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Integrated stratigraphy of the Jurassic and the Cretaceous: a tribute to Jacques Rey /
Stratigraphie intégrée du Jurassique et du Crétacé : un hommage à Jacques Rey

Sedimentary record of the "Austrian" tectonic pulse around the Aptian–Albian boundary in SE France, and abroad

Enregistrement sédimentaire de la pulsation tectonique autrichienne vers la limite Aptien–Albien dans le sud-est de la France, et à plus grande échelle

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Abstract. A tectonically-controlled forced regression occurred on the western margin of the French subalpine basin around the Aptian–Albian boundary. It nearly emptied the western part of the Vocontian Trough during the early and middle Albian. A compressional pulse associated with vertical movements along the Cevennes fault row and its satellites is inferred. This forced regression is correlated with an inverse transgressive trend, both in the Paris Basin and the northern subalpine chains. The black shales of the early Aptian OAE1a and Albian OAE1b of the Vocontian Trough succession occur within opposite regional sea level trends, transgressive for the former, regressive for the latter. The inferred tectonic pulse is also recorded on a broader scale from literature data. The overall picture also shows outphasings in relative sea level changes on a large scale, likely controlled by tectonics.

Résumé. Une régression forcée d'origine tectonique s'est produite sur la marge occidentale de la mer subalpine au passage Aptien–Albien. Elle a vidangé presque complètement la partie ouest de la fosse vocontienne pendant l'Albien inférieur et moyen. Une pulsation tectonique en régime compressif

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associée à des mouvements verticaux est suggérée le long du couloir de failles cévenol et satellites. La régression forcée est corrélée avec une tendance inverse transgressive dans le Bassin de Paris et dans les Chaines Subalpines nord. Les black shales vocontiens des événements anoxiques océaniques globaux OAE1a (Aptien) et OAE1b (Albien) s'inscrivent dans des tendances opposées en termes de variations du niveau marin relatif, largement transgressive pour le premier, fortement régressive pour le second. La pulsation tectonique déduite se manifeste à plus grande échelle d'après les données de la bibliographie. Elle est également responsable des déphasages constatés dans les variations locales du niveau marin à grande échelle.

Keywords. French Alps, Paris Basin, Lower Cretaceous, Sequence stratigraphy, OAE1a, OAE1b.

Mots-clés. Alpes françaises, Bassin de Paris, Crétacé inférieur, Stratigraphie séquentielle, OAE1a, OAE1b.

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1. Introduction

This paper is part of a broader research aimed at understanding the progressive closure of the Vocontian Trough (VT) in the French Subalpines Chains during the Cretaceous. The VT (Figure 1A) is a narrow basin oriented approximately perpendicular to the Alpine belt, but connected to the Pyrenean basin through the SW–NE "Rhodanian saddle" [Porthault, 1974], whose subsidence was controlled by the sedimentary play of the Cévennes fault row (Figure 1B). The geodynamic significance of the highly-subsiding VT remains poorly-understood between the Pyrénées and the Alps.

The work is accomplished by the analysis of the sedimentary record, through depositional facies analysis and stratigraphic correlation. A similar research was performed earlier in this basin for another short time interval spanning the Cenomanian–Turonian boundary [Grosheny et al., 2017]. In contrast to the marine flooding generally found elsewhere during the boundary event, the deposition of the OAE2 black shale occurred within a regressive context in the subalpine basin. This is why the present work aims at also integrating two of the other Vocontian black shale beds, namely the lower Aptian Goguel Level (OAE1a) and the lower Albian Paquier Level (OAE1b) into a regional sequence stratigraphic framework, including the Paris Basin on the stable European plate, outside the Alpine margin.

In addition to the data available in the literature, new subalpine sections have been logged and dated by planktic foraminifer assemblages and ammonites. This biostratigraphic control is indicated close to the logs in the figures hereafter. For abbreviations, symbols and significance of background colours, see Figure 2.

2. Stratigraphy

For convenience, we rely on the local substages that were once commonly used in France for the Aptian and the Albian. The Aptian is divided, in ascending order, into Bedoulian (lower Aptian), Gargasian (upper Aptian) and Clansayesian (uppermost Aptian). For the Albian, the upper part of the stage is divided into upper Albian *sensu stricto* and uppermost Albian or Vraconnian, the latter beginning with the Fallax ammonite zone [Kilian Group (Reboulet S. et al.), 2018]. In the following text, "upper Albian" will always refer to upper Albian *sensu stricto*.

The Aptian–Cenomanian succession in the VT is as follows (Figure 3). Lower Bedoulian deposits are a bed-scale limestone–marl alternation which is the basinal equivalent of the last sequences of the Urgonian platformal carbonates surrounding the basin. Uppermost Bedoulian beds are a marlstone layer hosting the Goguel black shale (a lateral equivalent of the Selli Level in Italy), overlain by a double limestone bed ["Niveau Blanc" of Friès and Parize, 2003] which marks the lower to upper Aptian boundary. Within the upper Aptian, Gargasian deposits are almost uniformly made of blue grey marlstone, which have given the Formation name "Marnes Bleues" (Blue Marls). The Clansayesian is mostly represented by a laterally-continuous bed bundle, the Fromaget Beds [Bréhéret, 1995] bearing a rich *Hypacanthoplites* ammonite fauna. In the eastern VT another bed bundle (Nolan Beds, from the *Nolaniceras* ammonites found in it) is found under the Fromaget bundle [Bréhéret, 1995] but it is less prominent or almost completely subdued in western sections. The

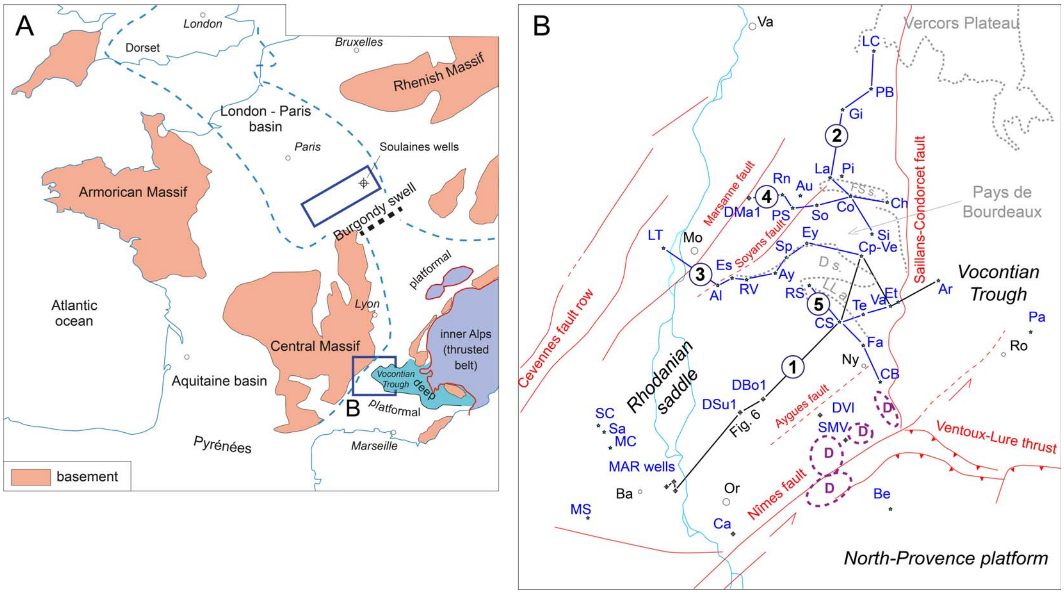

Figure 1. Location maps. (A) the two areas studied (boxed). Dotted, maximal areal extension of the connection between the Alpine sea and the London–Paris basin over the Burgondy swell. (B) detailed map of the subalpine margin. 1 to 5, correlation transects described. Abbreviations, see Figure 2.

stages and substages

Abi	lower Albian	Tu	Turonian
Cl	Clansayesian	Ce	Cenomanian
Gas	upper Gargasian	Vr	Vraconnian
Gai	lower Gargasian	Abs	upper Albian
Bds	upper Bedoulian	Abm	middle Albian
Bdi	lower Bedoulian	Abi	lower Albian

black shale beds

B	Breistroffer
P	Paquier
K	Kilian
J	Jacob
G	Goguel

biostratigraphic control

planktic forams	ammonites
Ce	Ce
Vr	Vr
Abs	Abs
Abm	Abm
Abi	
Gas-Cl	Cl
Gai	

background colours

- Vraconnian–lower Cenomanian marlstone
- Albian sandstones (cross-bedded)
- Albian basinal succession
- Clansayesian (uppermost Aptian)
- Gargasian (upper Aptian) marlstone

localities and other abbreviations

D, diapirs; LLa, La Lance anticline; Ds, Dieulefit syncline; FSs, Forêt de Saou syncline. **Cities**: Ba, Bagnols-sur-Cèze; Mo, Montélimar; Ny Nyons; Or, Orange; Ro, Rosans; Va, Valence. **Sections** (blue) : Al, Allan; Au, Auripples; Ay, Aleyrac; Be, Bédoin; CB, Chateauneuf-de-Bordette; Ch, La Chaudière; Co, Les Cosmes; Cp, Comps; CS, Combe de Sauve; Es, Espeluche; Et, L'Estellon; Ey, Eyzahut; Fa, Les Faviers; Gi, Gigors; La, Pas de Lauzens; LC, Le Chaffal; LT, Le Teil; MC, Mas Cagnet; MS, Mas Soulan; Pa, Palluel; PB, Plan-de-Baix; Pi, Piégros; PS, Puy-Saint-Martin; Rn, Roynac; RS, La Roche-Saint-Secret; RV, Rochefort-en-Valdaine; Sa, Salazac ; SC, Saint-Christol-de-Rodières; Si, Les Sibours; So, Soyans; Sp, Soupierre; Va, Valouse; Ve, Vesc. **Wells** : Ca, Cassanets (Fontannes 1882, revisited), DBo, Bouchet ; DMa, Marsanne; Dsu, Suze-la-Rousse; DVI, Villedieu; MAR, Marcoule; SMV, Saint-Marcellin-lès-Vaison (BSS, BRGM).

