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The Importance of Rift Inheritance in Understanding the Early Collisional Evolution of the Western Alps

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Abstract: We reassess the architecture and tectonic history of the Western Alps based on recent knowledge developed at rifted margins. First, we replace the main Alpine units of our study area into a synthetic rifted margin template based on diagnostic petrologic, stratigraphic, and structural criteria. We find that some units previously attributed to the internal part of the thick-crusted Briançonnais domain may rather derive from the thin-crusted Prepiemonte hyperextended domain. We assert that the Briançonnais and Prepiemonte domains were separated by a mega-fault scarp. Second, we revisit the Paleogeography of the Alpine Tethys, suggesting that the Briançonnais was a ribbon of little thinned continental crust between two overstepping en-échelon rift basins, namely the Valais domain to the northwest and the Piemonte domain to the southeast. We affirm that this uneven-margin architecture can explain most of the Western Alps' complexity. In our kinematic model, convergence between Adria and Europe was mainly accommodated by strike-slip movements in the Western Alps until the late Eocene. Orogeny began with the reactivation of the mega-fault scarp between the Briançonnais and Prepiemonte domains, which we name Prepiemonte Basal Thrust. Once hard collision started, the main shortening stepped inboard into the Valais/Subbriançonnais domain along the Penninic Basal Thrust.

Keywords: Western Alps; Briançonnais; Prepiemonte; collisional orogen; reactivation; rift inheritance

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Citation: Manatschal, G.; Chenin, P.; Haupert, I.; Masini, E.; Frasca, G.; Decarlis, A. The Importance of Rift Inheritance in Understanding the Early Collisional Evolution of the Western Alps. *Geosciences* **2022**, *12*, 434. https://doi.org/10.3390/geosciences12120434

Academic Editors: Enrico Tavarnelli, Robert W.H. Butler, Paolo Pace, Jesus Martinez-Frias and Olivier Lacombe

Received: 21 September 2022
Accepted: 17 November 2022
Published: 24 November 2022

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1. Introduction

In the past decades, an increasing number of studies have shown that the architecture of collisional orogens resulting from the closure of "narrow" oceanic domains, such as the Alps of Western Europe, is primarily controlled by the architecture of their former rifted margins [1–18]. However, most of these studies focused either on the primary/large-scale structural framework or on the reactivation of local/small-scale structures like former half-graben basins, often located in the external part of the orogen. In contrast, the internal parts of Alpine-type collisional orogens, which preserve remnants of the former distal margins and relics of the intervening (proto-)oceanic crust, are still incompletely understood. In the Western Alps, much uncertainty remains on the three-dimensional architecture of the inherited rift system: on the one hand, the along-dip structure of the European–Briançonnais margin remains debated, in particular the vertical relative position (i.e., paleo topographic highs vs. lows) of its distal domains, now exposed in the Subbriançonnais, Briançonnais and Prepiemonte internal Alpine units. On the other hand, the along-strike architecture of the European–Briançonnais margin remains an open question, in particular the number and position of transfer zones and/or individual rift basins. Better understanding the

Alpine Tethys rift template and the kinematic history of its closure may well be the key to unraveling the apparent complexity of the Western Alps.

Recently, several significant steps have been taken toward the understanding of how rift inheritance impacts orogeny. On the one hand, [19] defined a series of Building Blocks (BBs; Figure 1) to relate specific stratigraphic, structural and/or petrologic relationships observed in Alpine nappes to specific rift domains defined at magma-poor rifted margins. On the other hand, [12,14] highlighted that the along-dip (two-dimensional) architecture of the Pyrenean orogen can be largely unraveled when considering different reactivation styles for the different rift domains involved, depending particularly on their crustal thickness and the location of rift-inherited decoupling levels (see Section 2). They showed that the Pyrenean orogeny started with "soft collision" as the exhumed mantle- and hyperextended domains were largely subducted during convergence; and once the thick-crusted (>10 km) necking domain reached the subduction trench, it acted as a buttress because it was too buoyant to subduct, and thus "soft collision" gave way to "hard collision". Besides, [11] suggested that the along-strike complexity (non-cylindricity) of the internal parts of the Pyrenean orogen was largely controlled by the segmentation of the rift system involved, which included hyperextended rift basins either overstepping each other with an en-échelon geometry or limited by transfer zones.

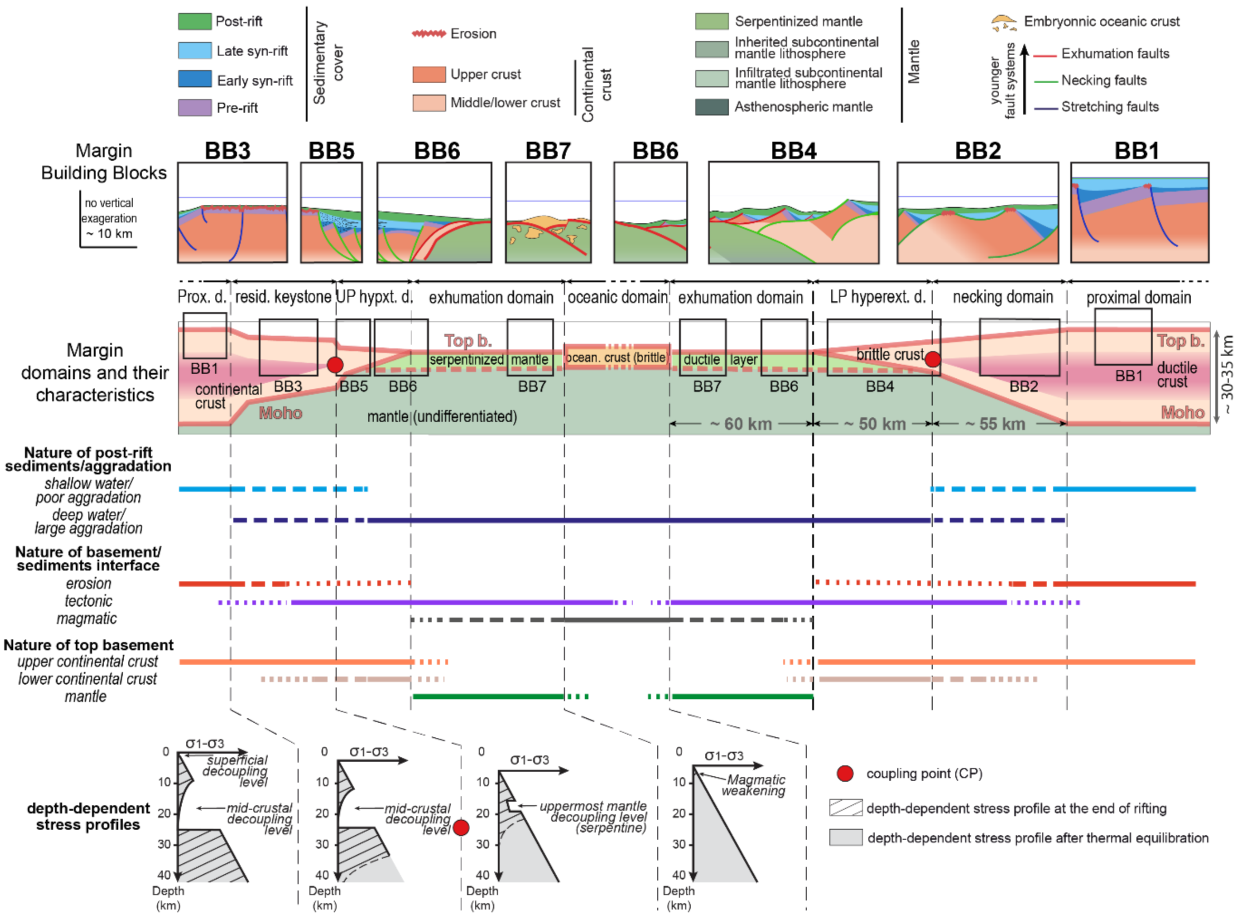

Figure 1. Schematic section across a pair of conjugate magma-poor rifted margins and location of the seven constitutive Building Blocks BBs (see text for details). The nature of the top basement, post-rift sediments, and their interface vary across the margin and are diagnostic to define rift domains (see [18,19]). The depth-dependent stress profiles at the bottom of the figure represent the rheological evolution along dip of the rifted margins schematized above, in particular the location of the decoupling levels, both at the end of rifting (hatched area) and after thermal equilibration (grey area). Abbreviations: b, basement; d, domain; LP, Lower Plate rifted margin; resid., residual; UP, Upper Plate rifted margin. Figure modified from [11,18,19].

