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Discussion

Late Miocene Mediterranean desiccation: topography and significance of the ‘Salinity Crisis’ erosion surface on-land in southeast Spain: Comment

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1. Introduction

One of the most striking aspects of the Mediterranean “Messinian Salinity Crisis” as observed in land-based sections, is the basin-wide synchronicity in facies change (Krijgsman et al., 1999a). The Messinian succession of the Caltanisetta Basin on Sicily serves as the classical standard for these facies changes, which can also be recognised elsewhere in the Mediterranean, i.e. on Cyprus, Crete, northern Italy and southern Spain. It starts with an alternation of open marine marls and sapropels, passes via diatomites into evaporitic limestones, gypsum and halite of the “Lower Evaporites” (of marine origin) and, following an erosional unconformity, ends with the “Upper Evaporites” and associated fresh to brackish water deposits of the Lago Mare that are essentially of non-marine origin and contain a caspi-brackish ostracode fauna. The erosional unconformity between the “Lower and Upper Evaporites” is assumed to reflect the phase of most extreme sea level drawdown in the Mediterranean that caused significant erosion and localised channel entrenchment on the continental shelves and slopes.

The search for the expression of Messinian sea level drawdown and desiccation in the marginal Sorbas and Nijar basins in southeastern Spain—basins with a well preserved and relatively complete Messinian record—has occupied earth scientists ever since the publication of Hsü et al. (1973) provoking paper on Mediterranean isolation and deep desiccation during this so-called ‘Salinity Crisis’. This search has stimulated a long-lasting debate and up till now no consensus has been reached on the stratigraphic position of the expected major erosional unconformity. Riding and co-workers are respected carbonate geologists who especially concentrated on the marginal reefal facies, whereas we primarily investigated the central basinal facies, concentrating on the recognition of cyclic patterns for astrochronological and/or paleoceanographical analysis. The marginal fill of the Sorbas basin differs from the central one (Fig. 1) and although the basin is relatively well exposed, margin to basin correlations are seldom if ever straightforward. Our astrochronological results as well as our field interpretations of the central basinal sections are conflicting with the stratigraphic model of Riding et al. (1998, 1999). A debate would have been

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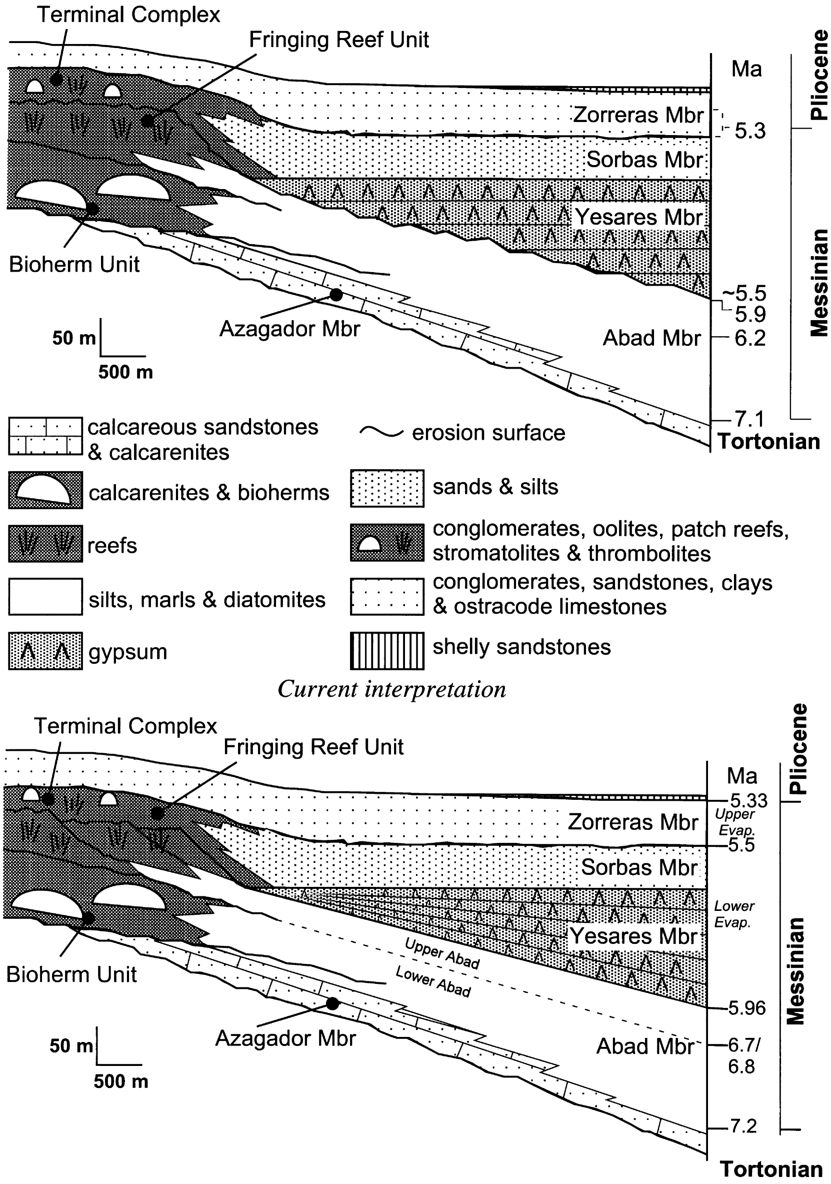