Figure 2. Abbreviations and biostratigraphic symbols used, and significance of background colours in figures.

first 70 m of the thick marlstone succession overlying the Fromaget beds comprises three black shale levels, i.e. in ascending order the Jacob, Kilian and Paquier levels [Bréhéret, 1995]. The Aptian–Albian boundary has been recently fixed on top of the Kilian level [Kennedy et al., 2000, 2014, Petrizzo et al., 2012], which leaves about 35 m of marlstone above the Fromaget bed bundle to be ascribed a latest Aptian age. The Albian marlstone succession is not perfectly uniform as it comprises several bundles of argillaceous limestone beds and other black shale layers [Paquier and Breistroffer levels, Bréhéret, 1995]. The Cenomanian succession is an alternation of well-marked bed bundles and marlstone-dominated intervals. The Albian–Cenomanian boundary was fixed by the first occurrence of the planktic *Thalmaninella globotruncanoides* in the Vocontian reference section of the Palluel Pass [Kennedy et al., 2014], within the upper part of the "Albian" marlstone succession, or about a few tens of metres below the first Cenomanian bed bundle.

Vocontian successions comprise numerous slump layers, and sandstone turbidite bodies, most of them channelled. The latter have been numbered from G1

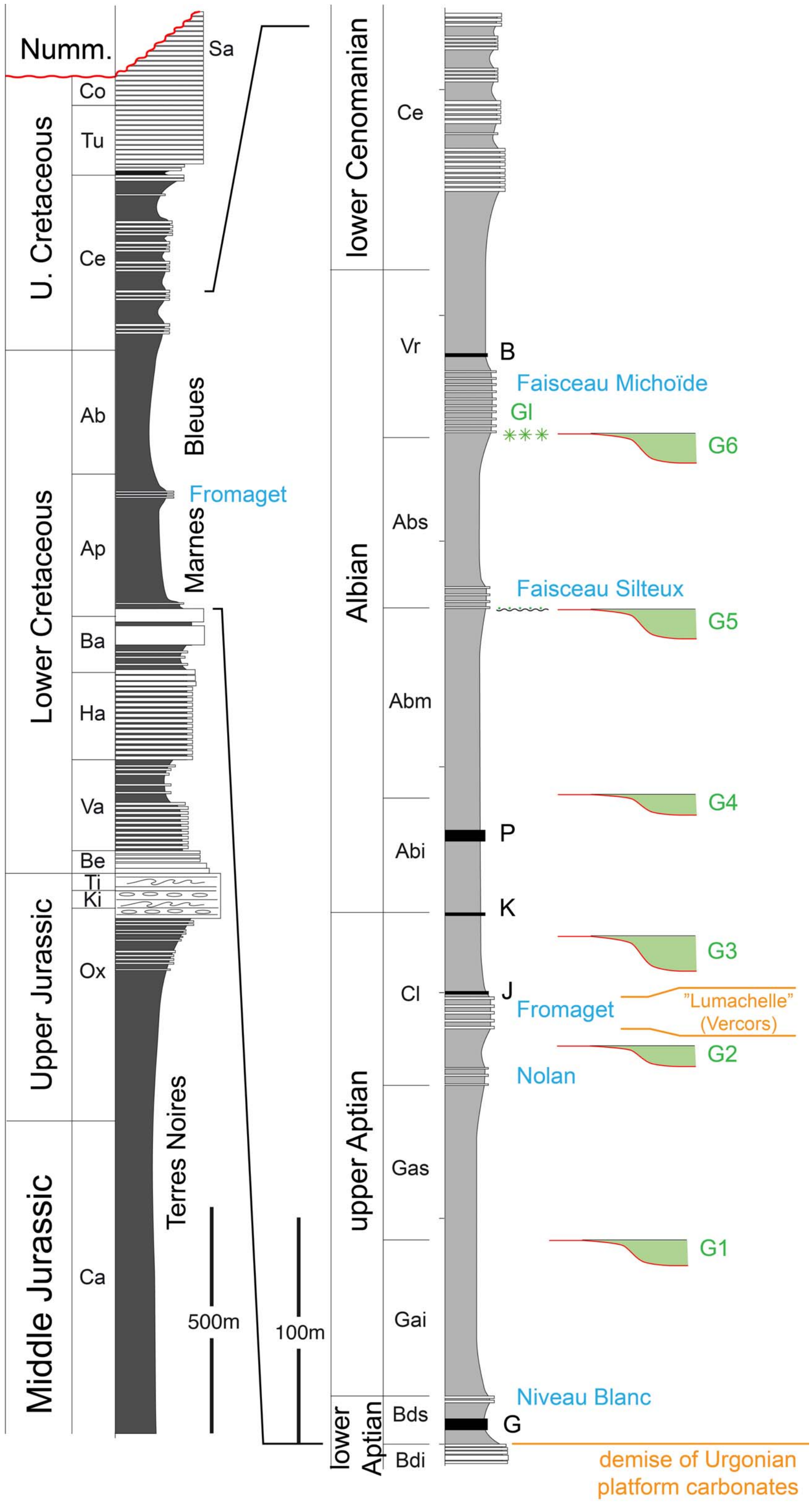

Figure 3. Caption continued on next page.

Figure 3 (cont.). The Vocontian stratigraphic succession with enlargement for the Aptian–Cenomanian. Abbreviations, see Figure 2. In blue, laterally-continuous limestone bed bundles as named by Bréhéret [1995]. G1 to G6, sandstone turbidite bed bundles. The "faisceau michoïde" was dated by Gale et al. [2011] and also by a glauconite bed bearing ammonites of the Fallax zone [lowermost Vraconnian, Kilian Group (Reboulet S. et al.), 2018] at its base [Vincent et al., 2020]. Correspondences with some peripheral platformal carbonates are indicated. Thicknesses are approximate.

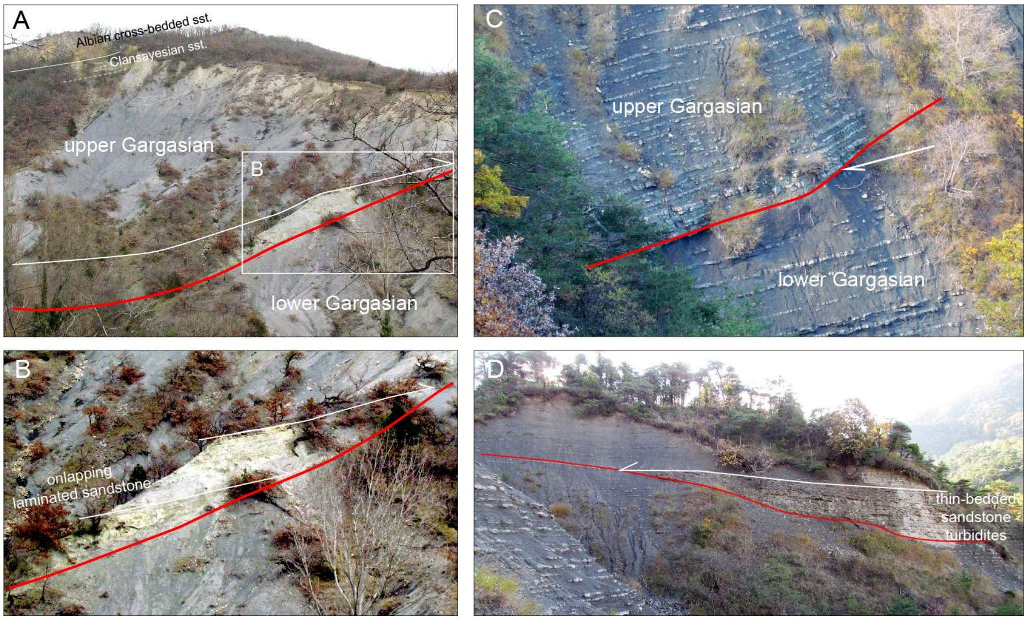

Figure 4. The mid-Gargasian regional erosional surface in slope deposits on the north-western Vocontian margin. (A, B), Roynac; (B, C), Gigors (for location, see Figure 1B).

to G6 (from the mid-Gargasian to the uppermost Albian) by Rubino [1989] but later studies identified more levels from T1 (G1) to G9, within the same stratigraphic range [Bréhéret, 1995, Friès and Parize, 2003]. The lower to upper Bedoulian and Bedoulian–Gargasian transitions are marked by mass-transport deposits covering large areas in the western VT (respectively the CL3 and CL4 debris flow beds of Ferry and Flandrin [1979]. Several bundles of thin-bedded turbidites (Pl for "plaquettes rousses", or red slabs) with reddish patina also occur within the black shale bearing upper Bedoulian sequence and in the lower part of the Gargasian marlstone. The G1–G2 turbidites are associated with a laterally-continuous erosional surface on the basin slope (Figure 4). This surface correlates with the mid-Gargasian [Conte, 1985] "Grès à Discoidea" found in the Rhodanian saddle, and which likely represents an incised valley fill (Figure 5).

