Seismic evidence for Messinian detrital deposits at the western Sardinia margin, northwestern Mediterranean

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Abstract

Based on new (‘SESAME 01’ cruise) and previous seismic reflection data, this paper evidences the effects of the Messinian Salinity Crisis on the sedimentation at the western Sardinian margin. In the lower part of the margin, Messinian detrital deposits are organized into two successive, ~300 m thick units. According to their shape, facies and extent, they are similar to alluvial fans, presumably fed by subaerial erosion of the upper margin. Whereas the earliest body is observed continuously all along the margin and the adjacent part of the deep basin, the youngest one is restricted to the vicinity of the canyons. This pattern could therefore sign a late Messinian sea-level rise, as suggested by detrital fan conglomerates sampled in a similar position along the northern Ligurian margin. We observe salt-related deformation of the Messinian detrital units, and the top of the salt layer gradually turn into a detrital delta seaward, implying that at the deep margin, most of the salt deposited before the low-stand Messinian delta emplaced, probably during the main Messinian sea-level drop or at the beginning of the low-stand sea-level.

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1. Introduction

The Messinian Salinity Crisis (hereafter referred as MSC) is known to have deeply reshaped the margins of the Mediterranean Sea and to have led, in the deep basin, to the deposition of a thick sequence of evaporates, which are found in three distinct units, the ‘Lower Evaporites’ (carbonates and evaporitic sediments), the ‘Salt’ (halite and anhydrite, i.e.; the mobile layer) and the ‘Upper Evaporites’ (marls and gypsum) (Ryan, 1973; Ryan et al., 1973; Clauzon, 1982; Réhault et al., 1984). Owing to this outstanding sea-level change, the ‘Messinian Mediterranean’ is recognized to represent an excellent target to understand the consequences of eustatic processes on both land and marine environments.

Although the main steps and timing of the MSC are nowadays broadly clarified (Clauzon et al., 1996; Krijgsman et al., 1999; Blanc, 2002), many aspects of this major event remain unresolved or unclear, and are still highly debated. The first stage of the Crisis (the ‘marginal evaporites’ from Clauzon et al., 1996) has been widely documented owing to the easy access to several markers of the Crisis onshore (Rouchy et al., 1998, and references therein). Conversely, studies devoted to the deep sea deposits of the second phase (the ‘basinal evaporites’ from Clauzon et al., 1996) are still limited (Dos Reis, 2001; Dos Reis et al., 2004a; Lofi et al., 2005). One of the most enigmatic points is the importance and the extent of the clastic detrital deposits resulting from the massive erosion of the continents during the second step (from ~5.60 to 5.32 Ma). Whereas MSC events recorded in the upper parts of the margins are well described
(e.g. the systematic cross-cutting of deep valleys and canyons by tributary rivers all around the Mediterranean shores, and the subsequent infill of drowned valleys by marine and later fluvial sediments during Pliocene, called the ‘Zanclean flooding’), the age, nature and/or extent of the deposits along the lower margin and in the deep basins are poorly known (Clauzon et al., 1996). For instance, no drilling has yet recovered the whole deep evaporites sequence. So far, seismic lines collected at the foot of the margins are generally unable to resolve the sedimentary sequences associated to the MSC and their chronostratigraphic relationships with the mobile salt and Upper Evaporites layers (Gorini et al., 1993; Mauffret et al., 1995, 2001; Séranne et al., 1995; Séranne, 1999). This is due to several reasons: (1) the sharply-different sedimentary processes allowing for the deposition of salt (i.e. evaporation process) and clastic sediments (i.e. gravity-driven process), and the subsequent highly-variable and poorly controlled deep sea deposition rates (Blanc, 2000); (2) the salt mobility, which induces thin-skinned tectonics on the continental slope and at the foot of the margin, from extensional to contractional deformation in the overlying brittle sedimentary units (i.e. the Upper Evaporites and the Plio-Quaternary cover; Gaullier, 1993; Gaullier and Bellaiche, 1996; Mauffret et al., 2001; Dos Reis et al., 2004a; Dos Reis et al., this issue); (3) the lack of stratigraphic control on the seismic facies; and (4) the lesser interest of the community for the MSC offshore, relative to other topics such as the deep structure of extensional margins (Mauffret et al., 1995, 2001) or Plio-Quaternary sediment dynamics near large canyons (e.g. Migeon et al., 2001).

In order to tackle these outstanding questions, we collected in September 2001 a new set of seismic data off western Sardinia onboard the R/V Tethys II (SESAME cruise, Fig. 1a). Combined with previous seismic lines, these data document in detail the central part of the Sardinian passive margin, and especially in and around one of the most important canyons of the margin, the Oristano canyon (Thomas and Gennesseaux, 1986).

The western Sardinia margin can be divided into three areas to study the MSC: (1) due to the insular location of Sardinia, the Plio-Quaternary sediment supply is weak compared with other sedimented margins such as the Gulf of Lion margin; (2) the sedimentary input since Oligocene has been captured by onshore grabens (Casula et al., 2001; Thomas et al., 1988); (3) no major tectonic deformation occurred after the rifting stage of the Mediterranean basin, allowing for a better preservation of the Messinian erosional surface and deposits compared to the other margins which were recently reactivated (Chaumillon et al., 1994); and (4) the salt-related deformation consists into normal faults with moderate vertical throws, which do not disrupt the continuity of the Messinian and post-Messinian units across the deformation zone, by contrast with most of the Mediterranean margins.

