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A new look at old debates about the Corbières (NE-Pyrenees) geology: salt tectonics and gravity gliding

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Abstract – In the Corbières area, a large-scale nappe has been identified at the beginning of the 20th century: the "Nappe des Corbières Orientales" (NCO) resting over a thick Triassic sole. This geological object is located at the NE of the Pyrenees, close to the Gulf of Lions. At this place, the chain changes in orientation from E-W to NE-SW and presents in detail, a great complexity. The existence of the nappe itself has never been contested. However, due to its overall complexity, several controversies exist regarding the style and chronology of deformation of its substratum in the so-called the "Pinède de Durban" in particular. We show that the new concepts of salt tectonics can clarify these old debates. Indeed, the rise of the Triassic salt during Mesozoic rifting episodes results in the development of characteristic sedimentary sequences (halokinetic sequences) on top of salt walls. It is along one of these, coinciding with the prolongation of the Cévenole Fault System, that the NCO has been individualized. During its Cenozoic emplacement, a gravity-gliding component, explaining the importance of the observed translation, could result from an uplift preceding the rifting at the origin of the Gulf of Lions.

Keywords: historical review / "Nappe des Corbières Orientales" / Pinède de Durban / rifting / salt tectonics / gravity gliding

Résumé – Un nouveau regard sur de vieux débats concernant la géologie des Corbières (NE-Pyrénées) : tectonique salifère et glissement gravitaire. C'est dans la région des Corbières que fut identifié au début du XX[e] siècle une nappe de charriage de grande ampleur reposant sur une semelle de Trias salifère : la Nappe des Corbières Orientales (NCO). Cet objet géologique est situé au NE des Pyrénées à proximité du Golfe du Lion. À cet endroit, la chaîne pyrénéenne change d'orientation, passant de E-W à NE-SW, et présente une grande complexité de détail. L'existence de la nappe elle-même n'a jamais été contestée, en revanche, au cours des années 1960 de nombreuses controverses, principalement entre des géologues des universités de Paris et de Montpellier, ont porté sur le style et la chronologie des déformations de son substratum, à la Pinède de Durban en particulier. Nous montrons que les nouveaux concepts de la tectonique salifère permettent d'éclairer ces vieux débats. En effet, l'ascension du sel triasique au cours des épisodes de rifting mésozoïques se traduit par le développement de séquences sédimentaires caractéristiques (séquences halocinétiques) au toit de murs de sel. C'est le long de l'un de ceux-ci, coïncidant avec la prolongation du système de failles cévenoles, que la NCO a pu s'individualiser. Lors de sa mise en place au Cénozoïque, une composante en glissement gravitaire pourrait résulter d'un soulèvement précédant le rifting qui a donné naissance au Golfe du Lion. Ainsi, s'expliquerait l'importance de la translation observée.

Mots clés : revue historique / Nappes des Corbières Orientales / Pinède de Durban / rifting / tectonique salifère / glissement gravitaire

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1 Introduction

The Corbières area is located at the NE front of the Pyrenees, where the orientation of the chain changes from E-W to NE-SW along the Gulf of Lions forming the Corbières virgation (Fig. 1). A large-scale thrust-nappe, the Nappe des Corbières Orientales (NCO), corresponding to the northeastern prolongation of the North Pyrenean Zone, is known since a long time in this area (Barrabé, 1922). It is an essentially Jurassic sedimentary pile (Doncieux, 1903; Bertrand, 1906) resting flat over a deformed Cenozoic footwall through a sole of Triassic salt. Thanks to it, the path of the basal thrust fault of the NCO, which extends the North Pyrenean Frontal Thrust (NPFT), can be easily follow in the field (Fig. 1).

The structure and timing of deformation in the footwall of the nappe was intensively discussed in the 1960s (Azéma *et al.*, 1963; Durand-Delga, 1964; Ellenberger, 1967). Several unconformities, attributed to Mesozoic compressive events, were recognized under the Aptian (Mattauer and Proust, 1962) and the Cenomanian (Durand-Delga, 1964) in addition to the general ante-Maastrichtian unconformity known at regional scale (review in Durand-Delga and Charrière, 2012). After a presentation of the general context and the details of the debates to which they gave rise, we will show that, in agreement with recent work in adjacent regions (Ford and Vergés, 2020; Crémades *et al.*, 2021), these early unconformities are well explained by the activity of Triassic salt (halokinesis) during the Mesozoic rifting phases and not by compressional events.

During the Cenozoic, the formation of the Pyrenees chain led to the development of a nice fold-and-thrust belt in the Corbières (Ellenberger, 1967). The tectonic heritage and the progressive counter-clockwise rotation of the tectonic transport direction (Cluzel, 1977; Averbuch *et al.*, 1992; Averbuch, 1993; Robion *et al.*, 2012) led to the cartographic bending of the chain: the so-called Corbières virgation. It is on this already structured substratum that the NCO has been emplaced as an out-of-sequence structure exhibiting an apparent displacement of about 15 km toward the northwest. Compared to the much smaller displacement observed further south, along the NPFT, such an important translation along an oblique branch of the chain is puzzling. We will show that the solution is likely to be found in the particular dynamics of the opening of the Gulf of Lions: an uplift preceding the rifting should be at the origin of the slope, which allowed an additional lateral sliding of the NCO.

2 Geological Setting and historical review

Along the Gulf of Lions, a wide oblique (NE-SW) strip connects the Pyrenees with the Provençal orogenic system (Fig. 1). More precisely, the Corbières virgation ensures the connection with the Pyrenees and, to the north; the Saint-Chinian Arc allows the transition with the Provençal Chain (Fig. 1) (Mattauer and Proust, 1962; Ellenberger, 1967; Crémades *et al.*, 2021). The complex geometry of the area is inherited from the NE-SW Cévenole Fault System (CFS), which recorded a long Mesozoic history since at least the Alpine Tethys rifting (Jurassic) up to Cenozoic inversions (Seguret and Proust, 1965; Arthaud and Matte, 1975; Bodeur, 1976; Roure *et al.*, 1992; Lacombe and Jolivet, 2005; Hemelsdaël *et al.*, 2021; Séranne *et al.*, 2021).

2.1 Geodynamic context of the Languedoc-Corbières Transfer Zone

Before the inversion of the basins, the Pyrenean domain has first undergone a Lower Jurassic rifting associated with the NW-SE opening of the Alpine Tethys during the dislocation of Pangea (Dercourt *et al.*, 1986). At that time the CFS, inherited from the Variscan orogeny (Arthaud and Matte, 1975), was reactivated as extensional faults (Roure *et al.*, 1992). Subsequently, during the Lower Cretaceous, the counter-clockwise rotation of Iberia allowed the opening of the Albian Pyrenean basins (Choukroune and Mattauer, 1978; Lagabrielle *et al.*, 2010; Tugend *et al.*, 2015; Tavani *et al.*, 2015; Mencos *et al.*, 2015; Nirrengarten *et al.*, 2017; Ford and Vergés, 2020). Thereafter, by 84 Ma, the inversion of the Pyrenean basins occurred in two distinct episodes. The first phase, sealed by the so-called "Garumnian" (Maastrichtian-Paleocene, see below) is particularly well expressed in the Eastern Pyrenees (Mattauer and Proust, 1962; Freytet, 1971) but is known at the scale of the whole orogenic system (Mouthereau *et al.*, 2014; Angrand *et al.*, 2018; Jourdon *et al.*, 2020; Izquierdo-Llavall *et al.*, 2020). It was followed by a period of relative tectonic quiescence during the deposition of the Garumnian (Freytet, 1971).

The major Pyrenean phase dates from the Middle-Upper Eocene (Sinclair, 2005; Bilotte and Canerot, 2006; Grool *et al.*, 2018; Ternois *et al.*, 2019). At that time, the major structures, including the NPFT, were active. They are responsible for the orogen building and associated foreland basins (Vergés *et al.*, 1995; Sainz and Faccenna, 2001; Christophoul *et al.*, 2003; Angrand *et al.*, 2018).

The final stage of compressional deformation is diachronous across the mountain range. The deformation seems to stop at the Eocene-Oligocene boundary (34 Ma) in the North Pyrenean foreland basin, while 13 km of Oligocene shortening was accommodated in the southern part of the orogen (7 km in the Spanish foreland and 6 km in the axial zone) (Grool *et al.*, 2018). The eastern Pyrenean was then affected by the opening of the Gulf of Lions during the Oligocene-Miocene, associated with the rotation of the Corsica-Sardinia block and the retreat of the Tethys slab to the south (Séranne *et al.*, 1995, 2021; Séranne, 1999; Mauffret *et al.*, 2001; Jolivet *et al.*, 2015). While the Pyrenean domain seemed relatively stabilized after this extensional episode, Parizot *et al.* (2021) (Corbières area) and Hoareau *et al.* (2021) (South Pyrenean foreland basin) highlight a Miocene deformation phase associated with the reactivation of large structures. The authors note, in particular, movements along the North Mouthoumet Fault, the Alaric anticline and the NPFT (Fig. 1) (Parizot *et al.*, 2021).