The exact stratigraphic position of turbidites "G" versus limestone bed bundles in Albian Blue Marls is approximate. In the model proposed by Rubino [1989], limestone bundles were thought to represent the basinal expression of lowstand deposits, therefore lined at the base by the so-called basin floor fan ("G" beds, here), in accordance with the Vail et al. [1977] sequence stratigraphy model, widely used in the eighties. But the limestone bed bundles and the turbidite "G" beds do not occur in superimposition in most real sections, so the sequence stratigraphic interpretation remains somewhat speculative.

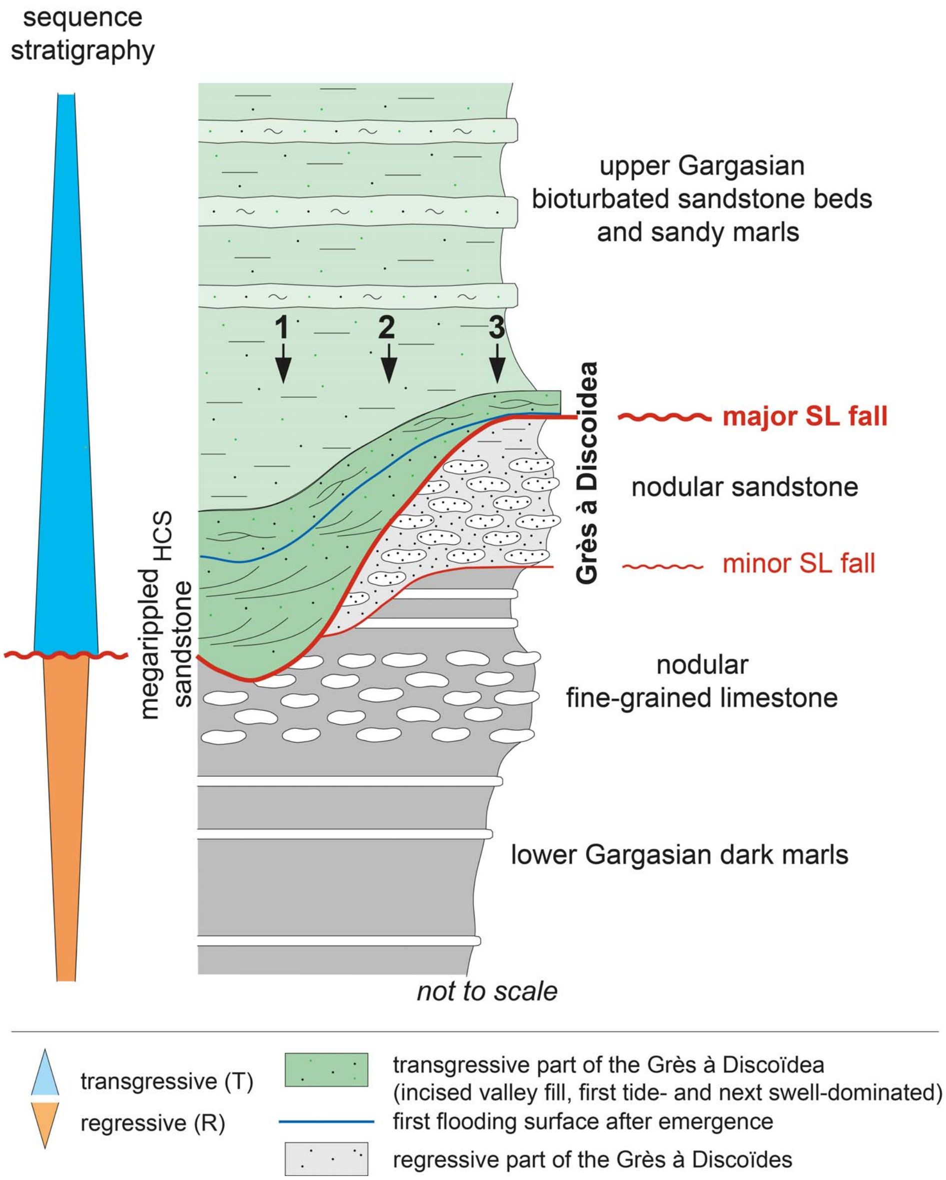

Figure 5. Sequence stratigraphic analysis of the mid-Gargasian Grès à Discoïdea in the Gard Department (Rhodanian saddle, Figure 1B). Type sections: 1, Salazac village; 2, Mas Cagnet ravine; 3a, Saint-Christol-de Rodières; 3b, Mas Soulan (Saint-Laurent-la Vernède road). From Ferry [1997, unpublished ANDRA Report]. For location of type sections, see Figure 12.

3. Description of the stratigraphic transects across the VT western margin

Five transects are described (Figure 1B). Transect T1 goes from the Rhodanian saddle to the VT proper. It integrates the results of the ANDRA exploration works in the early nineties in search for a suitable location for a repository of nuclear waste close to the Marcoule plant. Detailed analysis is mostly available in unpublished reports but a short synthesis was published later [Ferry, 1999]. Transects T2 goes across the northern margin from the Vercors platform to the Pays de Bourdeaux which geographically

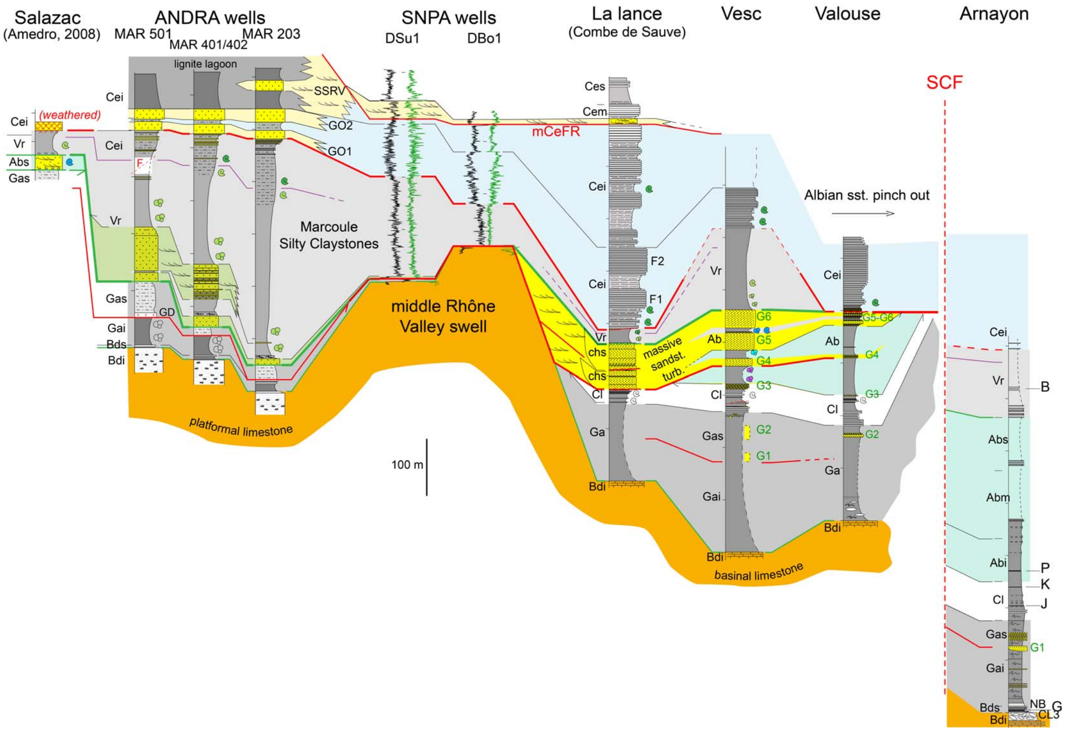

Figure 6. Transect 1 across the western Vocontian margin (upper–lower Aptian to mid-Cenomanian). Slightly modifed from Ferry [2017]. Location on Figure 1B. Chs, channelled massive sandstone; GD, mid-Gargasian "Grès à Discoidea"; GO, lower Cenomanian "Grès à orbitolines"; mCeFR, mid-Cenomanian forced regression; SSRV, lower to middle Cenomanian sandstone spit.

corresponds to what is called here the western VT. Transects T3 to T5 depict more detailed correlations on the western border of the western VT. Transect T5, along the La Lance anticline, is specially devoted to the relationships between cross-bedded Albian sandstones and massive turbidites, which cannot be understood along transect T3.

The narrow corridor between the Nîmes and Nyons faults is poorly-known due to the occurrence of salt diapirs (featured "D", Figure 1B). Ancient exploration wells (mostly by the SNPA company) have been used in areas covered by Miocene deposits of the Comtat basin (Middle Rhône valley). These deposits have prevented for long the reliance on the deposits of the Gard Department (also known as the Cèze River basin) and those of the VT.

