corresponding to a sandy turbidite in diatomaceous bed (d) and a sulphur-rich carbonate level in bed (III). These suspect lithologies were not sampled by us, but the marls directly above and below (< 10 cm) show normal polarities. We consider the correlation of these two reversed levels to chrons C3Ar and C3An.1r [6] erroneous and think that these reversed directions are probably diagenetic artefacts.

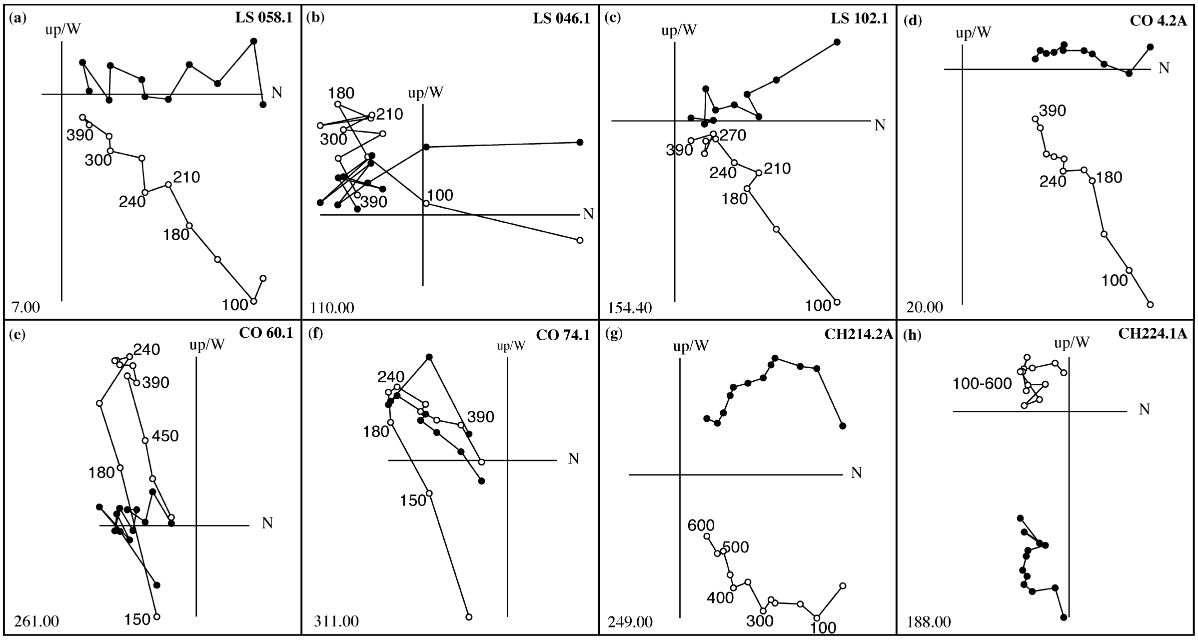

Fig. 4. Zijderveld diagrams for samples from the Serrata (LS) section of the Lorca basin and the Chicamo (CO) and Chorrico (CH) sections of the Fortuna basin. Filled symbols denote the projection of the vector end-points on the horizontal plane; open symbols denote projections on the vertical plane; values represent temperatures in °C; stratigraphic levels are in the lower left-hand corner.

only exceptions are made when the ChRM is clearly of reversed polarity. In most cases, the ChRM directions can be reliably determined if intensities are higher than 0.02 mA/m. In general, our results from the Chicamo section are in good agreement with the earlier paleomagnetic data [7], although upward extension of our section revealed an additional (N/R) magnetic reversal.

Thermal demagnetisation behaviour of samples from the downward extension of the Chorrico section is similar to the results of our previous study [21]. A ChRM is isolated above 300°C and shows both normal and reversed polarities (Fig. 4). The overall mean direction (reverse samples rotated to antipodal) yields a very substantial anticlockwise rotation of approximately 50° [21], which can be linked to the prevalent left-lateral shear of the associated NE–SW trending wrench fault [34].

5. Correlation to the astronomical polarity time scale

The magnetic polarity column of the Serrata section reveals three magnetozones with a reversed interval that is at least four times shorter than the normal interval below, and two times shorter than the normal interval above (Fig. 2). Magnetostratigraphically, this characteristic pattern can be perfectly correlated to the late Tortonian part of the late Miocene polarity time scale [23], while correlations to the Messinian are less likely. Clearly, the best pattern fit is obtained by the correlation to chron C4n.2n, C4n.1r and C4n.1n (Fig. 5). This magnetostratigraphic correlation is in agreement with biostratigraphic interpretations indicative of a late Tortonian age for the Serrata section.

