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Recent overdeepening of the middle Ouvèze riverbed (SE France) provides new data about the Pliocene infilling of the middle Rhône valley ria network

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Abstract: Over 3.5 km south of Roaix village, the middle Ouvèze riverbed has undergone an incision of 5-9 m into its substratum since 1995. The local nesting of the river and erosion of its banks reveals a more complex geometry of exposed Pliocene deposits than previously recognised. The Pliocene stratigraphic succession includes, at the base of the classical Blue Marls, a prograding-aggrading stack of more or less nested, sigmoidal sandstone-marlstone cycles, each comprising an erosive sandstone wedge followed by a draping aggrading marlstone. Sedimentary features suggest that the main depositional mechanism for sandstone was high-velocity hyperpycnal bottom currents linked to river floods updip. These findings are presented in the context of the ria network of the Middle Rhône valley, including mostly unpublished data from the Andra (French Agency for Nuclear Waste Disposal) exploratory works in the lower Cèze valley in the 1990s. The combined data fail to support the idea of a so-called "Zanclean Deluge" during the reflooding of the Mediterranean basin after the Messinian salinity crisis.

Keywords:

- Messinian;
- Pliocene;
- ria network;
- hyperpycnal currents;
- cyclic steps;
- Zanclean Deluge

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Résumé : *Un récent surcreusement du lit de la moyenne Ouvèze (SE France) apporte de nouvelles données sur le remplissage pliocène du réseau de rias de la moyenne vallée du Rhône.-* Sur environ 3,5 km de long au sud du village de Roaix, depuis 1995, le lit de l'Ouvèze s'est enfoncé de 5 à 9 mètres dans son substratum, alors que le cours est resté inchangé à l'aval et à l'amont. L'emboitement local du lit et l'érosion des rives ont révélé une géométrie des dépôts pliocènes

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beaucoup plus complexe que ce que les observations antérieures avaient reconstitué dans le bassin du Comtat. La succession stratigraphique inclut, à la base des Marnes Bleues classiques, un empilement progradant vers l'aval de cycles sédimentaires à géométrie sigmoïde, comprenant chacun un prisme à dominante gréseuse et à base érosive, suivi par un drapage à dominante marneuse. Les figures sédimentaires suggèrent que le mécanisme de dépôt des bancs gréseux était des courants de fond hyperpycnaux dans la ria, liés à des crues fluviatiles en amont. Cette découverte est replacée dans le contexte du réseau de rias de la moyenne vallée du Rhône, incluant des données restées mal publiées datant des travaux exploratoires de l'Andra (Agence nationale pour la gestion des déchets radioactifs) dans la basse vallée de la Cèze au cours des années 90. Mises bout à bout, ces données supportent difficilement l'idée d'un "Déluge zancléen" soudain lors du réennoyage marin des canyons creusés lors de la crise de salinité messinienne.

Motsclefs :

- Messinien ;
- Pliocène ;
- réseau de rias ;
- courants hyperpycnaux ;
- étapes cycliques ;
- Déluge zancléen

1. Introduction

A recent incision of the middle Ouvèze riverbed into its substratum is found just south of Roaix village, extending downstream for a few kilometres (Fig. 1). The overdeepening took place in two steps (Fig. 2.C) and its cause(s) are under study. The deepening was not evident in the 1990s (Fig. 2.A-B) as seen in photographs taken by the first author during Andra's geological investigations around Marcoule. The latter is a site subsequently ruled out for the construction of an underground laboratory for the French deep geological disposal facility project. The incision of the river well exposed an unexpected curious sandstone body at the base of the Pliocene infilling of the Ouvèze Messinian valley. The Messinian valley is part of the deeply cut river network that was carved in response to the dramatic lowering of the Mediterranean endoreic sea level in the latest Miocene, during what is widely known as the Messinian Salinity Crisis (MSC) (Hsü *et al.*, 1973). G. Clauzon (1979, 1982) proposed a now widely accepted dramatic drop in relative sea level which occurred during the MSC throughout the Mediterranean basin. Later studies imaged the geometry of the sedimentary system in the Rhône River valley from far inland to deep water in the Mediterranean basin. After decades of controversy, a two-step mechanism was inferred during the desiccation interval (Clauzon *et al.*, 1996; Suc *et al.*, 2025), which explains the basic differences between the marginal and deep-basin evaporites. It also explains the break in slope found from well data along the middle Rhône ria profile, south of Pierrelatte town (Clauzon, 1982, Fig. 4).

The reflooding of the Mediterranean basin is a more complicated matter, with respect to both theoretical calculations and the full integration of geological data (*e.g.*, Meijer & Krijgsman, 2005; Popescu *et al.*, 2021). Seismic profiles off the French Mediterranean coast show that reflooding apparently also proceeded through a two-step mechanism (Bache *et al.*, 2012). A well-documented, gently sloping transgressive surface (wave-ravinement surface) links the top of the lowstand Rhône delta to the mouth of the Messinian valley under the modern Rhône delta (Camargue delta), at a subbottom depth around 1,000 m. This first transgressive step would have been followed by the second step, *i.e.*, a catastrophic flooding of the ria network called the "Zanclean Deluge", and the deposition everywhere of the Pliocene Blue Marls.

But several lines of evidence cast doubt upon the way this second step operated. Seismic profiles in the lower Rhône ria and tributaries (Durance ria) show complex geometries at the base of the infilling, which were interpreted, consistent with the hypothesis of a Zanclean Deluge, as subaqueous mass transport deposits (MTDs) by Rubino (in Clauzon & Rubino, 1992). This interpretation is supported by Do Couto *et al.* (2024). But the data acquired in the 1990s in the lower Cèze ria (a west bank tributary of the Rhône river) raise doubts about this interpretation (Ferry *et al.*, 1997a, 1997b). The new mid-Ouvèze outcrops allow further consideration of this topic.

This paper comprises two parts, (a) the description and interpretation of the curious sandstone bed exposed at the base of the ria infilling, and (b) the integration of the data within the regional context. The initial sedimentological analysis of the sandstone body sheds new light upon the way rivers may have filled the network of rias.

Figure 1 shows the area studied which is situated within a region affected by Paleogene to Recent diapirism. Also note the shift of the courses of the Aygues and Ouvèze rivers from their Messinian locations to their modern ones (Ballesio, 1972; Monier *et al.*, 1998; Do Couto *et al.*, 2024).