3.1. *Transect T1*

Figure 6 summarizes the main stratigraphic results acquired after the ANDRA works in the Gard Department. It shows how the basinal Gargasian marlstone "pinches" out against Barremian slope limestone. The marsltone unit reappears modified west of the major hiatus of the middle Rhône Valley as a thin succession, where deposits of the upper Gargasian sequence are shallower than those of the first one, and fills a nested lowstand to transgressive estuarine sandstone system (Grès à Discoidea, GD, see also Figure 5). The most striking feature is the shift of cross-bedded Albian sandstone units to the east, where they appear "anchored" against a domal feature judged responsible for the Albian stratigraphic hiatus of the Middle Rhône Valley [Ferry, 1999]. Two superposed megarippled sandstone units have been described on the external platform by Rubino [1989]. Massive sandstones develop basin-

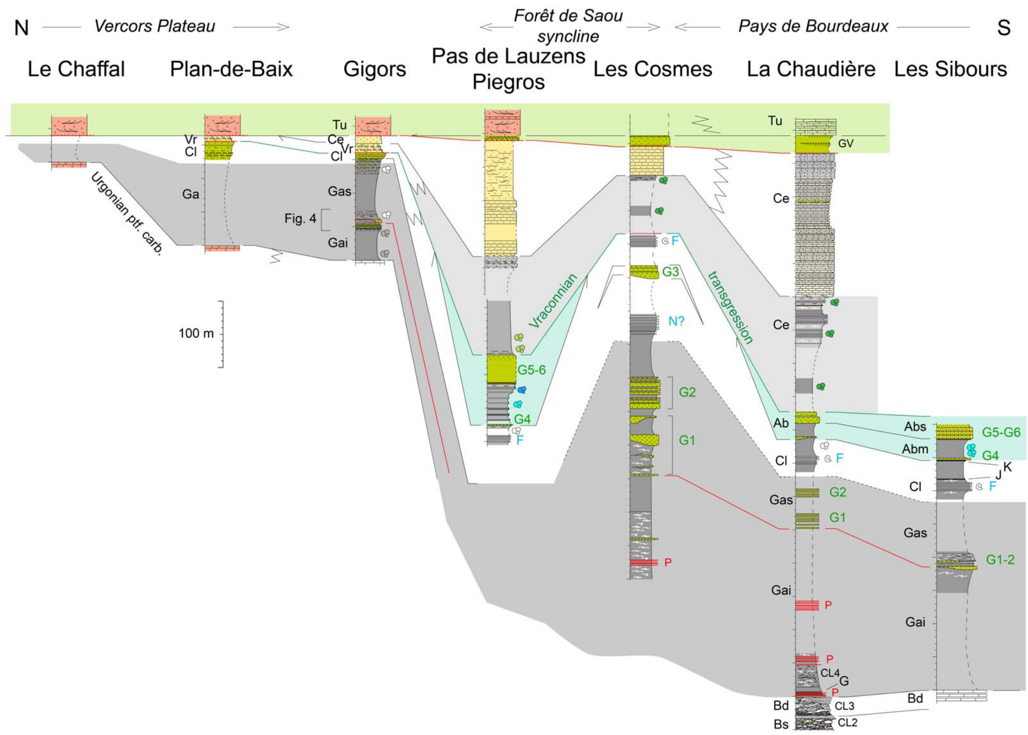

Figure 7. Transect 2 across the northern margin. For location, Figure 1B.

wards with all characteristics of turbidites. What is intriguing is that these massive turbidite deposits are rooted within (interfinger with) the megarippled sandstones of this margin [Rubino, 1989]. Albian deposits are lacking in ancient exploration wells of the Middle Rhône Valley where deposition resumes in the Vraconnian or the Cenomanian. Megarippled sandstone do reappear west of the hiatus area, but as a single sequence of late Albian age [Amédro, 2008] resting on the upper Gargasian sequence. A second striking feature is the large thickness of the Vraconnian sequence on the western part of the transect, suggesting a sharp increase in subsidence after the Albian hiatus. The Vraconnian sequence begins with a thick package of transgressive gravelly sandstone passing upward to a thick silty claystone (called "Couche Silteuse de Marcoule" in the ANDRA works). Ammonites found in the fully-cored wells show that the Albian–Cenomanian boundary [Amédro and Robaszynski, 2000] occur within a regressive trend leading to the two successive sequences of sandstone shore facies of the lower Cenomanian "Grès à Orbitolines" (GO1, GO2, Figure 6). The Grès à Orbitolines passes slopeward to a double thick package of evenly-bedded sandy limestone (F1 and F2, Figure 6). Their thickness reaches a maximum in La Lance anticline where F1 and F2 fills a large erosional surface lined at the base with superimposed shifting channels filled with fine to medium-grained sandstone. The slope erosional surface passes to a correlative conformity basinward (Valouse), which becomes strongly erosive again when approaching the N–S Saillans–Condorcet fault (SCF, Figure 6). This fault is a major lineament implying the basement according to a gravimetric survey [Flandrin and Weber, 1966]. Recent field work shows that, close to the fault (see further transect T3, Figure 8), the lower Cenomanian limestone rests directly on the lower part of the upper Gargasian marlstone. Also, the Albian G5 and G6 turbidite bundles thin before toplapping the erosional surface. East of the fault, a thick Albian marlstone succession occurs, devoid of turbidites, suggesting that the SCF fault uplifted the western part of the VT, and that the turbidite currents coming from the west waned against a relief.

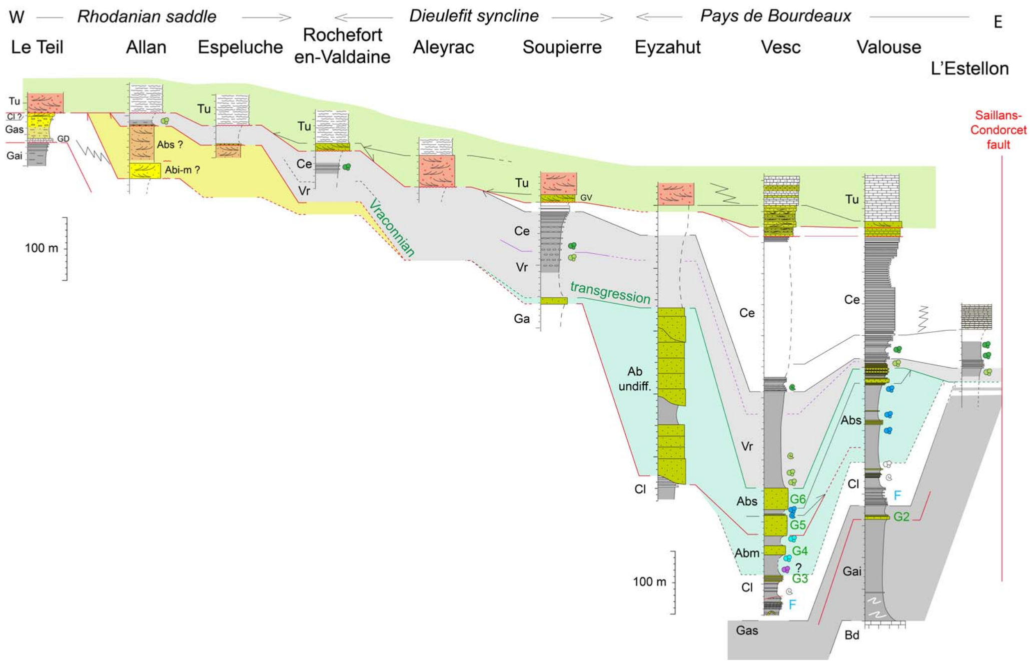

Figure 8. Transect 3 along the northern edge of the Dieulefit syncline. For location, Figure 1B.

3.2. *Transect T2*

This transect (Figure 7) is designed for imaging the pinching of the two gargasian marlstone sequences on the Vercors platform edge. The sequence boundary at the base of the upper sequence (Gas) shows the relationship between the slope channel of Gigors (Figure 4) and the G1 to G2 turbidite systems basinward. The sequence boundary is dated by planktic foraminifers to occur around the boundary between the *Martini* and *Nuttfieldensis* ammonites zones. The Clansayesian bed bundles and marlstone interbeds are laterally continuous. *Hypacanthoplites* ammonites of the Fromaget beds have been reported [Sibours, Bréhéret, 1995] or newly found (Les Cosmes section). The basinal fine-grained facies passes upslope to a bioturbated sandstone in the Gigors section and to cross-bedded sandstone a short distance to the north. Albian deposits are very thin. Turbidites are mostly represented by a sandstone package attributed to G5–G6 sandstone beds. A new discovery is the hiatus occurring along the southern flank of the Forêt de Saou syncline (Les Cosmes section) where the fine-grained limestone beds of the Fromaget bundle are directly overlain by Vraconnian to lowermost Cenomanian marlstone dated by planktic foraminifers. This is reminiscent of the uplift that occurred in the Middle Rhône Valley. The Vraconnian–lowermost Cenomanian marlstone passes upslope to a bioturbated sandstone bearing calcareous diagenetic nodules in the Gigors section, as for the Clansayesian deposits. Cenomanian deposits are represented here by shelfal to shore sandstones bearing wave features (HCS). They thin on the southern flank of the Forêt de Saou syncline (Les Cosmes) suggesting they onlap onto a swell. They pass to thicker finely-laminated, more or less bioturbated sandy limestone basinward (La Chaudière). The non-dated yellowish sandstone occurring under the transgressive Turonian calcarenite at Gigors and Plan-de-Baix were ascribed an Albian age until now [Porthault, 1974]. The strong areal restriction of Albian deposits in our correlation suggests they could either be the upslope facies of the Cenomanian sandy wedge called “Grès d'Auripples” by Porthault [1974].