In this paper, we aim to test whether the lessons learnt in the Pyrenean system can be applied to the Western Alps. Yet, the Alpine Tethys rift- and collisional systems display some marked differences compared to the Pyrenean ones. Indeed (1) the Alpine Tethys included a (proto-)oceanic domain (e.g., [20]), while the Pyrenean system did presumably not (e.g., [21]); (2) the kinematic evolution of the Alpine domain involved three successive and non-coaxial phases of convergence (e.g., [22–24]), while the reactivation of the Pyrenean rift system involved an essentially constant kinematic direction ([25,26]); (3) most of the Alpine Tethys (proto-)oceanic domains and most distal margins were subducted to significant depths before being exhumed (e.g., [27,28]), conversely to the Pyrenean system; and hence (4) at the surface, the Alps display metamorphic facies as high as eclogite (e.g., [29]), while no exhumed high-pressure metamorphic assemblage can be found in the Pyrenees.

In the following, we first introduce the concept of Building Blocks (BBs) defined by [19]. Second, we assign a BB affinity to key localities preserved in the Western Alps to identify their position in the former distal European magma-poor rifted margin. We reassess the pre-Alpine position of some internal Alpine units based on new field observations reported in this contribution. Then, we investigate the relationships between the main Alpine orogenic structures and the initial Alpine Tethys rift architecture. Finally, we discuss the relative impact of rift inheritance and plate kinematics on the dynamics of the continental collision and on the orogenic architecture of the internal parts of the Western Alps.

2. Concepts and Terminology: Building Blocks vs. Rift Domains and Location and Nature of Rift-Inherited Decoupling Levels

Building Blocks (BBs), as defined by [19], are typically kilometer-scale outcrops preserving primary rift relationships between basement rocks, faults and syn-rift stratigraphic levels (Figure 1). Relying on the nature of the top basement, the amount of accommodation, the sedimentary facies, the presence of erosional- or tectonic unconformities and/or the existence of magmatic additions, each BB can be linked to a specific rift domain [18,19]. In the Alpine system, the following seven BBs have been defined:

- BB1 displays classical tilted blocks and half-graben bounded by high-angle normal faults with only limited accommodation (Figure 1). Examples of BB1 include the Bourg d'Oisans Basin in the Western Alps ([30]; (1) in Figure 2e) and the Monte Generoso Basin in the Southern Alps ([31]; (2) in Figure 2e). BB1 is the typical fingerprint of a proximal margin, where the crust is 30 ± 5 km thick. There, crustal thinning is accommodated by high-angle normal faulting in the brittle upper crust and ductile deformation in the middle/lower crust (i.e., *decoupled deformation* sensu [32]). Two types of decoupling levels can typically occur in the proximal domain: intra-basin decoupling levels such as evaporite and/or clay-rich layers within the sedimentary cover; and crustal decoupling levels related to weak, ductile layers within the continental crust.
- BB2 (Figure 1) displays crustal-scale shear zones juxtaposing upper- and middle/lower crustal levels and/or pluri-kilometric offset extensional detachment faults exhuming crustal basements to the seafloor. Such detachment faults are typically overlain by detrital clastic sediments reworking the underlying footwall (usually sandstones or breccias) deposited in shallow-marine environments. Examples of BB2 include the Mont Blanc in the Western Alps ([33,34]; (3) in Figure 2e), and the Eita shear zone and Grosina detachment in the Central Alps ([35]; (4) in Figure 2e). BB2 is the typical fingerprint of a necking domain (Figure 1), where the crust thins from 30 to 10 km essentially via detachment faulting [35,36]. The oceanward limit of the necking domain corresponds to the coupling point (CP, see Figure 1), where the thinned continental crust first becomes fully brittle [37]. In the proximal part of the necking domain, decoupling levels are comparable to those of the adjacent proximal domain. They progressively decrease in thickness oceanward to finally disappear at the CP.
- BB3 displays a major syn-rift unconformity (so-called "Briançonnais-type unconformity"; Figure 1; [38]) resulting from pervasive erosion/karstification. The type locality

of BB3 is the Fond Froid—Lac de l'Ascension area in the Briançonnais nappes of the Western Alps ([39,40]; (5) in Figure 2e). BB3 is a typical fingerprint of a "residual keystone block", a ribbon of moderately thinned continental crust (20 ± 5 km-thick) that is characteristic of upper-plate rifted margins [41]. The distribution of decoupling levels is comparable to that of necking domains.

- BB4 displays successive, in-sequence, long-offset extensional detachment faults responsible for the tectonic exhumation of mid- and/or lower crustal levels at the seafloor (Figure 1). A typical example of BB4 is the Err detachment system in the Central Alps ([42,43]; (6) in Figure 2e). BB4 is the classical fingerprint of the hyperextended domain of lower-plate rifted margins, where the fully brittle crust tapers from 10 to 0 km. The main decoupling level in this domain lies within the serpentinized mantle, flooring the crustal taper. Other decoupling levels may arise from detachment systems and/or low-friction layers within the sediments (e.g., [14,44]).
- BB5 displays major breccia bodies and is a typical fingerprint of the transition between the necking domain/residual keystone block (topographic high) and the hyperextended domain (topographic low) of upper-plate margins (Figure 1). It usually represents a significant and long-lived topographic step (*mega-fault scarp* sensu [45]) that is an efficient source for the mega-breccia deposited at its toe [45]. Examples of BB5 include the Breccia Nappe in the Pre-Alps ([45]; (7) in Figure 2e) and the Monte Galero Breccia in the Ligurian Alps ([46]; (8) in Figure 2e).
- BB6 displays exhumed serpentinized mantle capped by extensional detachment faults and ophicalcites, which are in turn overlain by tectono-sedimentary breccias and deep-water sediments (Figure 1). The best example of BB6 is the Tasna Nappe in the Central Alps ([47]; (9) in Figure 2e). BB6 is the typical fingerprint of an exhumed mantle domain. There, the serpentine–sediment boundary is the most prominent decoupling layer.
- BB7 displays serpentinized mantle with many syn-exhumation mafic extrusive and intrusive rock bodies. Mantle exhumation faults are often affected by later high-angle normal faulting (Figure 1). The first overlying sediments are either tectono-sedimentary breccias reworking exhumed mantle and/or mafic extrusive rocks or deep-water sediments such as radiolarian cherts. Examples of BB7 include the Lower Platta Unit in the Central Alps ([48]; (10) in Figure 2e) and the Chenaillet Ophiolite in the Western Alps ([49]; (11) in Figure 2e). BB7 is the typical fingerprint of a proto-oceanic domain. Decoupling levels lie either in the serpentinized uppermost mantle or within the overlying sediments.

By linking BBs to rift domains and assuming that the dimensions of the Alpine Tethys rift domains were comparable to those of present-day magma-poor rifted margins, first-order synthetic profiles across the former Alpine Tethys rifted margins can be drawn [19]. In this paper, we apply this new approach to a transect across the former European–Briançonnais margin, now exposed between the Bourg d'Oisans and the Mont Chaberton in the Western Alps. We focus on the internal units of this transect, which preserve the most distal rift domains. These are framed by the external Alpine units (former proximal margin) on the one hand and remnants from the (proto-)oceanic domain that escaped subduction on the other.