2.2 Geology of the Corbières

The Corbières exhibits a quite important complexity in a restricted zone as displayed by a precise geological mapping (Lespinasse, 1982; Berger, 1982; Berger *et al.*, 1982, 1990; Ellenberger *et al.*, 1987; Berger *et al.*, 1997), associated to numerous detail studies (Azéma *et al.*, 1963; Vila, 1964;

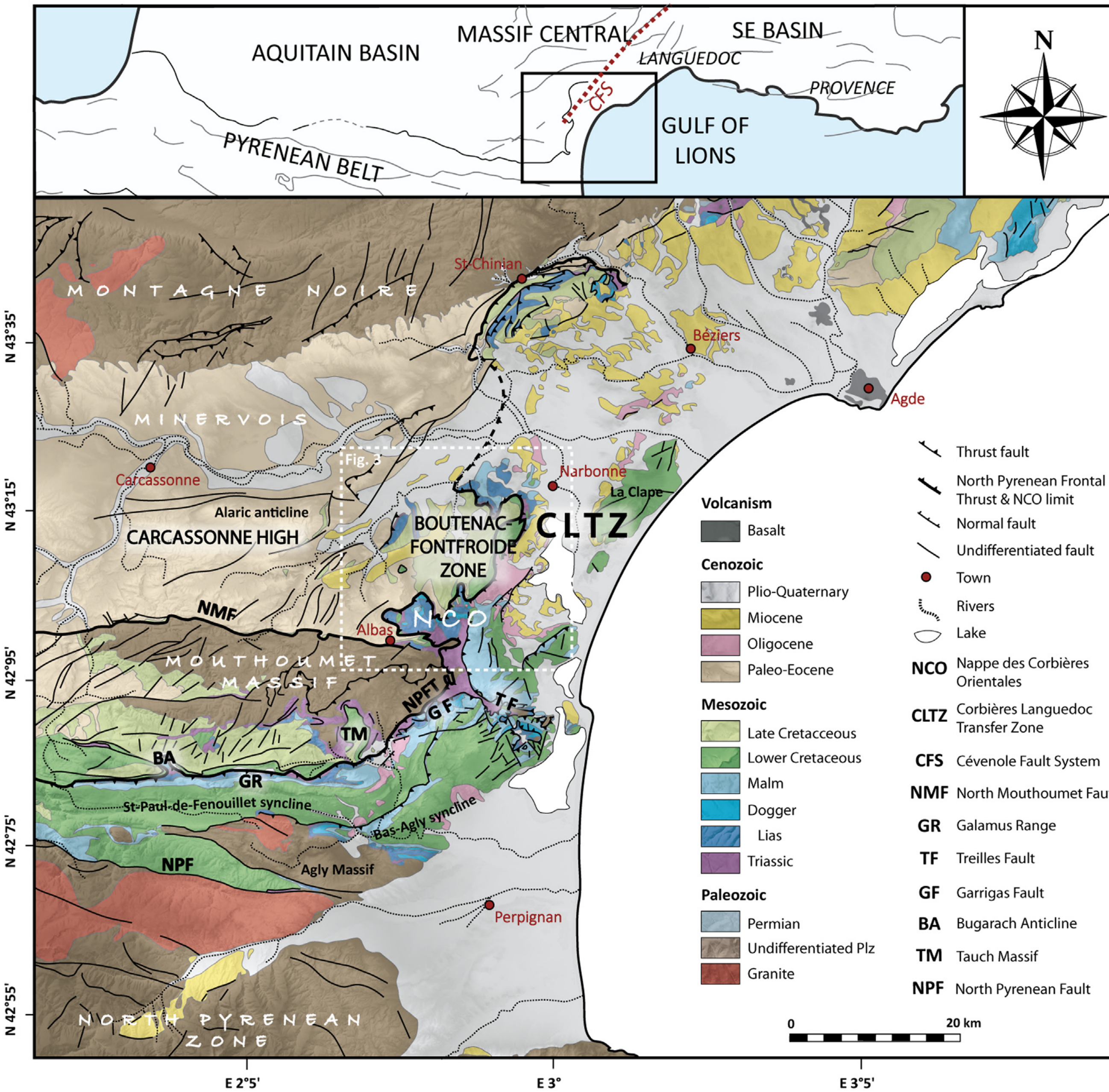

Fig. 1. Structural map of the Corbières area, Eastern Pyrenees. Modified after 1/50 000 and 1/80 000 BRGM geological maps.

Cluzel, 1977; Averbuch, 1993; Souque *et al.*, 2003). Two different paleogeographic-tectonic domains can be recognized in the area: the Pyrenean eastern foreland and the Corbières-Languedoc Transfer Zone respectively.

2.2.1 The Pyrenean eastern foreland

Two paleogeographic domains exist in the foreland from NW to SE (Fig. 2):

- The Carcassonne High (Fig. 1) is characterized by the absence of Mesozoic cover except thin Maastrichtian (*Rognacian Fm*) levels resting unconformably on top of the Paleozoic basement deformed during the Variscan orogeny (Barnolas and Courbouleix, 2001). The Rognacian Fm represents the base of mainly non-marine series constituting the so-called "*Garumnian*" covering the whole Paleocene. On top of the "*Garumnian*" a thick pile of blue marls with an alveolines-bearing limestone at the bottom ("*Ilerdian*" succession) marks a drastic deepening during the Ypresian. Finally, the continental "Molasse de Carcassonne" completes the filling of the Pyrenean northern foreland basin during the Priabonian.
- The Boutenac-Fondfroide Zone (Fig. 1) is exposed in the Boutenac Hills, the Pinède de Durban and the Fontfroide Massif (Fig. 3). In this zone, the Garumnian-Ilerdian-Molasse de Carcassonne litho-stratigraphic presents the same facies and thickness than the one observed above the

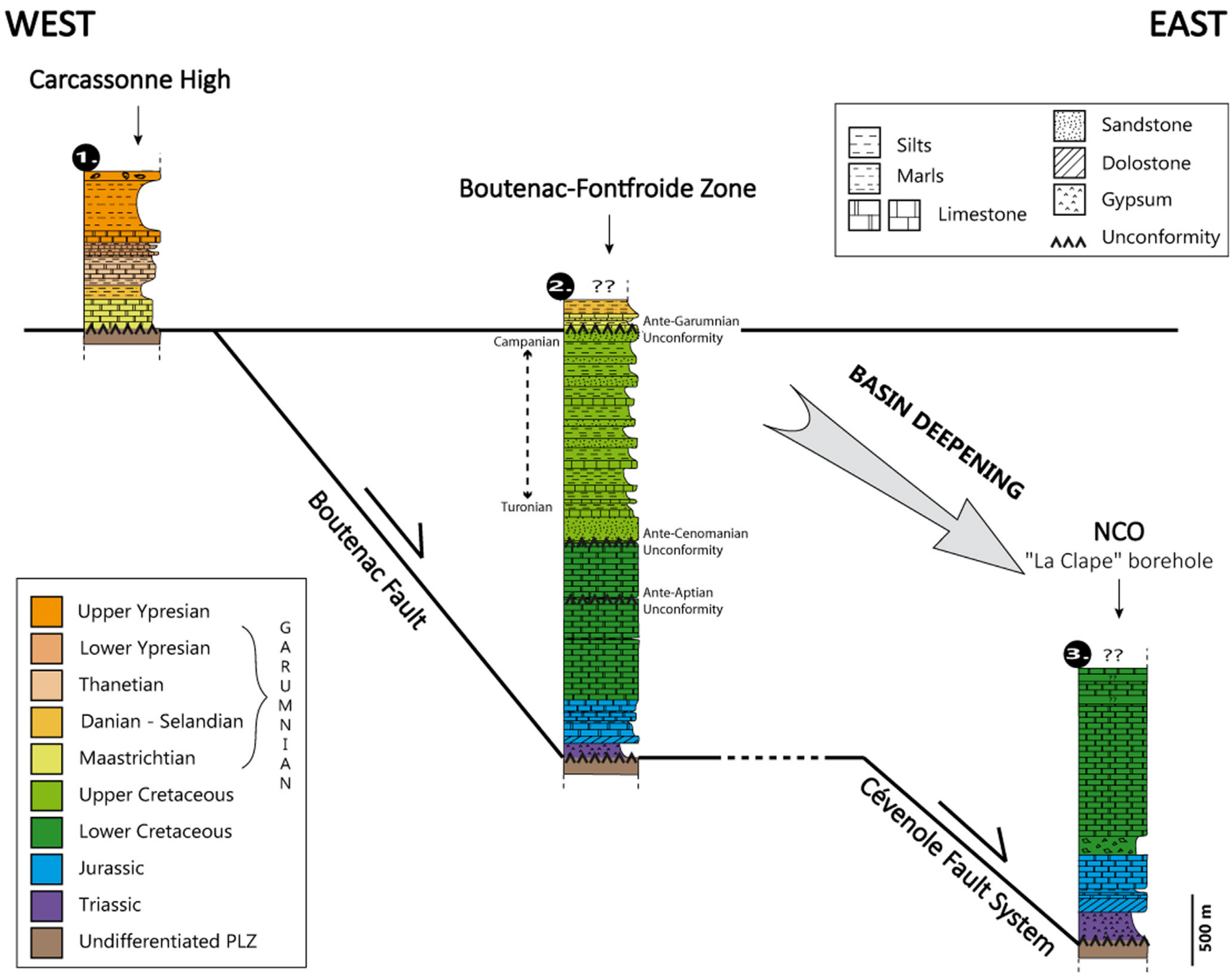

Fig. 2. Generalized litho-stratigraphical logs of the three paleogeographic sectors (Carcassonne High, Boutenac-Fontfroide Zone and the Nappe des Corbières Orientales) showing the eastward deepening of the basin (see Fig. 1 for the location of these zones). After Narbonne and Capendu BRGM 1/50 000 geological notes (Lespinasse, 1982; Ellenberger *et al.*, 1987). Both Carcassonne High and Boutenac-Fontfroide Zone belong to the eastern Pyrenean foreland, the NCO belongs to the Corbières-Languedoc Transfer Zone (CLTZ).

Carcassonne High. By contrast, it rests unconformably over an incomplete Mesozoic cover detached from the Paleozoic basement along an Upper Triassic décollement level. The Jurassic series are made up by basal dolostone, followed by marine limestone, more or less sandy with marls intercalations. In the Boutenac-Fontfroide Zone, the Lower Cretaceous corresponds to a thick series of marine limestone of several hundred meters. Clastic formations, sometime associated with reef, were deposited during the Upper Cretaceous. A significant variation in their thickness, from the Turonian to the Campanian, suggests a deepening towards the east: more than 2000 m at Fontfroide, only 200 m west of Boutenac and no deposits on the Montagne d'Alaric, where the Maastrichtian rests unconformably over the Paleozoic (Ellenberger *et al.*, 1987).