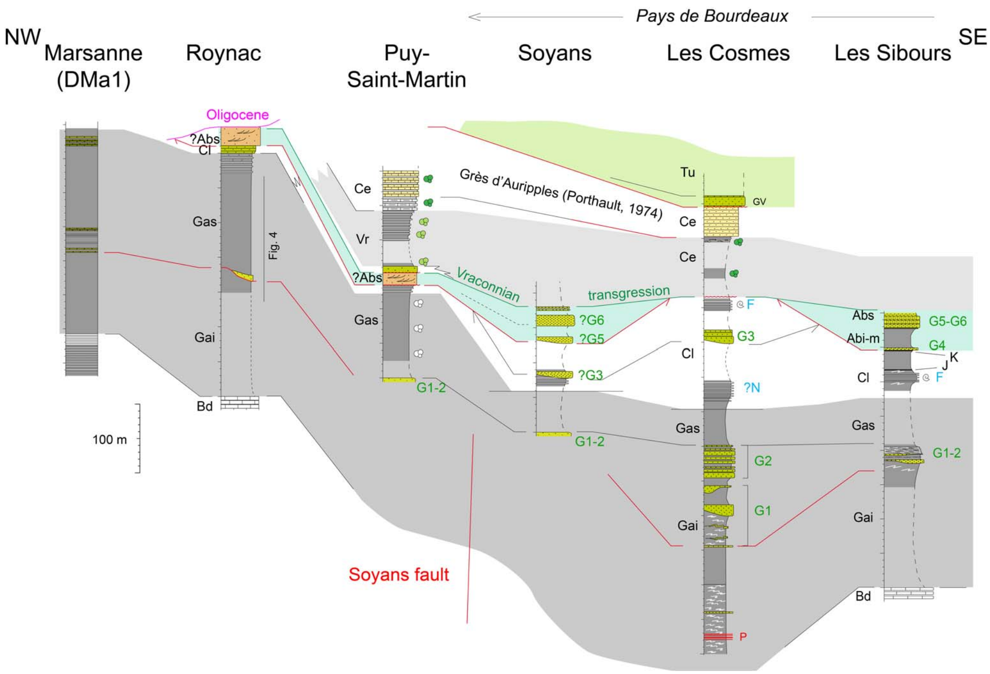

Figure 9. Transect 4 across the Pays-de-Bourdeaux. For location, Figure 1B.

3.3. *Transect T3*

This transect (Figure 8) runs along the edge of the restricted Albian basinal area NE of the Middle Rhône Valley hiatus area, which is represented by a sharp contact in Figure 6. To the west, the two Albian sequences of cross-bedded sandstone occur, from Allan to the NW termination of La Lance anticline, south of the Dieulefit syncline (resp. Al and RSS sections, Figure 1B), where their interfingering with massive sandstone beds occurs (see further transects T5 and T6, Figures 10 and 11 for details). Along transect T3, this interfingering is not visible. Massive sandstone turbidites suddenly appear on the northern flank of the Dieulefit syncline (Eyzahut). As shown on transect T1, these massive beds thin basinward where they interfinger (G4 to G6) with dark-grey marlstone beds, which have given middle to upper Albian pyritous ammonites [Moullade, 1966], in accordance with our findings on foraminiferal assemblages. As on transect T1, Gargasian to lower Cenomanian deposits toplap the erosional surface sealed by lower Cenomanian limestone when approaching the SCF. Well-dated by planktic foraminifers all along, the Vraconnian to lowermost Cenomanian marlstone is laterally-continous and transgressive on Albian deposits, either cross-bedded or turbiditic. As in the Rhodanian saddle (transect T1), its base is often lined by a lag of quartz gravels and coarse-grained sandstone, which may be given a regional stratigraphic value, as Albian sandstones are always fine-to medium grained everywhere. As in the Rhodanian Saddle (transect T1), the Albian–Cenomanian boundary lies within the upper part of the marsltone wedge. The transect also shows the truncation of the succession by the transgressive Turonian calcarenite [Porthault, 1974] after the major regional sea level fall that occurred around the Cenomanian–Turonian boundary [Grosheny et al., 2017]. The Venterol Sandstone [Porthault, 1974; GV, Figure 8] at the base of the calcarenite represents the lowstand deposit of the forced regression. At the western termination of the transect (Le Teil section, Figure 8), the Grès à Discoidea allows to identify the two Gargasian sequences, below and above. The full sandy facies of the upper one indicates it is closer to the shore than in the Rhodanian saddle. By comparison with transect T2, the overlying cross-bedded sandstone under the transgressive Turonian calcarenite could be assigned a Clansayesian age (shore facies of the basinal bed bundles and marlstone). This would be a rare case where Clansayesian deposits are preserved in the Rhodanian saddle where all Clansayesian ammonites cited in the literature are reworked in transgressive lags of later sequences.

3.4. *Transect T4*

This transect (Figure 9) runs perpendicular to the SW–NE Marsanne and Soyans faults. It is designed to show again the thinness of Albian deposits versus Gargasian ones in the Pays de Bourdeaux. There is only one unit of cross-bedded Albian sandstone (? the upper one) in this transect versus the two units occurring in transects T3 and T1. The cross-bedded sandstone is directly overlain by the characteristic transgressive gravelly sandstone of the Vraconnian sequence. The succession is perfectly dated by planktic foraminifers in the Puy-Saint-Martin section, except for the Albian sandstone whose likely age will be discussed further. The transition between the cross-bedded sandstone and the massive turbidite beds of the Soyans section is not visible, and therefore their sequence stratigraphic relationships, if any, are also hidden. The facies change was likely controlled morphologically by the Soyans fault.

3.5. *Transect T5*

The transition between Albian cross-bedded and massive turbiditic sandstones is best understandable along the SW flank of La Lance anticline (Figure 10). The figure shows two subtransects roughly perpendicular, one upslope in cross-bedded deposits, the other alongslope in turbidite deposits. The Tour d'Alençon-Le Brut subtransect shows that the two Albian cross-bedded units are nested in an incised valley likely perpendicular to the SW–NE fault row of the Middle Rhône Valley. Both the overall geometry and the cross-bedding suggest an elongated estuarine deposit. The Célas to Chateauneuf-de-Bordette subtransect shows both the interfingering of cross-bedded and massive sandstones, earlier described by Rubino [1989], and the progressive thinning downslope of the massive sandstone beds over rather short distances. Regarding the sequence stratigraphic relationships between the likely estuarine deposits and the massive turbidites between the two close sections of Le Célas, there are two possibilities *a-priori*. Either the cross-bedded deposits are transgressive over the massive turbidites, or on the contrary, turbidites are transgressive over cross-bedded ones. The most likely explanation is the reworking of backstepping transgressive estuarine sands by storm rip currents when sea level rose in a narrow lowstand valley. Vegetation cover and recent alluvial deposits between the two Célas section do not allow to obtain better field data. The exact age (? middle–upper Albian, Figure 10) of the two Albian sequences cannot be determined because of the absence of marlstone interbeds able to give micropaleontologic data. The sandstone wedge is sandwiched between the Clansayesian Fromaget bed that has given a rich *Hypacanthoplites* ammonite fauna, and the Vraconnian marlstone dated by planktic foraminifers. The evenly-bedded, coarse to gravelly sandstone of the Vraconnian transgression seals the lateral facies change in Albian deposits. The transect also pictures the large erosional channel evoked above at the base of the lower Cenomanian limestone bed bundles F1 and F2 (transect T1).

An additional correlation (Figure 11) is given between La Lance and Valouse (for location, Figure 1B) just to enlighten how channeled were Albian deposits in the western part of the Vocontian Basin. A similar channelled pattern was suggested by Friès and Parize [2003] at a larger scale in the basin for Gargasian turbidites.