The most striking feature of the Chicamo polarity sequence, with three normal and three reversed magnetozones, is that the lowermost two normal magnetozones are much longer than the reversed magnetozones. This pattern perfectly

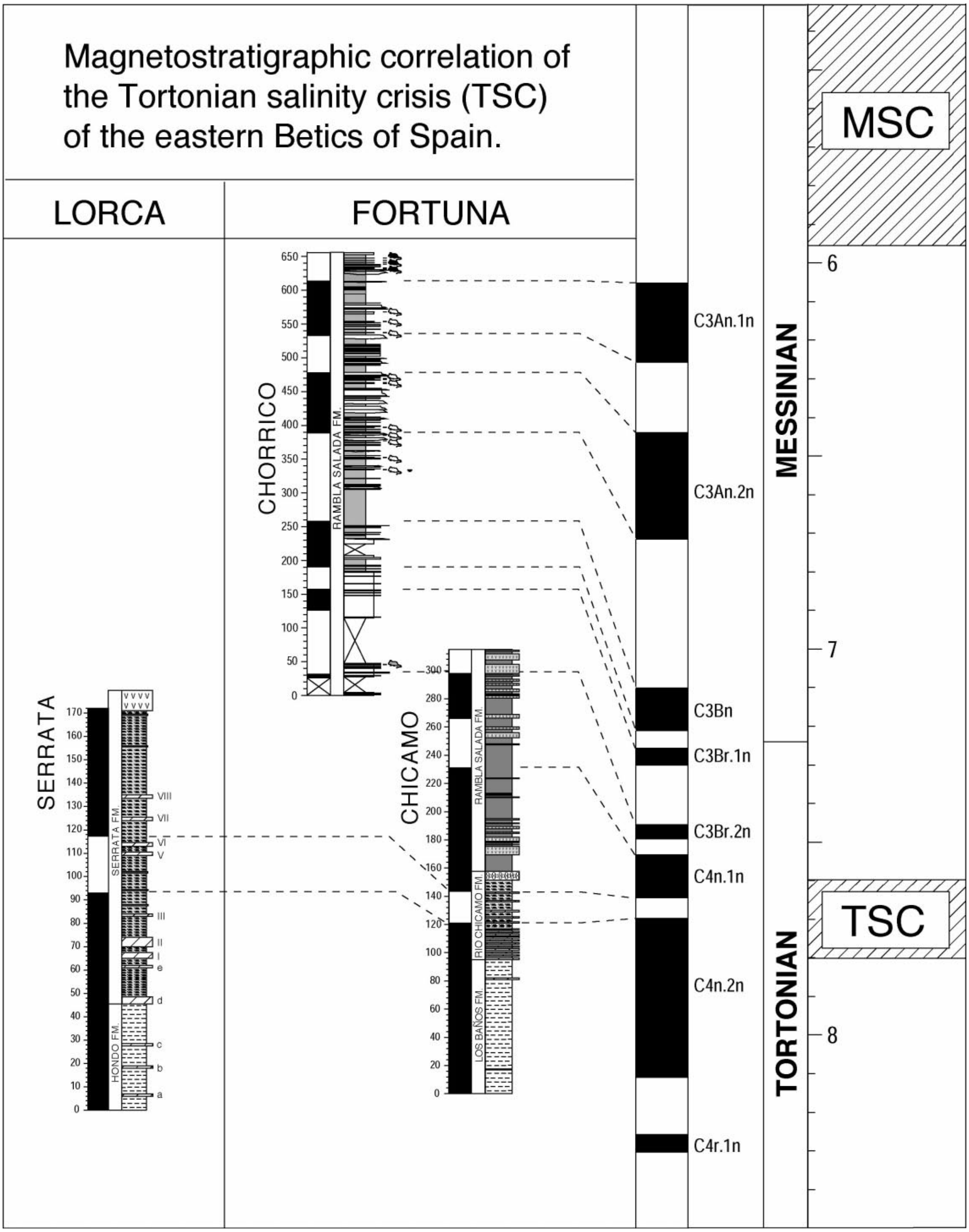

Fig. 5. Magnetostratigraphic correlation of the Serrata, Chicamo and Chorrico sections to the astronomical time scale of [23] modified for the Messinian part by [4]. We define the term 'salinity crisis' as the interval of evaporite deposition [4]. The onset of the 'Tortonian salinity crisis' (TSC) of the eastern Betics took place at an age of 7.8 Ma and had a duration of approximately 200 kyr. Note that this Tortonian salinity crisis occurred almost 1.8 Myr earlier than the Messinian salinity crisis (MSC) of the Mediterranean.