In addition to the ante-Garumnian unconformity, which is general at the scale of the Pyrenees, several unconformities have been described, in particular: an ante-Aptian unconformity (Mattauer and Proust, 1962) and an ante-Cenomanian unconformity (Durand-Delga, 1964; Freytet, 1971). The significance of these unconformities gave rise to many discussions (see a review in Durand-Delga and Charrière, 2012). We will see that these misunderstandings are, at least partly, the consequence of the ignorance at that time of the effects of salt tectonics. The role of the Triassic salt activity, firstly recognised in the Western Pyrenees (Canérot *et al.*, 2005) have been emphasized recently in the St Paul-de-Fenouillet syncline (Fig. 1) (Ford and Vergés, 2020) and in the Corbières in general (Crémades *et al.*, 2021).

2.2.2 The Corbières-Languedoc Transfer Zone (CLTZ)

The CLTZ comprises all the area located east of the CFS, which is currently detached along the Triassic décollement, and the Nappe des Corbières Orientales (NCO), which represents the allochtonous frontal part of this structural

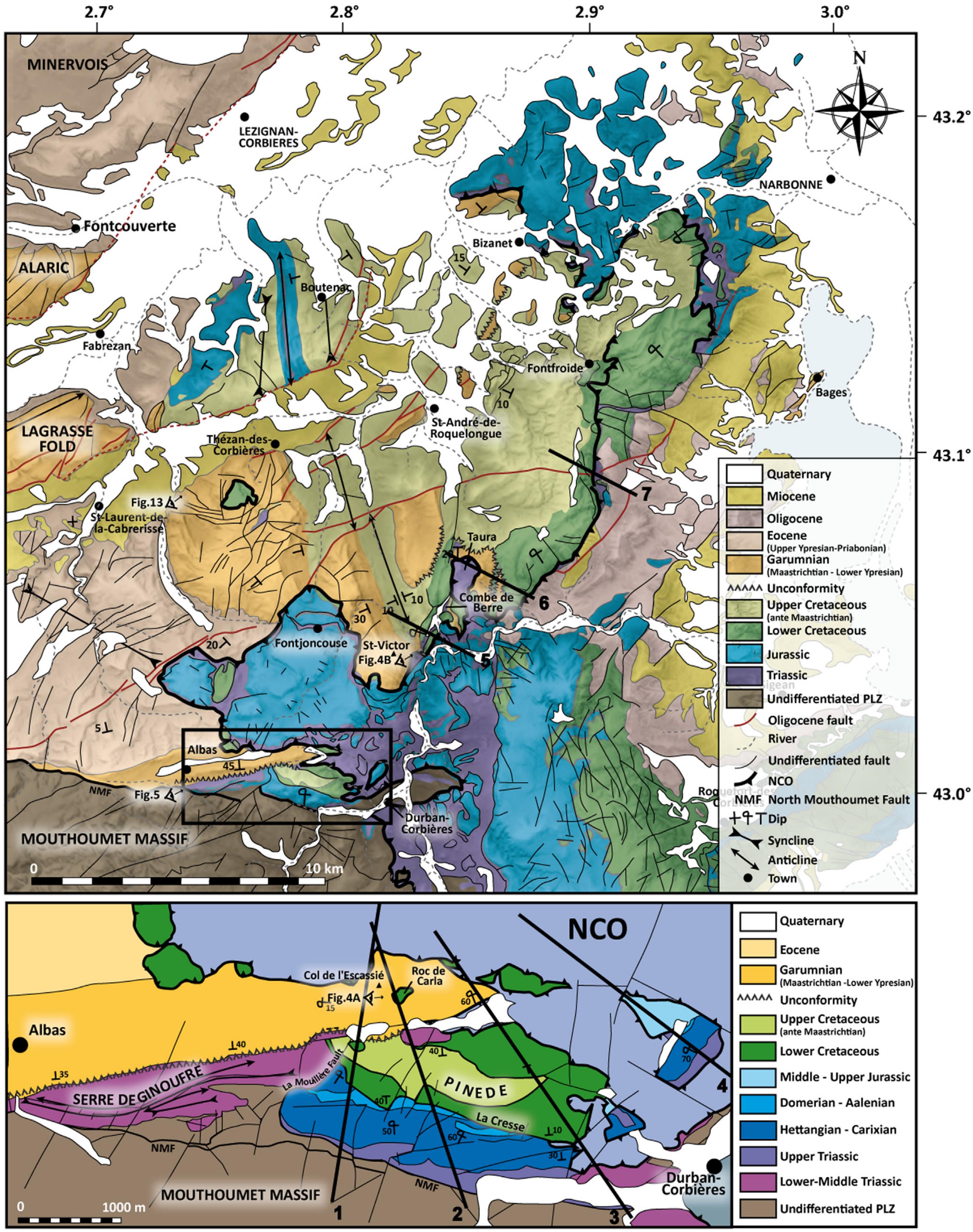

Fig. 3. Structural map of the NCO modified after Lézignan-Corbières, Béziers, Capendu, Narbonne, Tuchan and Leucate 1/50 000 BRGM geological maps (Ellenberger *et al.*, 1987; Lespinasse, 1982; Berger, 1982; Berger *et al.*, 1982, 1990, 1997) and focus on the geological map of the "Serre de Ginoufre" and the "Pinède de Durban" modified from Durand-Delga and Charrière (2012). Mapped cross-sections correspond to the geological sections in Figure 7.

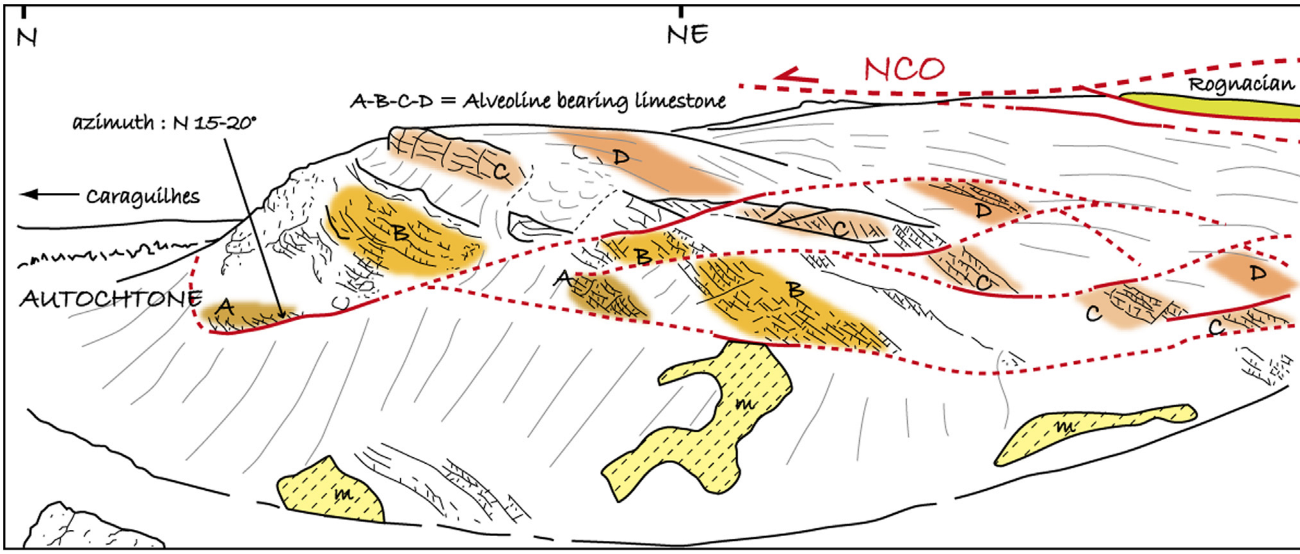

Fig. 4. View of the "Plateau de Poursan" illustrating the development of extensional listric faults developed in the footwall of the NCO. The "Rognacian" allochtonous block is associated with a big Aptian block, which is not visible on the drawing (see the Figs. 1 and 3). m: Miocene formations. The landscape, redrawn from Ellenberger (1967), is no longer visible today due to the vegetation growth.

domain. To the south, the CLTZ connects with the so-called North Pyrenean Zone and the floor-thrust of the NCO with the NPFT (Fig. 1). The NCO is recognized since more than hundred years by a typical basal contact putting older over younger rocks (Bertrand, 1906; Barrabé, 1922, 1923, 1948). It was interpreted as a nappe emplaced over an erosion surface (Azéma *et al.*, 1963; Ellenberger, 1967; Viallard, 1987; Durand-Delga and Charrière, 2012). The main argument was the drag folds in the footwall of the Nappe, interpreted as bending of layers truncated by a previous erosion surface. Due to the presence of numerous Oligo-Miocene hemi-grabens related to the Gulf of Lions opening (Gorini *et al.*, 1991; Bache *et al.*, 2010), the stratigraphic pile of the CLTZ is frequently masked. However, it can be reconstructed using the series exposed in the NCO completed by the BRGM data from the "La Clape" borehole (Fig. 2). The post-Paleozoic cover is detached from the basement along an Upper Triassic décollement level mainly composed of evaporites. From a lithostratigraphic point of view, the Lower Jurassic marine formations are constituted by dolomites. Then, an alternation of limestone, marls and dolostone is then identified up to the Upper Jurassic. Due to erosion, the Lower Cretaceous is missing in the Fontjoncouse area (Fig. 3) but is well identified in the "La Clape" borehole where it represents 1300 m of limestone deposits (Figs. 1 and 2). The post-Lower Cretaceous series are not visible in the CLTZ. A major unconformity marks the base of the syn-rift Miocene sediments filling a set of hemi-grabens (Séranne *et al.*, 1995).