4. Gargasian and Albian subalpine palaeogeographies compared

4.1. *Gargasian palaeogeography*

From the transects described above and also sections published by Friès and Parize [2003], the Gargasian marsltone succession is on average 200 to 250 m thick but may reach 350 m in the Pays de Bourdeaux. The succession pinches progressively on Urgonian platformal carbonates of the Vercors to the north (Figure 7), as well as on those of the Bas-Vivarais across the present-day middle Rhône valley to the west, or those of the Provence platform to the south. The palaeogeographic picture (Figure 12) is that of

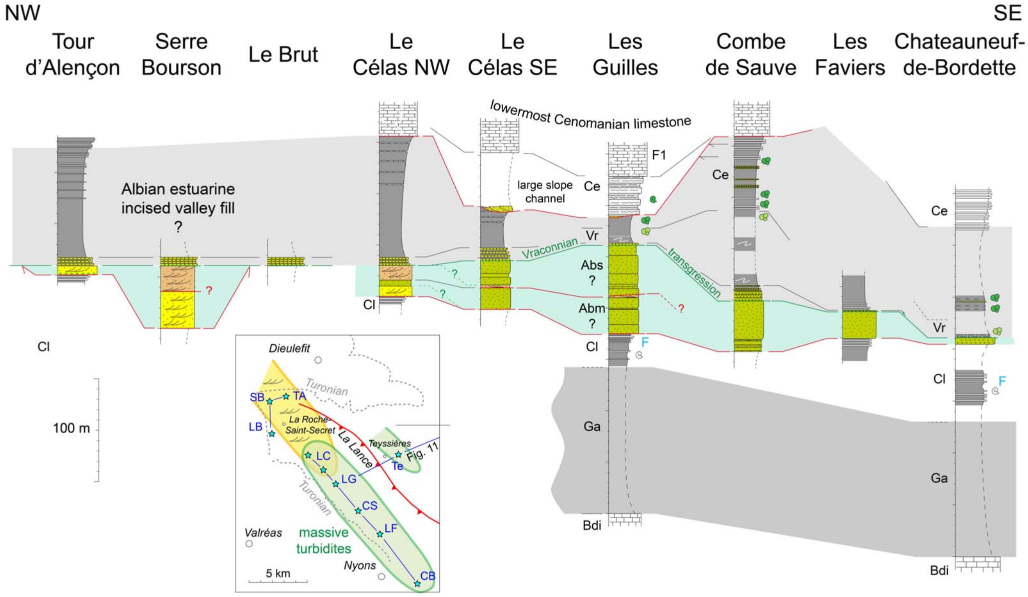

Figure 10. Detailed transect 5 along La Lance anticline. For location, Figure 1B.

a large basin including the platformal areas flooded after the demise of Urgonian shallow water carbonates surrounding the VT. The change from carbonate- to marlstone-dominated deposition is likely tied to a climate change, as suggested in other locations [Mutterlose et al., 2009]. The overall picture is complicated in the Rhodanian saddle by what will occur there around the Aptian–Albian boundary, as will be explained in detail in the next paragraph. These Gargasian marlstones may therefore be lacking but were probably present before Albian erosion. This is also true south of the Ventoux-Lure chain on what is known as the Albian Durancian Isthmus *auct.* [Masse and Philip, 1976] which separates the Vocontian domain and the south Provence basin to the south.

Vocontian Gargasian marls are interrupted in their middle part by a laterally continuous sandstone turbidite system [G1 of Rubino, 1989; G1/G2 of Bréhéret, 1995; T1a/T1b of Friès and Parize, 2003]. Later turbidite systems (Clansayesian to Albian) are more geographically restricted. The middle Gargasian turbidite system correlates to a major erosional surface in slope marls of the western margin (Figures 4 and 5), which allows to define two major Gargasian sequences. Into the Rhodanian saddle, this slope erosional surface correlates to a large incised valley hosting a probable estuarine system oriented to the NE (Figure 12). In the Rhodanian saddle, the lower Gargasian sequence is made of deeper marsltone than the upper Gargasian one which is more sandy (Figure 5), and accordingly shallower [Ferry, 1999]. This is not the case in the two slope valleys on the northwestern margin (Figure 4), where there are no differences in both facies and planktic foraminiferal abundances between the marls of the two sequences.

4.2. *Albian palaeogeography*

From the stratigraphic data presented above, the areal extension of Albian deposits in the western VT (Figure 13) is strongly restricted compared to that of Gargasian ones (Figure 12). The SCF played a major role in isolating, within the basinal environment, an upper terrace corresponding to the Pays de Bourdeaux, with rather thin successions, and a deeper eastern basin with expanded sections and very few turbidites. The change occurred after the deposition of the Clansayesian G3 turbidite system. The SCF is lined on its western side by a N–S anticline, the Montagne de Couspeau. Most Albian turbidites did not cross it, suggesting the occurrence of a submarine relief, by which they quickly decelerated and waned onto. Albian stratigraphy on the margins of the upper terrace is difficult to understand and interpret. The Clansayesian system underneath follows that of the

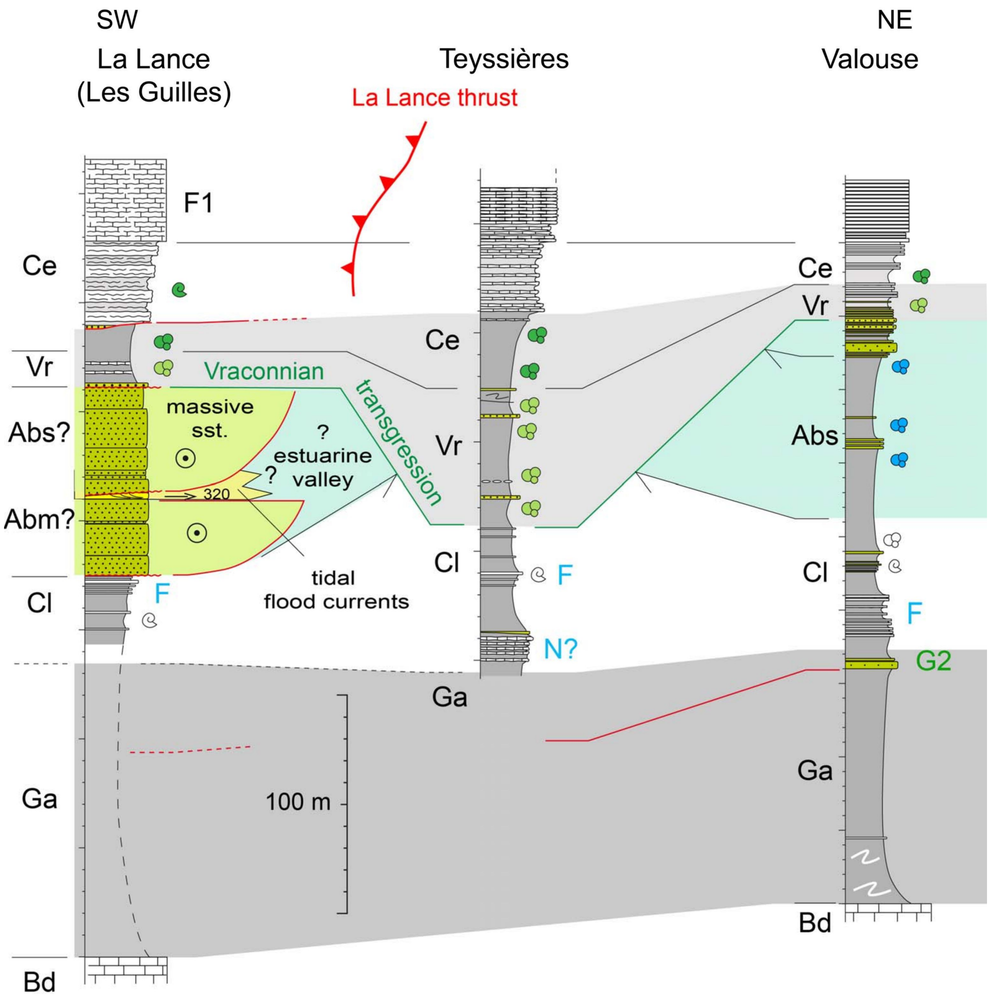

Figure 11. Correlation from La Lance to Valouse. For location, Figure 1B.

Gargasian one. Its marginal cross-bedded sandy deposits are recorded in the T1 to T4 transects. Vraconnian overall transgressive deposits seal everything. Of the two Albian cross-bedded units, the upper one is the most widely represented and dated upper Albian at Salazac [Amédro, 2008], on the North Provence platform [Joseph et al., 1987b,a], as on many other places of the VT margin according to Bréhéret [1995]. This is the reason why we ascribe a late Albian age to the second cross-bedded unit of La Lance anticline. This unit is clearly overall transgressive both in the Rhodanian saddle west of the hiatus of the Middle Rhône Valley and on the North Provence platform (Figure 13B). The areal extension of the mid-Albian marginal sandstone looks narrower but these deposits may have been truncated by the late (and especially the latest) Albian transgressions. The peculiar relationships between the first Albian cross-bedded unit and turbidites along transect T5 suggest that the lower to middle Albian shoreline may have been close to the limit of the light blue area in Figure 13A. Its shore facies may have been very narrow, even restricted to channelled estuarine deposits, as suggested in Figure 13A. Their extension along the Soyans fault may also have been eroded by the late Albian transgression. In the diapirs region (D, Figure 13), data are sparse. Outcrops [Masse et al., 1990] as well as well data allow to draw a