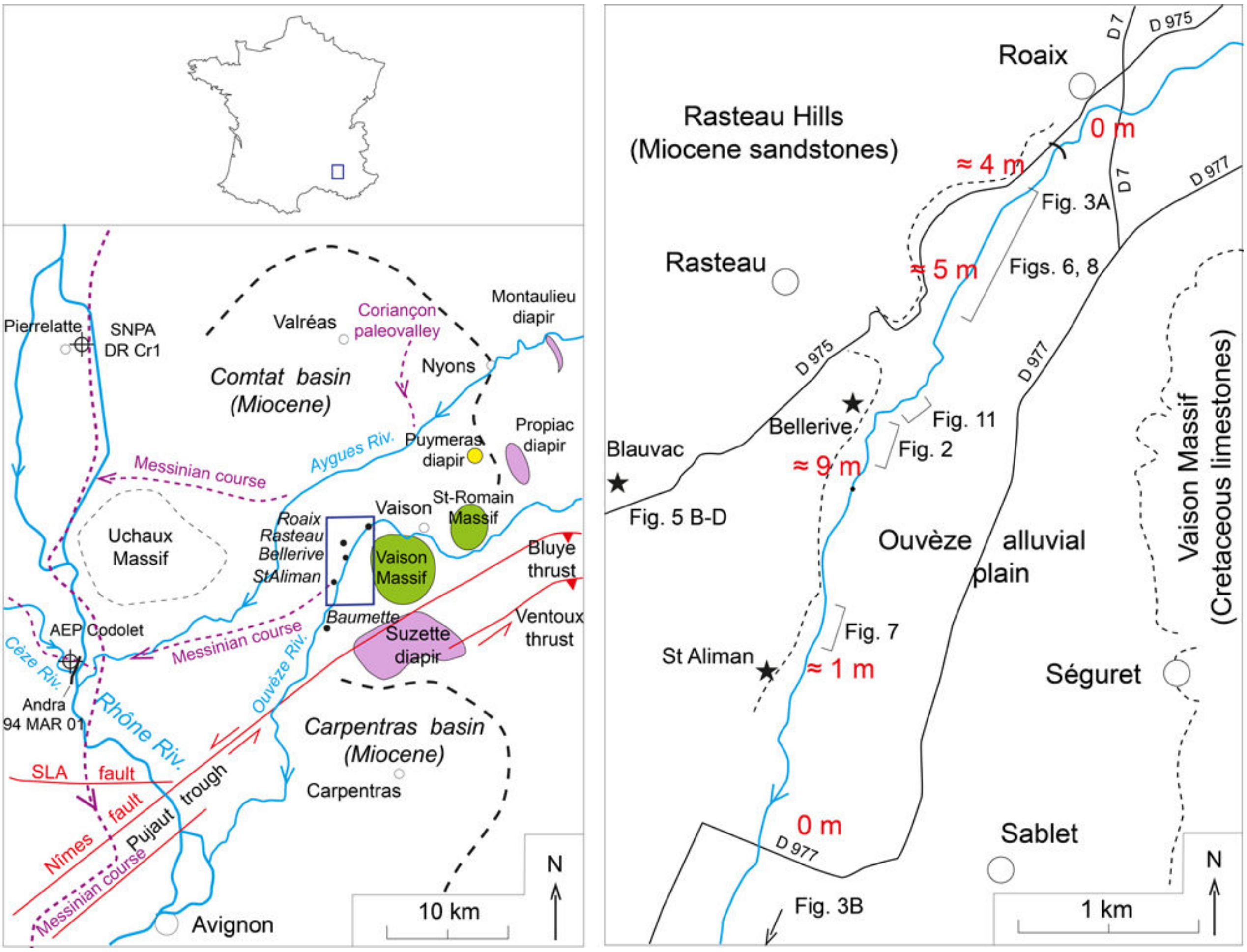


Figure 1: Location maps. Left: regional map showing the Miocene Comtat basin, the major faults, the main diapirs and the Messinian paleovalleys versus the modern courses of the rivers. Right: enlargement of the study area showing the depth of the recent incision of the Ouvèze riverbed (red numbers, in metres) south of Roaix village and the location of photographs in figures.

2. The Pliocene succession revealed by the riverbed lowering

In the Comtat basin (Fig. 1), the Pliocene succession in the infilling of rias usually begins with continental deposits called "ïnfra-Pliocène", overlain by the Blue Marls Formation (Ballesio, 1972) whose lowermost part contains a brackish fauna. Upsection, the Blue Marls bears a marine benthic fauna. Due to the narrowness of the rias bordered by steep slopes (Fig. 3), open-marine planktic foraminifers from the Mediterranean Sea were unable to enter the network of valleys. Thus, the planktic foraminifers found are mostly reworked fauna (Ferry, unpublished data) from the Aptian-lower Cenomanian marlstone of the exposed Vocontian Trough deposits in the backcountry (see detailed succession in Ferry *et al.*, 2022, Fig. 3). However, while Pliocene planktic foraminifers have never been recorded in the Pliocene sediments of the Rhône Ria, some calcareous nannofossils and dinoflagellate cysts have been observed in some locations (Suc *et al.*, 2026).

The incision of the riverbed south of Roaix village and the continuous observations made downriver permit the construction of a stratigraphic succession (Fig. 4). Here, Pliocene deposits infill the head of the Messinian valley where the Ouvèze carved Miocene deposits down to Tortonian sandstone and marlstone formations (MSP and SMV, Fig. 4). The fluvial deposits of unit 5 are a stack of pebbly lenses bearing metre-scale tabular oblique stratification and which represent nested prograding braid bars. The occurrence of a marine sandstone bed (unit 8, Fig. 4) in the middle of the Blue Marls Formation is new, and is not seen in outcrops studied by Ballesio (1972). This suggests it should onlap the Messinian slopes at a greater depth. Its depositional features are reported in detail below. The base of unit 8 is not sharp but transitional above what is informally called the lower Blue Marls here, as some lenticular sandstone beds are found in the upper part of unit 7. The thickness of unit 8 (between 10 and 15 m) is difficult to estimate, given the prograding-aggrading way it crops out on riverbanks

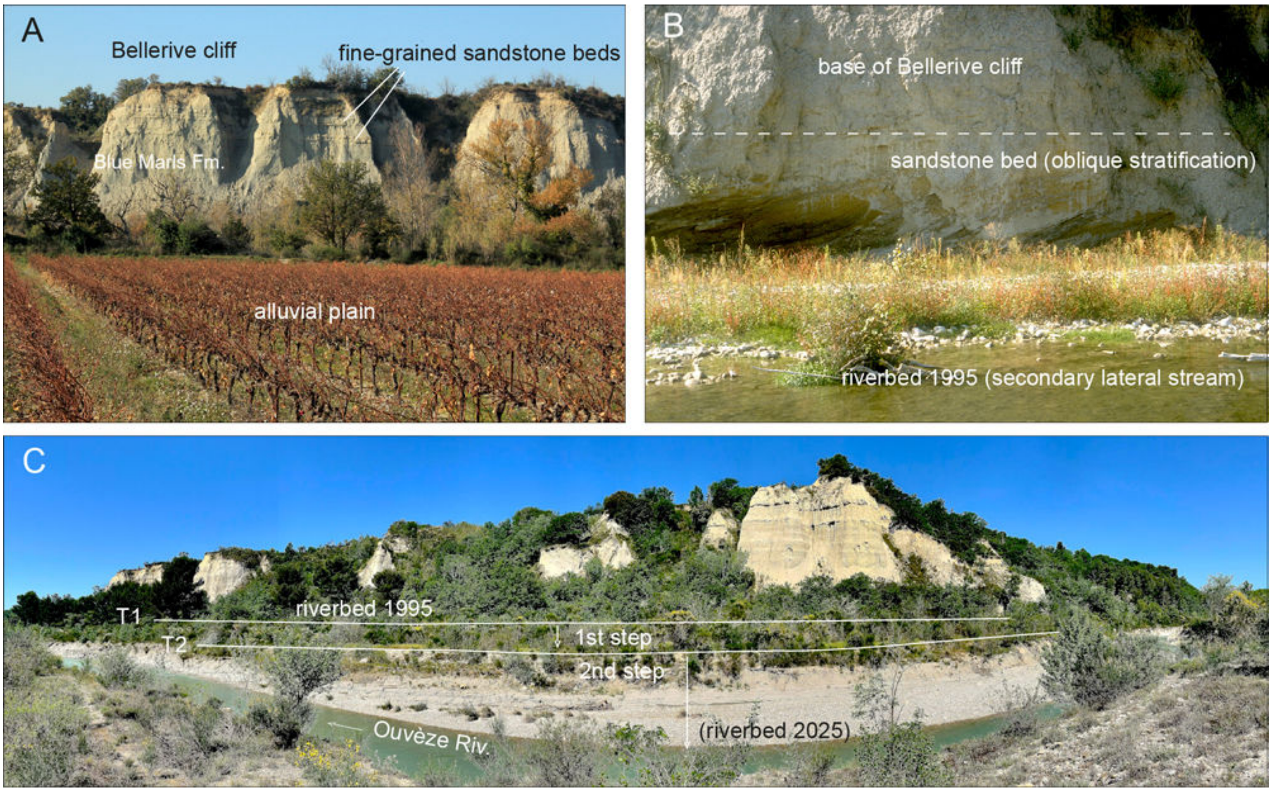


Figure 2: Photographic evidence of the lowering of the Ouvèze riverbed since 1995 south of Roaix village. **A**, Bellerive cliff in 1995; **B**, 1995 riverbed at base of the cliff; **C**, present-day elevation of the riverbed, about 9 m below the 1995 level, and the two pebbly terraces T1 and T2 corresponding to the two steps of the riverbed lowering.

