Tectono-stratigraphic evidences of extension and compression with salt during the Jurassique in the Corbières Orientales Nappe (Pyrénées, France)

Antoine Crémades[1], Mary Ford[1] et Julien Charreau[1]
[1] CRPG, UMR 7358 CNRS, Université de Lorraine, Vandoeuvre-lès-Nancy, France

In this work, we investigate the tectono-stratigraphic architecture of a major transfer zone in the Mesozoic Pyrenean rift system and its subsequent alpine inversion (Fig.1). The NE-SW to NS-oriented Corbières transfer zone (70 km long) lies between the EW-oriented Pyrenean (400 km long) and Provençal (300 km long) segments of the Pyrenean orogen. This salt-rich rift transfer zone was inverted during the Pyrenean orogenesis (Late Santonian - Early Miocene). During the Oligo-Miocene, most of the transfer zone was further reactivated to form the northern margin of the Gulf of Lion passive margin. Thus, only the lateral equivalent of the North Pyrenean Zone outcrops along the western French Mediterranean coast. Unlike the the North Pyrenean Zone, which is a narrow fold and thrust belt, this proximal part of the transfer zone was previously interpreted as a large thrust sheet (the Corbières Nappe, 70 km long) corresponding to Mesozoic cover decoupled from Variscan basement along Upper Triassic evaporites (Keuper, 0m to 655 m) and emplaced onto the Aquitaine retro-foreland basin during the Priabonian..

Our detailed study of the tectono-stratigraphic architecture of the Corbières Nappe (Figs 2, 3, 4, 5) demonstrates for the first time the existence of major Jurassic extensional structures linked to strong halokinetic activity. These structures were previously interpreted as compressional and Pyrenean in origin: (1) The Treilles Fault is a N110 trending, shallowly S-SW dipping fault at least 12 km long, which roots on Triassic evaporites (Figs 6, 7, 8, 9). This normal fault with 3.8 km of displacement cuts the Corbières Nappe into two distinct structural units. A 3D hangingwall dip fan associated with stratal thickening toward the fault demonstrates that this extensional fault was active during the full Jurassic and maybe during the early Cretaceous. (2) In the footwall of the Treilles Fault, the Valdria NE-SW trending fold pair (Figs 10, 11) was previously interpreted as a Pyrenean compressional fold. Detailed mapping of 3D thickness and geometry variations in the Jurassic series around these folds reveals NW verging syn-sedimentary folding during the Jurassic. We propose that this fold pair developed in three stages, the first is linked to the growth of the Feuilla salt diapir that lies immediately to the south, which was active during Lias to lower Kimmeridgian. The second Malm stage (lower Kimmeridgian to Tithonian ?) is linked to the Neocimmerian transpressional event and the third is final fold tightening by Pyrenean deformation.

The highlighting of these complex halokinetic and extensional structures of Early Jurassic to Early Cretaceous age have major implications for (1) the Pyrenean and Tethysian Mesozoic extensional systems in the eastern Pyrenees and (2) their impact as a major regional inheritance in later orogenic phases, in particular oin the evolution of the Pyrenean Corbières Nappe.

1. Geological setting

The Pyrenean-Provençal mountain range (Fig.1) constitutes a beautiful example of an orogen that records each stage of a Wilson cycle. Its specificity consists in four points (1) it develops from Late Santonian to Miocene in response to the positive inversion of a Mesozoic rift (2) the shortening is relatively modest (45-165 km), allowing good preservation of the rift architecture, (3) it includes a salt level above the Paleozoic basement, the Keuper, of variable thickness and sometimes absent. When it is present, the Keuper as a mechanical decoupling level between the basement and the sedimentary cover, notably by influencing the structuration of the basins. (4) During the Oligo-Miocene, opening of the Gulf of Lion (rifting to passive margin), the eastern part the Pyrenean-Provençal orogen was destroyed (negative inversion).

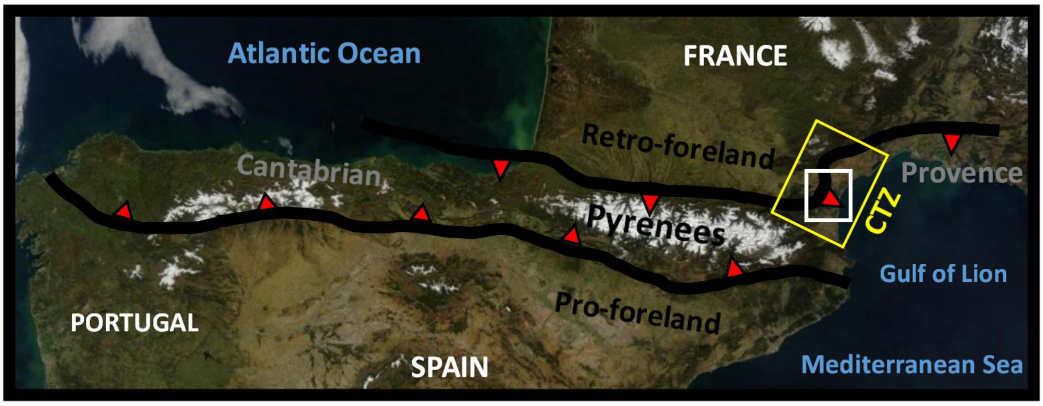

Figure 1. Simplified map of the Pyrenean-Provençal orogen. Location of the Corbières Transfer Zone in yellow. Location of Figures 2 and 3 in white.

By focusing on the tectono-stratigraphic architecture and the kinematic calendar of the Corbières Jurassic basins, this study aims to improve the understanding of a first order anomaly in the Pyrenean-Provençal orogen: the Corbières Transfer Zone (CTZ) (Fig. 1, 2, 3), currently interpreted as a NE-SW orogenic transfer zone between the Pyrenean and Provençal E-W segments (Tavani et al., 2018). The connection between the transfer zone and the E-W segments is supposed to be continuous and is made by means of two arcs.

This transfer zone includes (Fig. 2 and 3): (1) the NE-SW oriented crustal fault system of the Cevennes (in red), (2) the Mesozoic cover constituting the Corbières Nappe, (3) the foreland of the Corbières Nappe, the most eastern part of the Aquitaine retro-foreland basin, with NE-SW structures.