In this paper, our first objective is to evidence and characterize the detrital bodies deposited along the deep margin during the Messinian low-stand sea-level. A second objective is to better assess the chronological relationships between the Messinian evaporites sequence and these detrital bodies. In particular, we show that at the deep margin, the detritals postdate the Messinian salt deposition. Our seismic lines, which are limited to the deep margin, however, do not image the seaward termination of the detrital fans and their lateral transition to the deep basin evaporates located seaward from the study area. This lateral transition is thus discussed on the base of seismic lines located at the deep basin offshore Saint Tropez (northern Ligurian margin), in a similar context during Messinian time.

2. Seismic data set

This paper is based on two surveys offshore western Sardinia: respectively, the ‘SARD’85’ cruise, conducted in 1985 on the R/V ‘Catherine Laurence’, and the ‘SESAME’ cruise, carried out in September 2001 on the R/V ‘Tethys II’ (INSU-CNRS, France). The ‘SARD’85’ cruise collected 1250 km of single-channel seismic lines (Thomas and Gennesseaux, 1986; Fig. 1a). The ‘SESAME’ cruise collected 13 additional seismic lines using a 25 m long 4-channel streamer with a mini-GI air-gun shooting every 12–12.5 m at 140 bar, allowing for a 4-fold coverage.

Seismic processing includes gain recovery, normal move out correction, stack, post-stack migration in the FK domain, and band-pass filtering. For the final plot, a coherency filter was applied to the data, as well as a dynamic equalization and a filtering in the FK domain.

3. Morphological and tectonic setting

The western Sardinia margin can be divided into three morphological domains (Casula et al., 2001, and references therein). First, a 90 km wide amphitheatre facing Oristano is centered on the margin (Fig. 1b). It provides a smooth transition between the narrow continental shelf, 25 km wide, and the deep basin, at a 2850-m water-depth. The Oristano Amphitheatre is bounded to the north and to the south by a continental shelf twice wider, which is connected to the deep basin by two steep slopes, the Nurra and the Sulcis scarps, respectively, (Thomas et al., 1988; Fig. 1b). These morphological domains reveal a first order canyon/interfluve system. Inside the Oristano Amphitheatre, a net of convergent valleys defines a second order canyon/interfluves system (Fig. 1b).

The morphology of the Oristano Amphitheatre directly results from the formation of the margin during Oligo-Miocene times. Back-arc trans Austral tectonics, linked to the northwestern Mediterranean opening, reactivated
NE–SW and NW–SE late-Hercynian structures (Thomas and Gennesseaux, 1986; Thomas et al., 1988; Fais et al., 1996). The formation of the Oristano Amphitheatre is controlled by NNE–SSW listric normal faults and NW–SE transfer faults, which delineate horsts and half-grabens in the metamorphic basement, between the Nurra and the Sulcis scarps (Thomas et al., 1988; Fais et al., 1996; Lecca et al., 1997). Moreover, the deepest part of the amphitheatre is superimposed to a main graben bounded to the north by a steep scarp trending N120° (Fig. 1b). Such scarp is controlled by a major transfer fault that crosses the entire margin (Thomas et al., 1988). During the rifting and drifting stages, the grabens were filled by Oligo-Miocene sediment sequences, sometimes 1500 m thick (Thomas and Gennesseaux, 1986; Thomas et al., 1988; Fais et al., 1996; Lecca et al., 1997; Casula et al., 2001). In the study area, the margin is stable since the Messinian time, while the tectonics still affects the central part of the island (Casula et al., 2001).

4. Seismic stratigraphy of the study area

Beneath the continental margin, the deepest acoustic units observable on the seismic lines correspond to the pre-Messinian units, i.e. the metamorphic basement (MB) structured in horsts and grabens, and the Oligo-Miocene sediments (OM) infilling the grabens (Fig. 2a). In the deep basin, the basement cannot be properly imaged by the SESAME and SARD85 seismic lines, since the Messinian salt layer acts as a screen for the seismic waves.

In the upper part of the continental slope, the pre-Messinian units are truncated by the Messinian erosional
Fig. 2. Main seismic units described in the paper (a) inside the Oristano Amphitheatre and (b) outside the Oristano Amphitheatre, in the area drilled during DSDP Leg XIII (see location in Fig. 1). Pre-Messinian units: Metamorphic Basement (MB); Oligo-Miocene sequences (OM). Messinian units: Salt (S); Upper Evaporites (UE); Detrital units according to the present study (C), (C'), and (T). Post-Messinian units: Plio-Quaternary sequence (PQ). Two-Way Traveltime (TWT).
surface, which is characterized by a strong reflector (Fig. 2a). The pre-Messinian units are here directly overlaid by the Plio-Quaternary unit (PQ), which can be recognized all around the Mediterranean basin owing to a typical acoustic facies, transparent at its base and becoming more reflective upward (Réhault et al., 1984; Fig. 2a,b). In the lower part of the slope and in the adjacent part of the deep basin, additional units are observed between the pre-Messinian and the PQ sequences (Fig. 2a,b). Such units (called S, UE, C, C’, and T) are related to the Messinian event on the western Sardinia margin and constitute the main purpose of this study. They will be accurately described in Section 5.

5. The Messinian acoustic units: geometry and distribution

5.1. The S unit (salt layer)

The Messinian salt layer, identified as the S unit on the seismic lines, generally corresponds to the deepest clearly observable seismic unit in the basin (Fig. 2a and b). The top of the salt is characterized by a strong reflection, due to a high contrast of impedance between the salt and the overlying sediments. The S unit is represented by a rather transparent acoustic facies showing internal reflectors with low amplitudes, typically observed in the whole Mediterranean deep basins (Réhault et al., 1984; Gaullier et al., 2000; Dos Reis et al., 2004a). In some places, the salt layer forms diapirs disrupting the uppermost layers on the seismic sections (Fig. 2b). Near the margin, the diapirs generally affect reflectors of the base of the brittle sediment cover only; seaward, the diapirs grow through the youngest layers and sometimes reach the sea-bottom. Due to this salt diapirism, the top of the S unit depicts highly variable depths (between 4.5 s two way travel time (TWT) and 3.7 s TWT) in the deep basin, and numerous side-scared echoes are generated. Such artifacts can hardly be reduced by numerical processing of the data and prevent us from an accurate interpretation of the data within the deep basin.