3 Reassessment of the geometry of the "Nappe des Corbières Orientales" (NCO) and its footwall (Fig. 3)

At the northeastern border of the Mouthoumet Massif (Fig. 1) a narrow E-W strip of Mesozoic sediments lays out in the so-called "Serre de Ginoufre" and "Pinède de Durban" (Fig. 3). This domain is hidden northward under the NCO (Fig. 3). The footwall of the NCO re-emerges between Taura and Fontfroide but with almost only outcrops of Aptian and younger rocks (Fig. 3). It is on this particular area that all the debates mentioned above have focused. We propose revisiting it, starting with the NCO and then its footwall.

3.1 The "Nappe des Corbières Orientales" (NCO)

As indicated above, the path of the basal thrust fault of the "Nappe des Corbières Orientales" (Barrabé, 1922, 1948) is the north-eastward prolongation of the NPFT, front of the North Pyrenean Zone (Viallard, 1987) (Fig. 1).

It comprises Triassic to Aptian rocks resting over the lithostratigraphic sequence of the Boutenac-Fontfroide Zone up to the Molasse de Carcassonne (Priabonian). The horizontal displacement is of the order of 15 km in the NW direction and the floor thrust is remarkably flat at the scale of whole region (Ellenberger *et al.*, 1987; Viallard, 1987). An important feature of the NCO is the presence of Barremian-Aptian blocks embedded, as tectonic slices, in between the Nappe and its footwall (Fig. 4). Until today and as explain before, the NCO was interpreted as an allochtonous body emplaced over an erosion surface [the concept of "*epiglyptic*" nappe, Lutaud (1957); deriving from an "erosion thrust" (Willis, 1893); for the application to the NCO see Ellenberger (1967)]. Such a scenario supposes a succession of events:

1 a folding event occurring after the deposition of the Molasse de Carcassonne (Bartonian);
2 a post-Bartonian erosion after this folding event;
3 the emplacement of the NCO over this irregular surface leading to the development of drag folds in the footwall of the Nappe.

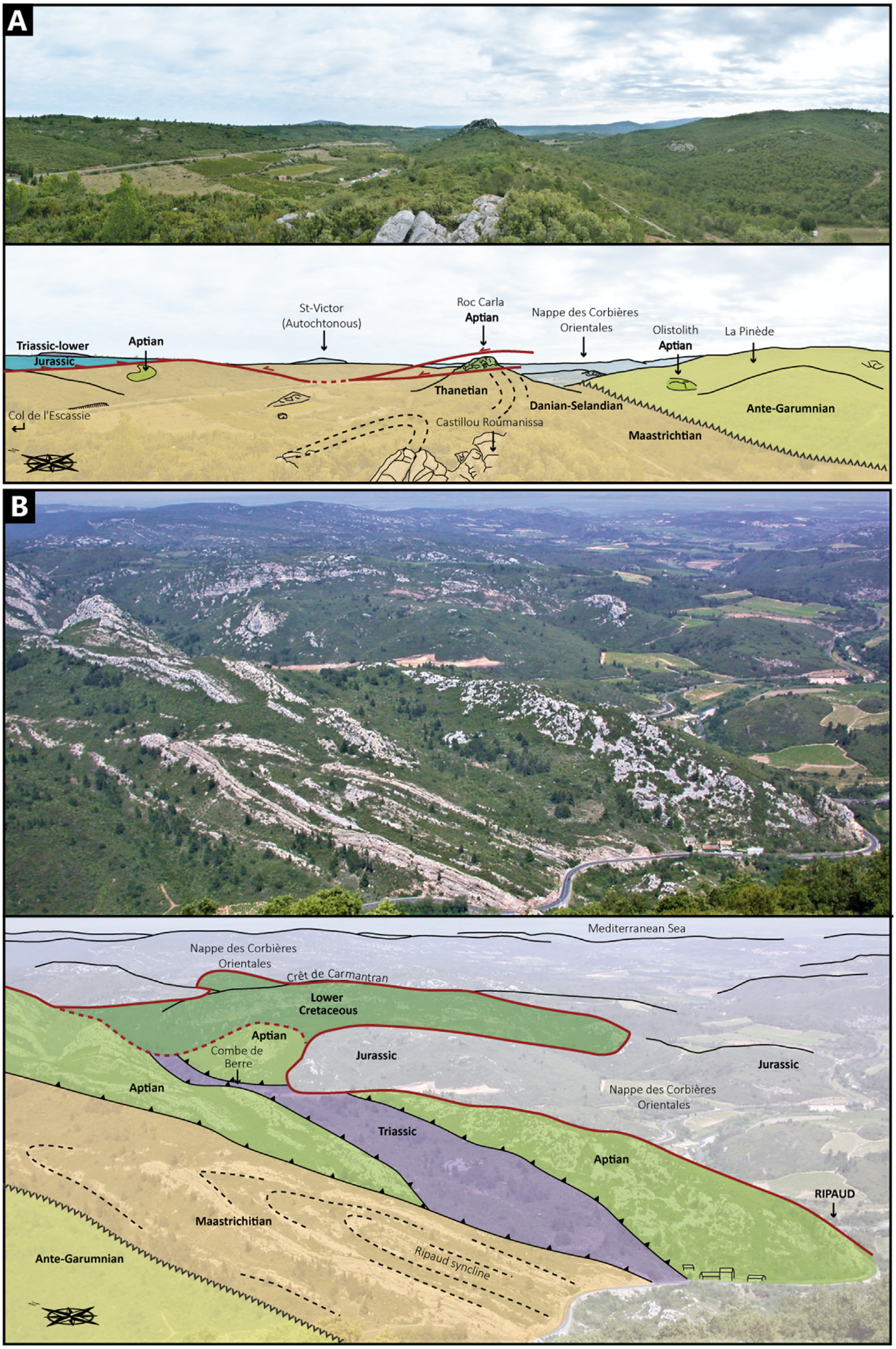

Fig. 5. A. View and interpretation of the "Roc Carla", from Castillou-Roumanissa hill looking to the east, showing the NW progression of the NCO and the overturning of its footwall. The "Roc Carla" is interpreted as an Aptian block, dragged under the NCO. See Figure 3 for the location. B. View and interpretation of the Ripaud syncline and Combe de Berre, from the Mont St-Victor looking to the east (see Fig. 3 for the location).

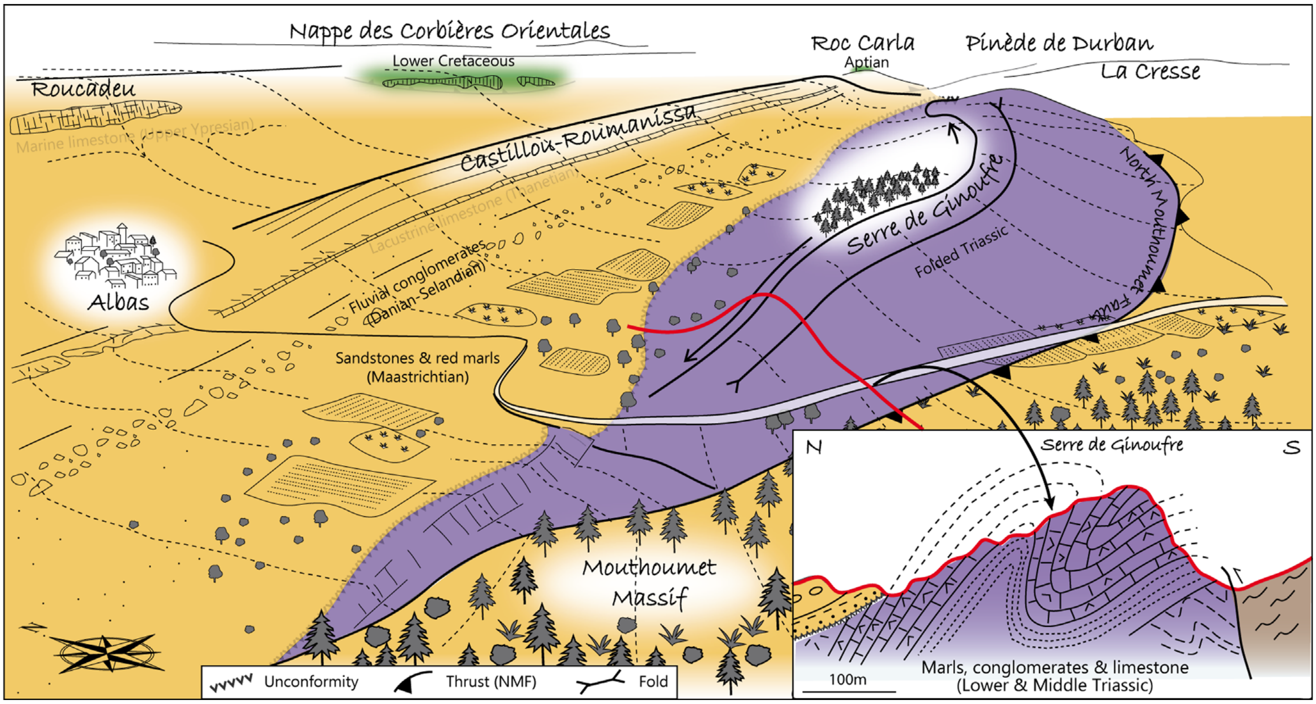

Fig. 6. Geology of the "Serre de Ginoufre", showing the unconformity between the Garumnian series (north) and the front of the North Mouthoumet Fault (south). The geological section of the "Serre de Ginoufre" demonstrates an ante-Paleogene deformation with the development of East-West folds in the Triassic series. See Figure 3 for the location.

This classic hypothesis comes up against several established facts among which we can mention two main ones:

1 erosion products resulting from the supposed post-Bartonian erosion phase are lacking and no unconformity is visible on the field;
2 based on rocks facies, the blocks scattered along the basal contact originate from the footwall of the nappe and not from the Nappe itself. Indeed, if the nappe has moved on an erosion surface, one can expect landslides along its moving front. In such a configuration, blocks resulting from these landslides (and coming from the nappe) should have been pinched under the allochtonous mass.