In this study we focus on the Corbières arc, that forms the southwest part of the Corbières Transfer Zone (Fig. 2 and 3)

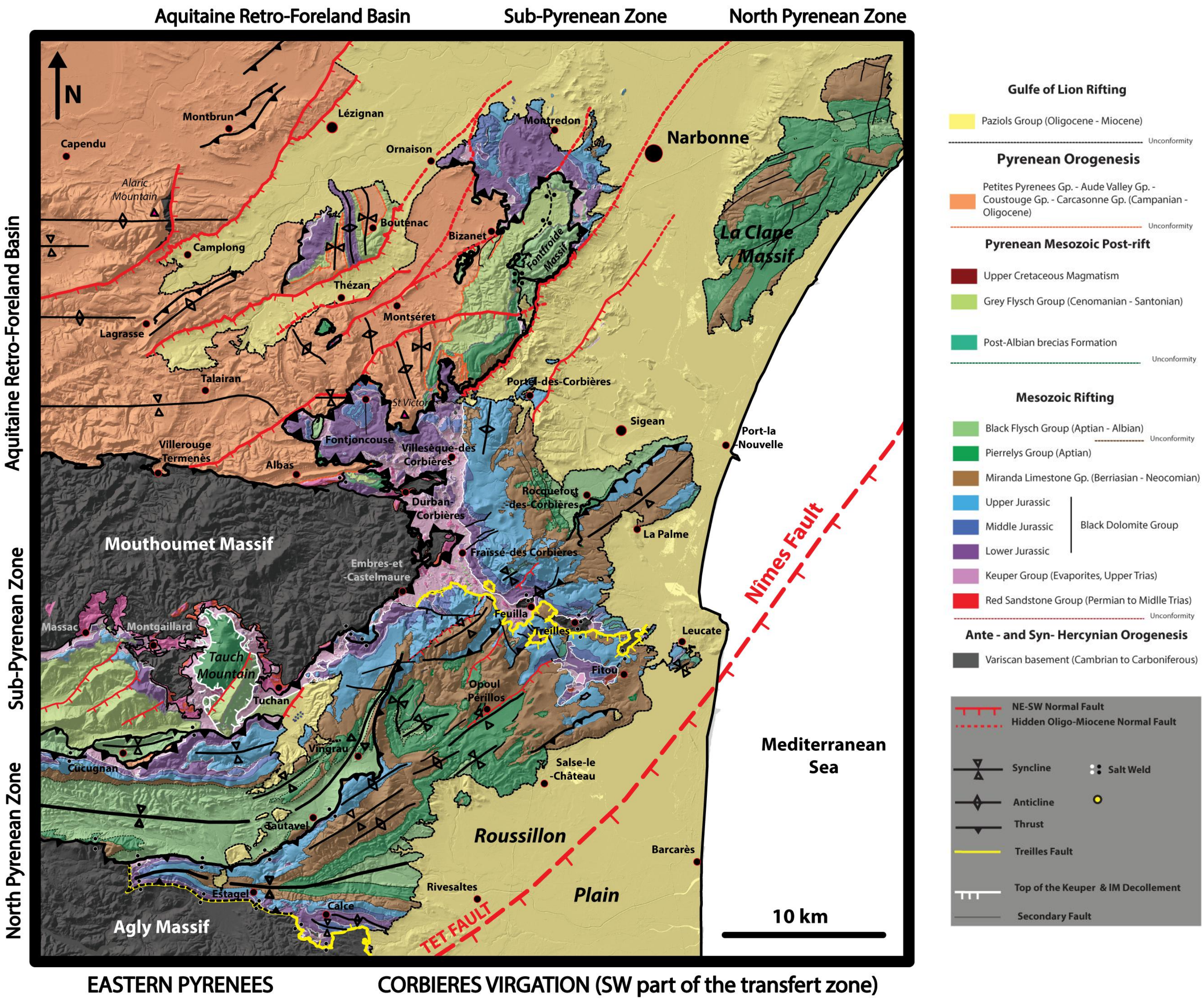

Figure 2. Geological map of the Corbières arc, SW part of the Corbières transfer area

The NW part of the Corbières Transfer Zone corresponds to the eastern Aquitaine retro-foreland basin (Figs. 2 and 3). It developed on the proximal part and the unthinned part of the transfer zone, in response to the tectonic inversion of the Mesozoic distensive system. The syn-orogenic sedimentary recording is complete (Campanian to Bartonian).

The Corbières Nappe (Figs 2 and 3) constitutes the continuous prolongation of the North Pyrenean Zone (NPZ) into the NE-SW transfer zone. In terms of tectono-stratigraphy, the Corbières Nappe is exclusively formed of Keuper to the Albian sedimentary series and represents the inverted paleo-sediementary cover of the mesozoic rift transfer zone. During the Pyrenean orogeny, the positive inversion of the NE-SW transfer zone caused the detachment of the cover above the Keuper. The obliquity between the NE-SW structures, playing the role of oblique ramps, and the N-S compression direction, would have helped the development of different structural styles between the eastern North Pyrenean Zone (strong shortening, weak thrusting) and the Corbières Nappe (weak shortening, strong tangential thrusting). Three structural ensembles are identified in the nappe (Fig. 3): (1) the basal detachment of the Keuper (marls and evaporites) and (2) the post-Keuper sedimentary cover, including (a) a frontal part and (b) the main body of the nappe.