Close to the margin, the salt layer is less deformed, with a layer top at 4.2 s TWT, gently rising up to 3.9–4.0 s TWT against the margin’s acoustic basement, where it pinches out (Figs. 2–6).

5.2. The C unit

The C unit is observed beneath the Oristano Amphitheatre and in the deep basin all along the western Sardinia margin (Fig. 6). It is characterized by a reflective acoustic facies composed of sub-parallel and irregular reflectors of high energy (Fig. 3–5), showing dominant frequencies around 50–70 Hz (Fig. 7).

In the deep basin, close to the continental margin, C unit corresponds to sub-horizontal reflectors and lies over the salt layer, with a gradual transition between the two facies characterized by an increase of the internal layering in the salt layer, from bottom to top of the layer (Fig. 3c). At depths shallower than 3.9 s TWT, the salt layer disappears and C unit lies directly over the acoustic basement of the margin with a low deposit angle, between 2 and 3° (Figs. 2, 4 and 5). Except for the seismic lines shot along the Oristano canyon axis (for example SM08, Fig. 5), C unit lies on a depositional surface, which is apparently formed by the western flank of the deepest structural block of the margin, showing an average slope of 8–9°. The C unit reflectors are dipping both toward the deep basin and toward the canyons axis, with an average angle of 5.3 ± 0.3° (Figs. 3 and 4).

The thickness of C unit appears rather constant within the few kilometers of the deep basin explored during the SESAME cruise, around 200 ms TWT, although its base is not always clearly visible, because of the gradual transition to the salt layer below. Conversely, its thickness significantly varies on the continental slope (Figs. 3 and 6): C unit is 50–100 ms TWT thick on the second order interfluvies of the Oristano Amphitheatre, whereas it reaches a maximum thickness of 200 ms TWT at the canyons axis, similar to the thickness observed in the deep basin.

The C unit tapers off in its upper part on the margin acoustic basement, at a variable depth, depending on its position relative to the canyons: the C wedge is observed at 2.4–2.6 s TWT depth in the canyon axis, and its depth increases gradually to 3.1 s TWT away from the canyons, since the C unit is more developed in the canyons. Close to the wedge, the top of C unit is often marked by toplaps, whereas it is generally concordant with the above T unit elsewhere (Fig. 4).

Upslope the C wedge, some deposits are still observed in the canyons axis, but present a chaotic facies and the top of the layer displays an irregular shape. It is impossible from our seismic lines to tell the time relationship between such chaotic facies and C unit described above.

Outside the Oristano Amphitheatre, the C unit observed in the deep basin tapers off at 3.3–3.4 s TWT depth against the marginal acoustic basement south of the amphitheatre, and at 3.8 s TWT along the Nurra scarp, north of the study area.

Along the slope out of the Oristano Amphitheatre, the acoustic facies of C unit laterally evolves into a different facies, called the C’ unit (Fig. 2b), composed of irregular reflectors showing low frequencies, generally less continuous than those described for the C unit, and becoming locally chaotic (Fig. 2b). The C’ unit appears to be thin, with an average thickness of about 70–100 ms TWT, although its base is not always clearly visible. When an internal layering is observed, the reflectors are roughly parallel to the deposition surface, contrastingly with the C unit. The deposition surface of C’ is generally much steeper than the one described in the Oristano amphitheatre, especially along the Nurra scarp where the basal slope is of about 10°.
5.3. The T unit

The T unit is observed between the C unit and the Plio-Quaternary sequence, both in the Oristano Amphitheatre and in the adjacent part of the deep basin (Fig. 6), gradually disappears southward, i.e. toward the Sulcis scarp, and lacks along the Nurra scarp, north of the Oristano amphitheatre (Fig. 6, and location on Fig. 1).

Fig. 3. Part of the SM11 seismic line recorded during ‘SESAME 01’ cruise (see location in Fig. 1). The line was shot parallel to the margin, across the main canyon observed in the Oristano Amphitheatre. (a) Processed seismic line; (b) interpreted section; (c) zoom on the Messinian units. From bottom to top, the Messinian units correspond on this line to: salt (S), C unit, and T unit. The transition between the Salt and the C unit appears to be gradual. The ductile salt, while migrating toward the basin (perpendicularly to the SM11 line) is responsible for the deformation in the brittle overlying sedimentary layers. Such deformation is characterized by extensional features at the edge of the canyon (which surimposes the N120° Scarp), and by contractional structures in the canyon axis. Both extensional and contractional features are deeply rooted on a low-frequency reflector which deeps towards the canyon axis, and is interpreted as the salt décollement. See Fig. 2 caption for units labels.
The T unit is characterized by a highly reflective facies (Figs. 3–5), with average frequencies higher than those described for the C unit, i.e. around 110 Hz on the SESAME data (Fig. 7). The seismic facies laterally changes along the margin: inside the Oristano Amphitheatre, the T reflectors are homogeneous and continuous on the interfluves, whereas they become more chaotic and discontinuous towards the canyons axis (Figs. 3–5). In this particular case, it is sometimes difficult to distinguish the boundary between the C and T units (Figs. 3 and 5). Locally, on the interfluves, the T unit facies becomes more transparent, and is there similar to the base of the Plio-Quaternary sequence (see for example Fig. 4, at the upslope termination of T unit).