Fig. 1. Schematic stratigraphic overview of the Sorbas Basin, after Riding et al. (1999); upper half of figure), contrasted with the 'classic' scheme sensu Ott d'Estevou (1980); lower half and essentially followed by many workers) showing conformable contacts between the Abad and Yesares members, with the gypsum beds pinching out towards the basin margin (where dissolution and collapse breccias may locally obscure the original facies relationships). Current interpretations about the ages have been added to the right of the schemes.

superfluous if both groups had completed their studies with slightly different age models. A thorough discussion is needed, however, if fundamentally different age models and interpretations come to light.

Basin specialists have found no clear evidence for a major erosional hiatus that is indicative of a large downdrop event (Roep et al., 1998). If there is any, they suggest, it is represented by local scours occurring at the top of the Sorbas Member (Fig. 1), i.e. at the contact with the overlying Zorreras Member. Roep et al. (1998) suggest that the Sorbas Basin was protected from vigorous erosion because it became barred from the latest Messinian onwards, and as such it does not necessarily provide signs of widespread erosion. This view was dismissed by marginal specialists (Riding et al., 1999, elaborating on ideas presented earlier by Martín and Braga, 1994; Martín et al., 1997; Riding et al., 1998) who claim to have found concrete evidence for a marked sea-level fall at a much lower stratigraphic level in the basinal succession. Their main conclusions are: (1) the erosional unconformity separating the Fringing Reef Unit from the overlying "Terminal Carbonate Complex" in the marginal settings (Fig. 1) manifests Messinian drawdown and subsequent desiccation; (2) this unconformity extends to the basin centre where it separates Abad marls from the overlying Yesares gypsum, implying total desiccation of the basin, with locally deep erosion, before onset of the gypsum deposition; (3) the marine Yesares and Sorbas members therefore postdate Mediterranean desiccation, thus implicitly suggesting that these deposits form a local equivalent of the "Upper Evaporites" in Italy (as explicitly suggested by Martín and Braga, 1994) and (4) that the Sorbas Member was deposited under normal marine conditions. In addition, the continental to lacustrine Zorreras Member is referred to be of Pliocene age (Martín and Braga, 1994). If true, the Messinian succession of the Sorbas Basin as pictured by Riding et al. (1998, 1999) deviates considerably from the successions encountered elsewhere in the Mediterranean. Nevertheless, Riding et al. (1999) stress the importance of these local effects in determining Mediterranean-wide patterns of sedimentation and sea-level drawdown.