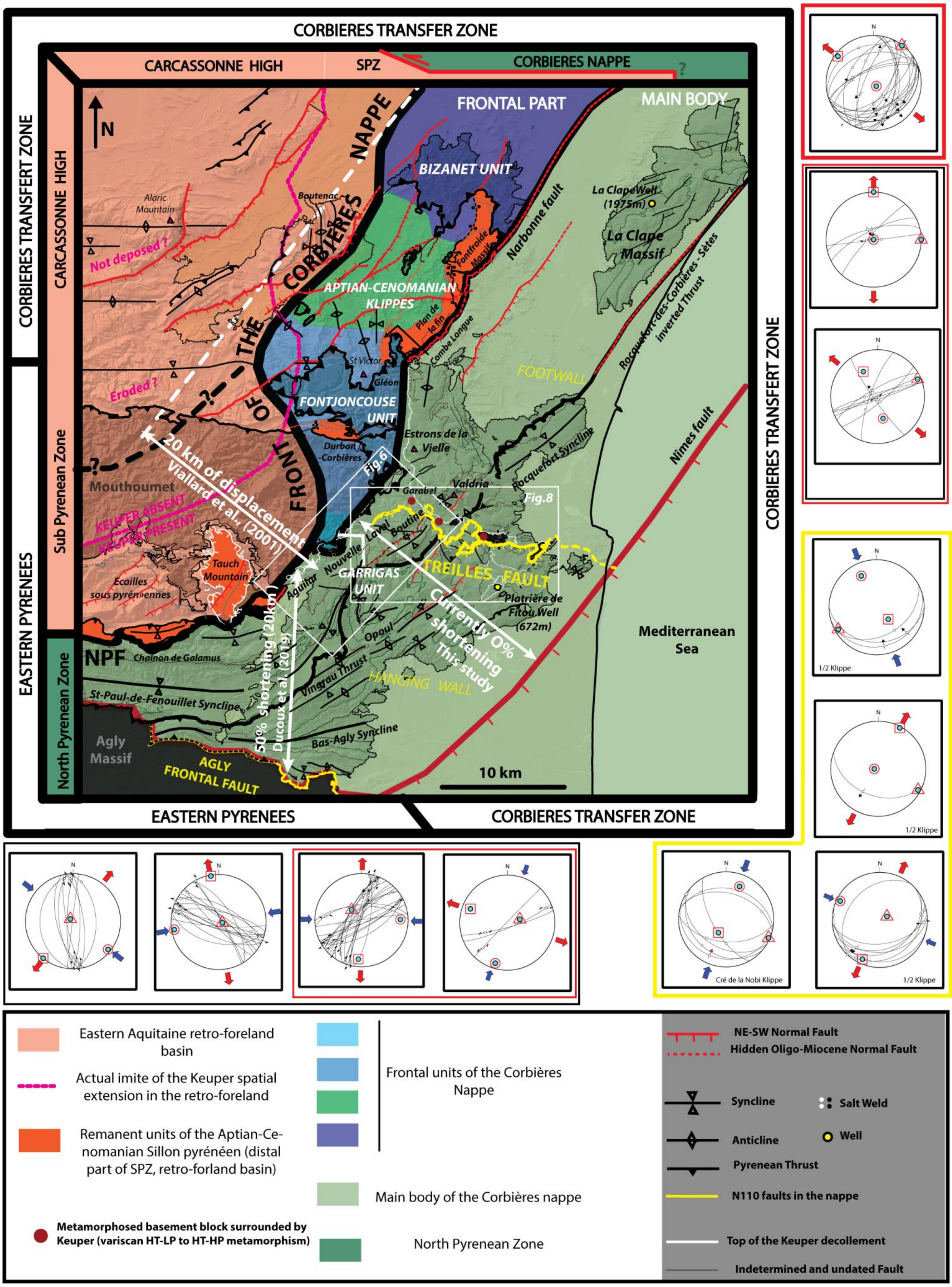

Figure 3. Structural map of the Corbières virgation, SW part of the transfer zone, compartmentalized into distinct structural units by NE-SW and E-W structures. The shortening rates of the eastern ZNP and the main body of the nappe are shown on the map, as well as the displacement of the Corbières Nappe (white line with arrows). The faults measured in the field have been projected in stereos (Win-Tensor 5.8.6., Delvaux and Sperner, 2003) by families of orientation, dip and kinematics, some will be discussed later. The color code of the stereographic representations is consistent with that of the faults on the map. The Figures 6 and 8 are located by white rectangles.

2. Jurassic detailed stratigraphy of the Corbières Transfer Zone

The detailed stratigraphy of the Jurassic basins is well documented. Generally, the different Jurassic terms do not show an accentuated paleogeographic differentiation (the facies are relatively homogeneous, Fig. 5). On the other hand they present strong thickness variations both from NW to SE and from SW to NE as summarised in figure 4.

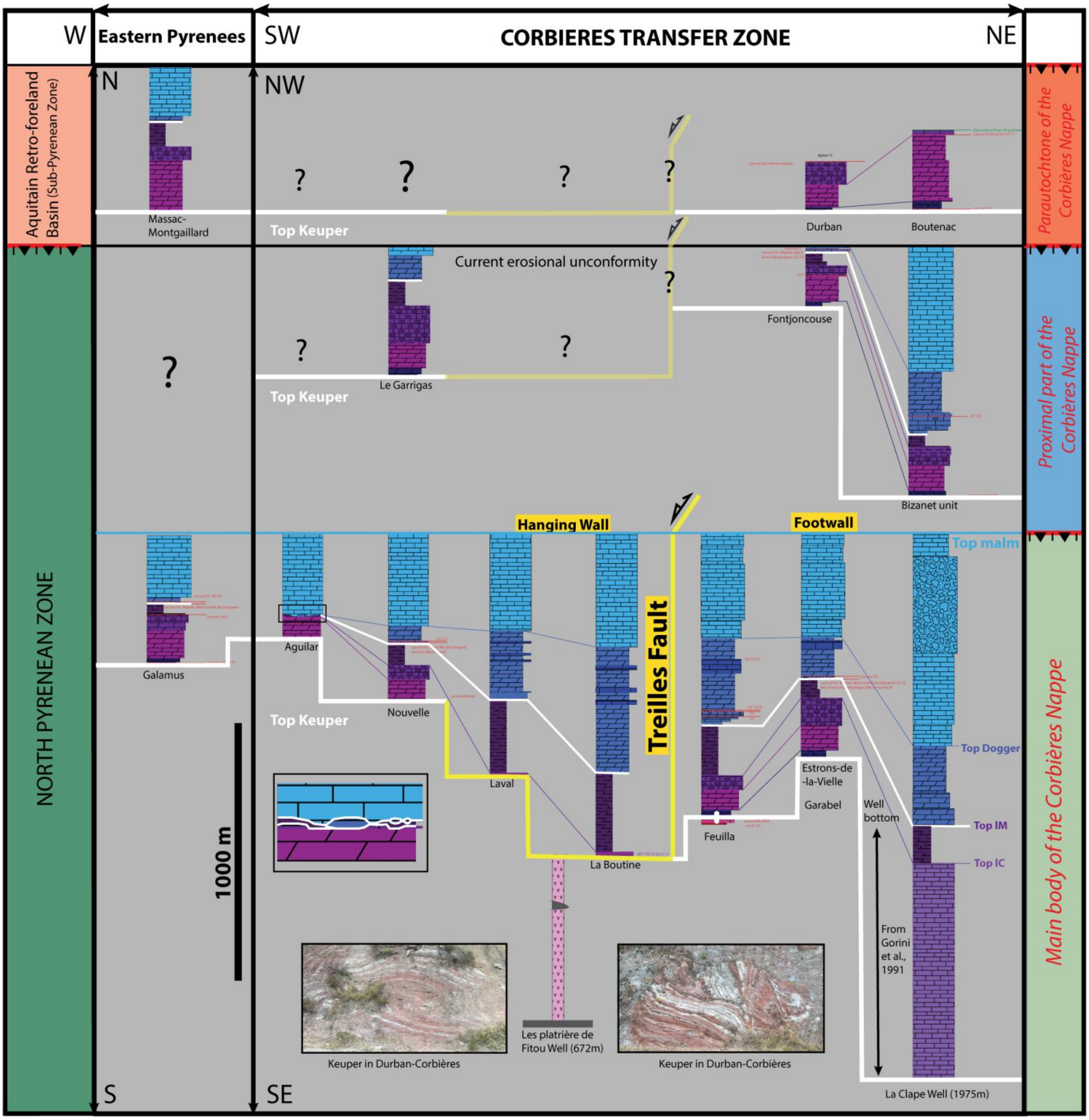

Figure 4. Jurassic stratigraphic correlation of each domain of the Corbières Transfer Zone, these domains and the different localities are shown in Fig. 3. The two detachment horizons are shown with white lines, top Keuper (major detachment) and top of the marly Lias (secondary detachment). The Treilles fault in the main body of the nappe is represented in yellow (Fig 6, 7, 8 and 9).