In the deep basin, since the T unit is concordant with the C unit, the distinction between the two corresponding seismic facies can generally be made by a greater regularity of the T unit reflectors, and by the frequency spectrum of the numerical data (Figs. 4 and 7). Moreover, beneath the continental margin, an angular unconformity generally marks the limit between the C and T units (Figs. 3 and 4), whereas T reflectors are always concordant with the Plio-Quaternary sequence (Figs. 3–5).

Above the C unit, the T unit tapers off on the pre-Messinian acoustic units of the margin (Figs. 4–6), at a depth of 2.25 s TWT (∼1800 m) at the canyon axis. The wedge’s depth increases up to 2.8 s TWT (∼2100 m) when moving far from the canyons (Fig. 4). In the deep basin, the unit thickness is rather constant at around 130–150 ms TWT.

5.4. The Messinian erosional surface

From upslope to downslope, the Messinian erosional surface marks successively the base of the Plio-Quaternary sequence and the base of the T unit. It gradually disappears beneath the C unit wedge. Under the C unit,
neither the strong reflector representing the erosional surface, nor the truncation of the Oligo-Miocene reflectors are observed deeper than 3.25 s TWT (≈ 2900 m). This apparent lack of the erosional surface may be due to the lack of the Messinian erosion in this area or to the scattering of the seismic energy by the C unit, which could prevent from further acoustic penetration.

The morphology of the erosion surface is mainly controlled by the nature of the rocks outcropping on the margin after the rifting: while the Oligo-Miocene sedimentary basins are preferentially submitted to erosion, the metamorphic horsts of the margin should have persisted longer. Indeed, the rifted structure of the margin is still clearly visible on the normal-striking lines (see for example Figs. 5 and 6). However, we note that the erosional surface is generally marked by a slope break located at the pinch-out of the C unit, suggesting here an imprint of the Messinian times. Assuming velocities of 1900 and 2500 m/s for PQ and T units, respectively, the average angle for the erosional surface upslope C unit C is 2.3–2.5°, whereas it reaches 8–9° for the deposition surface beneath the C unit.

6. Salt-related deformation in the study area

The transition zone from the continental margin to the deep basin is characterized, all along the margin, by 5–30 km wide deformation zone affecting the C, T and PQ units (Figs. 4 and 5). These units are cut by listric normal faults that define small tilted blocs that are 1–3 km wide (Fig. 4). The vertical throw along the faults is maximum (reaching values of about 150 m) for the sediments of the C and T units, and gradually decreases upward into the PQ sequence, which displays wedge-shaped reflectors. Most of
the faults reach the sea-bottom, which is slightly vertically shifted. Perpendicularly to the margin, the cumulated vertical throw across the deformation zone reaches 0.4–0.6 ms TWT (i.e. 300–500 m).

Similar salt-related faults are identified on the seismic lines parallel to the margin, across the major canyon of the Oristano Amphitheater (Fig. 3). The uppermost normal salt-related fault fits there with the structural boundary provided
by the N120° Scarp. The vertical shift of the C and T units between the canyon edge and the canyon axis reaches 0.4 s TWT in that case (Fig. 3).

The offset of the reflectors generally indicates a normal displacement component along the faults. However, reverse faulting is locally observed downslope from normal faults, where the acoustic basement forms some relief (Fig. 5).

The normal and reverse faults are deeply-rooted on a low-frequency reflector (Figs. 3–5). This reflector, located immediately below the C unit, dips towards both the deep basin, and the Oristano canyon’s axis (Figs. 3–5). It forms the upslope continuation of the salt wedge on the seismic lines.

Since sediments overlying a weak basal salt layer can easily glide and spread under the effects of their own weight where values of the basal and surface slopes are 3° or less (Vendeville, 1987; Dos Reis, 2001), the belt of listric normal growth-faults cutting the C, T units and the PQ sequence into small tilted blocks in the study area can be clearly attributed to salt-related deformation, i.e. to gravity gliding and/or spreading of the brittle sediment cover above the Messinian décollement. Loading of the Messinian salt triggered a thin-skinned tectonics, which typically causes proximal extension (normal growth faults), mid-slope translation, and distal contraction (folds and diapirs) (Gaullier and Bellaiche, 1996; Dos Reis et al., 2004a,b).

Gravity gliding occurs if the base of the salt décollement is dipping downslope (Vendeville, 1987) and, as shown by recent analogue modeling (Gaullier and Vendeville, in press), or field observations (Dos Reis et al., 2004a,b, this issue) gravity spreading can be caused by a differential sedimentary overload, and especially by detrital wedges.

Upslope, there is nearly no more salt, because it has been expelled toward the deep basin and replaced by a salt weld and locally by residual salt rollers (Figs. 4 and 5). Downslope, the compressive structures locally described on the seismic lines (Figs. 3 and 5) are also due to gravity gliding/spreading, and correspond to areas where local reliefs act as passive buttresses, thus preventing gravity gliding and spreading. The similar thickness of C and T units on both sides to deformation belt, together with the wedge-shape of the PQ reflectors, indicate that the salt migration towards the basin mainly occurred after the T unit deposition, during the Plio-Quaternary times. Fault scarp on the sea-floor show that salt tectonics was still recently active and indicate that small quantities of salt are probably still resting at the foot of the faults, which cannot be easily detected on the seismic data (Figs. 4 and 5).

Fig. 7. Frequency spectrum computed for (a) the C unit and (b) the T unit, showing dominant frequencies, respectively, of the order of 50–70 and 110 Hz.