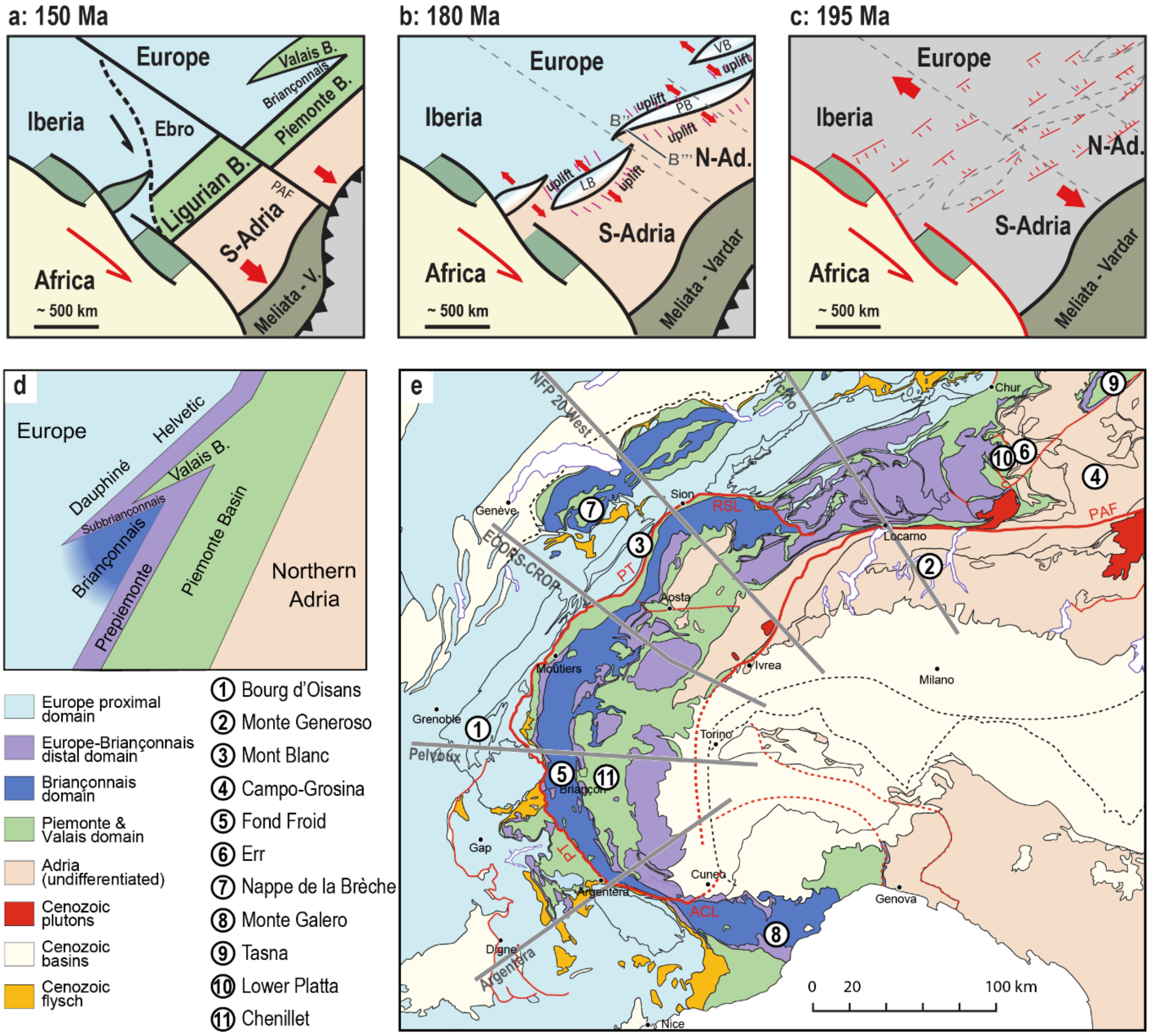

Figure 2. Schematic maps (modified from [19]) showing the paleogeographic evolution of the Alpine Tethys at (**a**) Late Jurassic (150 Ma; assumed end of rifting/spreading in the Alpine Tethys); (**b**) late Pliensbachian (180 Ma; individualization of the Ligurian, Piemonte and Valais basins as en-échelon rift segments separated by accommodation/transfer zones); (**c**) early Jurassic (195 Ma; early rift phase characterized by distributed deformation); Abbreviations: N-Ad., Northern Adria; PAF, Peri-Adriatic Fault; LB/Ligurian B., Ligurian Basin; PB/Piemonte B., Piemonte Basin; VB/Valais B., Valais Basin; LP: Lower-plate rifted margin; UP: Upper-plate rifted margin. (**d**) Schematic paleogeographic map showing the spatial relationships between the Briançonnais ribbon and the Valais and Piemonte domains of the Alpine Tethys. (**e**) Tectonic map of the Western and Central Alps (modified after [24]) displaying the present-day distribution of the paleogeographic domains represented in panel (**d**) and the location of the main outcrops mentioned in the text. Abbreviations: RSL Rhone-Simplon Line, PT: Basal Penninic Thrust, ACL Argentera-Cuneo Line.

3. Geological Setting

3.1. Rifting and Convergence in the Alpine Tethys Realm

Mesozoic rifting in the Tethys–Atlantic domain involved three major tectonic plates, namely the North American, African and Eurasian plates; two smaller plates, namely the Iberian and Adriatic plates; and a poorly constrained number of (transient) microplates, such as the Ebro plate (e.g., [50–52]). The first rifting episode occurred during the Late Triassic, linking the Central Atlantic to the Tethys system. During this stage, most extension was accommodated in the Meliata–Vardar domain, east and south of the Adriatic plate (e.g., [53]). Extension in the future Alpine Tethys realm *per se* began in the latest Triassic–earliest Jurassic (Figure 2c) and formed a segmented rift system comprised of three basins, namely from south to north (Figure 2b): the Ligurian Basin (LB) between Iberia and S-Adria, the Piemonte Basin (PB) between Europe/Briançonnais and N-Adria, and the Valais Basin (VB) between Europe and the Briançonnais. The three basins merged into the final Alpine Tethys during the Late Jurassic (Callovian–Bathonian; Figure 2a; [54]). The Ligurian and Piemonte basins were presumably separated by a major transform fault, a precursor structure of the present-day Peri-Adriatic Fault (PAF in Figure 2a; [22]). In contrast, the Valais Basin may have remained an embayment of the Alpine Tethys between Europe sensu stricto (s. str.) and the Briançonnais continental ribbon (Figure 2d). In such a scenario, the Briançonnais is best explained as a block of >15 km-thick continental crust framed by two necking zones [55], i.e., the overstepping Valais and Piemonte basins (Figure 2d). Thus, the former European–Briançonnais margin was presumably segmented and partially oblique to the Alpine Tethys (proto-)oceanic domain, a point whose implications will be further discussed later in this paper (Section 7.7).

The closure of the Alpine Tethys domain resulted from three successive and non-coaxial phases of convergence between Adria and Europe, expressed by three distinct orogenic phases, namely the Eoalpine, Mesoalpine and Neoalpine phases [22–24,56]. The Eoalpine orogenic phase took place from the Early-to-Late Cretaceous as the result of a N–NE directed the closure of the Meliata–Vardar domain (Meliata-V. in Figure 2a). It led to the construction of a strike-slip-dominated thrust wedge that propagated from the northeastern margin of Adria towards the W–NW [57,58]. During this event, the proximal and distal margins, as well as the Ocean-Continent Transition (OCT) of northwestern Adria, were stacked into a number of thrust sheets, which are today exposed in the Eastern and Central Alps. The geological record of this orogenic event is largely lacking in the Western Alps [22].

The Mesoalpine orogenic phase began at ca. 84 Ma (Late Cretaceous) when the N-NE-directed motion of the African plate relative to Europe rotated counterclockwise, generating an N–NNW-directed contraction [22,24,59]. This led to the subduction of the whole Piemonte Basin and parts of the Ligurian Basin beneath the Adriatic plate, to the telescoping of the European passive margin in the north, and eventually to the emplacement of the *Eoalpine Austroalpine-* and *Mesoalpine Penninic thrust complex* as an orogenic lid over the European proximal margin (Helvetic units; e.g., [60,61]). The Mesoalpine orogenic phase was associated with high-pressure metamorphism (e.g., [62,63]). How far and how intensively the continental European margin, which forms the present-day Western Alps, was affected by the Mesoalpine deformation phase remains a matter of debate and will be discussed later in this paper (Sections 7.4 and 7.5).