The rules of thrust tectonics developed by the end of the sixties can explain the geometries observed without assuming an erosion episode (Dahlstrom, 1969, 1970; Boyer and Elliott, 1982; Butler, 1982). In particular, footwall cut-offs are expected below ramps and the development of footwall synclines is the rule. Therefore, it seems convincing to suggest that the fold observed close to "col de l'Escassié" (Fig. 3) is a footwall syncline and that the flat contact below the "Roc Carla" is a former ramp subsequently flattened (Figs. 3 and 5A). Another well-known footwall syncline, generally interpreted as a drag fold, is observed close to the "Pont de Ripaud" (Fig. 5B). The thrust-fault over the syncline is quite sharp suggesting, in this case, a late steepening.

We have also to explain the existence of rocks already overturned below the ante-Garumian unconformity (Durand-Delga and Charrière, 2012). The authors suppose the development of recumbent folding during the Upper Cretaceous compressional event. Another remaining question is to understand why almost only the Barremian-Aptian rocks were sampled at the bottom of the NCO in the southern region of the studied area whereas, whereas more to the north Albian and Senonian blocks were also recognized (Lespinasse, 1982; Ellenberger *et al.*, 1987). The solution to these questions is to be found in the NCO footwall domains.

3.2 The footwall of the NCO revisited from south to north

It is interesting to begin this review by the Serre de Ginoufre, which allows us to assign the age of onset of compressional deformation. In this small area, the Paleozoic basement (Ordovician schists and sandstone) and its complete Triassic cover are folded together, the deformation being sealed by the ante-Garumnian unconformity (Fig. 6). This folding event corresponds to the Campanian event well known everywhere in the Pyrenees [first Pyrenean event (Roest and Srivastava, 1991; Teixell, 1996; Bilotte and Canerot, 2006; Mouthereau *et al.*, 2014; Grool *et al.*, 2018; Ternois *et al.*, 2019) and characterizing the whole Tethys realm (review in Frizon de Lamotte *et al.*, 2011)]. After the deposition of the Garumnian-Eocene series, the Late Eocene second Pyrenean event explains the emplacement of the NCO and the folding these series. Finally, the overthrusting of the Mouthoumet Massif along the North Mouthoumet Fault is a late event as shown by the cross-cutting relationships shown in the field and confirmed by U–Pb dating (Parizot *et al.*, 2021).

East of the Ginoufre Massif and separated from it by the "La Mouillère" Fault, the Pinède de Durban is a narrow strip (1.5 km wide; 3 km long) in between the North Mouthoumet

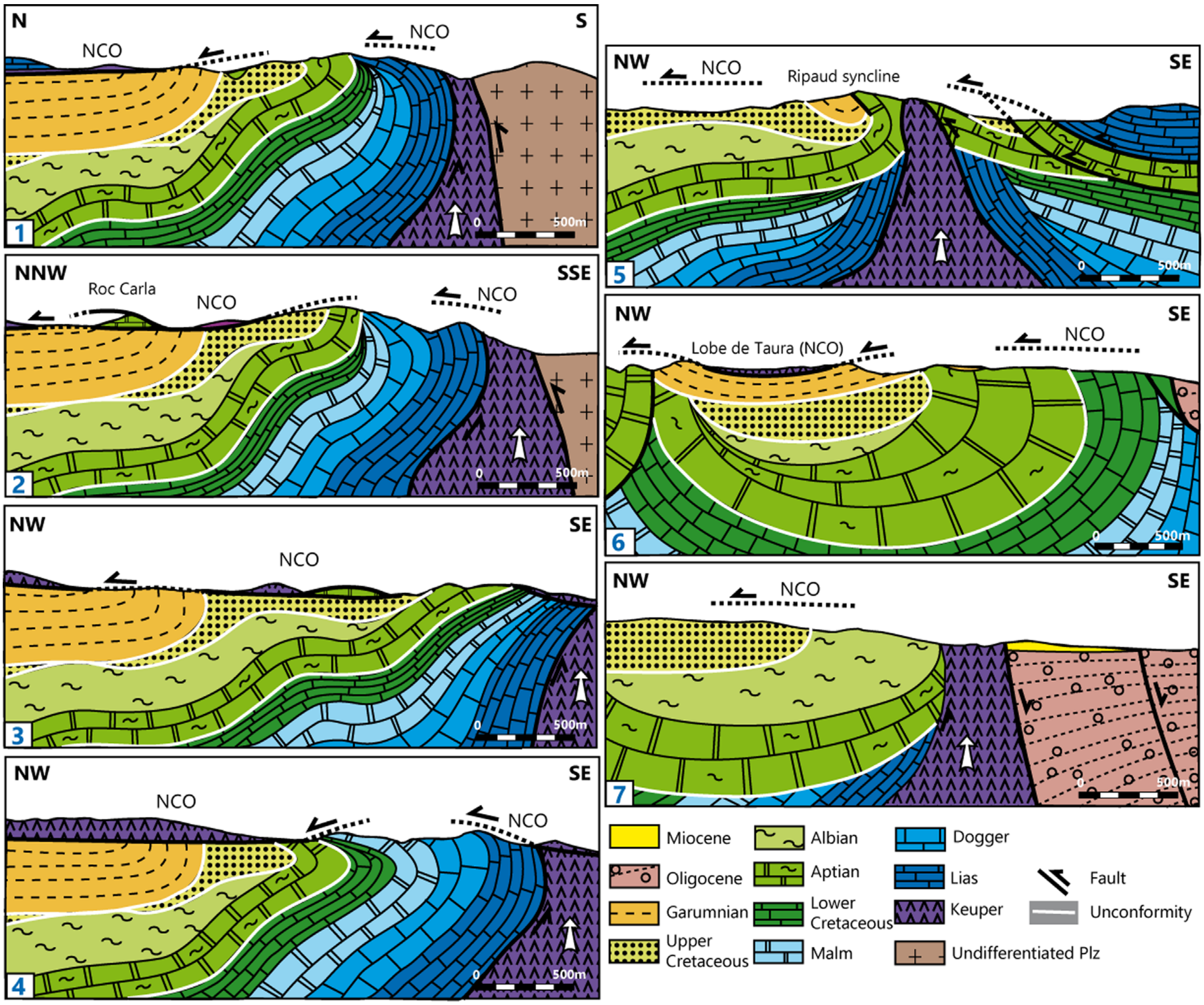

Fig. 7. Geological sections through the "Pinède de Durban" from West (1) to East (4) and geological sections through the NCO from south to north (5 – Combes de Berre; 6 – North of Taura lobes; 7 – South of Fontfroide). Location on Figure 3.

Fault and the ante-Garumnian unconformity (Fig. 3). The NCO rests over both the Pinède Massif and its Garumnian-Eocene cover. Geological cross-sections (Fig. 7, sections 1 to 4) show the following vertical to overturned succession from south to north: gypsum and marls (Keuper); black dolomite (Hettangian); oolithic and sandy limestone (Sinemurian); carbonate and black marls (Pliensbachian-Toarcian). The Middle and Upper Jurassic do not outcrop except along the sections 2 and 4 and white limestone (Aptian) forming the crest of the Massif are usually resting unconformaly over (or against) the Lower Jurassic. The absence of the Dogger-to-Neocomian sequences (known laterally) led Durand-Delga and Charrière (2012) to invoke the existence of a "substractive fault" (*i.e.*, extensional) in between: the so-called La Cresse Fault (Fig. 3). However, given its geometry (Fig. 7, sections 1 to 4), we consider that this contact is better explained as an unconformity with the Aptian over older rocks as already proposed by Mattauer and Proust (1962).

With this new drawing, the cross-sections evoke syn-sedimentary structures looking like typical halokinetic sequences indicative of salt activity during sedimentation (see a review in Giles and Rowan, 2012). More precisely, the bottom of the Aptian carbonate platform appears as an onlap surface sealing Dogger-to-Neocomian sedimentary wedges below. Consequently, the Aptian (at least the upper-middle Aptian, see below) appears as reflecting a period of relative quiescence in between two rifting episodes (Fig. 7, sections 1 to 4). At the base of the pile the Liassic carbonates are isopach, mimicking a megaflap drapping the Keuper evaporites (Giles and Rowan, 2012).

Further to the north, the "Combe de Berre" area is located in a half-window in between two elements of the NCO: the Fontjoncouse and Taura lobes (Figs. 3 and 7, section 5). This area is of large interest for several reasons: (1) it is the only place in the region where a diapir was already explicitly recognised (Mattauer and Proust, 1962; Durand-Delga, 1964);