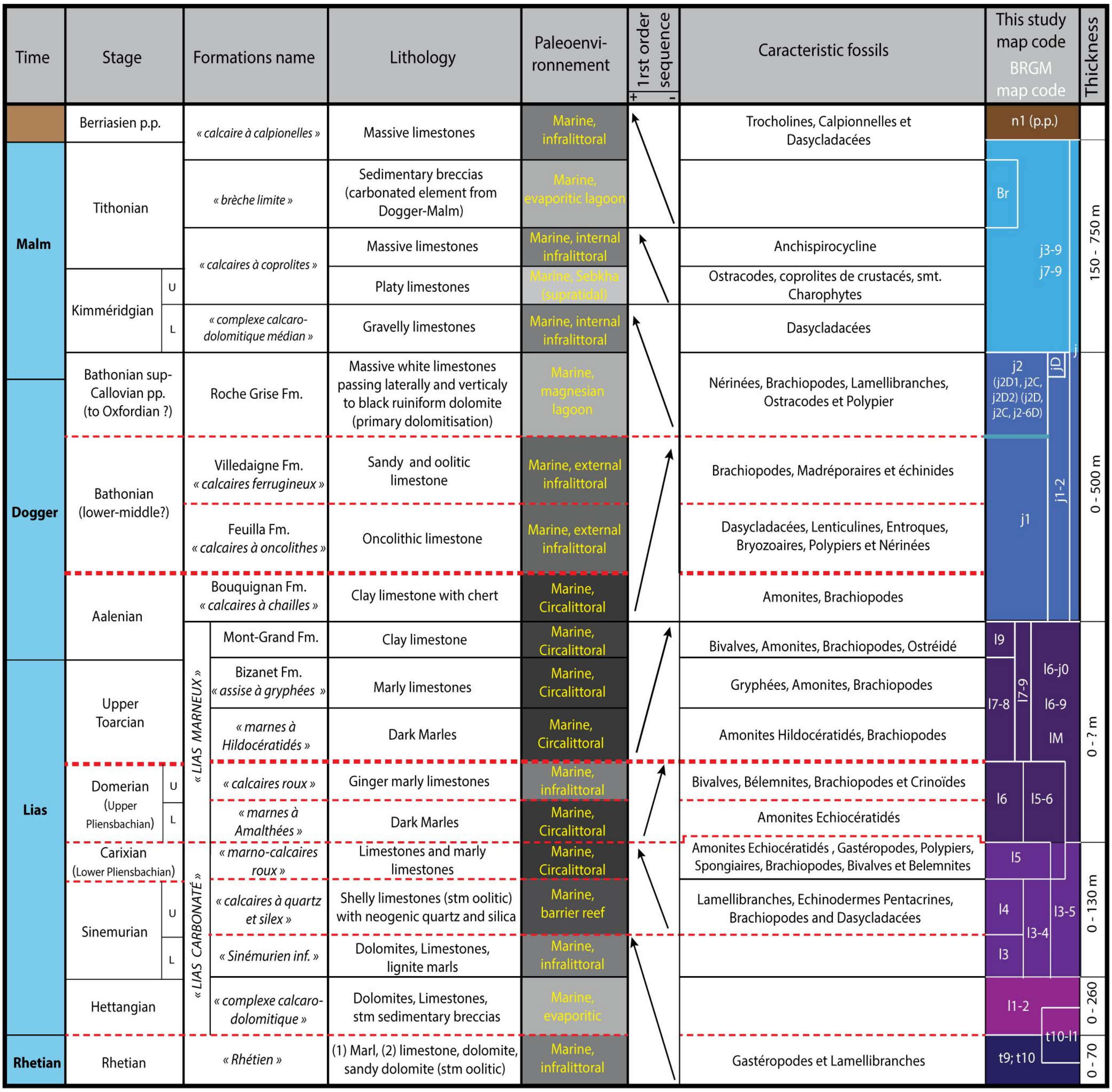

Figure 5. Jurassic detailed stratigraphy of the Corbières (Black Dolomites Gp.). Red dashed lines represent unconformities.

Mechanical stratigraphy: The Keuper constitutes the major detachment level. The evaporites contain a considerable number of blocks of sub-salt lithologies (unmetamorphosed to HT-LP, HT-HP metamorphosed Paleozoic, unmetamorphosed Muschelkalk) as well as Jurassic blocks of variable size (centimeter to kilometer) (Figs 2, 6 and 8). We stress the regional importance of the secondary detachment in the marly Lias, which is often deformed and incomplete or absent (sheared out). In certain localities where shearing was particularly intense, the intervening Liassic limestones are thin to absent so that the two detachment levels merge (Fitou half-window, Fig. 8) or onlt a thin trace of the Liassic carbonates remains (Castelmaure, Fig. 7a; Roc Traucat, Fig. 9b; Fitou window, Terres Noires half-window, Fig. 8; Aguilar Castel sector, Fig. 6).

3. Tectono-stratigraphic evidence of extension during Jurassic: THE TREILLES NORMAL FAULT

The map of the Figure 6 shows the Corbières Nappe detached on the Keuper above the Mouthoumet basement massif (part of the retro-foreland). The main body of the nappe overthrusts the Garrigas frontal unit. The NE-SW cc' cross-section (cross-section in Fig. 7c) crosscuts the Treilles Fault (in yellow Fig. 6), oriented N110 and dipping shallowly SSW. Its map trace can be followed over 12.5 km from the SE border of the Mouthoumet massif to the Mediterranean Sea (Figs 2, 3, 6 and 8). This fault has been interpreted as a N-NW verging thrust (Donnadieu, 1973). The fault cuts the Corbières nappe into two structural units (footwall to the NE and hanging wall to the SW) and roots on the Keuper. As strata are systematically younger in the hangingwall (Fig. 6, 8, 10a) this fault has a major normal component of displacement downthrowing to the SW.