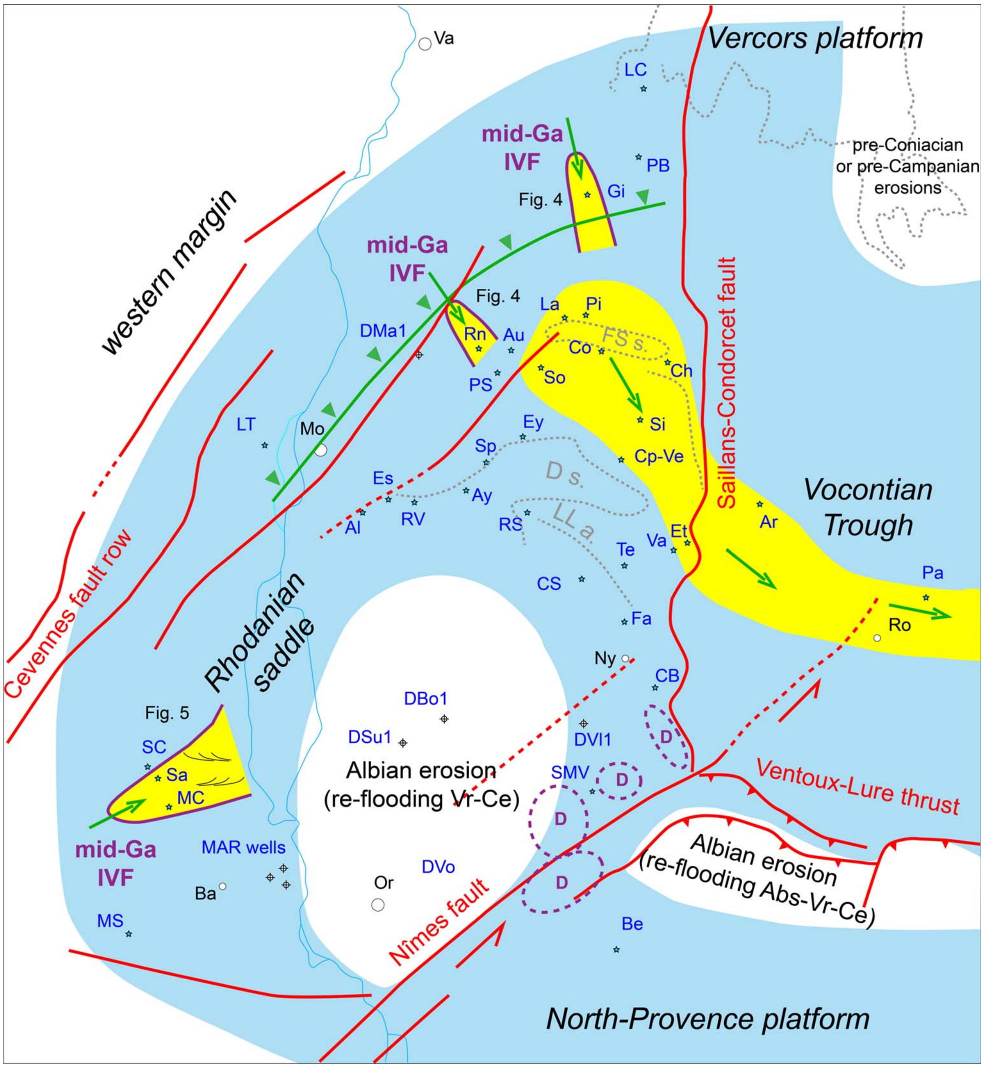

Figure 12. Gargasian facies map.

narrow band where a probably upper Albian cross-bedded sandstone unit is sandwiched between Gargasian and Vraconnian to lower Cenomanian marlstones (Figure 13B). Lower to middle Albian deposits are lacking.

The Middle Rhône Valley hiatus (Figures 6 and 13) is explained by an uplift that occurred around the Aptian–Albian boundary, as on the Durancian Isthmus on the Provence platform. Most of the western margin of the VT was then exposed during the early to middle Albian. This is consistent with other data from the Albian bauxites of southern France, which support a strong denudation of the sedimentary cover of the Variscan basement of the Massif Central [Marchand et al., 2021]. Deposits of later transgressions (late Albian, Vraconnian, Cenomanian) onlapped in a stepped way the Middle Rhône Valley swell.

In front of the Ventoux-Lure thrust, upper Albian breccias were described [Moullade and Porthault, 1970, Montenat et al., 2004] suggesting the occurrence of a rocky shore. Parts of the thrust emerged during the Albian [Montenat et al., 1986], with Cenomanian deposits resting directly on Bedoulian limestones.

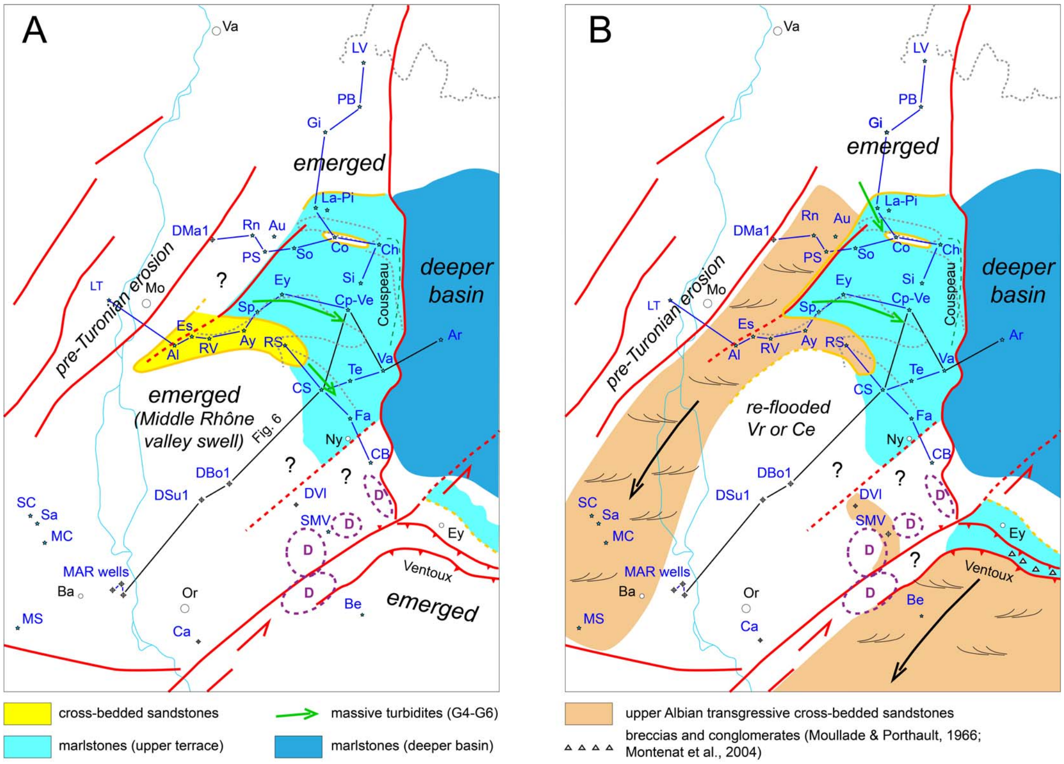

Figure 13. Albian facies maps.

Cross-bedded Albian sandstones were interpreted as relatively deep shelfal deposits under a north-Thetyan peri-Vocontian contour current [Delamette, 1988, Rubino and Delamette, 1988]. Newly acquired stratigraphic data hardly support such an interpretation. The new picture proposed is that of a restricted basin instead.

5. Connection with the Paris Basin

Figure 14 shows the correlation that can be done from the Alpine margin to the eastern border of the Paris Basin (Figure 1A). If the Vocontian margin experienced an uplift, the story is not the same on the European craton in front of the Alpine domain, according to the stratigraphic synthesis of Aptian–Albian deposits in the Paris Basin [Amédro et al., 2021]. In the ANDRA site of Soulaines (Figure 1A), which was cored extensively, the uppermost Bedoulian Argiles à Plicatules rest on a weathering profile covering at least the early Bedoulian and affecting underlying (? upper) Barremian sandstone and claystone [Ferry, 1997, unpublished ANDRA report]. The correspondence of the Argiles à Plicatules with the OAE1a Vocontian black shale is supported by δ^{13}C data [Deconinck et al., 2021]. Although the detail of upper Bedoulian transgressive tract may be somewhat complex (Figure 14), the picture is therefore that of a quick late Bedoulian transgression on a large regional scale after the demise of the Barremian–lower Bedoulian Urgonian carbonate platform on the Alpine margin. Should a cold snap [Mutterlose et al., 2009, Khunt et al., 2011, Millan et al., 2014] and a possible short-lived sea-level fall due to polar ice cap growth had occurred during OAE1a, the largely transgressive event recorded in front of the Alpine belt during the upper Bedoulian sequence did likely hide it.