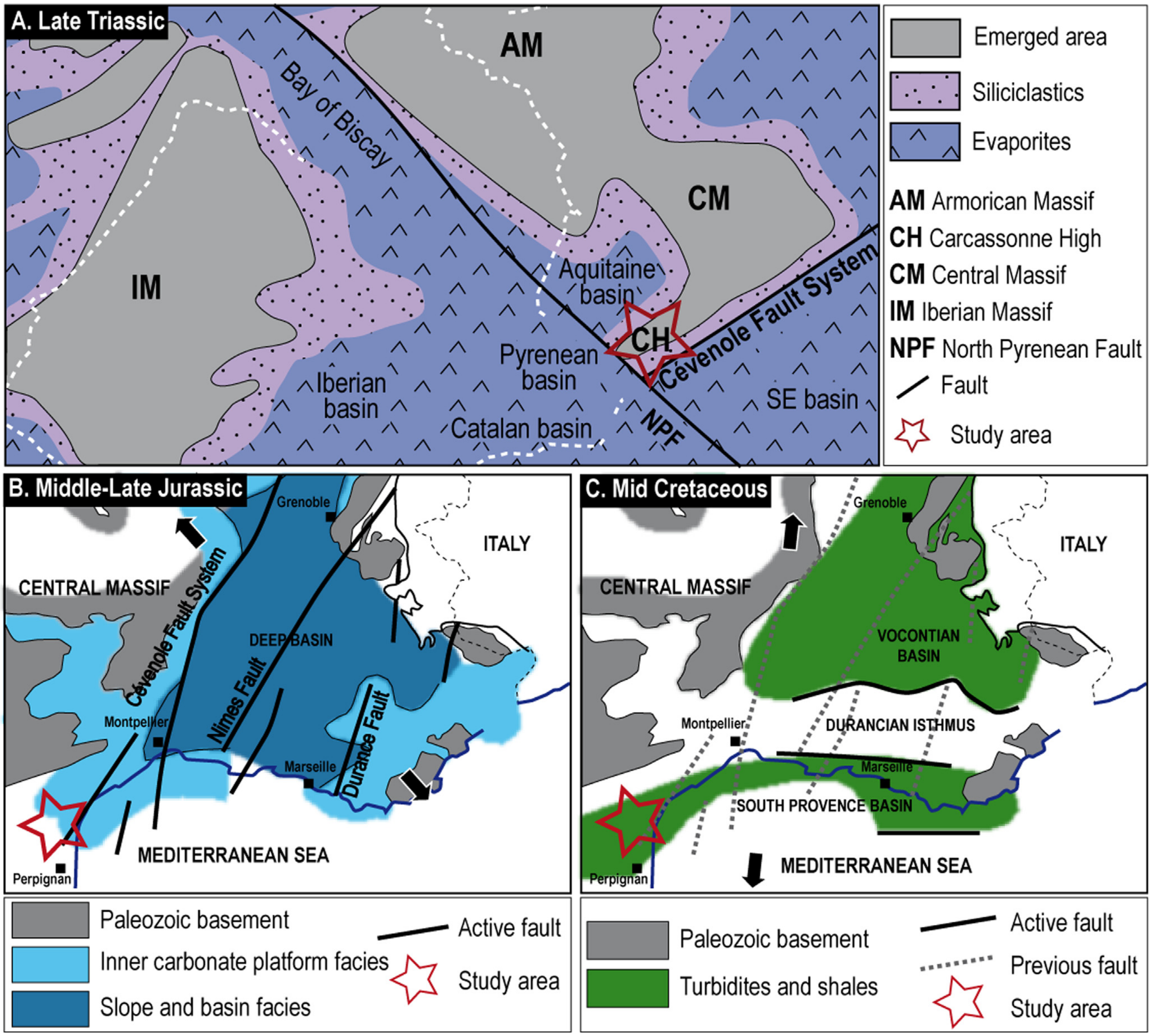

Fig. 8. A. Paleogeographic context of western Europe during the Late Triassic period. The dotted lines correspond to the current boundary between Spain and France. Modified after Ortí *et al.* (2017). B. and C. Paleogeographic context of the Southeast Basin and faults activity during the Middle-Late Jurassic (B) and Mid Cretaceous (C). Modified after Debrand-Passard (1984).

(2) it is also the only place where the two limbs of the diapir remain accessible (elsewhere, the southeastern flank constitutes the NCO). At the Combe de Berre, the oldest autochtonous formations are of Aptian age (except Triassic evaporites). Therefore, on the section, the geometry of older rocks is interpreted using the Pinède de Durban as reference. Along the eastern limb of the diapir, the Aptian carbonates are unconformably covered by the Garumnian (Durand-Delga, 1964) showing that this formation was at the Earth surface before the deposition of the Garumnian. Dujon *et al.* (1964) described the same configuration with Garumnian resting over Aptian carbonates in an allochtonous Aptian block on the Poursan Plateau (see also Ellenberger, 1967). This big block is interpreted as an element dragged at the bottom of the NCO.

The next two cross-sections (Fig. 7, sections 6 and 7), located further north, do not show Jurassic rocks either. The geometry at depth is consequently unconstrained and extrapolated from the Pinède de Durban model. Nevertheless, an important point is the considerable thickening of the Upper Aptian observed east of Taura (section 6). On this section, between the Combe de Berre diapir located to the west and the main diapir, a kind of mini-basin appears marked by an extreme thickening of the marly Upper Aptian. This shows that in this particular sector halokinesis starts again from the Upper Aptian.

Further to the north, the sedimentary series also shows a thick Albian made up of sandy limestone and showing important thickness variation (Fig. 7, section 7). This facies do not outcrop on the previous cross-sections further south (Fig. 7, sections 5 and 6) due to the importance of the ante-Cenomanian and ante-Garumnian unconformities. This difference is also underlined by the presence of Albian and Senonian allochtonous blocks (unknown in the southern region) at the base of the NCO (Durand-Delga, 1964).

The revision of the geometry of both the NCO and its footwall from Albas to Fontfroide suggest that the inheritance, and in particular rift-related Mesozoic salt activity, plays a major role in the localization of subsequent inversions. In the following section, we will discuss the paleogeography and propose kinematic scenarios for both Mesozoic and Cenozoic geodynamic agenda.

4 Discussion

Based on the very precise geological report and mapping (Lespinasse, 1982; Berger, 1982; Berger *et al.*, 1982, 1990, 1997; Ellenberger *et al.*, 1987) and on progress in the knowledge of geological structures, we propose to discuss two important aspects: the role of structural inheritance (in particular salt-related structures) and the mechanisms of NCO emplacement.

4.1 The role of structural inheritance and salt activity

The studied area is located at the junction of two major structures: The NE-SW CFS and the E-W North Pyrenean Fault (– NPF – south of the NPFT, Fig. 1). At large scale, the CFS forms the limit between the Massif Central to the west and the French South-East Basin (currently partly integrated in the Alpine orogeny) to the east (Fig. 1). In the region, the boundary between the Carcassonne High and the CLTZ extends the CFS to the southwest. The NPF is the boundary between the Eurasian and Iberian plates. Both CFS and NPF are inherited from a long history but, for the purpose of this paper, the interesting point is that, during the Late Triassic, they form together a corner at the junction between two salt basins: the south-east and Pyrenean basins respectively (Fig. 8A).

As emphasized by Ford and Vergés (2020) and Crémades *et al.* (2021), the Keuper salt has been activated during the successive rifting events, which characterize the Mesozoic geodynamic evolution of Western Europe. Accordingly, in the studied area, the identification of these events is indirect and comes from the interpretation of the halokinetic sequences, as shown schematically in Figure 9. After the Triassic rifting and the salt deposition (Fig. 9A), we have distinguished two sedimentary wedges, Middle-Jurassic to Lower Cretaceous and Upper Aptian-Cenomanian respectively, both being associated with salt activity. At the bottom of the sedimentary pile, the Lower Jurassic carbonates form a basal “megaflap” (Giles and Rowan, 2012) that is draped along the diapir and overlapped by a Middle-to-Upper Jurassic growth wedge showing that the halokinesis was active at that time (Fig. 9B). The lower Aptian carbonate forms an isopach cover onlapping and overlapping the first wedge (Fig. 9C). This geometry explains the ante-Aptian unconformity emphasised by

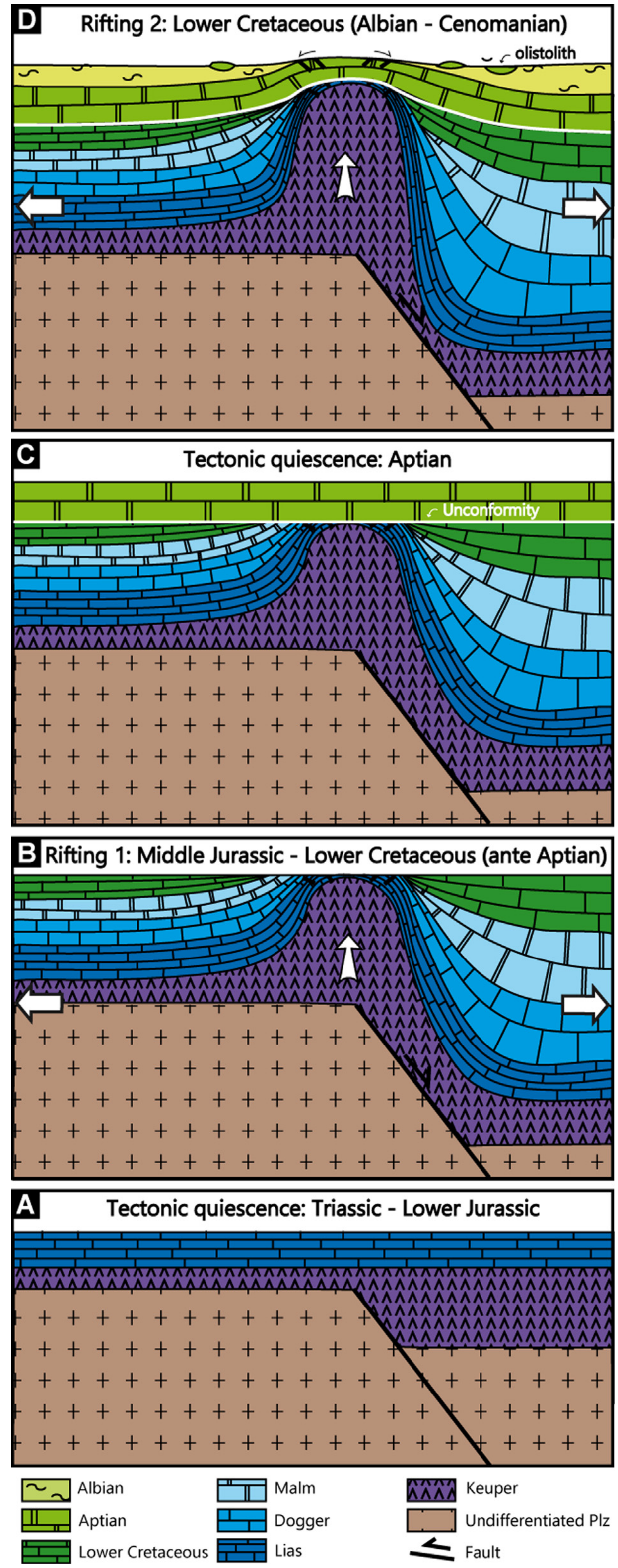

Fig. 9. Sketch illustrating the development of a salt diapir during the Mesozoic rifting episodes, from the Lower Jurassic to the Lower Cretaceous. Demonstrating the detail of the halokinetic sequences with the formation of the two distincts sedimentary wedges (Middle Jurassic-Lower Cretaceous, and Albian-Cenomanian). See the text for more details.