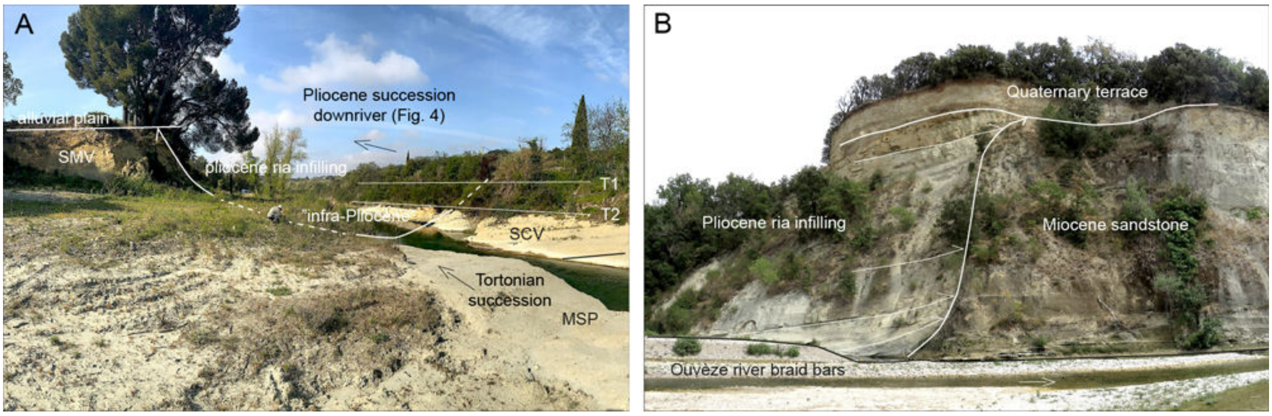


Figure 3: Illustration of the narrowness of the Pliocene rias. **A**, head of the Ouvèze ria, south of Roaix village; terraces T1 and T2 (Fig. 2.C) linked to the recent overdeepening; Tortonian Formations : MSP, Marnes de Saint-Pantaléon); SCV, Sables du Château de Visan. **B**, head of a tributary of the Ouvèze ria, close to Violès village, La Baumette cliff (location in Fig. 1 - left).

downstream (see further illustrations). Unit 8 is overlain by the succession cropping out in the Bellerive cliff (Fig. 2.A), that is, the Blue Marls proper, as found in the regional sections studied by BALLESIO (1972). Several sandstone beds are intercalated in the Blue Marls upsection (Fig. 2.A). Unlike the homogeneous, almost structureless marlstone (Fig. 5.A) intercalated between sandstone beds within unit 8, the marlstone of the Bellerive cliff, especially its upper part where sandstone beds occur again (Figs. 2.A, 4), is finely laminated, made of a succession of event strata, millimetric to centimetric in thickness, and interpreted as deposited from surface, river-flood plumes within the ria. This facies is well exposed (Fig. 4.B-D) behind the Trapadis wine cellar at Blauvac (location, Fig. 1), better than in the Bellerive cliff. The laminated facies announces the coarse-grained final infilling of the ria (*e.g.*, the Coriançon section in BALLESIO, 1972), which is lacking here, due to Quaternary erosion.

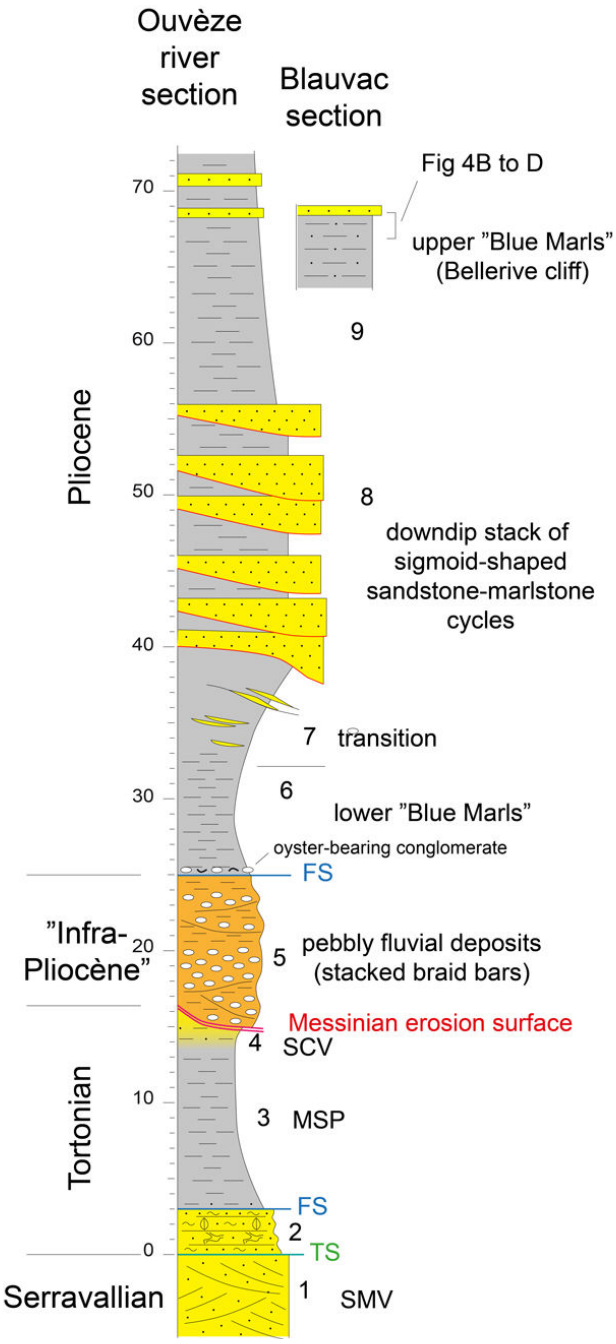


Figure 4: The sedimentary succession logged along the banks of the Ouvèze River, south of Roaix village. 1 to 9, stratigraphic units. Abbreviations: TS, transgression surface; FS, flooding surface; MSP, Marnes de Saint-Pantaléon; SCV, Sables du Château de Visan; SMV, Sables du Moulin à Vent.

3. Analysis of the sandstone bed (unit 8) within the Blue Marls Formation

Several examples of the depositional geometry and internal features of unit 8 are illustrated, either at its base (Pl. I), or at its top (Fig. 7) near Saint-Aliman (location in Fig. 1.B), and detailed further. The overall geometry of unit 8 is heterolithic, comprising a lateral stack of gently inclined sandstone-dominated intervals, alternating with marlstone-dominated ones (Pl. I, fig. A). Because of their repetitive nature, these couplets represent depositional cycles. The sandstone bodies have a sigmoidal geometry. The marlstone cap is prograding-aggrading (draping) (Pl. I, fig. A). Some cycles are overall more sandstone-prone (upriver of Bellerive), others more marlstone-prone (downriver of Bellerive). They are stacked downdip into a generally prograding-aggrading pattern, although some cycles may be nested into the previous one through a strong erosional surface (Pl. I, figs. B-C). Some basal surfaces may be deeply nested, such as to erode the marlstone-dominated upper half-sequence of the previous sequence (Pl. I, fig. B). This stacking pattern may be continuously observed downriver to Saint-Aliman, where the last sandstone-dominated cycles are found (Fig 6.A). The cycles at Saint-Aliman are possibly the downdip part of an uppermost sandstone-dominated subpackage within unit 8, linked to the sandstone bed observed at the base of Bellerive cliff (Fig. 2.B). The stacking of cycles is regular in the downriver (that is, downria) direction, but there is some evidence of lateral shift (Pl. I, fig. C).

3.1. Depositional features of the sand-prone half-cycles

The sandstone-dominated half cycles comprise a stack of sandstone beds which are event beds bounded by erosional surfaces. Marlstone intervals are few and thin. The strongest erosional surfaces are within the lower part of the half-cycle (Fig. 7.A-B ; Pl. I, figs. D-E). The most common internal features are laterally-continuous planar lamination or wavy lamination (Pl. I, fig. D), the latter often showing upstream accretion (Pl. I, fig. E). The most prominent internal features found are wavy bedforms whose crest on the steep stoss side is moving upstream while the lamination on the gently inclined lee side is accreting upstream (Fig 6.B). Such features are characteristic of cyclic steps occurring in high-velocity currents whose flow is marked by hydraulic jumps. (*e.g.*, Cartigny *et al.*, 2011; Slootman & Cartigny, 2020; Slootman *et al.*, 2021). All the observed depositional features are therefore characteristic of supercritical currents with respect to Froude number or at the boundary between super- and subcritical (planar lamination).