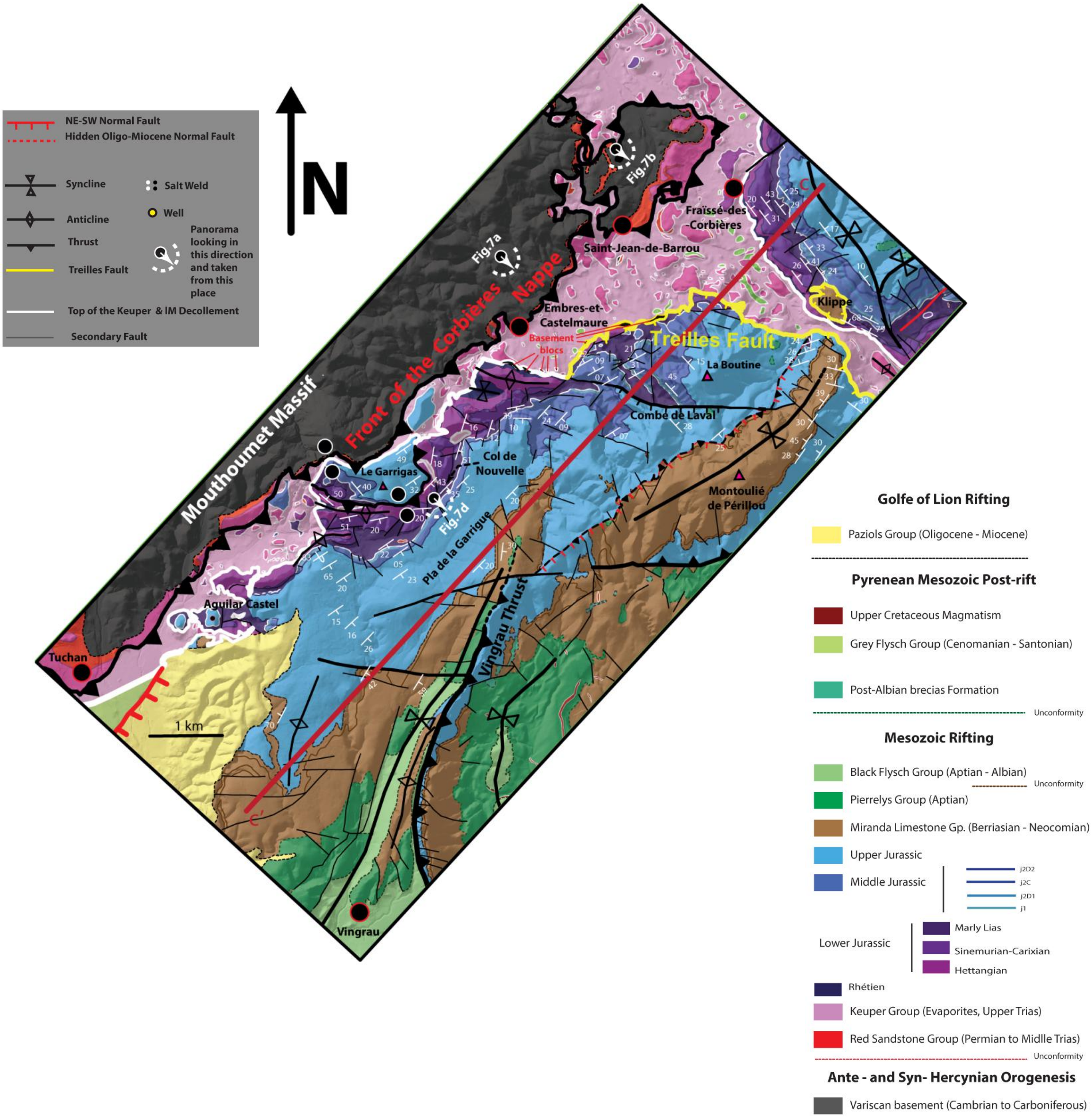

Figure 6. Geological map of the SE border of the Mouthoumet massif. The red line represents the trace of the NE-SW cc' cross-section that cuts the Treilles Fault. Location of the panoramas of the Figures 7a, 7b, 7d.

In accordance with the Figure 4, the hangingwall Jurassic series thickens towards the NE (e.g. 20m to 500 m for the Dogger) and show a large scale dip fan over 15 km. Marly Lias to Malm strata terminate downward onto the SW dipping Treilles Fault plane. The growth fan is clearly visible in Figure 7a, with dips gradually decreasing up section from 45° at the base of the Dogger to 15-20° in the Malm.

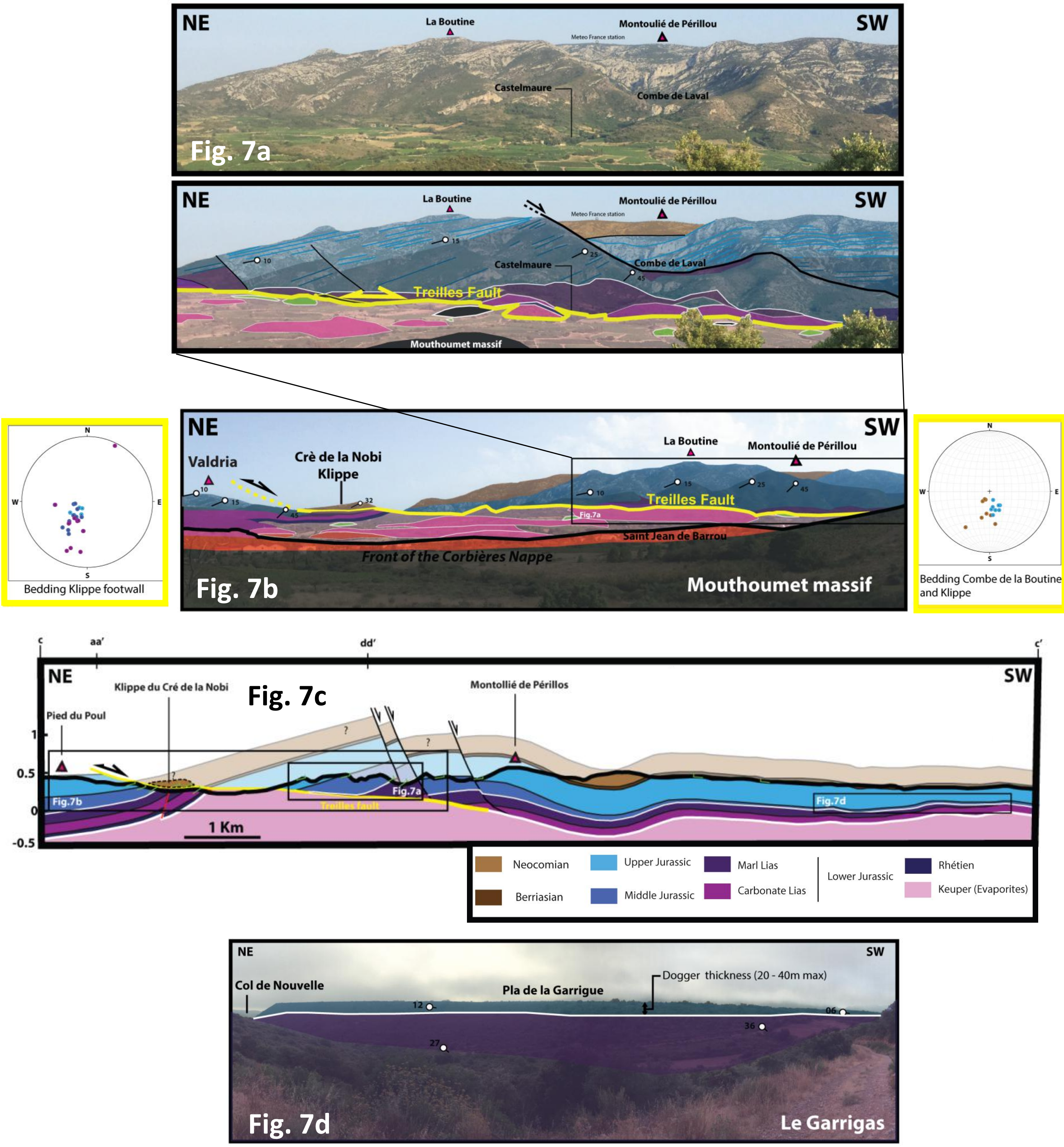

Figure 7a. SE view of the Dogger-Malm growth fan in the hangingwall of the Treilles Fault. b. SE view of the Treilles Fault showing the relationship between its hangingwall and its footwall. c. Cross-section cc' showing the hangingwall and the footwall of the Treilles Fault. Panoramas of the Figures 7a, b and d are located by black rectangles. d. SE view of the Pla de la Garrigue sector showing the weak thickness of the Dogger in the SW part of the hanging wall.