Clearly, field data are crucially important to assess the validity of the far-reaching conclusions of Riding et al. (1999) for Messinian drawdown in the Sorbas Basin. Apart from extensive field data collected from all over the Mediterranean (e.g. Krijgsman et al., 1999a,b), we can also rely on many reports and maps provided by Amsterdam MSc students, who have surveyed, described and mapped the Sorbas basin in great detail during the past 10 years.

2. Results from integrated stratigraphy

Continuation of the debate about the position of the erosional unconformity in the Sorbas and adjoining Nijar basin was fuelled in particular by the lack of an accurate (relative) age control for the Mediterranean Messinian. An excellent age control, however, can be achieved by using astronomical tuning of sedimentary cycles in combination with an integrated stratigraphic approach. This has been successfully employed in the Mediterranean Plio–Pleistocene and the pre-Messinian–Miocene, and is now also applied to the Messinian (Krijgsman et al., 1999a). Application of this method has resulted in the astronomical tuning of the pre-evaporite Messinian, indicating that the onset of the major phase of evaporite formation is remarkably synchronous across the Mediterranean with an age of 5.96 ± 0.02 Ma. It was concluded that: (1) the pre-evaporite succession is conformably overlain by the "Lower Evaporites"; (2) that the "Lower Evaporites" contain almost exactly the same number of precession controlled (gypsum) cycles in northern Italy (16) and on Sicily (15–17); (3) that the "Upper Evaporites" and Lago Mare start around 5.50 Ma and contain 7–8 sedimentary cycles, and (4) that all these units possess a reversed polarity. The erosional unconformity that separates the "Lower Evaporites" from the "Upper Evaporites" marks an hiatus with a duration of less than 100 kyr.

Meanwhile, integrated stratigraphic research in the Sorbas basin (Sierro et al., 1999; Krijgsman et al., 1999a, 2000) has revealed: (1) that the top of the Abad marls has exactly the same astrochronometric age as pre-evaporite successions elsewhere in the Mediterranean; (2) that the Yesares Gypsum contains 14 and the conformably overlying Sorbas unit 3 cycles (= 17 cycles); (3) that the Zorreras contains 8 cycles with caspi-brackish ostracode fauna's in the two distinct whitish limestone beds and (4) that all these units possess a reversed polarity. In our opinion, the conspicuous—integrated stratigraphic—similarities with the classical Mediterranean succession cannot be interpreted other than that the Sorbas basinal succession reflects essentially the same depositional history as other Mediterranean basins during the Messinian.

Astronomical forcing for evaporite cyclicity is demonstrated by field observations in northern Italy, which reveal how the gypsum cycles of the Gessoso-Solfifera Formation evolved from normal sapropel cycles via sapropel/limestone alternations (Krijgsman et al., 1999b). This replacement cannot be interpreted other than that the gypsum cycles basically have the same origin as the sapropel cycles and thus reflect dominantly precession-induced "dry–wet" alternations in (circum-) Mediterranean climate. The most obvious conclusion is that the gypsum cycles of the Yesares also reflect precession-forced climate oscillations since this gypsum shows the same type of cyclicity and has the same age (although not according to the scenario of Riding et al., 1999). The alternative tectonic "yo-yo" mechanism suggested by Riding et al. (1999) is unlikely, also because similar explanations for the Tripoli diatomite cycles on Sicily (Pedley and Grasso, 1993) have proven to be wrong (Hilgen and Krijgsman, 1999).

Evidently, an astronomical forcing scenario for the Yesares gypsum cyclicity is inconsistent with the age model proposed by Riding et al. (1999) for the basinal succession in the Sorbas Basin. Equating the base of the Yesares Gypsum with a post-desiccation (thus at least younger than 5.59 Ma according to our astronomical age model) re-flooding of the Mediterranean, as implied by the Riding et al. (1998, 1999) scenario, simply results in too many precession controlled cycles ($25 = \pm 525$ kyr) in the remaining reversed interval of chron C3r ($= 370$ kyr), even if part of the Zorreras Member is of (earliest) Pliocene age. Assigning an (early) Pliocene age to the Zorreras Member (Martín and Braga, 1994), a stratigraphic unit with 8 cycles, a reversed polarity and caspi-brackish ostracode fauna's, is also conflicting, the more so since unconformably overlying marine Pliocene sediments forming the top of the Zorreras Member belong to the Pliocene, which in the Nijar basin can be assigned to the early Pliocene *Globorotalia margaritae* Zone. Fig. 1 contrasts our results with those of Riding et al. (1999), using their stratigraphic scheme (their Fig. 2).