When preserved from the erosion by the next event bed, the top of the sandstone bed shows the transition from the upper regime to the lower regime of the flow, represented by the passage from planar lamination to ripples (Fig 6.C). The ripples atop event beds are usually poorly preserved due to the nesting of erosional surfaces (Fig. 7.C-D). They may look like nearly symmetrical wave ripples but their internal lamination is oblique (Fig 6.C), indicating current ripples, and not oscillation ripples.

Figure 5: View of the different kinds of marlstone comprising the Blue Marls Formation. **A**, homogeneous marlstone within unit 8; **B-D**, laminated silty marlstone at top of the formation, close to the Trapadis wine cellar (Blauvac, location Fig. 1 - right). DWS, downwards-shift (relative sea level fall) surface at base of a sandstone bed within the marlstone.

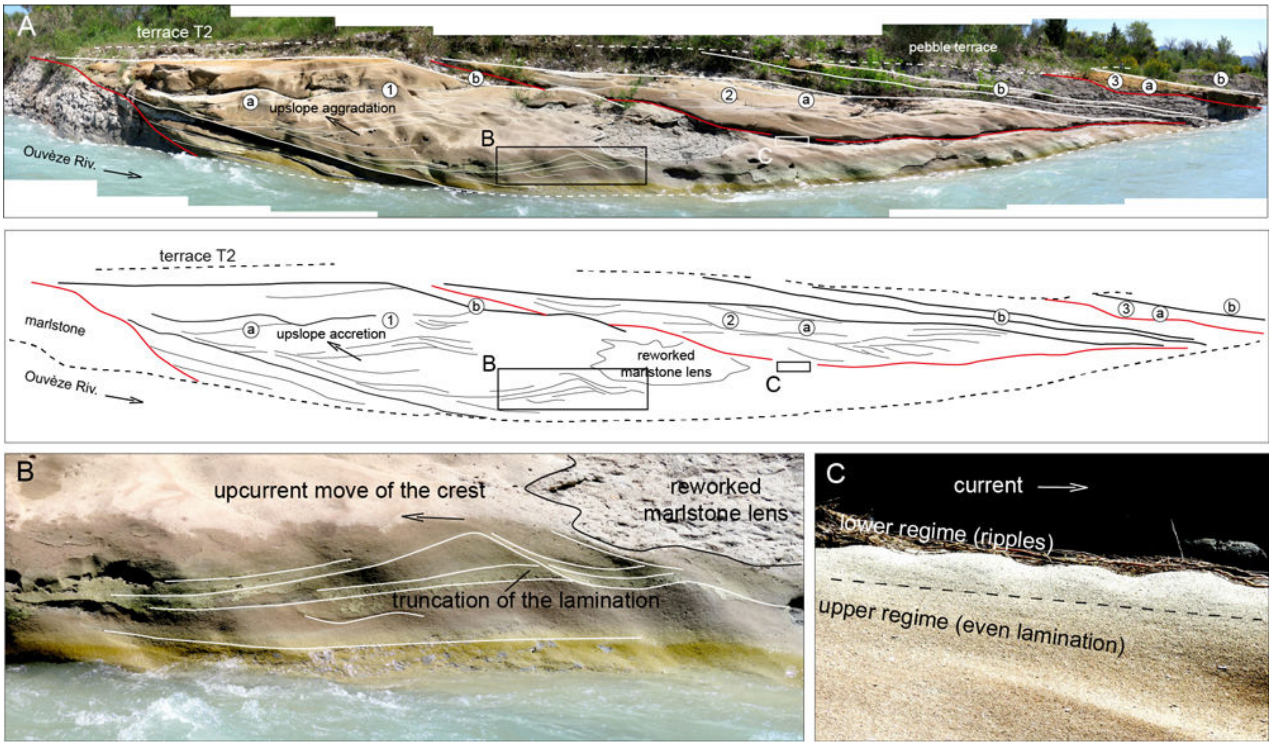


Figure 6: A, view of the lateral stacking of the uppermost three nested sandstone-marlstone sequences (1 to 3) close to St. Aliman irrigation channel inlet, downriver. a, sandstone-dominated lower part of sequences; b, marlstone-dominated upper part. Sequence 1 shows at least three successive sandstone event beds in its lower part. Also note the low elevation of terrace T2 (Fig. 2.D) here. **B**, enlarged view of cyclic steps at base of the sandstone lens. **C**, enlarged view of the transition from upper flow regime (even lamination) to lower regime (oblique lamination in current ripples) atop a sandstone bed.

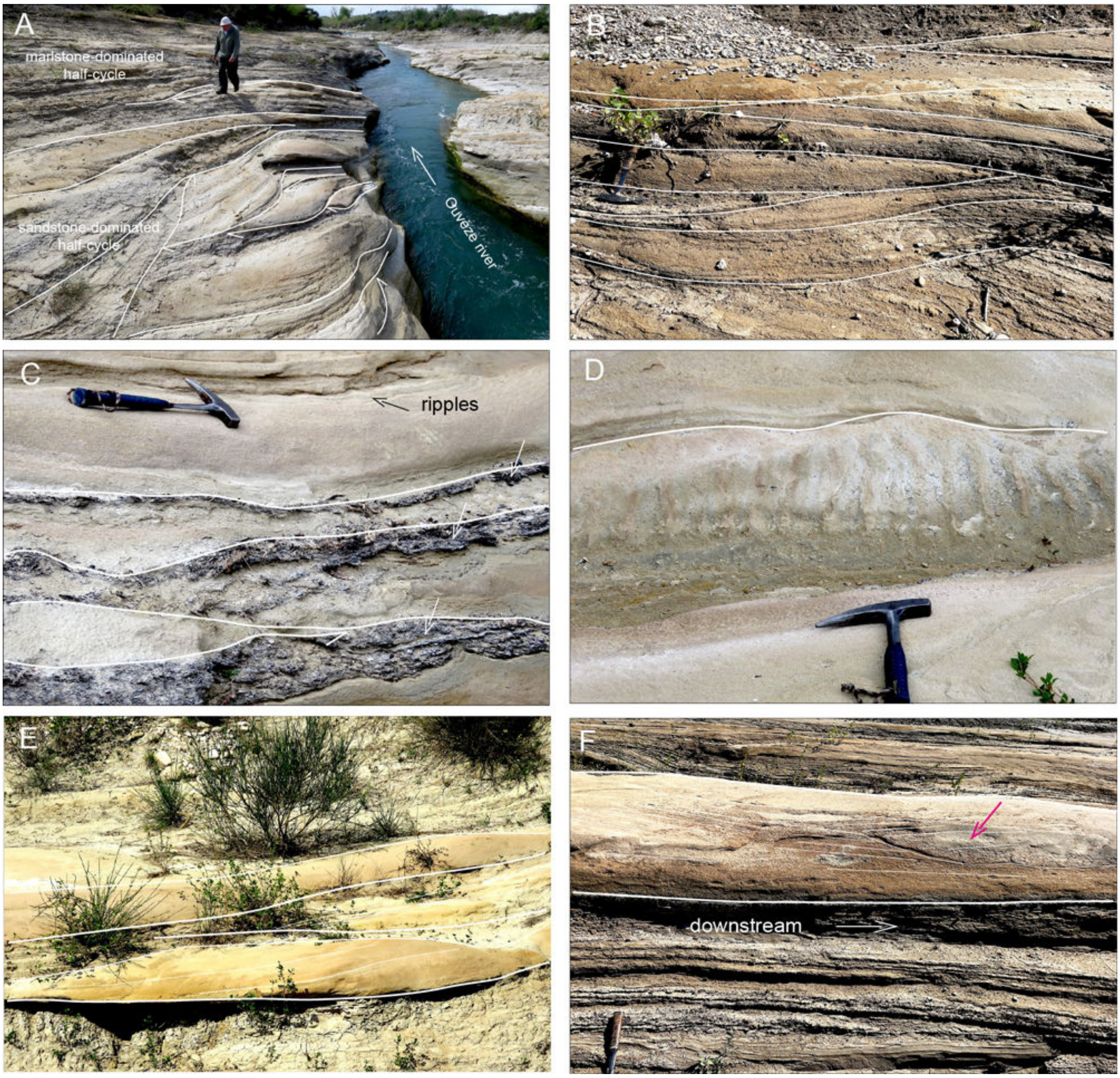


Figure 7: Other features found in sandstone beds (A- D, in the lower, sandstone-dominated part of sequences; E-F, in the marlstone-dominated upper part). **A-B**, internal erosional surfaces; **C**, shell hash veneers, sometimes with wood debris, atop of event beds; **D**, preserved current ripples atop event beds; **E**, domal features with internal sigmoidal lamination; **F**, complex lamination within a bed showing upcurrent accretion (red arrow).