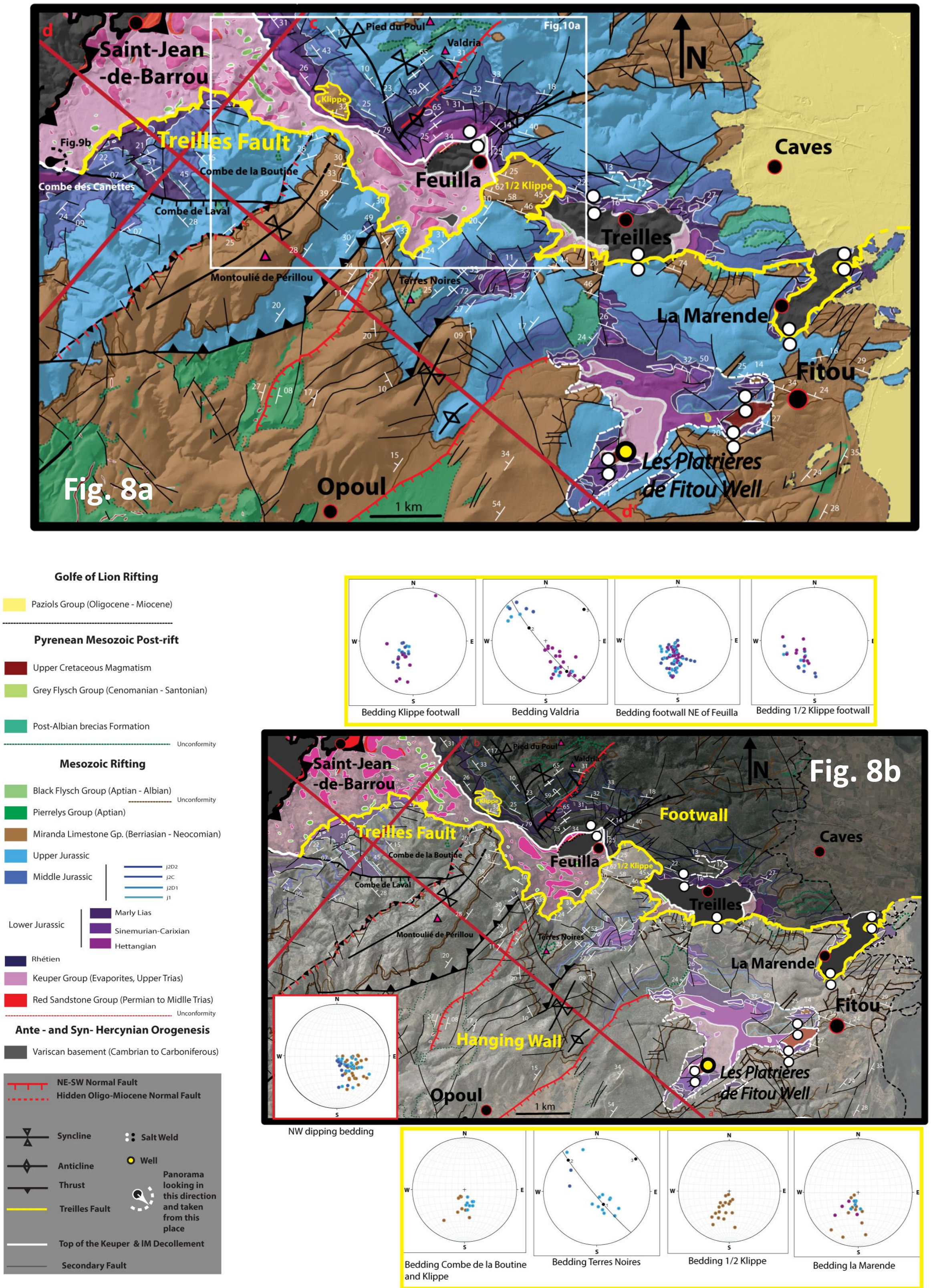

Figure 8.a. Geological map of the Treilles Fault and Feuilla half window. Note the N110 alignment of three basement inliers (Feuilla, Treilles, La Marende). The location of the panorama of the Figure 9b, is shown. b. Structural map of the Treilles Fault hangingwall and footwall. Poles of Jurassic to Neocomian bedding are plotted on Schmid lower hemisphere stereographic projections by sector of the fault hangingwall (below map) and footwall (above map), (colour code of poles is identical to stratigraphic colour code on map Fig.8a). The NW-SE red line represents the trace of the dd' cross-section intersecting the hangingwall of the Treilles Fault and the Mouthoumet massif. It intersects the NE-W cc' cross-section.

The stereonet plots of bedding in Figure 8b show that the Jurassic to Neocomian strata in the Treilles Fault hangingwall and footwall generally have a N to NE dip, except (1) along the dd' cross-section (red framed stereo, Fig.8a) and (2) in two very localized folds, one in the footwall (Valdria fold, Figs 10 and 11), the other in the hangingwall (Terres Noires fold). Both folds trend NE-SW with a NW vergence.