Along the salt weld lying upslope the salt wedge, the root of the uppermost normal salt-related fault thus indicates the landward limit of initial deposition of the massive salt, before the salt moved toward the deep basin (yellow line on Fig. 6). The salt landward paleo-boundary classically lies down roughly parallel to the margin, but shows two reentrants toward the continent, which coincide with the two main canyons of the western Sardinia margin (Fig. 6). The first one, centered on the Oristano Amphitheatre, is 12–30 km wide, and enters the margin 20 km towards the continent; the second one, much smaller in size, faces a smaller canyon, north of the Oristano Amphitheatre. Bathymetric lows thus already existed at those places, when the salt emplaced, and were much narrower than the present-day depressions. The other canyons, of smaller size and crossing the margin, do not look like salt reentrants toward the continent.

7. Discussion

7.1. The C unit: a detrital coalescent delta, coeval with the Messinian low-stand sea-level

7.1.1. Nature of the C unit

We have shown that the C unit is observed on the continental margin, only within the Oristano Amphitheatre, and in the part of the deep basin explored during the SESAME cruise, where it is continuous all along the western
Sardinian margin (Fig. 6). Beneath the continental slope, its upslope extension is clearly correlated to the canyons (Fig. 6). Moreover, the geometry of the C unit depicts a general dipping and thickening towards both regional low (the deep basin) and local lows (the canyons axes), where its thickness reaches its maximum value (~300 m). According to these geometrical criteria, we interpret the C unit as a detrital deposit accumulated downslope and shaped as coalescent deltas (Dunne, 1998; Nemec, 1990b; Postma, 1990; Richards et al., 1998). The top of the C unit forms a rather smooth topography, suggesting that the C sediments levelled the pre-existing relief of the deposition surface.

The detrital origin of the C unit is also supported by the existence of an acoustic unit of similar facies described at the foot of the northern Ligurian margin, below the Pliocene deposits (Guennoc, 1998) emplaced close to the shoreline (Rohais, 2002). Off Sardinia, the same kind of information is described in both cases (see for example (Einsele, 1996; Guzzetti et al., 1997; Garcés et al., 1998; Harvey, 2002) for sub-aerial alluvial fans).

The basal onlaps on the margin basement suggest the aggradation of the detrital delta, and thus a gradual rise of the sea-level during the C deposition.

7.1.2. Geometrical and time relationships between the Messinian deltas and the deep salt layer

During the Messinian low-stand sea-level, the upper margin is eroded whereas the evaporites precipitate in the deep basin. Detrital deposits are thus expected to be a time-equivalent of the evaporites (massive salt and/or Upper Evaporites), emplaced between the evaporites of the deep basin on one hand and the erosional surface at the upper continental slope on the other hand. This general scheme applies to the western Sardinia margin, but with some differences.

The salt tectonics observed both in the C and T units implies that the salt deposits along the margin occurred prior to the detrital deposits. The anteriority of the salt deposition in the study area is also supported by the stratigraphic relationship between the salt and the C unit. The C unit is observed directly above the landward termination of the massive salt layer (Figs. 3–5). Moreover, the upward increase of the internal layering in the massive salt layer (Fig. 3c) suggests that the detrital deposits coming from the continent have gradually emplaced at the base of the slope and have been mixed with the salt layer, to become finally dominant at the top of the C unit.

Detrital deposits coeval with the proximal salt, if they exist, should be easily seen on the seismic lines, upslope from the salt layer in lateral transition with it, that is now upslope from the salt weld since the proximal salt moved away toward the deep basin. Indeed, the vertical throw from one side to the other of the salt-related deformation zone described for both C and T units, indicates that the salt thickness reached 300–500 m at the present salt weld, before the salt moved away. Assuming similar sedimentation rates for salt and coarse grained detrital deposits in the order of a few centimetres per years, (Blanc, 2000; Rouchy, 2001a,b; Nemec, 1990a; Richards et al., 1998), we can hardly explain the total lack of detrital body upslope from the initially-thick salt layer. Another reason for low detrital supply during salt deposition may be climatic, with regional aridity marking this period (Bertolani-Marchetti, 1985). The seismic lines, however, clearly indicate that the detrital sedimentation on the margin postdates the salt deposition against the continental slope. The anteriority of the salt deposition with respect to the Messinian delta emplacement and the lack of sub-aerial erosion/deposition processes imply that the reentrants formed by the basal surface of the salt at the deep slope (Fig. 6) do not correspond to canyons produced by sub-aerial erosion before the salt precipitated. We propose that such reentrants are primarily explained by the initial structure of the margin in horsts and grabens. Indeed, existence of inherited scarps on both sides of
the Oristano Amphitheatre is in particular inferred from structural data, as detailed above (Thomas and Gennesseaux, 1986; Thomas et al., 1988; Fais et al., 1996).

Sub-marine erosion of the slope prior to the major sea-level drop also probably contributed in emphasizing the inherited morphology. It has been shown elsewhere that huge detrital units may emplace as a consequence of sea-level drops (Nemec, 1990a), as argued during the last major glaciation in the western area of the Mediterranean Sea. This implies a transfer of large amounts of sediments across the margin, which are supposed to erode marine valleys on the continental slope (Eisenele, 1996; Nemec, 1990a). In the Gulf of Lion, a chaotic acoustic unit interpreted as a detrital unit is described within the deep basin, close to the continental slope, and extends 15 km into the deep basin below the salt layer (Dos Reis et al., 2004b; Lofi et al., 2005). This detrital unit is explained by a massive emplacement of debris flows during an early stage of the Messinian sea-drop (Lofi et al., 2005). In the case of the western Sardinia margin, an equivalent sedimentary unit could lie below the salt layer, but cannot be imaged with the available seismic lines.