3. The pre-Yesares erosion surface

Apart from integrated stratigraphic arguments, the fundamentally different interpretation of the Abad/Yesares contact (conformable vs. a major erosional unconformity; Fig. 1) plays a crucial role to discriminate between the diametrically opposite models. Indeed, a conspicuous and important hiatus separates the fringing reef unit and the overlying Terminal Complex, or its lateral equivalent, the Sorbas Member, but this erosional surface cannot be traced unambiguously towards the basin centre. Where the distal parts of the reefal unit are found close to gypsum deposits, the evaporites are disturbed due to dissolution and collapse processes that locally affected the uppermost parts of the Abad marls as well. The resultant chaotic contact extends from Hueli westwards to Contreras along the southern margin. Similar features are also common in e.g. the NW Nijar basin. Evidently, the (erosional) interpretation of the Abad/Yesares transition favoured by Riding et al. (1998, 1999) at the locations specifically mentioned in their papers can be seriously questioned. For instance, the schematic cross-section by Riding et al. (1999) for the Hueli area (their Fig. 3) is oversimplified. In fact, the reefal unit overlies the "Upper Abad", but it is found also in stratigraphic contact with partly brecciated, deformed strata which include blocks and slabs of gypsum. Because this dissolution facies also affected the underlying "Upper Abad", the contacts between gypsum and marls are not necessarily erosional. The fact that towards Hueli the stratigraphic thickness of the Abad member decreases and its cyclic pattern becomes less prominent is not a matter of erosion, but of lateral facies change towards the margin.

Riding et al. (1999) state about the erosional aspects of the sub-Yesares surface that it "has much more deeply transected parts of the softer and laterally equivalent Abad Marls in the basin centre". In other words, the number of cycles recorded in the "Upper Abad" can be expected to vary due to this deep erosion. However, the same cycles are found in a number of sections, including the Gafares section in the Nijar Basin, the Los Molinos section—almost exactly where Riding et al. (1999) postulate a 30 m erosional depression (their Fig. 5)—and the Los Perales section (which is very close to the El Tesoro section of Riding et al. (1999) in the Sorbas Basin.

Field details shown by Riding et al. (1999) to demonstrate infill of deep scours in the Abad marls by basal gypsum beds are not valid examples. In these cases, the authors seem to be mislead by local faulting and mass wasting due to the superposition of the more indurated gypsum on top of the softer marls and diatomites in this cuesta. Already Ott d'Estevou (1980)