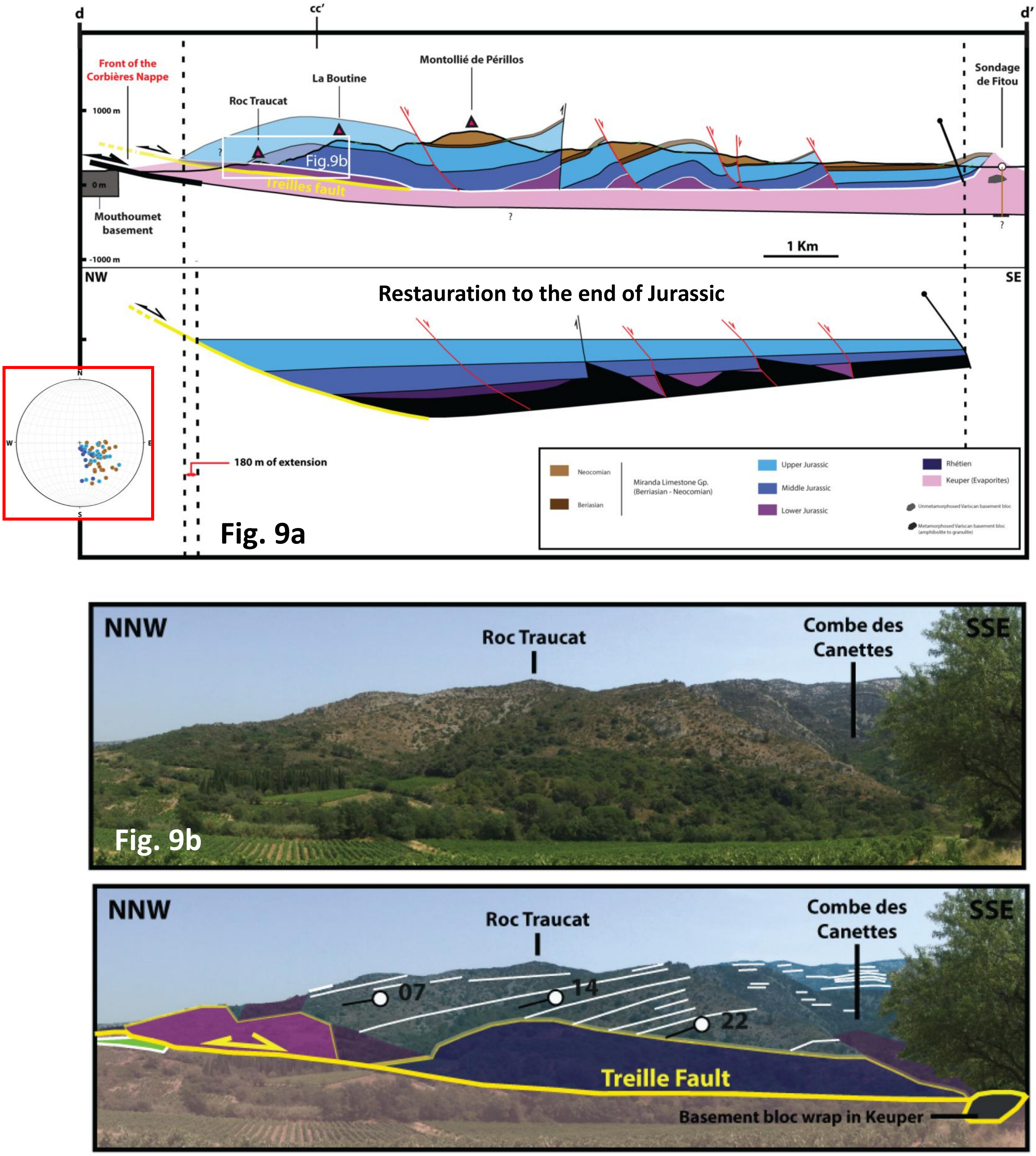

Figure 9.a. NW-SE dd' cross-section and its restoration to end Jurassic. The black areas on the restaured section represent volume deficit. The red framed stereo plot represent bedding poles in relation with red NE-SW normales faults. Figure 8b is located by a white rectangle. b. Uninterpreted and interpreted ENE view of the NW part of cross-section dd' showing the dip fan in Dogger strata above the Treilles Fault. Lias blocks lie along the Treilles Fault. between the Keuper and marly Lias detachment.

On the dd' cross-section (Fig. 9a) Jurassic strata also present a large scale dip fan (15 km) with strata thickening towards the NNW,.Marly Lias to Malm strata dip NW down onto the shallowly SE dipping Treilles Fault plane, as shown in the panorama in Fig. 9b. The hangingwall is cut by a series of late NE-SW trending normal and reverse faults dipping mainly SE. A restoration of these faults (Fig. 9a) shows that there is no NW directed shortening (Fig.3) in the Corbières nappe but instead, a slight extension (180m). This is explained by the presence of normal and reverse faults, which compensate for each other («0% of shortening currently», Fig.3). The volume deficit in lower Jurassic units on the restored section may be due to material moving in or out of section along the basal contact.

The orthogonal cc' and dd' cross-sections show that the Treilles Fault is a normal fault that was active during the Jurassic to create a 3D hangingwall growth dip fan. The Neocomian dips in the hangingwall (Fig. 8a and b) and the normal flat faults mesured in the Neocomian of the klippe du Cré de la Nobi and the half-klippe of the Pla de Crouzal (Fig. 3, fault stereographic projections framed in yellow) suggest that the fault was also active during the late Early Cretaceous (Aptian-Albian) and may have been slightly inverted during Pyrenean orogenesis.

4. Tectono-stratigraphic evidence of extension and compression during Jurassic: THE VALDRIA GROWTH FOLDS

The NW-SE aa' cross-section (Fig11.c) of the Feuilla half-window shows that the Jurassic units of the NW part of the half-window are folded (NE-SW Valdria syncline and anticline, Fig11.a). This folding was previously interpreted as Pyrenean folding by Donnadieu (1973). However, our tectono-stratigraphic study shows, that the Hettangian to lower Kimmeridgian series thins towards the NW and towards the SE with a maximum thickness in the NE-SW synclinal hinge zone. Similarly the NE-SW bb' cross-section (Fig. 11e) shows a thickening of the series towards the NE into the NW-SE trending syncline in the immediate footwall of the Treilles Fault. Thus the thickness variations in the Treilles Fault footwall are 3D. We suggest that a Lias to Malm extension phase created the Treilles normal fault with synchronous initiation of the Valdria fold pair due to growth of a small diapir in the fault footwall (Feuilla diapir). The overturned limb includes a strong dip fan in Malm strata recording Late Jurassic fold growth (Lower-middle Kimmeridgian to Tithonian ?) (Figs 8b 11c b). This folding associated with the formation of progressive growth unconformity (Fig.11b) may be the consequence of a NW-SE transpressional phase and/or continued salt tectonics during the Malm. The Neocimmerian phase was accompanied by erosion and could be at the origin of Tithonian intraformational breccias (Br), which contain only elements of the Dogger-Tithonian series (terms most often overlapped by the progressive growth unconformity).

The SE limb of the Valdria anticline is cut by a late NE-SW normal fault and is also affected by secondary folding which we interpret as the consequence of the indentation of a basement block against the Jurassic cover during a slight Pyrenean tightening (10-15% of the folding).

In the the Treilles Fault hanging wall, syn-Malm growth fold were observed: (1) at the level of the Terres Noires massif, located on the SE of the Feuilla half-window (Fig.8a, stereo Fig.8b), (2) between the Aguilar Calstel and Col de Nouvelle sectors, on the SE border of the Mouthoumet massif (Fig. 6).