Sandstone event beds may show at their top either a veneer of oyster shell hash transported from a shallower area or wood debris, or both (Fig. 7.C). Wood debris occurs within just a single sequence in the middle of the downriver stack, probably originating in large forest fires that occurred in the hinterland.

3.2. Depositional features of the marlstone-prone half-cycles

In marlstone-dominated half-cycles, scattered sandstone beds may be structureless, or show laterally continuous planar lamination. In some cases, the tops of the beds are undulatory, forming domes, in which the lamination is sigmoidal and prograding (Fig. 7.E). Sandstone beds may also occur as aligned metre-scale domes. No cyclic step features are found, except for small-scale upcurrent accretion wtithin some sandstone beds (Fig. 7.F, red arrow), probably indicating pulses in current speed during deposition of the event bed.

3.3. Depositional model

Cyclic steps and antidunes are two kinds of supercritical currents as defined by their Froude number. They may occur in very different depositional environments from fluvial to deep marine (Slootmann & Cartigny, 2020, Fig. 3). Cyclic steps differ from antidune features by the occurrence of hydraulic jumps responsible for regularly spaced overcuttings in the sand bed. They move slowly upstream and are progressively sealed by aggrading to retrograding lamination on the lee side

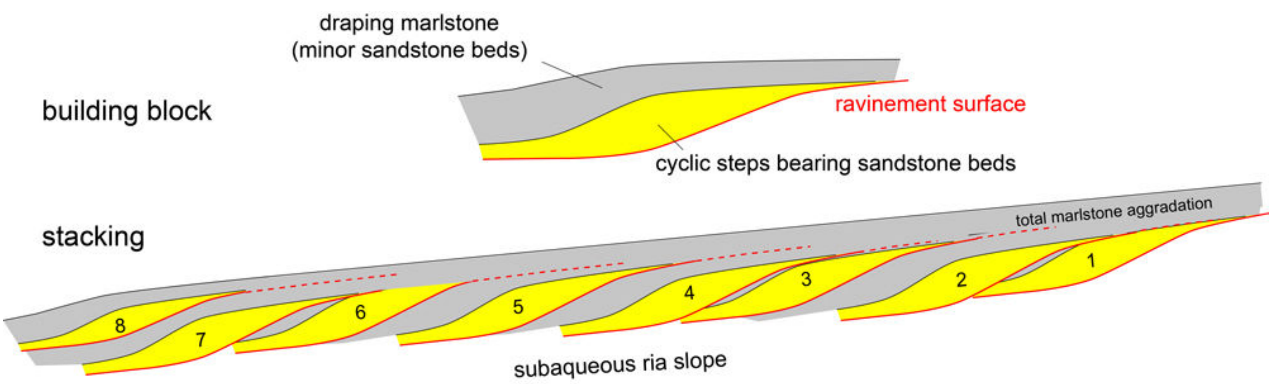
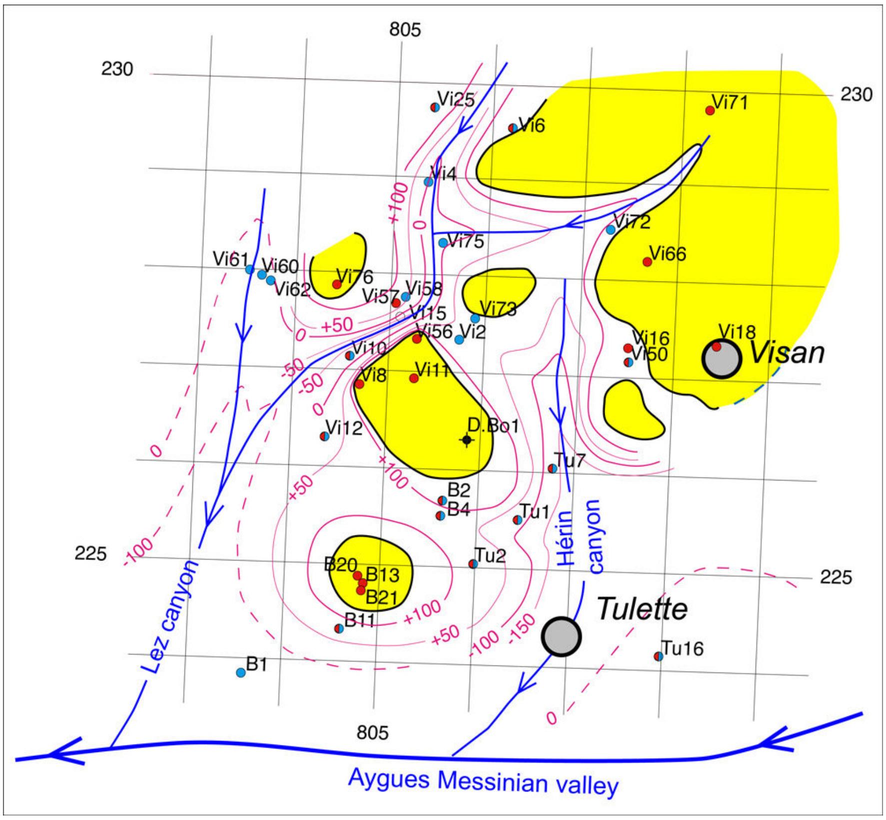


Figure 8: Sedimentary model proposed for unit 8.



◀ **Figure 9:** Reconstruction of the castellated Messinian morphology based on water-well data from the private Geoapplication data base (owner Georges TRUC) collected around Visan village. Red contour lines of the Miocene-Pliocene contact are absolute elevation *versus* sea level. Yellow for outcropping Mocene sandstone (absolute elevations west of Visan village are between 100 and 130 m). For instance, the bottom of the Herein canyon beneath Tulette village is at a depth of more than 350 m. Location of the Messinian Aygues River course, see Fig. 1.

of the bedforms (SLOOTMANN & CARTIGNY, 2020, Fig. 6). The observed features (Fig. 7.B ; Pl. I, figs. D- E) accord with this process. Within stratigraphic unit 8, cyclic steps occur at the base of the sandstone-marlstone cycles or sequences. Higher up in the sequences, only the wavy lamination of antidunes and planar lamination are encountered in sandstone event beds. Furthermore the frequency of sandstone beds diminishes in the upper part of the cycles, judging by the increasing thickness of interstratified marlstone beds. Such a change suggests that both discharge loads and overall velocity waned in the course of the depositional cycle.

RUBINO and PARIZE (2025) suggested that the sandstone-marlstone cycles in unit 8 could be equinoxial tidal cycles. However, we found no evidence of subcritical bedforms (dunes) attributable to tidal ebb currents but, rather, evidences of supercritical currents alone. In addition, although the depositional depth where marlstone interfingers with sandstone beds is difficult to estimate, the sequence stratigraphic context (see further discussion) supports a deep-water depositional environment. Thus, we conclude that unit 8 was deposited by river-flood-derived hyperpycnal bottom currents in a flooded ria.