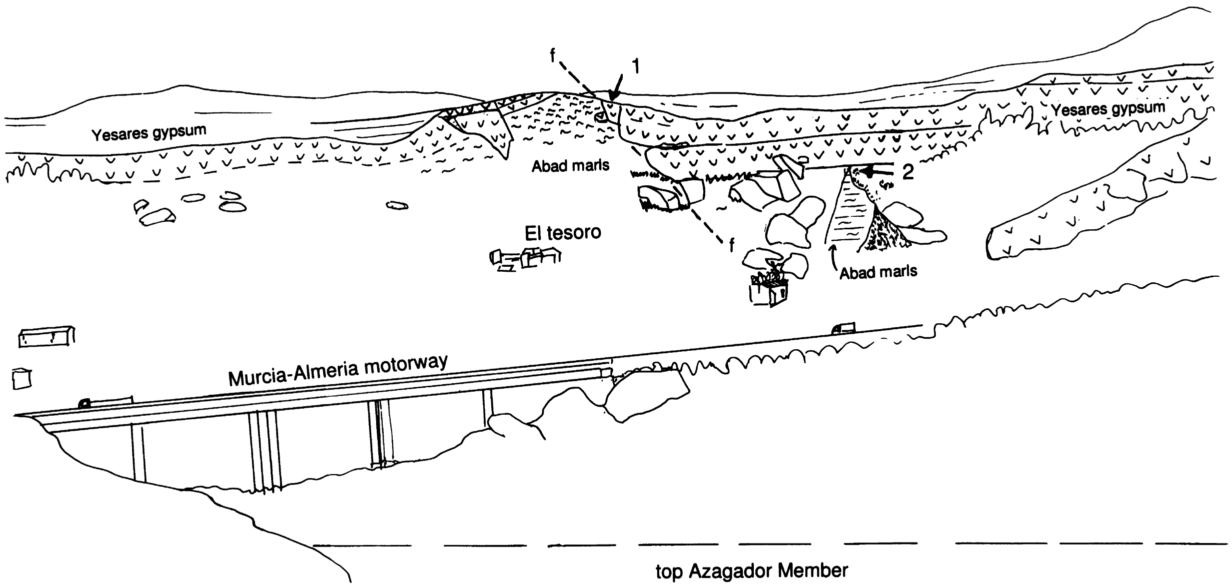

Fig. 2. Sketch (after photograph) showing the Abad–Yesares cuesta N of the ruined houses of El Tesoro, as seen from the south. In the foreground the motorway viaduct of the road Murcia-Almeria, located just E of Los Molinos del Rio Aguas. A minor reverse fault crosses the locality, bringing slightly deformed Abad marls in contact with a faulted quasi channel-shaped gypsum bed, depicted in Fig. 6 of Riding et al. (arrow 1). In fact, the normal Abad–Yesares contact is more reliably exposed at the bottom of the eastern gypsum ridge (arrow 2), where a cliff section of Abad marls is not covered by rockfall of large gypsum blocks, or overgrown by vegetation.

noted this locally deformed character of the contact ("le contact est schistoïde, plissoté et gypseuse", p. 55). So, what is going on? The Abad–Yesares contacts in the central part of the Sorbas are mainly exposed along a roughly SW–NE oriented, generally steep escarpment which runs from a marginal position near Hueli to the more central parts of the basin, with an additional occurrence further West (see Fig. 4 of Riding et al., 1999). Where the Yesares can be traced basinward as a coherent ledge, i.e. from the Cerron de Hueli, the Abad and Yesares strata are in conformable contact (dipping 8° NW at Hueli). Although, steep and partially scree and shrub covered steep ridges hinder close observation in many places, there is not a single locality which allows to describe "a highly irregular erosion surface". Fig. 6 of Riding et al. (1999) indeed seems to show a channel, but at this locality a minor NW–SE oriented reverse fault in the axis of a small fold disturbs the laterally continuous gypsum strata (Fig. 2). Their picture shows the "channel", together with upward squeezed Abad marls along the fault. At a lower level, however, just E of this locality the normal contact with the lowermost gypsum bed is visible in a steep gully (Fig. 2). Also the 30 m deep depression shown in Fig. 5 is an unrealistic interpretation of the very thick, but laterally continuous and partly scree covered basal Yesares bed. In contrast to these spots, the undisturbed marl-gypsum cuesta SW of Molino de Rio Aguas shows perfect parallel bedding between the uppermost Abad diatomites and the lowermost Yesares bed, an observation in line with the stratigraphic continuity mentioned by previous investigators.

Also in the smaller gypsum occurrence West of Sorbas (S of Los Yesos), a road cut exposes an abrupt, but straight and conformable contact between "Upper Abad" sediments and the first thick Yesares gypsum bed. Influxes here of shallow marine debris and a slump bed in the uppermost Abad marls might indicate tectonic activity and also some shoaling cannot be ruled out. Thus, in our view the transition from the "Upper Abad" to the basal Yesares reflects neither a basinwide discontinuity, nor a significant paleobathymetric change, it is dominantly a critical increase in salinity, which already started during "Upper Abad" time (Sierro et al., 1999). The gypsum beds therefore do not onlap over an eroded palaeotopography as interpreted in Fig. 2 of Riding et al. (1999), but rather pinch out towards the margins of the basin, as shown by Ott d'Estevou (1980), and indicated in our version of Fig. 2. Onlap over a palaeotopography, moreover, implies a general transgressive trend, whereas the overall tendency of the Yesares is shallowing up (Dronkert, 1985; Rosell et al., 1998).