The Neoalpine orogenic phase began in the late Eocene (ca. 35 Ma) when a substantial shift from essentially N-directed- to W–WNW-directed shortening occurred at the scale of the future Western Alps [22,24]. This shift was linked to the anticlockwise rotation of the Adriatic plate, likely following the kinematic reorganization of the Alpine orogenic system (transition from a collision in the Mesoalpine system to subduction in the Mediterranean system; [64]). Most of the relief of the Western Alps along the French-Italian boundary formed during this final phase (post 25 Ma; [65]). In the Western Alps, the Neoalpine orogenic phase was largely expressed by the transition from N–S- to E–W-directed transport direction [22]. It was associated with moderate-pressure (Barrovian) metamorphism (e.g., [66]). Noteworthy, the high-pressure metamorphic rocks exposed in the Western Alps formed during the Mesoalpine phase and were exhumed in an accretionary wedge before the onset of the Neoalpine phase (i.e., prior to 35 Ma; [62,67]).

The kinematic reorganization between the Meso- and Neoalpine orogenic phases was accompanied by local magmatic activity (e.g., Periadriatic plutons emplacement between 33 and 31 Ma; [68]) and onset of dextral strike-slip movements in the Periadriatic system. The details of this kinematic reorganization remain largely debated, in particular, whether the change from N–S to E–W shortening was due to a relative motion between Africa and Europe (global kinematic framework) or was controlled by the retreating subduction systems in the Alpine realm (local kinematic framework). When and how far N-directed shortening affected the future Western Alps also remains an open question. While [57] suggest significant N-directed convergence before the late Eocene (35 Ma), other authors argue that the effects of N–S-directed convergence were largely limited to the most distal parts of the European-Briançonnais margin and (proto-)oceanic domain prior to 35 Ma [69]. Below we discuss both aspects based on new field observations and a new tectonic approach (Sections 7.4 and 7.5).

3.2. Structure of the Western Alps

At first order, the present-day Western Alps can be regarded as a three-part system comprising two buttresses formed by the European and Adriatic proximal domains (external units of the Alpine orogen), framing a polyphase accretionary wedge essentially made of basement and sediments derived from the former distal margins and (proto-)oceanic domain (internal part of the Alpine orogen; Mohn et al., 2014; Figure 3a). High-pressure metamorphic facies (blueschist and eclogite) are largely limited to the internal part/former hyperextended- and (proto-)oceanic domains (Figure 4; [28,62]; see also discussion Section 7.3).

The nappe stack forming the Western Alps comprises remnants from all rift domains of the former European–Briançonnais margin. It includes, from external to internal: the Dauphinois nappes, which sample the former proximal domain; the (Sub-, Lower- and Middle-) Penninic nappes, which sample the former Valais Basin and Briançonnais ribbon; the Prepiemonte nappes, which sample the distal part of the European–Briançonnais margin facing the Piemonte Basin; and the Piemonte nappes, which sample the former (proto-)oceanic Piemonte Basin. A major complexity of the Western Alps is their non-cylindricity and arcuate shape, which results from the complex inherited rift architecture, the changing kinematics of convergence during the continental collision [24] and/or the complex 3D dynamics of the Alpine and Appeninic subductions [70].

3.3. Study Area

In this study, we use a W–E transect across the Western Alps between Bourg d'Oisans and Mont Chaberton (Figure 5) to introduce the main structures and units forming the Alpine nappe stack in this region. From external (west) to internal (east), or from bottom upwards, five major Alpine tectonic units can be identified, namely (Figure 5): the Dauphinois (grey color), the Subbriançonnais (light blue), the Briançonnais (dark blue), the Prepiemonte (violet), and the Piemonte units (green). On the one hand, the Dauphinois is consensually recognized as representing the former proximal domain of the European margin [71,72]. On the other hand, the Piemonte units and the *Schistes Lustrés* are consensually recognized as remnants of the former Alpine Tethys (proto-)oceanic domain. The units in-between belong to the former distal margin. They are still incompletely understood and are the main subject of the present study.

In the following sections, we present the characteristics of each of these units, including the relationships between basement type, rift structures and pre-Alpine stratigraphy. We use the Building Block (BB) approach described in Section 2 (Figure 1) to locate the main outcrops/units in a rifted margin template. This allows us to link the original location of a BB in the former rifted margin with its present location in the orogenic section. We identify the first-order deformation structures in each unit and examine whether they are inherited from the rifting event and were reactivated during convergence or were newly formed during the orogenic phase. Finally, we review the metamorphic facies associated with each Alpine unit in the study area.

4. Identification of BBs along a Transect across the Western Alps

In this section, we attempt to assign a BB affinity to key units/large-scale outcrops exposed along our study transect across the Western Alps. We first briefly describe the well-understood Dauphinois (proximal) and Piemonte (proto-oceanic) domains before focusing on the intervening, more controversial, Subbriançonnais, Briançonnais and Prepiemonte units.

4.1. The Dauphinois Units

In the study area, the Dauphinois units are mainly formed by the Oisans Massif sensu lato, which includes the Taillefer, Grandes Rousses and Pelvoux massifs. All of them belong to the *External Crystalline Massifs (ECM)* like Belledonne and Mont Blanc further north. The ECM lie at the boundary between the thin-skinned-dominated fold-and-thrust belt (e.g., the Vercors and Chartreuse sub-Alpine chains (Figure 3), also called "chaînes sub-alpines") and the more complex internal units of the Alps. The ECM basement mainly consists of Variscan polymetamorphic basement rocks intruded by Carboniferous to Permian granitoids. In the Oisans Massif, two areas preserve pre-Alpine relationships between basement, pre- and syn-rift sediments, and rift-related structures. The first one lies in the La Mure–Bourg d'Oisans area, here referred to as *the external Oisans*. The second corresponds to the Les Deux-Alpes–La Muzelle area, here referred to as *the internal Oisans*.