In summary, we infer from the available seismic lines that the salt deposits started before the emplacement of the detrital delta fed by the sub-aerial erosion of the margin. The salt emplaced in the basin and at the base of the continental slope, which was initially shaped by the margin deep structure and later probably emphasized by a stage of submarine erosion, may be related to the earliest stage of the Messinian sea-level drop. The salt deposited first with little or nearly no detrital element as shown by its ductile behaviour allowing for its later migration toward the basin. Then, the detrital elements gradually came from the upper margin, being progressively incorporated into the salt layer, and thus changing its mechanical behaviour. Finally, sedimentation at the deep margin became mostly composed of detrital elements to form the C unit. At that time, the evaporites (salt and/or Upper Evaporites) were probably still accumulating further away into the basin, their landward limit being shifted offshore whilst the delta was building up.

The stratigraphic relationship between the salt and the detrital delta corresponding to the C unit may be related to a delay in the record of the drastic Messinian environmental change. On one hand, the initiation of the erosion-transfer-deposition processes requires a sea-level drop at the margin. It probably takes time to settle and produce detrital units sufficiently important to be detected on the seismic lines. On the other hand, the salt is expected to precipitate at a relatively high sea-level, immediately once the requested saturation is reached (Blanc, 2000; Martin et al., 2001), and then before and/or during the sea-level drop. Such quick response of the salt precipitation to the closing of the open connections with the surrounding oceanic masses, together with the high sedimentation rates expected for the salt, on the order of a few centimeters by year, may explain why the C unit appears later, over the salt.

7.2. The T unit: a sub-marine detrital fan

7.2.1. Nature of the T unit

The stratigraphic location of the T unit, between the C unit and the PQ sequence, is similar to that of the Upper Evaporites described at Hole 134 during DSDP Leg XIII (Ryan et al., 1973). The acoustic facies (i.e. highly reflective) and the thickness of the both units are also similar, suggesting that the T unit may correspond to the drilled Upper Evaporites. Such interpretation would agree with previous studies, which described transgressive Upper Evaporites over the continental margins in western Mediterranean (Réalhaut, 1981; Réhault et al., 1984; Thomas et al., 1988).

Within the deep basin, the drilled Upper Evaporites are described as an interbedding of playa salts made of bandded halite alternating with laminae of anhydrite on one hand, and marls on the other hand (Ryan et al., 1973). Towards the slope, the levels include nodular gypsum and dolomitic silts, which characterize a supratidal sabkha observed at a present depth of 3100 m. While the evaporitic levels constitute the landward end of the Messinian brine pool, the faunas included in the alternating marls indicate a marine open environment (Ryan et al., 1973). The Upper Evaporites are thus interpreted as the last markers of the Messinian low-stand sea-level, with regularly spaced incursions of the sea.

The Upper Evaporites nature, with alternating playa and open marine environments, is thus strongly controlled by the water depth at a given time, implying a rather constant depth of deposition along the whole margin. In the Oristano Amphitheatre area, the T unit is described from 3000 m depth in the deepest part of the slope, up to 1880 m in the canyon axis. The T unit is, however, lacking out of the Oristano Amphitheatre at similar depths, and there are no evaporite deposits in Hole 133, where the Messinian level is lying at 2623 m depth on the margin basement, suggesting different types of sedimentation in the Oristano region and away from it, at similar depths. Moreover, the positive correlation between the occurrence of the T unit and the canyons location strongly suggests that the presence of the T unit is controlled by the terrigenous feeding from the uppermost margin rather than by sea-level changes. The variability of the acoustic facies of the T unit in and outside of the canyons, together with the layer thickening and dipping toward the canyons also suggest a detrital nature of the unit. This interpretation is supported by the similarity of the acoustic facies of T and C units in the canyons axis, where it difficult to decipher the two units from one another. Therefore, we infer from our data that the T unit mainly corresponds to a detrital fan.

Despite the acoustic facies described for the T unit presents numerous similarities with that of the C unit, especially in the canyons axis, the clear angular unconformity observed almost everywhere between the C and T units, together with the increased continuity of the reflectors
depicted for the T unit, suggest a significant depositional change between these two units.

Some arguments favour a submarine origin for the T unit, and suggest that the sea-level has significantly risen after the C deposition. These arguments are: (1) the generalized concordance between the T unit and the Plio-Quaternary sequence, (2) the local changes in facies observed within the T unit, which becomes sometimes transparent, similarly to the base of the Plio-Quaternary sequence; and finally (3) the location of the wedge of the T unit on the continental slope, which always lies upslope from the C unit wedge, on the erosional surface (Fig. 6).

On the northern Ligurian margin, submersible dives observed a detrital unit over the massive conglomerates attributed to the C unit, made of coarse grained conglomerates alternating with levels of silts and sandstones (Savoye and Piper, 1991; Bigot-Courmier et al., 2004; Sosson and Guennoc, 1998) in increasing proportion when moving upward in the unit (Savoye and Piper, 1991; Rohais, 2002).

The element organization indicates a sub-marine reworking upward in the unit (Savoye and Piper, 1991; Bigot-Courmier et al., 2004; Sosson and Guennoc, 1998) in increasing proportion when moving upward in the unit (Savoye and Piper, 1991; Rohais, 2002). The element organization indicates a sub-marine reworking of pre-existing deltas (Savoye and Piper, 1991) and a deepening of the detrital emplacement relative to the underlying massive conglomerates (Rohais, 2002). Seismic lines shot in the diving areas show that this detrital unit corresponds to a highly reflective acoustic unit, which is locally discordant on the underlying acoustic unit interpreted as the low-stand Messinian delta (Bigot-Cormier et al., 2004; Rohais, 2002; Camera, 2002; Sage et al., 2002). The reflective seismic unit is observed in the vicinity of the canyons, but gradually disappears on the interfluves (Sage et al., 2002; Camera, 2002). Following the Sardinia example, the existence of this detrital unit thus seems to be conditioned by the alluvial supply.