The downriver stacking of sandstone-marlstone sequences is illustrated schematically in Figure 8. Some cycles are strongly nested within the previous ones (Pl. I, figs. B-C). This situation is more prominent upriver at the base of unit 8. Conversely, some cycles bear a well-developed marsltone-dominated half-cycle. This is more common downriver. Nevertheless, cycles bearing cyclic steps are still encountered close to the canal inlet of Saint-Aliman (Fig 6.A) where the stratigraphic unit disappears under recent alluvial deposits. According to observations made by one of us (GT) in local wine cellars carved in hill slopes, the contact between Pliocene and Miocene deposits (as also shown in Fig. 3.B) is most often vertical or even overhanging. The water-wells data base of Geoapplication Co. (GT) around the village of Visan also shows (Fig. 9) that the Messinian morphology of the Comtat basin was probably the result of castellated erosion, given its similarity to Bryce Canyon on the Colorado Plateau of Utah. These observations suggest that the stacking of hyperpycnal sequences in the Ouvèze ria was strictly constrained in the downstream direction, that is, with limited lateral shifting (Pl. I, fig. C) in a compensational mode, due to the likely narrowness of the ria bottom, as supported by the morphological reconstruction of DO COUTO *et al.* (2024).

3.4. Singular interstratified oyster bed

In the middle of the prograding stack, a layer of unbroken oysters seals a gently-inclined surface truncating a sequence down to its sandstone lower half (Fig. 10.A). The truncation surface cuts the sandstone updip (Fig. 10.C), and the marlstone of the sequence downdip (Fig. 10.D, I). Because the oysters are in life position and tightly packed (Fig. 10.B), this bed has a different origin from that of the oyster shell hash veneers found within the sandstone-marlstone sequences (Fig. 7.C), which are clearly transported from an upstream location. Detailed observations show that the oyster layer is associated with intense bioturbation of the underlying sandstone (Fig. 10.E). Such bioturbation is not observed in other sandstone-marlstone sequences of unit 8. The base of the oyster bed also shows aligned hollows carved into the bioturbated sandstone, possibly due to some kind of bioturbation (Fig. 10.E). The sandstone beds may bear comminuted debris of oysters and, more commonly, shells of the Lucines group (*Loripes* sp.) within the beds, probably due to their greater buoyancy (Fig. 10.H). These were reworked from shallower environments updip, and broken during their transport by the powerful hyperpycnal flows. The small hollows cut into the bioturbated top of the truncated sequence (Fig. 10.E) host venerid bivalves (*Pelecyora* sp.) (Fig. 10.F) that are known to thrive in very shallow-water sands or sandy clays (intertidal zone in open seas). They are overlain by the bed of stacked oysters but may also be associated with them (Fig. 10.G). This undisturbed fauna is clear evidence that the oyster bed that truncates the sandstone-marlstone sequence (Fig. 10) was emplaced close to sea level, in sharp contrast with the underlying sandstone beds deposited at a greater depth. It therefore represents a marked fall in relative sea level during the deposition of the Blue Marls Formation. The interpretation is that a first package of deep-water cycles was exposed, truncated, and then reflooded, the oyster bed representing the first stage of the transgression.

3.5. Discussion

From the data acquired in the lower Cèze tributary of the Rhône river (FERRY *et al.*, 1997a), the bottom of the Rhône ria at the confluence with the Ouvèze river would be at a depth around 600-650 m below the surface. According to paleogeographic reconstructions (BALLESIO, 1972; DO COUTO *et al.*, 2024) the confluence of the Messinian Ouvèze river was close to that of the Cèze river. The distance from the confluence to the outcrops of the middle Cèze river is short (Fig. 1). So, the slope of the Messinian Ouvèze valley was particularly steep, even taking into account a Quaternary peri-Alpine uplift likely to have steepened the ria profile updip. Therefore, it is likely that Pliocene flood events entered the ria directly as hyperpycnal bottom currents, shunting possible narrow deltas whose deposits may have been fully reworked by megafloods.

The significance of the whole shingled package of sandstone-marlstone cycles of unit 8 within the Blue Marls is difficult to interpret. Although emplaced by deep hyperpycnal bottom currents as discussed above, is it linked to a sea-level fall during the fully flooded stage of the ria, that is, to a closer injection point of river floods in the ria? The upper reaches of the ria are not known because they are now eroded, precluding investigation of the updip extension of the sedimentary body. Also are the sandstone-marlstone sequences within the package the expression of changes in relative sea level, as for the whole package? The more "distal" character of the upper deposits within a sandstone-marlstone sequence could either reflect a climate-controlled declining intensity of flood events with time, or be the result of down- and upria moves of the injection point of river floods. This remains therefore an open question. The occurrence of the very shallow oyster bed within the prograding stack, as well as its characteristics, are nevertheless evidence that strong relative sea-level falls may occur during the fully flooded stage of the ria. Such fluctuations in sea level have been evidenced in some places (CLAUZON *et al.*, 2015; DROMART *et al.*, 2024).

In his latest work on turbidite systems and the disputed turbidite paradigm, E. MUTTI (2023) highlighted the connection between river floods and turbidites via hyperpycnal subaqueous flood currents (hyperpycnites) instead of resulting from gravitational slope collapses. The data acquired in the middle Ouvèze river suggest that there could be a continuum of transport mechanisms between the depositional features observed in the sandstone-marlstone half-cycles. Sedimentary features found in sandstone event beds may indeed