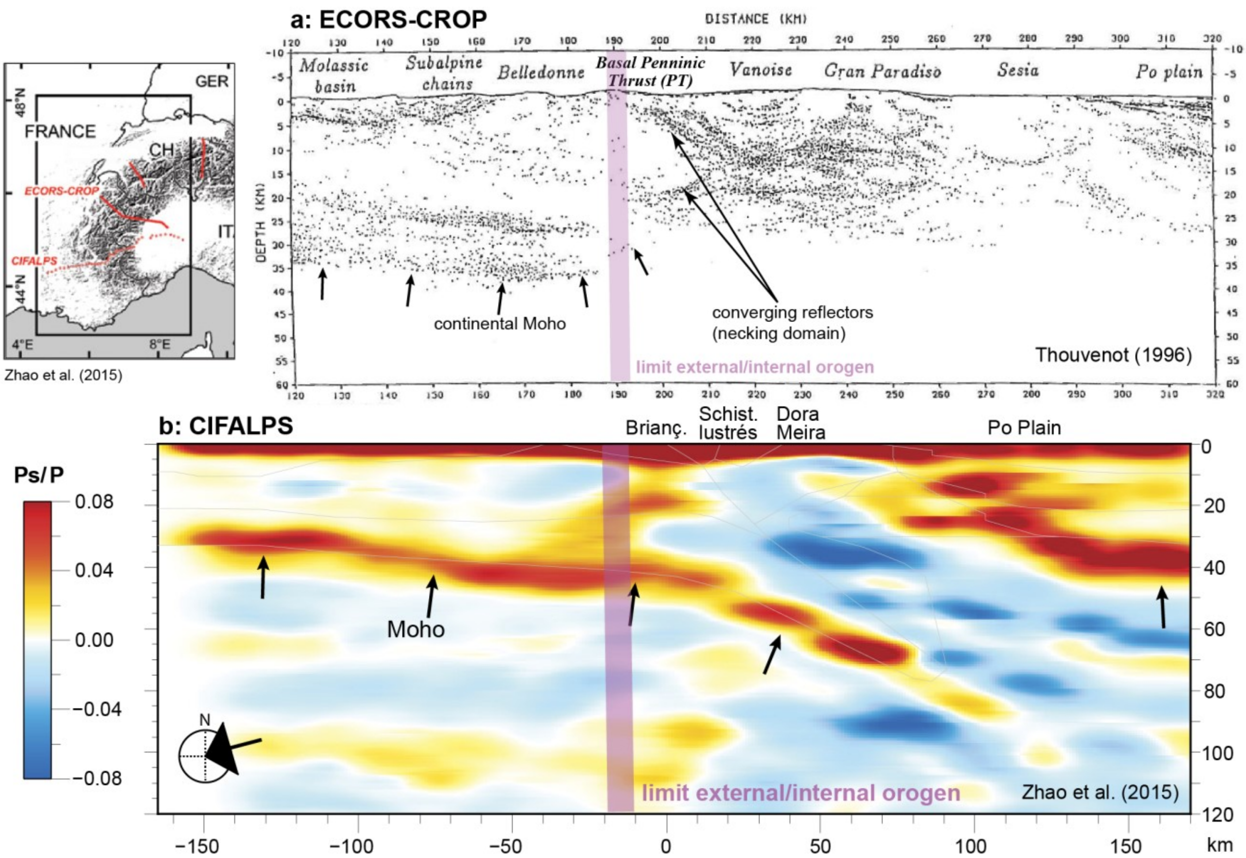

Figure 3. (**a**) ECORS-CROP seismic profile in depth (modified after [73]). (**b**) Synthetic common conversion point depth section from the China-Italy-France Alps seismic survey (CIFALPS; modified after [74]). Abbreviation: Brianç.: Briançonnais.

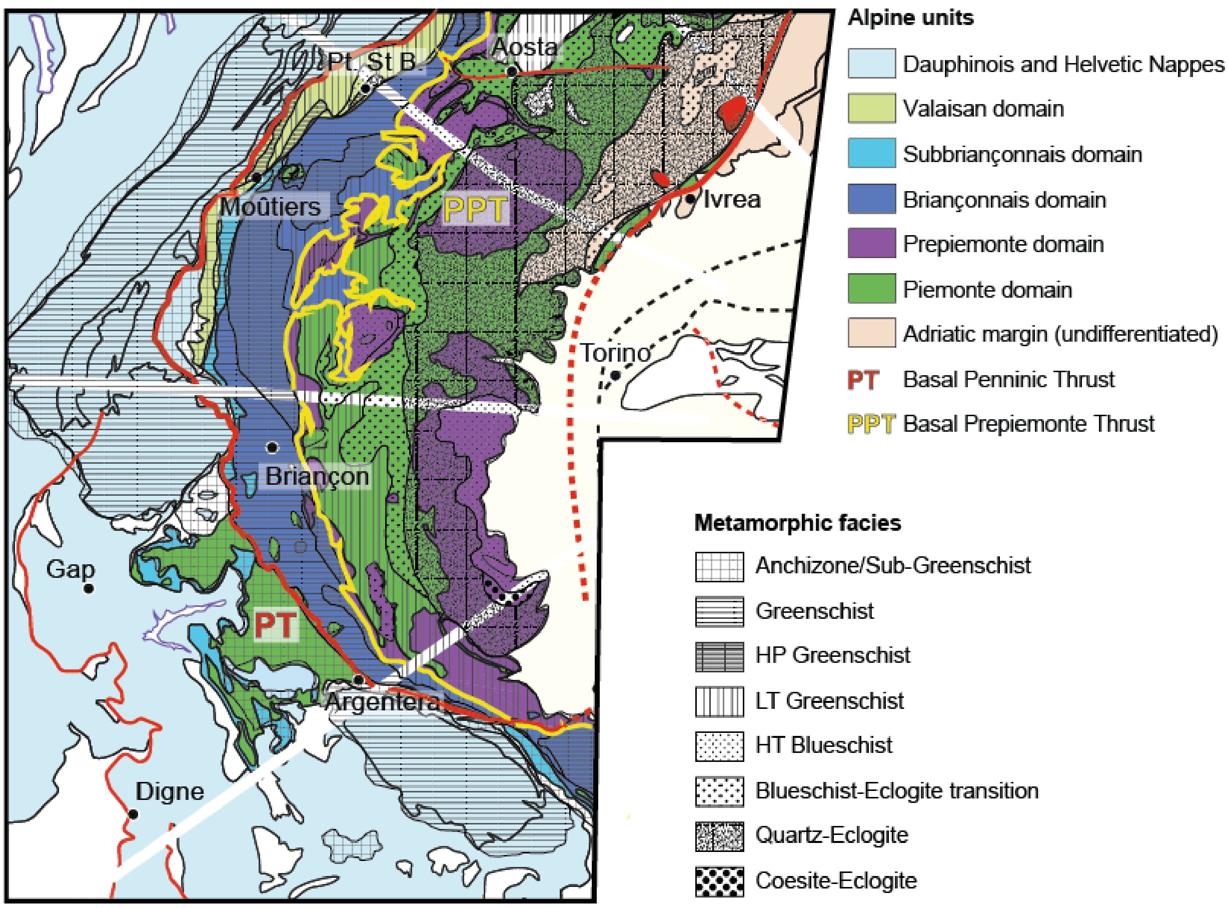

Figure 4. Map showing the distribution of the main Alpine units (colors) discussed in the text (modified from [24]) together with the distribution of the metamorphic facies (patterns) in the Western Alps (from [28]). Note that no high-pressure facies can be found external to the Basal Prepiemonte Thrust (PPT) as defined in the present study (see text for details and discussion). The white strips correspond to the trace of the seismic lines displayed in Figure 2e. Abbreviation: P. St B.: Petit Saint Bernard.

4.1.1. The External Oisans

Rift-Related Observations

The La Mure and Bourg d'Oisans basins in the external Oisans are consensually interpreted as former half grabens inherited from the Lower Jurassic rifting (Figure 6a). These basins are bounded by high-angle normal faults [72,75,76]. In the footwall and the hanging-wall of the Ornon normal fault bounding the Bourg d'Oisans Basin, the pre-rift basement/sediment contact is capped by a regional unconformity that was attributed to a late Hercynian emersion and peneplanation [77]. This unconformity is covered by a thin sequence of pre-rift Triassic sandstones. The latter are overlain by Middle- to Upper Triassic dolostones, which were attributed to a wide, shallow-marine carbonate platform covering the entire Dauphinois domain.