The marked erosional unconformity that separates the Fringing Reef Unit from the TCC can be traced all along the basin margin, but passes basinward in a conformity. We relate it to an interregional sea level fall in the order of 100 m (Troelstra et al., 1980; Dronkert, 1985) during late Abad times and to the ensuing, but variable low-stand during deposition of the marine Yesares Gypsum. This interpretation of an approximately 100 m sea-level drop is less dramatic than total desiccation claimed by Riding et al. (1999) and is in line with quantitative pinning point studies of sea-level fluctuations in the coeval reefal complex of Las Negras (Nijar Basin; Goldstein and Franseen, 1995; Franseen et al., 1998).

Both Riding et al. (1999) and we agree about the presence of a late Messinian barrier that separated the Sorbas Basin partly and sometime wholly from the Mediterranean. In case of a total downdrop of sea level, is it logical to assume that the basin would be emptied and incised, but it would not remain empty. With a barrier at hand, one would expect that continental or lacustrine clastics start to be accumulated in the drying basin, at least towards the barrier. Such indicators, however, cannot be found at the sub-Yesares level.

4. The Sorbas and Zorreras members

All Sorbas Basin investigators agree that the Yesares gypsum is conformably overlain by the Sorbas Member, a unit developed either as chiefly muds in the basin centre, or as prograding coastal sequences, well developed around the town of Sorbas (Roep et al., 1998). Riding et al. (1999) conclude that the Sorbas Member reflects a normal marine environment and therefore has been deposited following marine reflooding of the basin after the drawdown event when the sill separating the basin from the Mediterranean was eliminated. This conclusion, however, is incorrect insofar that many Sorbas strata have been deposited under raised salinities, as shown by the total lack of bioturbation in the laminitic basinal and lagoonal muds and presence of halite pseudomorphs in the latter (Roep et al., 1979). There are, however, levels that yield either relatively poor foraminiferal assemblages (Ruegg, 1964; of the same type as described by Van de Poel (1992) for coeval strata in the adjacent Nijar Basin), or—such as in the sandy top—which display beautifully preserved ichnofossils. Apparently, the Sorbas member was deposited under fluctuating salinities. The microfauna, however, never shows a normal open marine association, comparable to that of either the underlying Abad, or early Pliocene in the region. Also a faunal list in Riding et al. (1998) hints in that direction. Ruegg (1964) opted for the possibility of minor marine ingressions (he found one level) under fluctuating salinities, with at least partial reworking judging the often broken and abraded morphology of the foraminifera. We interpret the Sorbas Member as a generally less saline unit than the underlying Yesares Member, which is also suggested by the gradual upward disappearance of gypsum interbeds.

Finally, the Sorbas Member is overlain by continental deposits of the Zorreras Member. The contact is abrupt, but seems conformable, although the lowermost continental interval thickens eastward, overlying strongly burrowed shallow marine sands of the uppermost Sorbas cycle. The top part of the Zorreras Member is of Pliocene age. It is this Sorbas-Zorreras contact that we consider the most likely candidate to reflect the Messinian drawdown event in the Sorbas Basin. As pointed out by Roep et al. (1998) visual effects of erosion at this level are only locally developed, probably because the Sorbas Basin has been protected from vigorous erosion during the major drawdown event, caused by its topographically almost enclosed position towards the end of the Messinian. Indications for local, vigorous erosion that could be related to a downdrop event at this level can be found in the adjoining Vera Basin (Fortuin et al., 1995). Let us be clear, in our zeal to cover the entire Messinian episode with our measuring rod of cyclic patterns, we do not oppose the idea of an important desiccation event. But such an event has to be visible for any geologist, which is certainly not the case with the sub-Yesares surface.

Acknowledgements

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