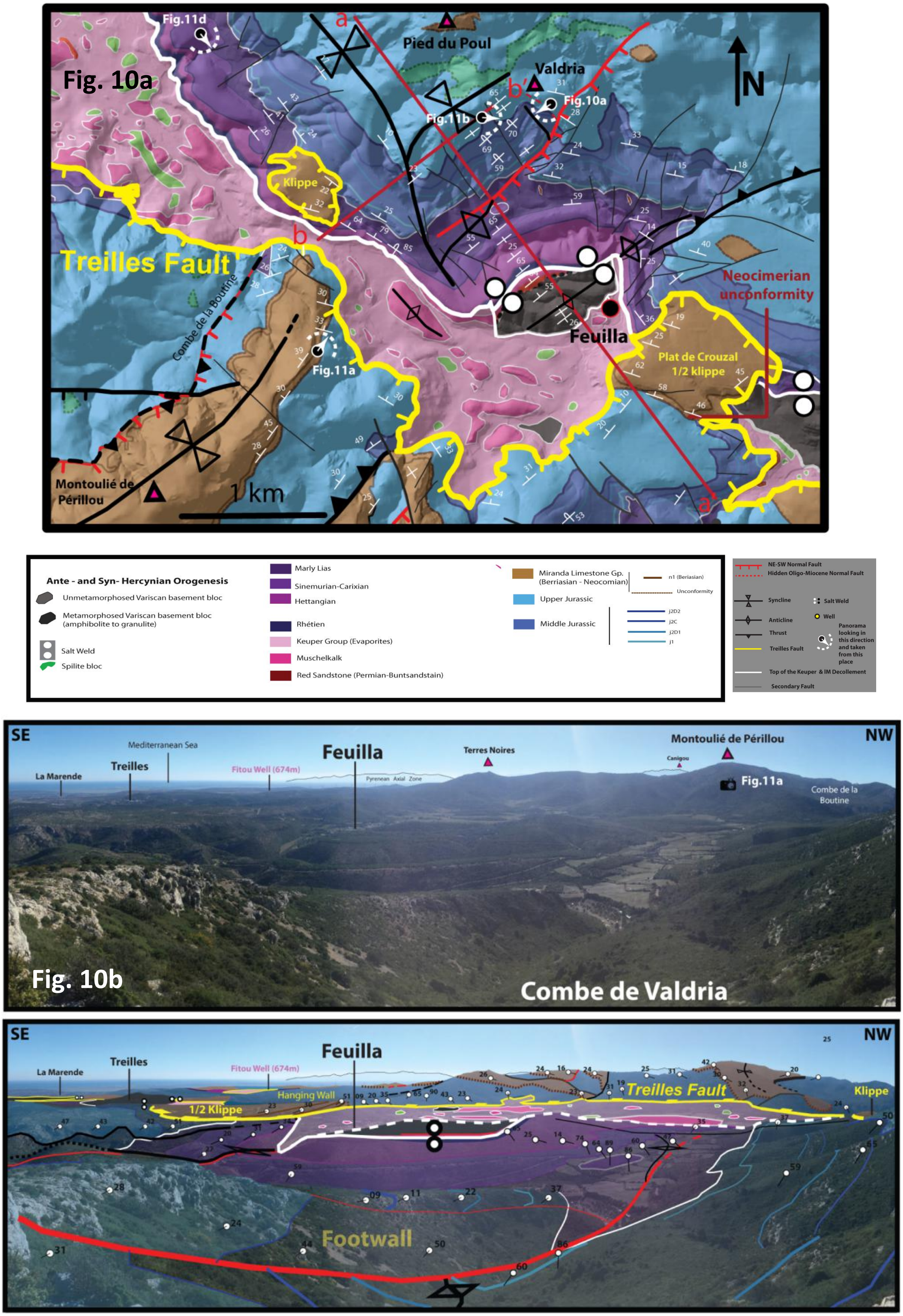

Figure 10.a. Geological map of the Feuilla half-window. Locations of aa' and bb' cross-sections (red line) and locations the panoramas in Figures 11a, 11b, 11d. b are shown. Uninterpreted and interpreted SW view of the Feuilla half-window showing the rotation of the Jurassic strata above the half-window as well as the subhorizontal trace of the Treilles Fault.

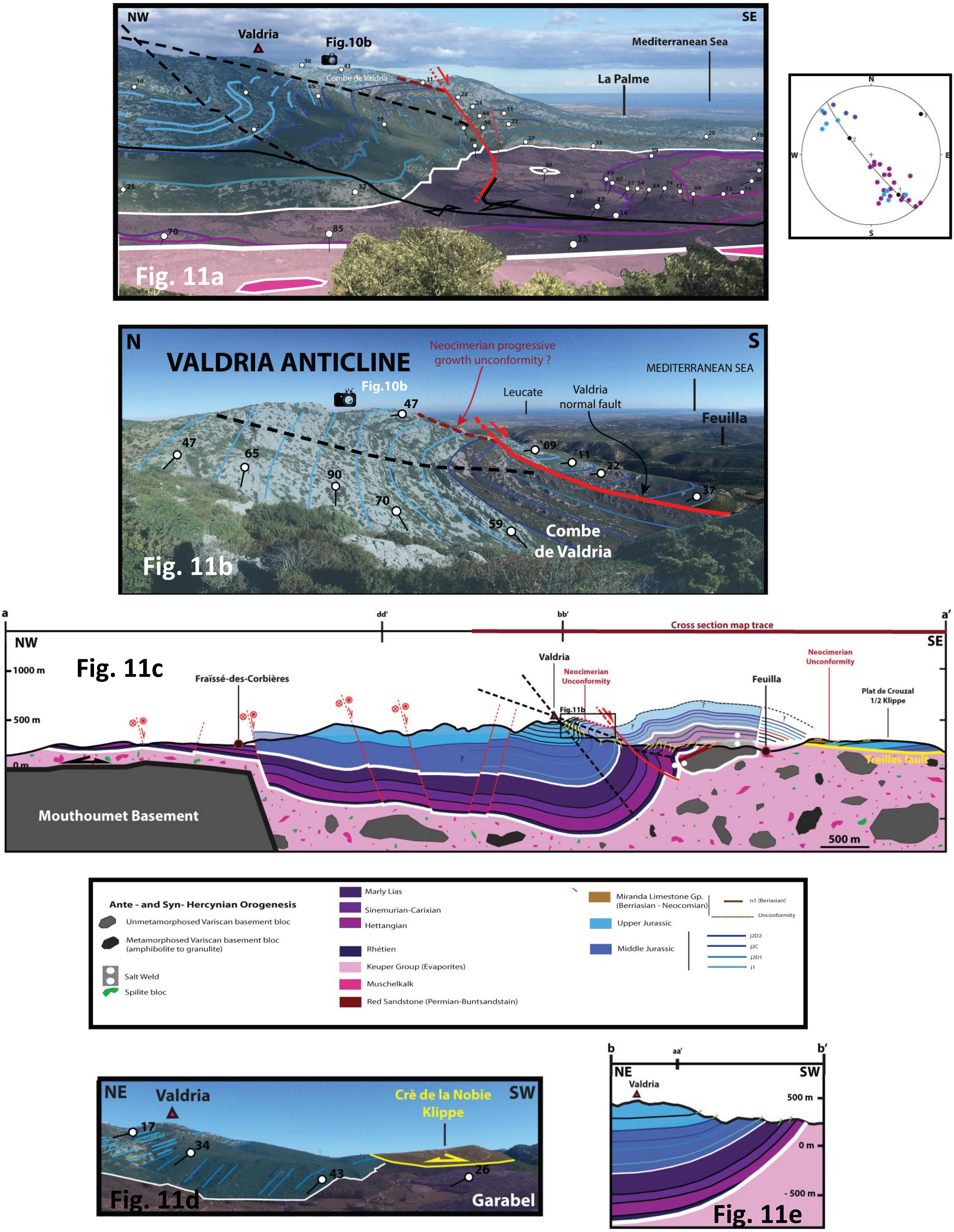

Figure 11.a. Interpreted NE view of the Valdria fold pair in the NW part of the Feuilla half-window. Stero plot b. Interpreted East view of the Valdria anticlinal hinge zone. c. NW-SE aa' cross-section of the Feuilla half-window. d. Interpreted SE view of the NW Valdria massif slope taken from Garabel. e. NE-SE bb' cross-section of the Valdria massif.

5. Discussion

At the scale of the Corbières Transfer Zone, we propose that there was a Lias-early Kimmeridgian extension phase (Fig. 4). This phase of extension is marked by a strong segmentation of the basins between oblique cover structures, the N110 flat faults (Treilles Fault and Bordière fault of Bas-Agly) and NE-SW structures (Fig. 3). This segmentation delimits the future domains of the Corbières Nappe and constitues a Jurassic inheritance (Fig. 3). To explain (1) why NE-SW structures develop at the intersection with the Pyrenean N110 structures in the Corbières and (2) why the Jurassic succession thickens towards the SE and NE in the transfer zone, we propose that the Lias-lower Kimmeridgian extension was controlled by the opening of the Tethys ocean. Tethyan rifting was controlled by NW-SE extension (Mohn et al., 2011). We suggest that the Corbières area lay at the intersection between the Pyrenean domain and the Tethyian domain. Thus we propose that the prncipal elements of the structural framework of Corbières area were created during Mesozoic rifting.

We note that folding at Valdria during the Malm is contemporaneous with the enigmatic Neocimmerian transpression event described elsewhere in the Pyrenees (Canérot, 2005). This implies that NE-SW folding currently attributed to the Pyrenean phase throughout the Corbières Nappe, may include a component of Neocimmerian deformation.

cc BY