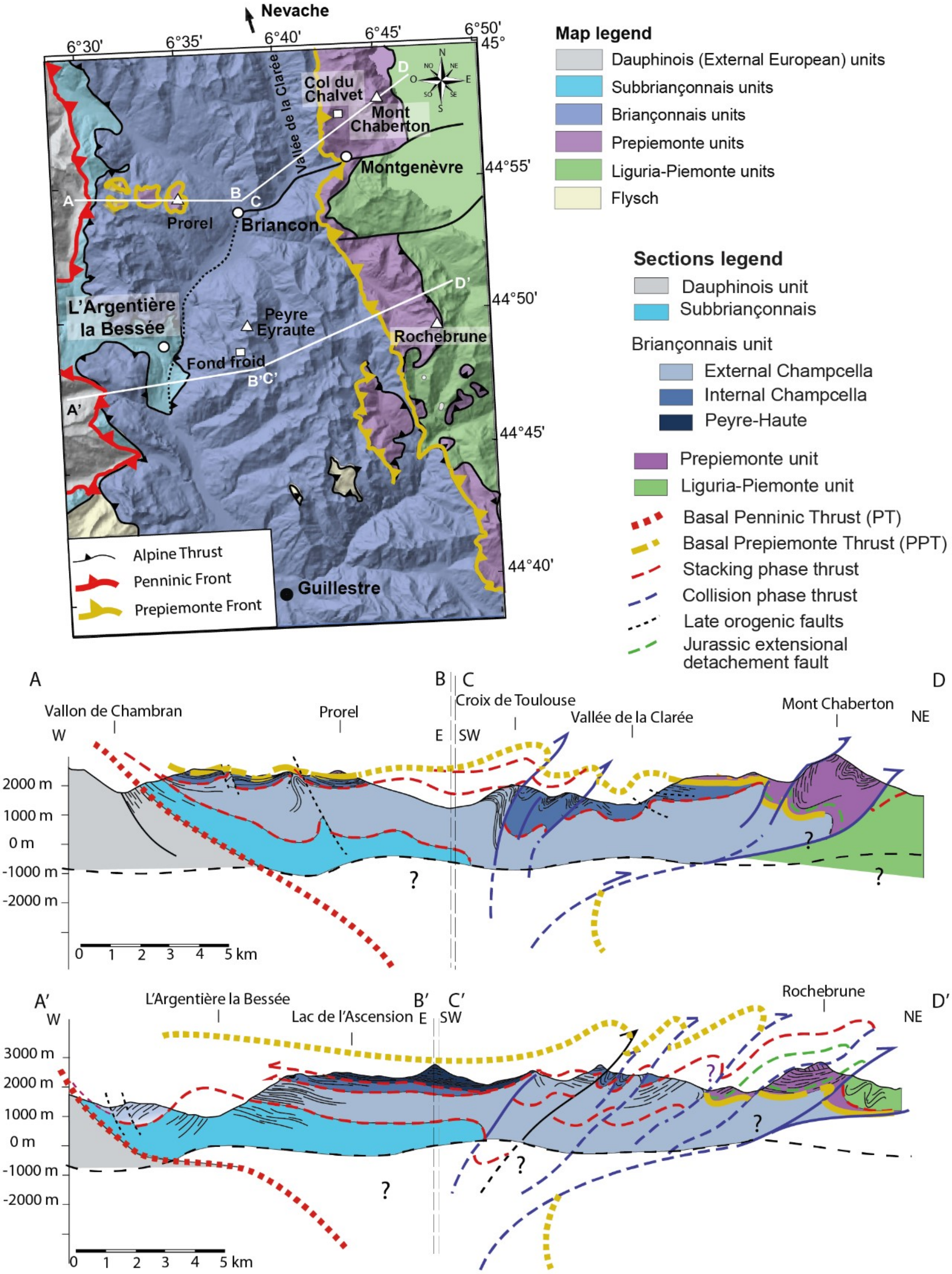

Figure 5. Tectonic map and geological sections across the study area. Five main Alpine units separated by major Alpine thrusts can be distinguished, namely the Dauphinois, the Subbriançonnais, the Briançonnais, the Prepiemonte and the Piemonte units. The Basal Penninic Thrust (PT; red line) between the Dauphinois and the Briançonnais s. str. units and the Basal Prepiemonte Thrust (PPT; yellow line) between the Briançonnais s. str. and the Prepiemonte units are both major rift- and orogenic structures (see text for details and discussion).

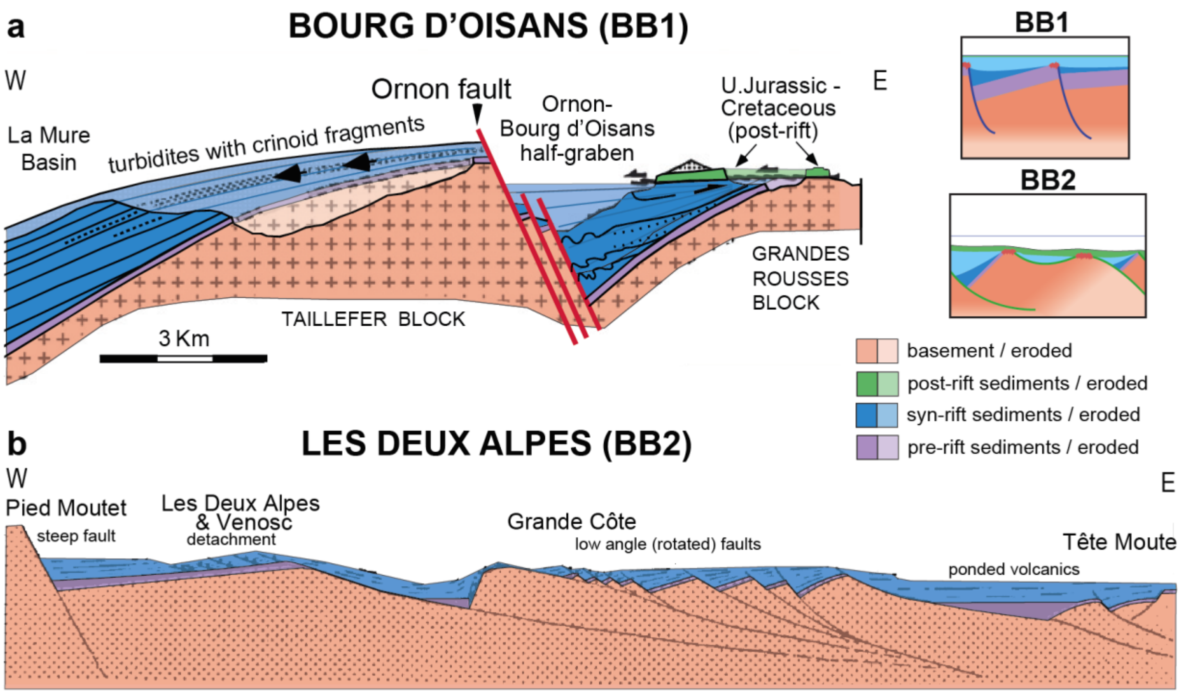

Figure 6. Examples of BB1 and BB2 in the Western Alps: (**a**) in the external Oisans, the Bourg d'Oisans Basin represents a half graben of the former European proximal margin and is typically a BB1 (figure modified from [71]); (**b**) in our study area, the Les Deux Alpes–La Muzelle region belongs to the internal part of the Oisans Massif. It displays relics of low-angle extensional detachment faults that exhumed the basement to the seafloor and is therefore interpreted as a BB2 (see text for details and discussion; figure modified from [78]).

Over the pre-rift Triassic sediments, Hettangian to Pliensbachian limestones and marls display the first wedge-shaped geometries in both the La Mure and the Bourg d'Oisans basins (Figure 6a). As their sedimentary facies indicate a progressive deepening of the depositional environment, these were interpreted to mark the onset of rifting [79]. The wedge-shaped deposits thicken toward the La Mure and the Ornon normal faults, respectively, showing that these faults controlled the syn-rift depocenter. These structures and related wedge-shaped deposits are sealed by post-tectonic (passive infill) Upper Jurassic–Lower Cretaceous pelagic to hemipelagic limestones and marls, followed by a succession of Cretaceous carbonate platforms [80]. The overall depositional environment remained shallow, i.e., $\leq$400 m throughout the post-rift evolution in both the La Mure and Bourg d'Oisans basins [80], which implies that neither the crust nor the lithosphere were significantly thinned during the Jurassic rifting beneath these basins. This hypothesis is supported by the ECORS-CROP section [81], which displays a ca. 10 s TWT-thick crust (i.e., ca. 30 km) in the external Oisans area (Figure 3a).

The evidence for equilibrated, ca. 30 km-thick continental crust, the limited accommodation, and the presence of high-angle normal faults bounding major half grabens prompt us to assign the external Oisans to BB1 (cf. Figure 1) and to interpret this domain as belonging to the proximal domain of the Alpine Tethys. Such an interpretation is in accordance with previous studies [19,71,72].

Orogen-Related Observations

Alpine reactivation of the La Mure and Bourg d'Oisans basins was mainly expressed by basin inversion [76,78,82,83] and nappe stacking. The Jurassic syn-rift sedimentary sequence shows large folds only slightly detached from the underlying basement [75]. During the early stages of shortening, the upper part of rift-related normal faults often acted as buttresses, resulting in basin inversion. In contrast, the deeper parts of the normal faults, likely listric, may have been preferentially reactivated as thrusts. In more advanced stages of convergence, top-to-the-west thrusts locally truncated the footwall of Jurassic normal faults, resulting in shortcut structures [2,78,82] that produced large-scale basement folds forming the present-day ECM [76]. Nappe stacking occurred simultaneous to, and continued after, the deposition of the "*Priabonian Trilogy*", a late Eocene (ca. 35 Ma) syn-convergent sedimentary sequence composed of nummulitic limestones, hemipelagic marls and turbidites [84,85].

In the Bourg d'Oisans region, Alpine metamorphic peak conditions were reached during the late Oligocene (ca. 25 Ma) with temperature estimates of 320–350 °C and pressure estimates of 0.2–0.25 Gpa [86]. Such greenschist facies conditions (Figure 4) indicate a maximum overburden of 8.6–12.5 km [86].