correlates with the late Tortonian polarity sequence of chrons C4n.2n, C4n.1n and C3Br.2n (Fig. 5). Another good pattern fit is obtained in the early Tortonian (10.4–9.5 Ma) part of the GPTS, but this correlation is regarded unlikely from a biostratigraphic point of view. Correlations to the Messinian [7] again clearly result in unrealistic changes in sedimentation rate and/or hiatuses and are in disagreement with the biostratigraphic data.

The upper part of the Chorrico section was already correlated to the GPTS [21] with the two normal zones corresponding to C3An.1n and C3An.2n, respectively (Fig. 5). The downward extension of the Chorrico section reveals an additional five magnetozones, making a total polarity sequence of ten magnetozones (five normal and five reversed). The downward extension of the Chorrico section perfectly correlates to the expected polarity sequence characteristic for the interval straddling the latest Tortonian/earliest Messinian and implies that the additional normal zones correspond to C3Bn, C3Br.1n and C3Br.2n (Fig. 5).

6. The 'Tortonian salinity crisis' of the eastern Betics

The first open-marine conditions in the Lorca (Hondo Fm) and Fortuna basin (Los Baños Fm) are recorded after some ill-defined period in the early-middle Tortonian [9]. An important change in basin configuration took place in the late Tortonian, accompanied by uplift of the basin margins [6,9]. This uplift was most likely related to major wrench fault activity along the SW–NE striking Alhama de Murcia fault system, and resulted in an increase of detrital input and reworking of earlier deposited sediments. The basinal response to this tectonic period was an increase in salinity and a change in facies from marls to diatomites and evaporites. Our new chronology shows that this salinity crisis began in the upper part of chron C4n.2n at an approximate age of 7.80 ± 0.05 Ma, both in the Lorca and Fortuna basin. The transition to continental deposits, marked in Lorca by the deposition of a very thick evaporite unit [14], took place at approximately 7.6 Ma (chron C4n.1n). Continuous subsidence of the basin centres accommodated a thick series of late Miocene continental deposits (Rambla Salada Fm.), which comprise a time interval of more than 2.3 Myr.

Evaporite deposition in the eastern Betics thus resulted from a local tectonic phase in the late Tortonian that caused basin restriction by uplift of several structural blocks at the basin margins. Consequently, no relation exists with the Mediterranean Messinian salinity crisis. In fact, the Lorca and Fortuna basins experienced their own phase of restriction and desiccation, 1.8 Myr earlier than the Mediterranean, and thus could better be referred to as the 'Tortonian salinity crisis' of the eastern Betics. This Tortonian salinity crisis is now accurately dated at 7.80 ± 0.05 Ma and had a duration of approximately 200 kyr.

7. Discussion

In the present-day situation of the Mediterranean, the loss of water by evaporation is more than double the gain by precipitation and runoff. This net loss of fresh water in the Mediterranean is compensated by the inflow of saline surface waters from the Atlantic and the Black Sea. To conserve salinity in the Mediterranean, there must be export of excess salt. This export is maintained by outflow at depth of dense and saline water through the Strait of Gibraltar. Restricting this outflow would increase the salinity in the Mediterranean which would ultimately result in the deposition of evaporites.

Tectonic uplift in the Gibraltar area during the Messinian [4,35,36] may have restricted the outflow of excess salt, while the inflow of Atlantic surface waters continued, which in the end resulted in the formation of the Messinian salinity crisis evaporites. During the Tortonian salinity crisis of the eastern Betics, outflow has probably been restricted by tectonic uplift of the SW–NE striking metamorphic complexes (Orihuela-Callosa massif and Carrascoy massif) of the Internal Betics (Fig. 1), which separated the Lorca and Fortuna basins from the Mediterranean. Uplift