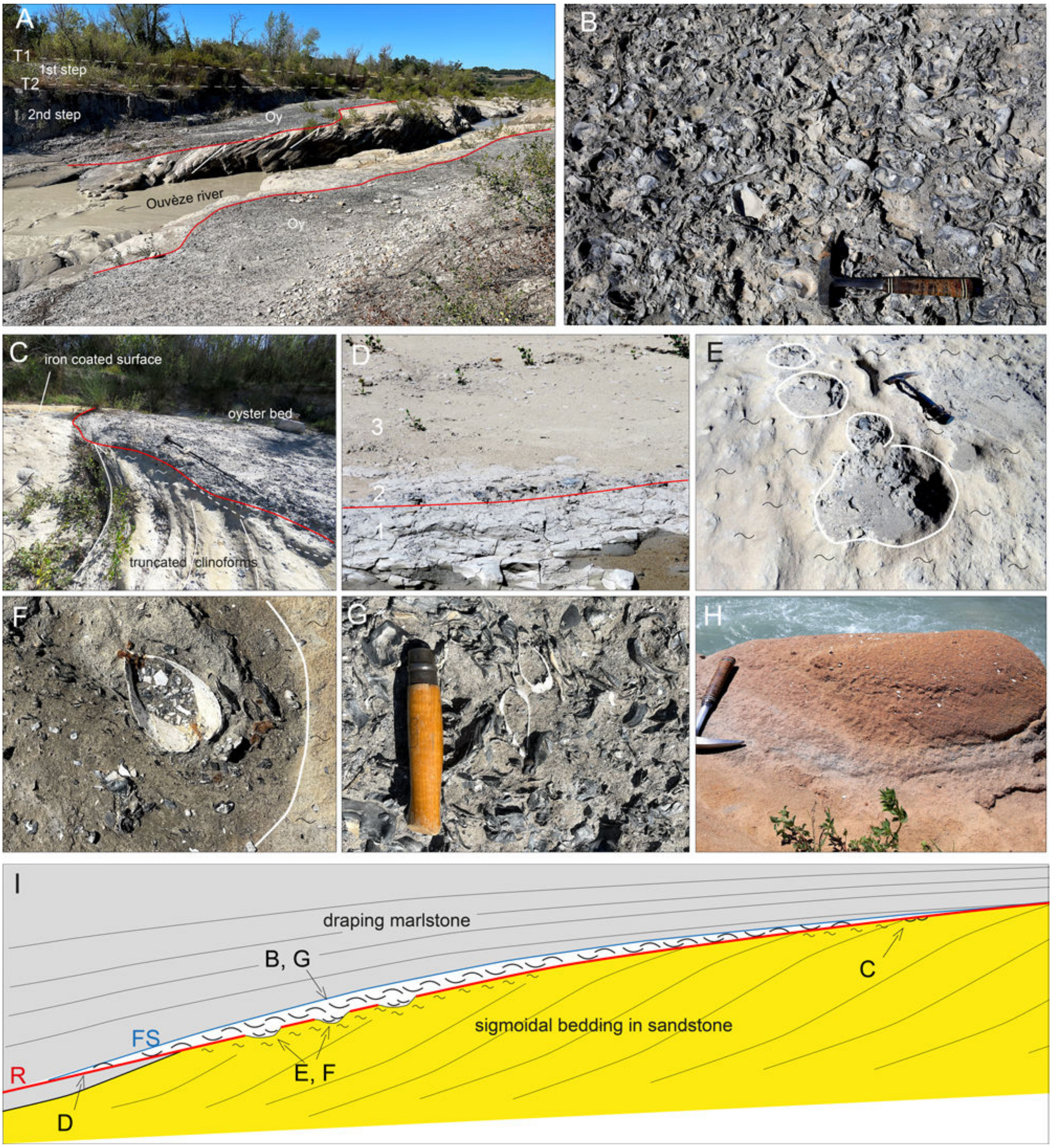


Figure 10: Oyster bed sealing a truncation surface in the middle of the sequence stack. **A**, general view of the truncation; **B**, close view of the oyster bed; **C**, close view of the truncation surface underneath the oyster bed; **D**, view of the oyster bed resting on marlstone downdip; **E**, bowls cut into the bioturbated top of the sandstone prism; **F**, view of a venerid bivalve within a bowl; **G**, venerid vivalves associated with oysters in the oyster bed; **H**, broken, thin-shelled lucinid bivalves within the hyperpycnal sandstone beds; **I**, cartoon summarising all observations.

appear "proximal" in the sandstone-dominated half-cycle, and "distal" in the marlstone-dominated half-cycle. In other words, it is suggested that the sandstone event beds may have a proximal facies bearing cyclic steps, and a distal facies featuring mostly planar lamination, which is similar to turbidite beds. Unfortunately, the limited outcrops along the Ouvèze river banks (Pl. I) prevent observation of the bottomsets of the sandstone-dominated half-cycles. The Pliocene succession of the Cèze river ria (especially the finely-laminated marlstone to siltstone observed behind the Trapadis wine cellar; Figs. 4, 5.A) is an excellent illustration of the two kinds of river-flood beds deposited in a proximal marine environment: hyperpycnites at base, and "plumites" (Mutti, 2023) at the top of the succession. The latter correspond to dilute river flood plumes laid down through a pure settling process, instead of the high-density bottom currents responsible for the former.

4. Integration of the data into the regional ria network

The exploration works carried out by Andra in the 1990s in the Cèze River basin close to the Marcoule nuclear site comprised a number of deep, fully cored wells and seismic profiles. They permitted correct replacement of the Codolet water well (Fig. 11) within the seismic imaging (Fig. 12 - upper left). The stack of sandstone beds at the base of the well was previously assigned a Cenomanian age until the seismic profiles showed they are in fact the base of the Pliocene ria infilling. The Pliocene succession (Fig. 12 - upper left) comprises a poorly imaged succession, probably sandy, at the base, overlain by a stack of laterally continuous reflectors corresponding to the sandstone aquifers found at base of the Codolet well, and finally the classical Pliocene Blue Marls of the Rhône valley network at the top. The lower part of the Blue Marls shows inclined reflectors (lined in white in Fig. 12 - upper left) suggesting the occurrence of a prograding body.

Subsequent investigations downria in the Pujaut trough (FERRY *et al.*, 1997a) showed that the base of the Pliocene infilling comprises nested sandstone-marlstone sequences likely to be correlated with the very base of the Pliocene succession in the Andra seismic profile 94 MAR 01 (Fig. 12). The nesting of the basal sequences suggests a complex depositional geometry which would explain the lack of continuous reflectors at base of the Andra profile.

Despite the lack of cores (and thus of interpretable sedimentary features) in the Codolet aquifers, it is unlikely that the continous reflectors could be mass transport deposits (MTDs) in a fully flooded ria, as concluded by DO COUTO *et al.* (2024). We suggest instead that the lower half of the Pliocene infilling represents a stack of deltaic sequences encroaching (Fig. 12 - bottom) on the break in slope south of Pierrelatte (CLAUZON, 1982, Fig. 4). The Andra seismic profile is oriented N-S close to the confluence of the Cèze and Rhône rivers. If the interpretation of stacked delta sequences is correct, the main delta was the Rhône River's, but that it also filled the mouth of the tributaries which were at the same relative sea level. The sandstone stack should therefore onlap the Messinian slope in the Ouvèze ria (Fig. 12 - upper right). Consequently, the prograding sandstone body newly found in the Ouvèze River is correlated with the equivalent prograding unit in the 94 MAR 01 profile (Fig. 12 - upper left). According to this interpretation, the infilling of the ria network would comprise a very thick sandstone-dominated transgressive tract marked by a number of relative sea-level oscillations responsible for the sandstone-marlstone alternation in the Codolet well. The top of this transgressive tract would be the real flooding surface (Fig. 12 - upper left and bottom). The prograding bed of the middle Ouvèze river banks is not part of the delta

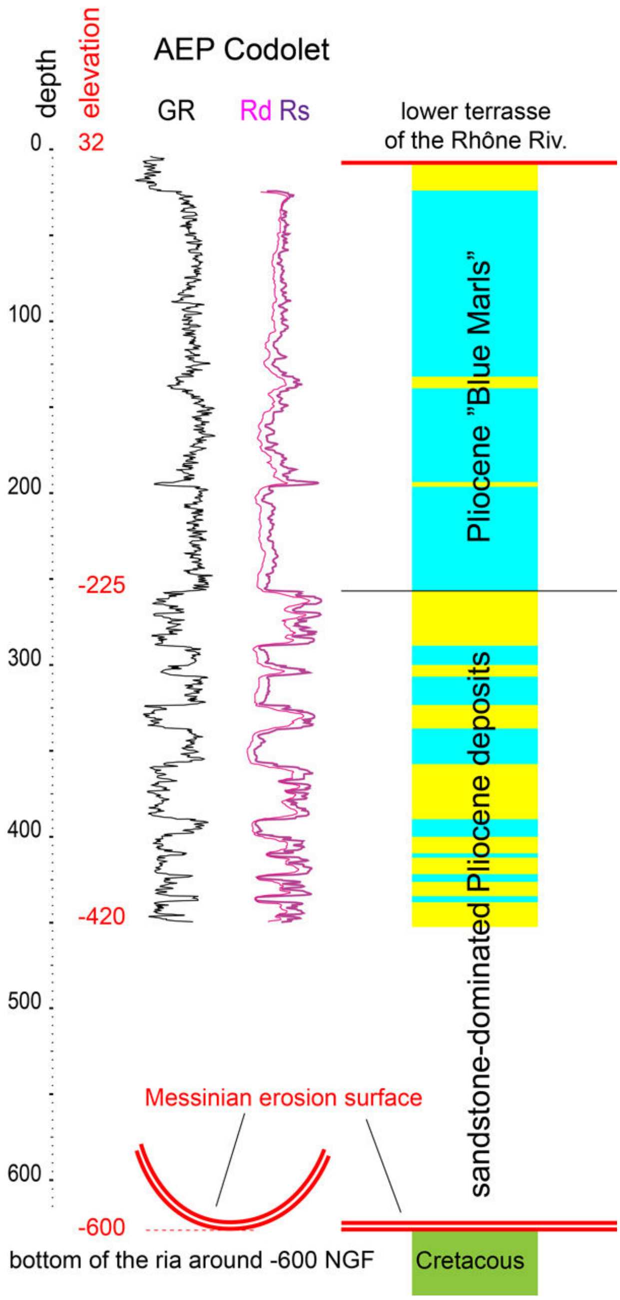


Figure 11: The Codolet water well (location on Fig. 1 - left). GR, gamma-ray log, Rs, Rd, resistivity logs (shallow, deep). Red numbers, absolute elevation *versus* sea level.

stack but an uncommon subaqueous body deposited on the slope within the late flooding stage. The homogeneous marlstone facies (Fig. 5.A) found within this body is deeper than that of the Bellerive cliff because it lacks any evidence of river-plume deposition (Figs. 2.A, 5.B, 12 - upper right) which represents the beginning of the final infilling of the ria. The maximum flooding surface in the system is therefore placed just above the newly found sedimentary body (Fig. 12 - upper right). These data therefore challenge the commonly held interpretation of a sudden and full reflooding of the desiccated Mediterranean basin (Zanclean Deluge), in favor of a progressive, likely stepped flooding of the Messinian subaerial valleys.