4.1.2. The Internal Oisans

Rift-Related Observations

In the Les Deux-Alpes half-graben and La Muzelle region of the internal Oisans massif, [78,87] described low-angle faults that juxtapose syn-rift Toarcian sediments interleaved with Liassic breccias directly onto basement (Figure 6b). These authors recognized that these structures are fundamentally different from those observed in the external Oisans to the west (see the previous section) and interpreted them as long-offset faults that exhumed the basement to the seafloor. In their view, the low dip-angle of the faults was due to syn-extension footwall rotation. A few years later, [88] concluded that most of the tectonic surfaces in the internal Oisans were inherited from the Jurassic rifting. [89] described fault rocks capping the internal Oisans basement, which show similar fabrics to those found along the Jurassic detachment fault zone in the internal Mont Blanc Massif [33]. Besides, [88] noticed the presence of mainly north-south striking Jurassic 'neptunian dykes' within the granitic basement of the internal Oisans, nearby the basement/sediment interface. These structures prompted them to suggest that this domain used to lie at shallow water depths during rifting of the Alpine Tethys and was affected by east-west-directed rift-related extension.

The occurrence of low-angle, long-offset syn-rift detachment faults exhuming basement to the seafloor and the evidence for syn-rift shallow water depths impel us to suggest that the internal Oisans corresponds to BB2 (cf. Figure 1), and thus used to belong to the necking zone of the former European margin. In that view, it would be an along-strike analogue of the Mont Blanc detachment system identified by [34]. This interpretation is compatible with the common lack of pre-rift sediments and the subsidence history of this domain, both of which compare well with observations reported from the internal Mont Blanc area [33].

Orogen-Related Observations

In the internal Oisans, like in the internal Mont Blanc Massif [33], the Upper Jurassic–Cretaceous post-rift sedimentary cover was detached and thrust westward. In this region, the Jurassic normal faults were often reactivated as thrusts, possibly due to their lower dip-angle compared to the high-angle faults of the external Oisans [78]. Locally, undeformed sediments of the "Priabonian Trilogy" were directly deposited onto the deformed basement [90], indicating that the top basement deformation was pre-Priabonian.

The internal Oisans underwent greenschist facies Alpine metamorphism (Figure 4), like the external Oisans [28]. Ref. [91] reckoned peak metamorphic conditions to have been reached during the early Oligocene with temperature estimates of ca. 280 °C. These would record the deposition of the last sediments over the internal Oisans, which were dated Eocene/Oligocene.

4.2. The Piemonte Units

4.2.1. Rift-Related Observations

Here we define the Piemonte units as those sampling the former (proto-)oceanic Piemonte domain of the Alpine Tethys. These units are characterized by the occurrence of serpentinites, basalts and gabbros (e.g., [92–95]). The most illustrative example is the Chenaillet ophiolite exposed south of the village of Montgenèvre at the French/Italian border [96–98]. The Chenaillet ophiolite consists of serpentinized peridotites and gabbros capped by an extensional detachment fault that is, in turn, overlain by pillow lavas and sediments reworking both the mantle and mafic rocks [49,99]. The Chenaillet ophiolite was interpreted as a portion of the proto-oceanic crust [99–101]. While syn-rift Late Jurassic to Early Cretaceous radiolarian cherts can locally be found directly over serpentinites and/or basalts [102], the dominant sedimentary sequence of the Piemonte unit is formed by the *Schistes Lustrés*. These deep-water sediments are often strongly deformed and metamorphosed. They represent the detached post-rift Late Jurassic (?) to the Cretaceous sedimentary cover of the (proto-)oceanic Piemonte domain [103,104]).

The ophiolitic nature of the basement, the deep-water facies of the overlying sediments and the presence of mafic magmatic products prompt us to assign the Piemonte units to BB7 (cf. Figure 1), consistent with previous interpretations that attribute the Piemonte units to the (proto-)oceanic domain of the Alpine Tethys rift system (e.g., [93,95,105,106]).

4.2.2. Orogen-Related Observations

In the Piemonte domain, Alpine convergence was associated with the deposition of the "Helminthoid Flysch" [69,71,107]. The Piemonte units are characterized by blueschist- (e.g., Schistes Lustrés) to eclogite metamorphic facies (e.g., Mont Viso, Grand Paradiso; [28] and references therein; Figure 4), except rare units that escaped subduction (e.g., the Chenaillet ophiolite and Helminthoïd Flysch).

4.3. The Subbriançonnais, Briançonnais and Prepiemonte Units

Several tectonic units were defined between the remnants of the proximal margin (Dauphinois domain; BB1 & BB2; cf. Figure 1) and the (proto-)oceanic domain (Piemonte domain; BB7; cf. Figure 1), however, the related terminology is confusing since names change along strike and depending on authors. Here we follow [108] and use the terms *Subbriançonnais*, *Briançonnais sensu stricto* (*s. str.*) and *Prepiemonte* as domain and unit names. This subdivision was first mainly based on pre-orogenic stratigraphic criteria, and, thus, on their pre-convergence palaeogeographic position. From the 1970^{ies} onwards, based on the study of present-day rifted margins, these units were additionally described as remnants of a former European–Briançonnais rifted margin [71]. In the following, we revisit these three units with the aim to assign them a BB affinity, establish their position in the former European margin, and characterize their Alpine evolution.

4.3.1. The Subbriançonnais Units

Rift-Related Observations

In the study area, the Subbriançonnais units are essentially exposed in the Argentière half-window, where they consist of a stack of detached Mesozoic cover successions. The basement of the former Subbriançonnais domain is not exposed and thus unknown. The sedimentary succession is largely discontinuous, either because of a pervasive Alpine overprint and/or a complex primary rift- or pre-rift-inherited stratigraphic architecture. The pre-rift section is locally made of thick Triassic dolostones associated with evaporites (Keuper). The sedimentary depositional environment became progressively deeper during the Jurassic and Early Cretaceous [109], which indicates the significant creation of accommodation space. The age, width, structural architecture and paleogeographic significance of this depocenter are, however, highly debated (see Section 7.2.2 for discussion). From a paleogeographic perspective, many authors consider the Subbriançonnais units as belonging to the southern margin of the Valais Basin. [47,110,111] showed that the eastern part of this basin was floored by the exhumed mantle. Although the poor preservation of the Subbriançonnais unit in the study area renders it challenging to attribute it a specific BB, its large syn-rift accommodation and the occurrence of exhumed mantle remnants in the Petit Saint Bernard area in the Versoyen ([110]; see Figure 4 for location) indicates that this domain was strongly extended. We suggest that the Subbriançonnais corresponded to BB4 and BB5 in the west (hyperextended crust; cf. Figure 1) and to BB4, BB5 and BB6 in the Petit Saint Bernard area and further east.

Orogen-Related Observations

The occurrence of black schists and sandstones of Eocene and Oligocene age (e.g., "Flysch Noir" of [112–114]) indicates that nappe stacking did not start before the Oligocene in the Subbriançonnais domain. The Subbriançonnais units underwent low metamorphic conditions, reaching pressures of 2–4 kbars and temperatures of 200–250 °C ([115]; Figure 4).

4.3.2. The Briançonnais Units s. str.

Rift-Related Observations

The Briançonnais units s. str., referred to as the *external Briançonnais* in [71], are well exposed near the city of Briançon (Figure 7). They include Permo-Carboniferous sediments ("*Zone Houillère*") overlying the highly metamorphosed Variscan basement. The pre-rift sedimentary cover comprises Early Triassic sandstones and Middle- to Late Triassic carbonates. These are directly overlain by Middle Jurassic transgressive deposits (neritic limestones), which reached deeper pelagic conditions in the Late Jurassic (clayey limestones with nodular Ammonitico Rosso facies; [116]). The main characteristic of the Briançonnais units s. str. is the unconformity between Triassic and Middle Jurassic deposits, which is associated with a widespread and up to 300 m-deep karstification of the Triassic carbonate platform [40,117,118]. This unconformity is generally attributed to an episode of uplift and emergence of the Briançonnais domain. Upsection, the occurrence of Upper Cretaceous limestones directly onto the Jurassic Ammonitico Rosso indicates a significant sedimentary hiatus of Early Cretaceous age, locally marked by a hardground, and thus attributed to either condensed sedimentation, or non-deposition [39,109,119]. Upper Cretaceous to lower Eocene sediments are essentially pelagic (e.g., the "*marbres en plaquettes*" of [120]).