Therefore, we propose that the T unit corresponds to a detrital unit fed by the margin through the valleys of the Oristano Amphitheatre. We explain the angular unconformity between the both C and T detrital units by a sea-level rise, and an open-marine environment for the T unit, that predates deposition of the classical PQ sequence. We explain the facies variation along the margin by a submarine redistribution of the alluvial sediments supply. Indeed, while the coarse grained elements were deposited in the canyon axis, the thinner elements were transported laterally rather far away from the canyon axis, (Bardaji et al., 1990).

The restricted extension of the T unit in comparison with that of the underlying C unit could mark a decreasing surface of the margin area submitted to erosion owing to the sea rising. The restriction in the detrital supply related to sea-level rise may be particularly clear on the Sardinia margin because most of the feeding is provided here by the erosion of the margin itself, since the alluvial sediments provided by the hinterland were captured by the grabens onshore (Thomas and Gennesseaux, 1986; Casula et al., 2001; Lecca et al., 1997). The restricted extension of the T unit may also be due to a channeling of the transported elements, subsequent to the sea-level rise. We therefore propose that the lack of T unit inferred from the seismic lines out of the Oristano Amphitheatre is mainly related to the absence of large feeding channels able to provide and transfer detrital sediments across the margin.

7.2.2. Geometrical and time relationships between T unit and the deep basin evaporites

Because of the lack of seismic line joining the Oristano Amphitheatre to the area drilled during DSDP Leg XIII, it is impossible to directly observe the stratigraphic relationship between the T unit on one hand, which is observed beneath the continental slope inside the Oristano Amphitheatre and the adjacent part of the deep basin, and the Upper Evaporites on the other hand, which were drilled in the deep basin. Two distinct interpretations are proposed below, which are both compatible with the observation above.

7.2.2.1. Is the T unit coeval with the Upper Evaporites? The stratigraphic location of the T unit, between the PQ sequence and the C unit, together with the unit thickness and depth, suggest that T could be considered as a time-equivalent of the Upper Evaporites, although we assumed they are different in nature. In the Upper Evaporites, the marls levels include assemblages of siliceous microfossils, which suggest that an open marine environment existed intermittently for short periods of time at the end of the MSC. The Upper Evaporites are thus believed to mark the initiation of the transgression at the end of the Messinian crisis (Ryan et al., 1973), implying a globally higher sea-level than at earlier times. The T unit assumed to be deposited in a marine environment (i.e. deeper than for C unit) would thus correspond to the time-equivalent of the Upper Evaporites. Nevertheless, the T unit is observed up to 1800 m depth in its uppermost part, whereas the Upper Evaporites are described at about 3100 m depth. This depth difference in the order of 1000 m can be explained by two factors: (1) a differential subsidence between the margin and the deep basin since the Messinian times, and (2) the collapse of the post-salt units at the deep basin edge because of the migration of the underlying salt toward the basin. According to previous studies conducted on the northern Liguro-Provencal basin, the subsidence at the foot of the margin since the Messinian age could reach 800–1000 m in amplitude (Savoye and Piper, 1991), and could explain a differential depth in the order of 400–500 m between the upslope part of the T unit and the deep basin edge. The vertical shift across the salt-related deformed area at the margin-basin connection also gives a 400–550 m collapse of post-salt units lying downslope from the deformed area linked to the salt tectonics. The present-day depths of both T and UE units are thus compatible with a similar depth of deposit at Messinian times.

In that case, the detrital T unit would be the upward continuation of the C unit, deposited whilst the uppermost margin was still submitted to erosion (Fig. 8a). It is then coeval with the initiation of the transgression, i.e. with
the deep Upper Evaporites, but is still at a low-stand sea-level. In this interpretation, we cannot exclude that the detrital T unit locally contains some evaporites, although evaporites were never sampled on the basin margins (Fig. 8a).

7.2.2.2. Is the T unit Pliocene?. Although the stratigraphic relationship inferred above between T unit and the Upper Evaporites appears satisfactory when comparing the seismic lines in the Oristano Amphitheatre and in the drilling area, it assumes that the type of sedimentation is identical whether it takes place off a wide feeding system (Oristano Amphitheatre) or away from it (drilling area). Because there are no seismic lines connecting the two areas, we can compare our observation with available seismic lines shot parallel to the northern Ligurian Margin, seaward from the Saint-Tropez canyon, in order to appreciate how the acoustic units vary in the deep basin when crossing a major canyon (Fig. 9). Although these two areas are far away from one another, similar acoustic sequences are observed at the basin edge, both in the canyon axis and away from it.

In the deep basin, while approaching the canyon axis, a more or less chaotic and highly reflective unit gradually emplaces and thickens between the salt and the Upper Evaporites (C1 and C2 on Fig. 9). Based on its facies and stratigraphic location, such unit is interpreted as the SARD’85 and SESAME C unit equivalent, emplaced above the salt layer. Toward the basin, C2 unit laterally passes to the Upper Evaporites (Fig. 9). The coeval Upper Evaporites and C2 unit are overlaid by the PQ sequence, which is transparent at its base away from the canyon (base of the PQ sequence on Fig. 9), and becomes highly reflective at the canyon axis (P on Fig. 9), with a seismic facies similar to the T unit observed along the western Sardinian margin. Off Saint-Tropez canyon, the lateral variations of the different units since the Messinian times can be explained by the sedimentation of terrigenous influx in the canyon axis, which laterally passes to the basal sedimentation. Over the salt layer, the C1 unit extends far from the canyon axis during the main Messinian erosion stage. While the Upper Evaporites deposit in the deep basin, the erosion and its related deposition continue (C2 unit), but are restricted to the vicinity of the canyon axis. Finally, a channel-levee system emplaces during the Pliocene at a deep sea-level. The observed variation of the Pliocene acoustic facies perpendicularly to the canyon is explained by the transition between coarse grained sediments lying at the canyon axis and its lateral levees composed of thinner sediments, as previously observed in the Var deep sea fan system for instance (Savoye et al., 1993; Migeon et al., 2001).