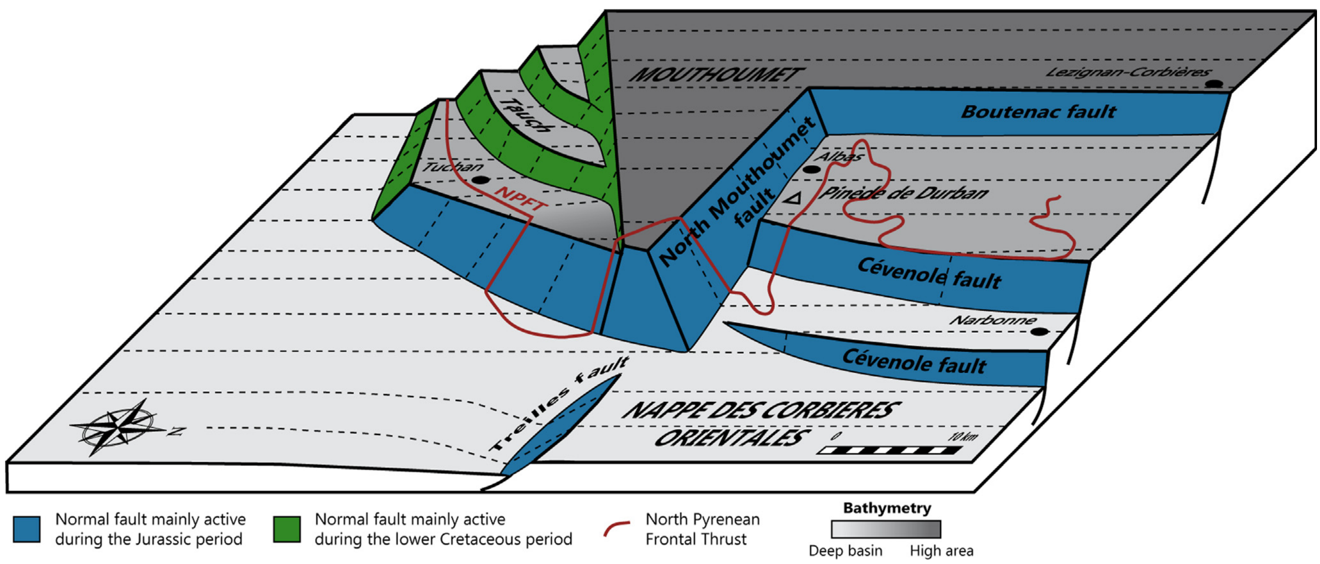

Fig. 10. 3D block showing the paleogeography of the study area during Mesozoic times. The current NCO front is shown in red. The faults, blue and green, highlight their main periods of activity: Jurassic and Albian-Cenomanian respectively.

Mattauer and Proust (1962) and suggests that the lower Aptian was a period of relative tectonic quiescence. The second wedge developed during the upper Aptian-Albian and Cenomanian with an unconformity in between (Durand-Delga, 1964) (Figs. 7 and 9D). This wedge is indicative of a reactivation of normal fault at depth during this period. We interpret as olistholiths, still linked to halokinesis, the Aptian blocks sandwiched between the "Pinède sandstones" and the ante-Garumnian unconformity (see the review by Durand-Delga and Charrière, 2012). Moreover, the fact that Aptian rocks were cropping out at the surface before the deposition of the Garumnian is testified by remnants of Garumnian-over-Aptian unconformities found in some blocks at the bottom of the NCO and in the Combe de Berre (Dujon *et al.*, 1964; Durand-Delga, 1964).

Therefore, the development of the observed halokinetic sequences can be correlated to the successive Alpine Tethys and Pyrenean rifting events and be interpreted as the consequence of reactivation of extensional faults at depth (Figs. 8B, 8C and 9). In the literature (see a review in Tavani *et al.*, 2018], the Tethys rifting event is described as resulting from NW-SE extensional forces and the Pyrenean rifting from rather N-S forces, even if it is more complex in detail. This context should have favoured the successive activation of the NE-SW and E-W faults, in this order (Figs. 8B and 8C). In the study region, the kinematics of the different rifting events is poorly constrained. Indeed, the place where the Jurassic activity is most obvious is the Pinède de Durban, which is E-W oriented (Fig. 10) and the best evidences for mid-Cretaceous activity are found along the Narbonne Fault, oriented NE-SW (Fig. 10). In accordance, in the CLTZ, Crémades *et al.* (2021) show evidence of salt activity during Jurassic times along both the ESE Treilles Fault and the NW Garrigas Fault, east of the Mouthoumet Massif (Fig. 1). In the E-W North Pyrenean Zone, Ford and Vergés (2020) show halokinesis evidence from the upper Aptian up to Upper Cretaceous but the authors also consider that the salt structures were likely active during Jurassic times. The observed geometric pattern (Fig. 10) shows that the two categories of faults have to play at the different stages of the tectonic scenario. The NE-SW faults were successively characterized by extensional then strike-slip movements. Conversely, the E-W faults should have likely displayed strike-slip then extensional movements. However, we do not find convincing kinematic indicators.

During Upper Cretaceous times, the geodynamic context changed drastically and became compressional. This event is documented by different structures sealed by the Garumnian locally (Fig. 6). The already existing diapirs were likely reactivated at that time (Ford and Vergés, 2020; Crémades *et al.*, 2021). Moreover, Charrière and Durand-Delga (2004) point out the presence of reworked Triassic elements in the Garumnian.

To broaden the discussion, we should note that our approach is in line with the one recently implemented by Graham *et al.* (2012) and Célini *et al.* (2020) on the Digne Nappe (Southern Alps), Callot *et al.* (2014) on the Sivas Basin, (Turkey) or Ford and Vergés (2020) (Northern slope of the Pyrenees). In these three examples, known and well described geological objects have been reinterpreted in the light of salt tectonics. It must be recognized that this mode of deformation provides an elegant explanation for twisted geometries, overturned, and otherwise inexplicable contacts.

4.2 The mechanisms of Nappe des Corbières Orientales (NCO) emplacement

Galamus Range (GR) and the NCO are two elements associated with the same major structure, the NPFT (Fig. 1), inherited from a complex paleogeographic history (Fig. 10). To understand the particularities of the NCO, a comparison with GR is therefore necessary.

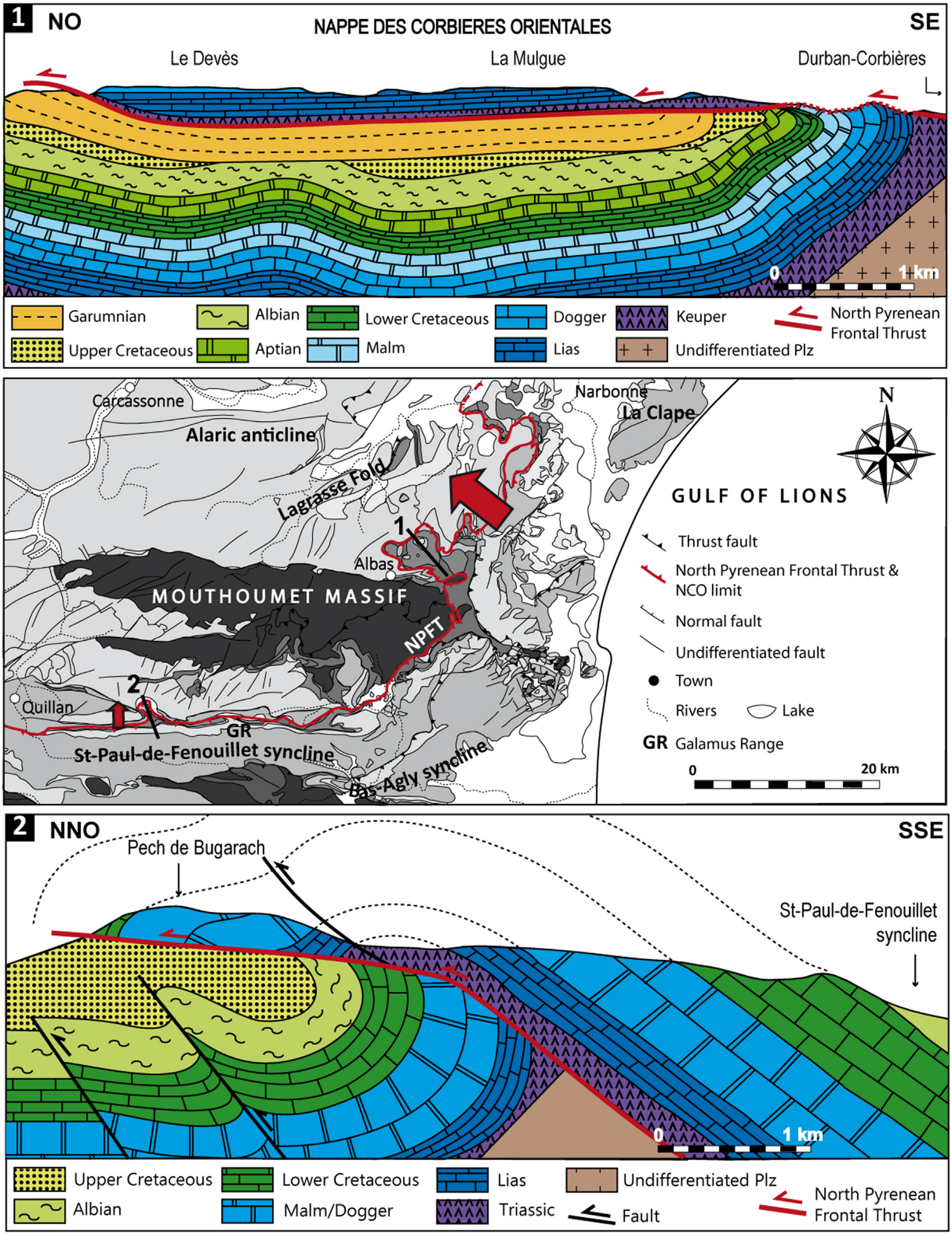

Fig. 11. Geological sections through the NCO (1) and the Bugarach ramp-anticline (see Fig. 1 for the location) (2) showing the shortening variation between the two structures. Refer to the Figure 1 for formations ages.