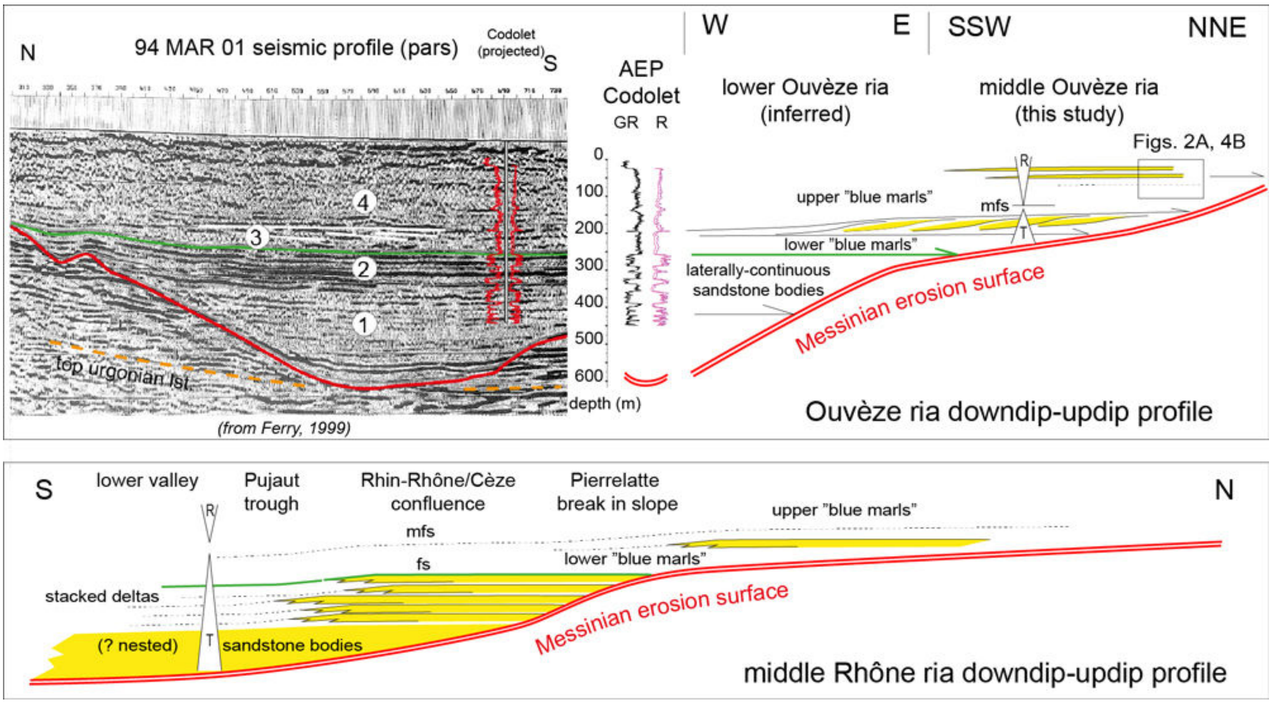


Figure 12: Relation of the data from the Ouvèze ria to those acquired once in the Cèze ria (location in Fig. 1 - left, where the Andra seismic profile 94 MAR 01 is indicated by a solid line). Explanations in the text.

Consequently, the question arises as to why the infilling of short Mediterranean rias does not feature such a sandstone transgressive tract, which has popularized the "Deluge" interpretation? A possible explanation is that the Rhône River cannot reasonably be compared to the short Mediterranean coastal rivers with respect to both their catchment areas and geology. Moreover, in the early late Pliocene, the Rhine River flowed for some time to the south, through the valleys of the Doubs and Saône rivers in eastern France (PETIT *et al.*, 1996; GIAMBONI *et al.*, 2004). In addition, the upper Rhône River at that time flowed across the Helvetic Molasse basin before merging with the Rhine river (MADRITSCH *et al.*, 2010). As a consequence, when the Rhine-Rhône river reached the modern middle Rhône valley, it carried a huge sandy bedload which was not entirely deposited within the subsiding Bresse-Dombes basin, north of Lyon city. The Rhine River course then changed to the north about 3 Ma ago (GIAMBONI *et al.*, 2004), which is roughly coincident with the beginning of the incision of the fluvial network in the uplifted peri-Alpine domain of eastern France. The fact that the Pliocene Rhine-Rhône river was for some time a powerful sand-bed river is shown by the huge prodeltaic clinoforms cropping out in the Domazan area (Pujaut trough) and the deltaic cross-bedded sandstones of Saint-Laurent-des-Arbres a little updip (FERRY *et al.*, 1997a).

The occurrence of the exposure surface within the stack of sequences (Fig. 10) is difficult to explain because it requires a marked fall in relative sea level in the ria, notwithstanding the imprecision regarding the depositional depth of the blue marls.

Pliocene oxygen isotope curves derived from marine benthics show that a brief cold snap occurred in the Zanclean around 3.2 Ma (LISIECKI and RAYMO, 2005). Evidence of a coeval climatic shift is also known on land (*e.g.*, AMARATHUNGA *et al.*, 2024; CZWAKIEL *et al.*, 2025). Are the tectonically driven changes of river courses evoked above around 3 Ma associated with this cold snap ? Was a glacial drop in sea level strong enough to expose the hyperpycnal unit 8, if really coeval with the other data ? Fully answering these questions requires additional data (cores, seismic profiles, age dating) to integrate the local observations into the whole corpus of data of the Mediterranean reflooding.

5. Conclusions

A local 5 to 9 m recent overdeepening of the Ouvèze riverbed south of Roaix village exposed an unexpected, distinctive sandstone marine bed at the base of the Pliocene Blue Marls which filled a flooded Messinian canyon at the end of the MSC. This bed is a prograding-aggrading stack of sandstone-marlstone cycles deposited at some depth by hyperpycnal bottom currents linked to flood events updip. The layer is integrated into the larger context of the middle Rhône valley network, especially with the discoveries made during the Andra works in the 1990s at the confluence of the Rhone and Cèze rivers. The data cast doubts upon the reality of the so-called Zanclean Deluge, or abrupt reflooding of the Messinian canyons. The existence of a thick sandy transgressive tract comprising a large number of stacked deltaic sequences onlapping the break in slope south of Pierrelatte, and likely to also occur in tributaries (Cèze, Aygues and Ouvèze rias), is suggested.

The reflooding of the Mediterranean basin was therefore progressive, interrupted by small drops and/or pauses, leading to a series of updip jumps of the shoreline in the rias, especially in the first stage of reflooding. These oscillations in relative sea level also occurred within the upper part of the ria infilling (Blue Marls) which represent the final reflooding of the Rhône river system.

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Plate

Plate I: Views of the inclined heterolithic stratification within unit 8 in the Ouvèze River banks. A, typical organisation of sandstone-dominated to marlstone-dominated packages forming laterally accreting sequences (red lines, sequence boundaries); B, stacking of more or less nested successive sequences; C, stacked sequences showing changes in the direction of progradation (white arrows); D, wavy stratification (cyclic steps) at base of a sequence; E, detail showing upstream accretion.


A
T2
2nd step
marlstone-dominated
sandstone-dominated
Ouvèze river
B
base of unit 8 (nested sandstone to marlstone sub-units)
top transition (unit 7)
(Fig. A)
marl-prone
sand-prone
sand-prone
(Fig.E)
nested erosional surfaces
Ouvèze river
C
draping marlstone
Ouvèze river
D
upstream accretion
Ouvèze river
E
upstream accretion