It is clear from this example that similar acoustic facies successions can be explained differently depending on their position relative to the canyon. In particular, the Upper Evaporites facies commonly described in the deep Mediterranean basin can be similar to that of the Pliocene sequence observed at the canyons axis, corresponding to coarse-grained sediments. Such control of the deep basin sedimentation by the canyons feeding may also be expected off western Sardinia, since the Oristano area concentrates most of the channels of the margin. Therefore, we cannot exclude that the T unit may correspond to a Pliocene sedimentation, passing laterally to the transparent lower Pliocene, explaining the observed changes in the T acoustic facies. In that case, it corresponds to deep water sediments, emplaced at a canyon axis (Fig. 8b), and the Upper Evaporites are coeval with the uppermost part of the C unit (Fig. 8b).

At the drilling sites of Leg XIII, the lowermost Pliocene is lacking, indicating a gap of 80,000 years at the base of the PQ sequence (Ryan et al., 1973). The above sediments correspond to Pliocene nanofossil calcareous marl oozes including large rounded cobbles of metagreywacke and numerous fragments of feldspathic schist (Ryan, 1973). These marls are interpreted as pelagic marine sediments, except for some allochthonous fragments of rocks (Ryan, 1973; Hsu et al., 1973). Some of the lower Pliocene collected cores display moreover contemporaneous deformational structures including folding and overturned strata that are intercalated into layers typical of current-controlled deposition. The deformation of the lower Pliocene sediments, together with the occurrence of fragments of rocks in the layer tend to indicate that part of the lower Pliocene was
emplaced as large slumps from the continental slope (Ryan et al., 1973; Hsu and Ryan, 1973). Consequently, if it is Pliocene in age, the detrital T unit may be a time-equivalent either to the stratigraphic gap or to the following slumping stage both observed in the drilling area, but located in the Oristano Amphitheatre region which was widely fed by the margin alluvial system. It could be a deep fan deposit of very limited size associated with turbidity currents and debris flows triggered by the rapid Pliocene flooding. (Fig. 8b)

8. Conclusions

A synthesis of new and previous seismic data collected off the western Sardinian margin accurately image the effects of the Messinian Salinity Crisis from the salt deposit up to the Pliocene flooding.

In this study, we characterize for the first time the Messinian detrital bodies emplaced in the lower part of the western Sardinian margin, in response to the sub-aerial erosion of the continental slope. The detrital deposits are organized into two successive alluvial fans (C and T units), reaching together 500–600 m of maximum thickness. We infer that both are fed by the subaerial erosion of the margin itself owing to the upstream capture of most of the hinterland sediments. The earliest sedimentary body (C unit) is observed continuously all along the margin and the adjacent part of the deep basin, whereas the youngest one (T unit) appears to be restricted to the vicinity of the detrital supplying systems. This upward evolution is attributed to a sea-level rise that has two main effects: (1) to limit the surface of the margin submitted to erosion, and (2) to allow for a channeling of the sediments in an open marine environment. This interpretation is in good agreement with results from dives conducted along the northern Ligurian margin where similar seismic units are made of detrital fan conglomerates deposited close to the shoreline, showing an upward deepening of the deposit environment. The earliest detrital delta (C unit) is thus inferred to develop as long as the sea-level remained at its lowest stand (i.e. coeval with the salt layer, and/or with the Upper Evaporites), since the second one (T unit) can be interpreted in two different ways: the T unit could be the upward continuity of C unit, deposited under slightly higher sea-level at the end of the Messinian low-stand sea-level, and corresponds in that case to a time equivalent of the Upper Evaporites (Fig. 8a); the T unit could also be interpreted as the first coarse grained sediments emplaced off the major canyon at Pliocene time, once the sea-level rose up. In that case, the uppermost part of C unit would be the time-equivalent of the Upper Evaporites (Fig. 8b).

We also show evidence for (1) a vertical transition between the salt layer and the detrital delta, and (2) salt tectonics, which affects both C and T detrital units. This
implies that the salt began to emplace at the base of the continental slope before the alluvial fan. The collapse of the sedimentary layers deposited over the salt is related to salt flows toward the basin and indicates that 300–500 m of ductile salt (i.e. salt containing little detritic fraction) were deposited before the low-standing Messinian delta emplaced. This result supports the idea suggested by recent modeling that the salt began to precipitate at a rather high stand sea-level, as soon as the saturation required for chloride precipitation was reached. The seismic lines, which are restricted to the vicinity of the continental margin, do not provide information on the stratigraphic relationship between the seaward termination of the detrital bodies and the evaporitic sequences, which lies out of the study area. We can however, suppose that the evaporites (massive salt and/or Upper Evaporites) still precipitate seaward of the detrital fan, as long as the sea-level is low. Detrital emplacement at the deep margin thus probably moved the landward extension of the deep evaporites toward the deep basin.

The sub-aerial Messinian erosion is marked by a sharp reflector which is evidenced on our seismic lines down to the apex of the Messinian alluvial fan, at around 2000 m depth. At this depth, a general slope break together with a change in the slope of the canyons flanks suggest that the erosion surface progressively becomes downslope a depositional surface, which could be either sub-aerial or sub-marine. This could indicate that the shoreline was stable around this depth for most of the duration of the crisis, during the Unit C edification. There is no evidence from our data, that the sea-level was lying much deeper under C unit for a long time, even before the salt deposition. The lack of detrital bodies on the landward termination of the salt layer leads us to propose that the pre-salt morphology is due to sub-marine erosion emphasizing an irregular morphology inherited from the Oligo-Miocene geological history of the margin.

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