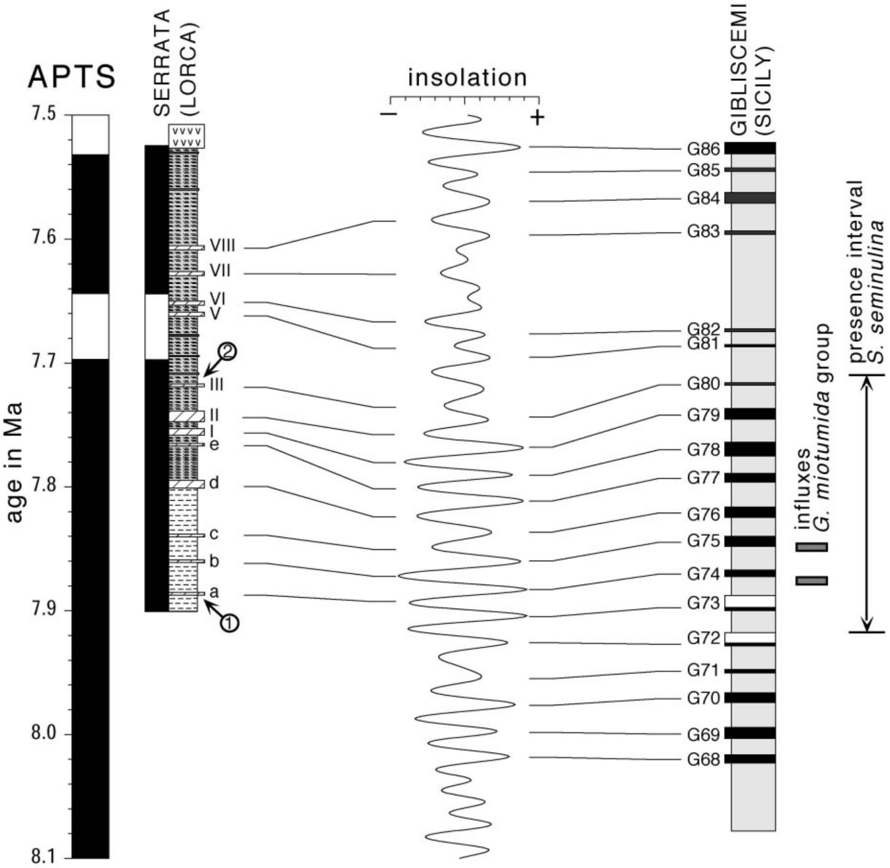

Fig. 6. Tentative astronomical calibration of the Serrata section to the insolation curve of Laskar [44] using the paleomagnetic reversals as age constraints. Astronomical polarity time scale (APTS) is after [23]. Numbered arrows denote the bioevents recognised in the Serrata section: 1, level with conical forms of the *G. miotumida* group, being indistinguishable from *G. conomiozea*; and 2, first level of dominant dextral coiling *N. acostaensis*. The calibration of the Gibliscemi section from Sicily [23] is shown on the right-hand side for comparison with the Mediterranean record. Downward calibration of the sedimentary cycles of the Serrata section reveals that the level with the *G. miotumida* group perfectly correlates to one of the two influxes in Gibliscemi. Upward calibration of cycles VII and VIII is less straightforward because this interval is marked by low amplitude variations and precession/obliquity interference patterns in insolation, related to the ∼400 kyr eccentricity minimum around 7.6–7.7 Ma. Regarding the increased thickness between the diatomite layers, it is possible that the diatomite VII and VIII correspond to the relatively highest peaks in the insolation record. The uppermost part of the section (between cycle VIII and the massif gypsum) is the most problematic because the sedimentary expression of the climate fluctuations is completely lacking. Assuming a relatively constant sedimentation rate, the transition to the main evaporites closely coincides with the amplitude increase in insolation following the ∼400 kyr eccentricity minimum dated around 7.6–7.7 Ma. The normal polarities at the base of the evaporites clearly demonstrate that the age of the transition to evaporites is older than 7.532 Ma. Note, furthermore, that the two diatomite levels (white) of Gibliscemi predate the onset of the Hondo/Serrata transition by approximately 80 kyr.

of these sill complexes probably originated in concert with strike-slip activity along the SW–NE trending fault zones like the Alhama de Murcia Fault, as a consequence of Africa–Europe collision. These strike-slip faults can be traced throughout the Alboran basin and Morocco and largely determined the tectonic evolution of the Gibraltar arc. [35,37,38]. Cyclically bedded evaporites and diatomites were deposited in a restricted basin to the northwest, while open marine

Mediterranean sequences prevailed to the southeast, including the well-known Messinian evaporites of San Miguel de Salinas (Fig. 1).

Quite a few studies have obviously misinterpreted the diatomite and evaporite deposits of the Lorca and Fortuna basin as equivalents of the Messinian salinity crisis because of facies similarities. Indeed, both the Messinian and Tortonian salinity crises are materialised by a regressive sequence and a significant increase in biosiliceous deposits (diatomites). This suggests that the diatomaceous facies is an essential element in the process of basin restriction.