The Argiles à Plicatules are sharply covered (sequence boundary) by a Gargasian glauconite-rich sandstone unit, next by a marlstone succession bearing lowermost Albian ammonites at its base. The whole Albian marlstone succession looks like com-

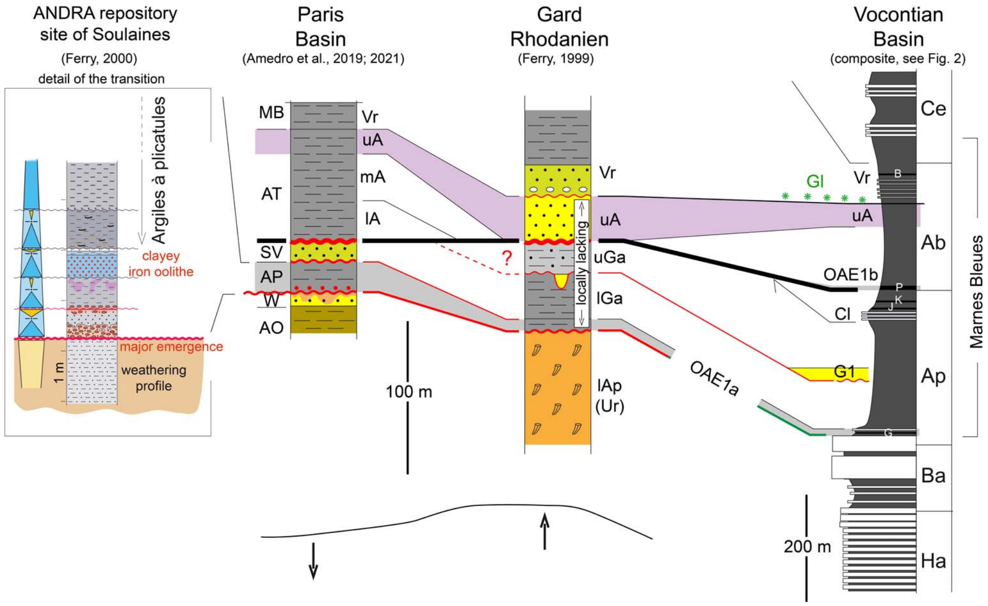

Figure 14. Stratigraphic correspondence between the Alpine margin and the Paris Basin around the Aptian–Albian boundary. For stage names abbreviations, see Figure 2. Formation names in the London–Paris Basin (in ascending order): AC, Atherfield Clay; AO, Argiles ostréennes; HB, Hastings Beds; W, Wealden deposits; AP, Argiles à plicatules; SV, Sables verts; AT, Argiles tégulines; MB, Marnes de Brienne.

plete from the ammonite record, notwithstanding the significance of the discontinuities lined by phosphatic nodules found in it. Without ammonites it is not possible to link the Gargasian sandstone unit to one of the two Gargasian sequences recorded in the Vocontian margin. As the deposits of the upper Gargasian sequence are shallower on the Alpine margin, the second sequence is likely lacking in the Paris Basin. The sea level changes recorded in the Paris Basin in the early to middle Albian are therefore exactly opposite tothose of the VT margin, i.e. emergence on the Alpine margin, submergence in the Paris Basin (Figure 14).

Regarding the OAEs recorded in the VT (Figure 3), the upper Bedoulian OAE1a is clearly within a large transgressive trend. But the three next ones (Jacob, Kilian and especially the lowermost Albian Paquier) are within an opposite regional sea level trend. The basin areal restriction during the deposition of these black shales is in accordance with the results of Heimhofer et al. [2006] and Okano et al. [2008] that suggest an increased riverine input during their deposition. Therefore Vocontian black shales do not occur as a result of increased organic matter production during transgressions as often proposed in the literature. The Vocontian case rather suggests an occurrence related to a global phenomenon but not linked to local relative sea level. The same is also found for the younger OAE2 in the VT [Grosheny et al., 2017].

6. Discussion

From the above, the emergence of the Rhodanian margin of the VT, as well as the near emptying of thebasin west of the SCF during early to middle Albian times is explained by a tectonic uplift along the Cevennes fault row. This uplift is likely related to a N–S contraction of the Provence domain (the Durancian Isthmus *auct.*) likely triggered by the Iberian plate rotational move during the Albian, as shown by earlier works [Hibsch et al., 1992, Montenat et al., 1997]. Gindre et al. [2002] even suggested that the South Provence Basin, until then judged extensional, could have been instead a compressional foreland basin, and the Durancian Isthmus some kind of forebulge. In this respect, what is described here along the westen margin of the subalpine basin would appear as the result of a transpressional regime involving the Cevennes fault row and its satellites (Nîmes fault, for instance).

In the northern subalpine chains, the story is different, as a thin, channelled sequence of lower to middle Albian marlstone to sandstone is transgressive on condensed upper Aptian deposits [Delamette, 1986]. There, the early Albian transgression correlates to that of the Paris Basin which was flooded in the early Albian after an emergence that possibly spanned the latest Gargasian (the missing Gargasian sequence, see above). The story is therefore more or less similar along the large seaway that connected both areas (Figure 1). The Rhodanian uplift peaked later.

The occurrence of upper Albian breccias along the front of the Ventoux-Lure thrust (Figure 13), was interpreted by Moullade and Porthault [1970] as the result of a tectonic event they related to the early compression recorded in the eastern Alps, although such a connection still remains elusive in terms of a stress field on such a scale within the context of the overal convergence between Africa and Europe. We therefore use the term "Austrian tectonic phase" mainly on a historical basis.

Work in progress also shows that W–E Vocontian folds may have formed as early as the Turonian as a consequence of such a compressive context. The Albian crisis would just be a precursor. It should also be remembered that the local sedimentary record of the Cenomanian–Turonian Boundary Event [Grosheny et al., 2017] looks like very similar to what is recorded around the Aptian–Albian boundary, with also a short-lived, but stronger and larger, areal reduction of the Vocontian basin and the deposition of the OAE2 black shale within a regressive context, like the Albian OAE1b.

On a larger scale, other data are in accordance with the outphasing of ups and downs of the ground we see in France. Some, among many others, are listed hereafter.

On the Iberian Atlantic margin [Rey et al., 2009, and other references therein], Albian aggrading fluvial deposits suddenly occur, after a short-lived hiatus, on Aptian marine ones, implying a strong seawardshift of the facies belt, likely as a result of a long-lasting uplift of the margin. Nothing such is recorded on shelfal deposits of the Moroccan margin to the south [Jaillard et al., 2019]. In the western Pyrenean basin, the Aptian–Albian transition corresponds to the breaking of the Clansayesian platform, and the progressive onlap of breccia-lined Albian carbonate sequences onto the Iberian margin [Canerot et al., 2012, and other references therein], as a result of the opening of the Biscay Bay "rift" and Iberia rotation.

On the southern shores of the Tethys, work in progress in correlating well logs of the so-called "Continental Intercalaire" across the Saharan craton supports the early views of Busson [1970]. It shows that Panafrican arches were reactivated around the Aptian–Albian boundary, that is what is kown among local oil geologists as the "Austrian phase". In the Saharan Atlas, the unconformity is dated around the Aptian–Albian boundary [Emberger, 1960]. The lower Aptian carbonate unit (the "Aptian bar") on Barremian sandstones is lacking on arches due to an Albian erosion that may locally cut down to Hauterivian sandstones. This carbonate bar is also eroded close to the major Gafsa–Jeffara lineament (southern Tunisia), which was likely uplifted at that time. But in Central Tunisia, the story is somewhat different. The platform carbonate Serdj Formation spans the whole latest Aptian [Ben Chaabane et al., 2019]. It is covered by a thin marlstone to platformal carbonate of lower Albian age. The major hiatus is here dated to middle Albian [Jaillard et al., 2013].

On the Arabian plate, a progressive nesting to the north of uppermost Aptian to lowermost Albian platformal carbonates wedges is recorded [Greselle and Pittet, 2005, Rameil et al., 2012], associated with incised valleys [Raven et al., 2010] indicating a stepped relative sea level fall, which was interpreted by Maurer et al. [2013] as a result of glacio-eustasy. Given the whole context, a purely tectonic explanation is more likely.

This short and incomplete survey shows that the local Aptian–Albian boundary tectonic event in France is part of a widespread tectonic event that spanned the latest Aptian to the middle Albian. The outphasing of relative sea level changes during this time span, as quoted above, casts some doubts about a eustatic component in controlling depositional sequences. Or extracting a eustatic component from such a complex stratigraphic record would be difficult.

7. Conclusions

A strong contraction of the western part of the VT, associated with an uplift of the western and southern margin occurred around the Aptian–Albian boundary. This western VT was restricted during the early to middle Albian to a narrow gutter that channelled massive sandstone turbiditic units. These were rooted in a rather elusive marginal megarippled sandstone wedge, perhaps restricted to narrow estuaries. In contrast to the Gargasian turbidite system that was emplaced within a larger basin, most of the Albian massive sandstone beds never reached the eastern part of the basin that remained deep. This was due to an uplift along a major N–S fault crossing the VT that blocked their spreading. This uplift also resumed around the Albian–Cenomanian boundary.

The overall regressive trend recorded on the alpine margin correlates with an inverse trend in the Paris Basin, where one of the two Gargasian depositional sequences (probably the upper one) is lacking, and where lower Albian marlstones are transgressive instead. These data suggest that tectonic deformation occurred on a large scale in front of the French Alps. A sinistral transpressional movement implying the SW–NE faults of the Cevennes fault row is inferred along the alpine margin, associated with uplift.

While the deposition of the Aptian Goguel black shale (OAE1a) is associated with a "flash" marine transgression on a lateritic weathering profile in the Paris Basin, the Jacob, Kilian and Paquier (OAE1b) black shales of the VT were deposited in a basin restricted by the tectonic pulse.

This short-lived tectonic event, which is clearly compressive in SE France, is also recorded on a larger scale along the Atlantic margin, on the North African craton and the Arabian platform, as suggested by the analysis of both literature and work in progress. It is responsible for the outphasings in relative sea level changes depending on location.

Conflicts of interest

Authors have no conflict of interest to declare.

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