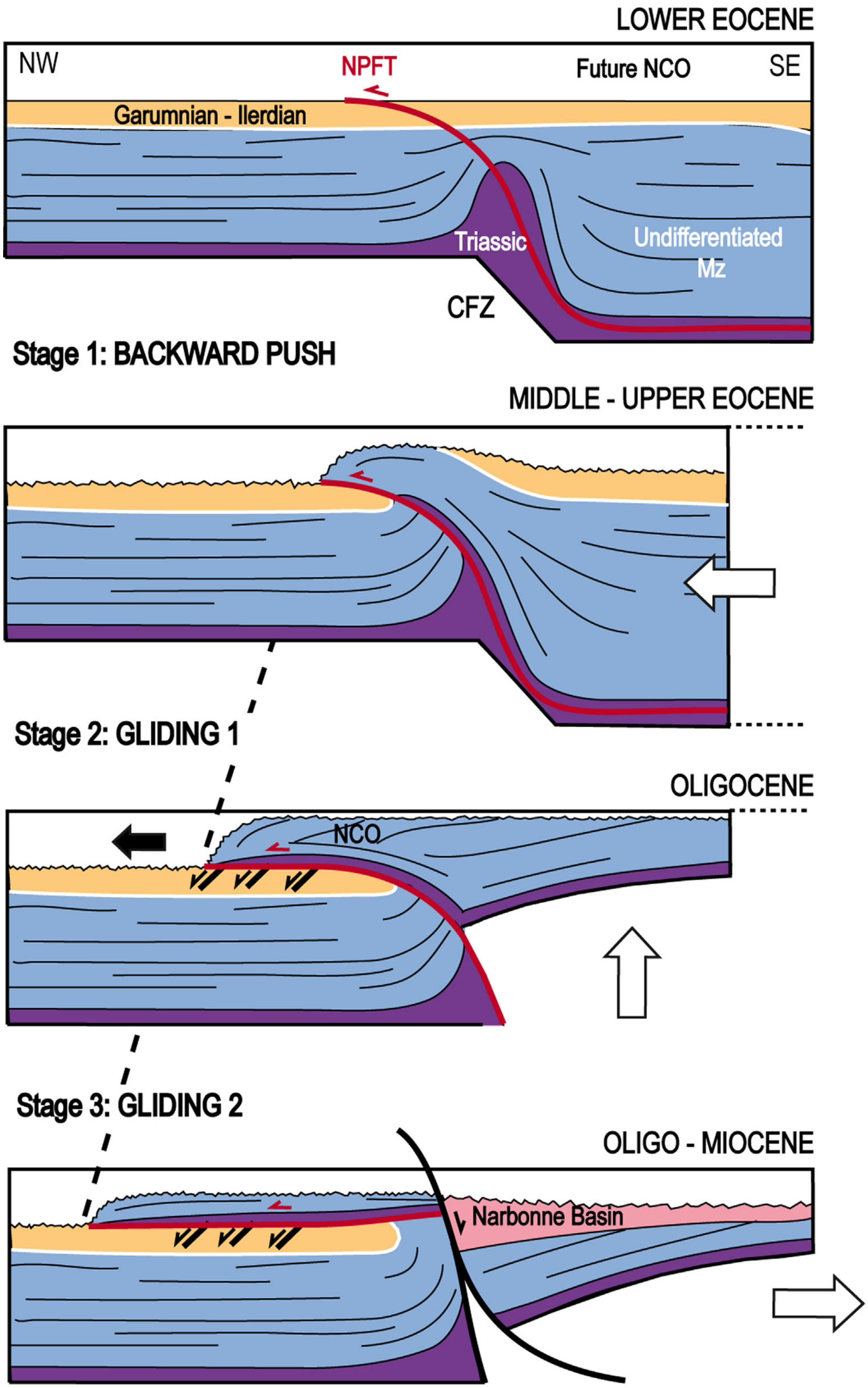

Fig. 12. Sketch illustrating the mechanisms of NCO emplacement from the Lower Eocene to the Oligo-Miocene. Stages 1 and 2: a thrust fault (prolongation of the NPFT) was developed during the Pyrenean orogeny along the Cévenole Fault System, thanks to a previously emplaced salt diapir. The thrust-fault has been then uplifted and flattened during two consecutive geodynamic episodes: an Oligocene uplift (stage 3) predating the Gulf of Lions rifting and the subsequent Miocene rifting (stage 4), creating a rift shoulder, west of the Narbonne basin.

Along the GR, the value of the overlap is measurable on the famous Bugarach anticline (Casteras, 1933; Carez, 1889; Bilotte and Canerot, 2006) (Figs. 1 and 11). The distance between the hangingwall and footwall cut-offs is only 3 km. This low value is, in any case very, much lower than the one measured along the NCO where the displacement is about 15 km (Ellenberger *et al.*, 1987; Viallard, 1987). At the junction of the two structures, the Tauch Massif as long been considered as a tectonic klippe pertaining to the NCO (Fig. 1) (de Graciansky, 1962). However, recent studies (Auzemery, 2015; Ford and Vergés, 2020) show that this structure is better interpreted as an extensional allochton developed during the "Mid-Cretaceous" rifting. Finally, and taking into account the overall N-S shortening, one can observe that the displacement is greater on the lateral branch than on the frontal branch of the thrust system. This may seem paradoxical because the shortening is likely more important along a frontal structure than along an oblique one.

Both branches are localized by previous salt structures (Ford and Vergés, 2020; Crémades *et al.*, 2021; this work). So, this structural inheritance cannot be used to differentiate the structures. We note that at the rear of the NCO the previous ramp is currently horizontal and in continuity with the upper flat forming the main body of the Nappe (Fig. 12). We also note that the rear of the NCO is cut out by NE-SW extensional faults reworking the CFS during the Oligo-Miocene (Gorini *et al.*, 1991). Therefore, we suggest that the tilting of the ramp could be related to the extensional movement along the reactivated CFS, the NCO (already emplaced) playing at that time as a rift shoulder. This mechanism may have accentuated the displacement NCO by gliding. Nevertheless, it is probably not sufficient to explain the whole translation.

Could one imagine that before its collapse during the Oligo-Miocene (see a review in Jolivet *et al.*, 2020), the CLTZ was uplifted, thus promoting the north-westward un-roofing of a part of its sedimentary cover? This remains at this stage a working hypothesis. However, we can notice that a major pre-Oligocene erosion, accompanied by volcanism is expressed not only at the eastern end of the Pyrenees (Jolivet *et al.*, 2020) but also all along the Gulf of Lions and the Valencia Gulf (Etheve *et al.*, 2018). This erosion, which clearly predates the development of Oligo-Miocene extensional deformation, should be related to an upward flow of asthenosphere in a back-arc setting (Fang *et al.*, 2021). It is the reason why we rather favour a thermal uplift preceding the extensional collapse. In addition, this hypothesis provides a possible explanation for the extra-translation observed in the NCO. It is worth noting that the structures developed during the NCO emplacement are extensional as beautifully illustrated by Ellenberger (1967) (Figs. 3 and 4). This supports our view and strongly suggests gravity played a major role in this process.

5 Conclusion

The Corbières area, including the Nappe des Corbières Orientales and its footwall, is one of the emblematic regions of the French geological literature. Since the 1960s, generations of geologists have been trained there, learning the basics of cartography and discovering tectonics and sedimentology. One may be surprised that their teachers chose such a complex – and debated – terrain for a field school. This is probably the proof of their fascination for its spectacular geological structures. Even today, many universities come to present the Corbières to students of all levels: Brest, Cergy-Pontoise, Clermont-Ferrand, Montpellier, Nancy, Nantes, Orléans, Orsay, Paris, Toulouse. It is a perfect region to present not only beautiful geological structures but also how their interpretation has varied over time.

Thus, the reinterpretation of the NCO footwall done in the present paper was only possible thanks to the emergence and maturity of new concepts in the field of fold-thrust belts geology in general (notions of detachment level, hangingwall and footwall cut-offs) and of salt tectonics in particular (vertical and horizontal mobility of salt, halokinetic sequences, salt-related olistolithes and unconformities). The fact that these concepts have not yet emerged (or were ignored) is the main cause of the ancient controversies. For more than 50 years, the debate has remained like vitrified. The present work is therefore the result of the integration of new concepts, resulting of technological advances in subsurface imaging, on a region already perfectly described and mapped.

Regarding the NCO itself, its existence has never been questioned since its discovery a hundred years ago. However, its emplacement mechanisms have rarely been addressed. We propose that its large horizontal translation results from the addition of several causes related not only to the Pyrenean orogeny but also to the rifting of the Gulf of Lions. Thus, we show that to understand a complex geology, it is often useful to extend the framework of the investigations to adjacent or more distant regions.

We bet that the evolution of the concepts on the one hand and that a better integration in the regional geodynamics on the other hand will allow in the future an even better understanding of this beautiful region.

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