Astrochronology has revealed that evaporite cyclicity during the Messinian salinity crisis is dominantly driven by dry-wet climate oscillations in the precession frequency band of orbital forcing [4,39]. Evaporite deposition occurred during precession maxima (insolation minima), during relatively dry periods when evaporation exceeded precipitation. During precession minima (insolation maxima) and relatively wet periods, high freshwater runoff resulted in deposition of laminated marls. Obliquity controlled glacio-eustatic sea level changes may only have added a minor contribution to the formation of evaporites. Evaporite cyclicity in the Tortonian salinity crisis is best demonstrated in the Chicamo section of the Fortuna basin where a regular alternation of six evaporite-marl cycles are present immediately below the Wichman-conglomerate. A similar cyclicity is exemplified by seven gypsum cyles in the marginal facies of the Serrata Fm. (Cortijada del Pozuelo section) of the Lorca basin. These gypsum layers can easily be traced to the Serrata section where they have been replaced by sulphur-bearing carbonates [6]. The magnetostratigraphic results from the Chicamo and Serrata sections indicate that approximately three to four evaporite cycles are present in the reversed interval correlative to C4n.1r. Precessional forcing for the observed evaporite cyclicity, implying a duration of approximately 60–80 kyr for the reversed interval, is in good agreement with the astronomical duration of chron C4n.1r is 53 kyr [23]. Clearly, obliquity and eccentricity can be ruled out because they would result in unrealistic long polarity intervals.

Precessional forcing for the evaporite cyclicity can, furthermore, be used to make a tentative correlation of the Serrata section to the astronomical curves. The paleomagnetic reversals of C4n.1r are located between cycles III and V and between VI and VII. Unfortunately, cyclicity is not very clear in this interval, but the reversed interval comprises approximately three or four sedimentary cycles. Downward correlation of the diatomite beds to subsequent peaks in insolation minima (Fig. 6) reveals that the influx of the *G. miotumida* group corresponds to one of the two influxes in the Gibliscemi section of Sicily [22,23].

The evaporite deposits in the Fortuna basin have long been regarded as evidence for the existence of a Messinian marine gateway between the Mediterranean and Atlantic [18]. This so-called 'Iberian Portal' or 'Betic Corridor' is thought to have persisted until the late Messinian and, as such, to have provided the oceanic waters required for deposition of the marine evaporites of the Messinian salinity crisis [36]. Our data from the Lorca and Fortuna basins, however, clearly indicate that marine conditions already disappeared during the late Tortonian, 1.8 Myr before the onset of the Messinian salinity crisis. This is in agreement with the pioneering work of Montenat [17] who dated the pre-evaporitic marls as late Tortonian and the evaporites as latest Tortonian–earliest Messinian because they were found in direct superposition. A late Tortonian phase of basin restriction is also reported from other Spanish basins that were part of this hypothetical Messinian gateway. Sedimentological studies from the Guadix-Baza and Granada basins, located in a more central position in the Betics, show a change from marine to continental sediments in the late Tortonian [40–43]. Hence, our data provide further evidence that the Betic Corridor which connected the Mediterranean with the Atlantic during the Tortonian, became emergent well before the Messinian.

8. Conclusions

A detailed and integrated magnetostratigraphic, biostratigraphic, and cyclostratigraphic study of the sedimentary sequences of the Lorca and Fortuna basins revealed that the entire marine succession was deposited during Tortonian times. An important tectonic event which strongly restricted these basins from the open marine waters of the Mediterranean occurred at 7.80 ± 0.05 Ma. This phase resulted in the deposition of cyclic alternations of diatomites and evaporites, which strongly favour a precession-induced climatic control. The final isolation of the basins resulting in a transition from marine to continental deposits is dated at 7.6 Ma. The isolation and desiccation of the Lorca and Fortuna basins from the Mediterranean was related to a local tectonic phase and has no relation to the isolation and desiccation processes of the Mediterranean that occurred 1.8 Myr later. Consequently, the evaporites of the Lorca and Fortuna basins do not correlate to the Messinian salinity crisis of the Mediterranean (5.96–5.33 Ma), but to a Tortonian salinity crisis of the eastern Betics (7.8–7.6 Ma). This late Tortonian phase of basin reorganisation is, furthermore, in good agreement with the geodynamic evolution of the other basins that formed the Betic Corridor in Tortonian times and provides more evidence that this marine gateway was closed during the Messinian.

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