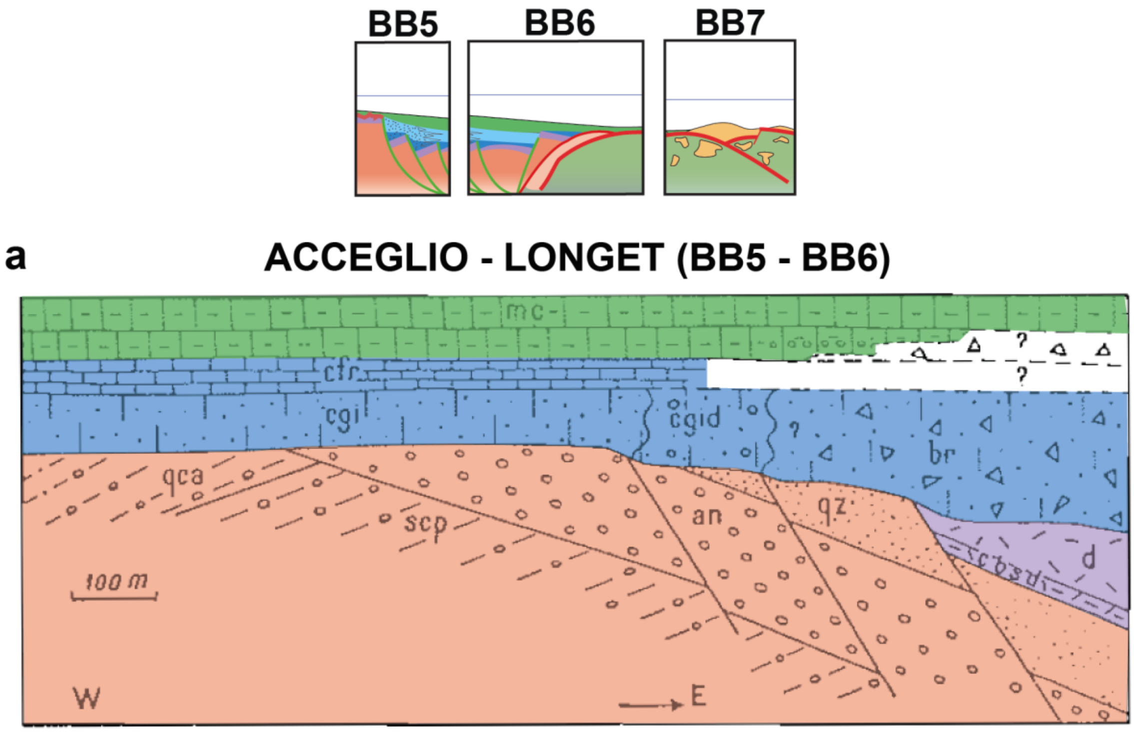

Figure 7. *Cont.*

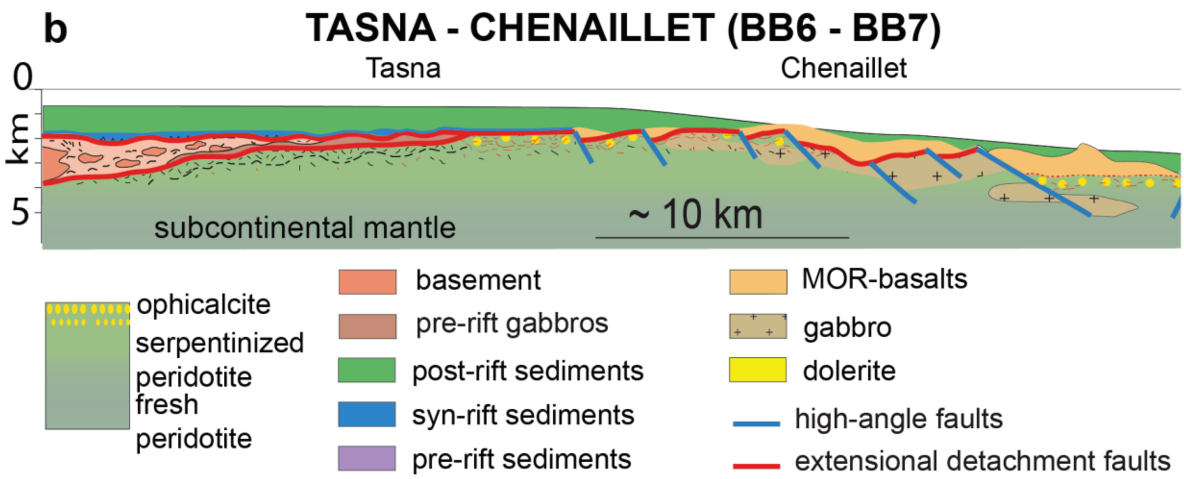

Figure 7. Examples of BB5, BB6 and BB7 in the Western Alps: (**a**) The Acceglio and Col du Longet outcrops display Jurassic sediments directly over basement and/or mega-breccia bodies, which are here interpreted as characteristic of a distal margin (BB5 and/or BB6); Figure modified from [121] see text for details and discussion); (**b**) The Tasna Nappe is consensually recognized as preserving an ocean–continent transition (OCT) between thinned continental crust and exhumed mantle, and thus was regarded as a BB6 by [19]. The Chenaillet ophiolite displays remnants of an embryonic seafloor spreading system, and thus was regarded as a BB7 by [19]. Figure modified from [100].

Ref. [19] attributed a BB3 affinity (cf. Figure 1) to the Briançonnais units s. str. Here we follow this hypothesis and additionally suggest that the Briançonnais s. str. formed a ribbon of moderately thinned crust between the overstepping en-échelon Valais and Piemonte basins, which individualized during the Pliensbachian–Toarcian lithospheric necking. The two basins eventually merged during crustal breakup, so that the Briançonnais ribbon was attached to the European margin in the southwest, while it was separated from the European margin by the V-shaped Valais Basin in the northeast (e.g., [122]; see Section 7.2.3 for discussion). Note that comparable rift architectures can be seen today along the southern North-Atlantic distal margins (e.g., Orphan Knoll, Flemish Cap, Galicia Bank; [55,123]).

Orogen-Related Observations

The formation of the Briançonnais nappe stack is recorded by the deposition of the middle Eocene to Oligocene "Priabonian Trilogy" [84], which documents a transition from marine/carbonate to more detrital sedimentation (micro-breccias and sandstones). This shift was interpreted to mark the arrival of the Briançonnais domain in the proximity of the accretionary prism [77]. Metamorphic facies in the Briançonnais units s. str. reached greenschist facies with temperatures of 250–375 °C and pressures of 0.2–0.5 GPa in the *Zone Houillère* ([124]; Figure 4).

4.3.3. The Prepiemonte Units

Rift-Related Observations

The term "Prepiemonte" was initially used to refer to the units derived from a domain between the Briançonnais s. str. (a basement high) and the Piemonte (a (proto-)oceanic domain). It was attributed to units located between the Briançonnais and Piemonte units in the Alpine nappe stack that neither showed the typical "Briançonnais unconformity" nor ophiolitic material. In the following, we describe these units, which include two types of sequences: (1) breccia-bearing sequences overlying the basement, such as in the "Acceglio Zone" of [125] and in the Prorel–Grand Chalvet–Rio Secco units ([116,126]; Figure 7a); and (2) "complete" (continuous) Late Triassic to Early Jurassic sequences such as in the Rochebrune unit [127].

The Acceglio and Prorel–Grand Chalvet–Rio Secco units consist of a polymetamorphic Variscan basement, whose top is intensely hydrated and deformed. The latter is overlain by reworked basement clasts (including mantle rocks in the Acceglio area; [128]) and Late Jurassic to Cretaceous limestones alternating with massive and chaotic breccias with large blocks (Figure 7a). In the past, this unconformable succession was interpreted to reflect a pervasive late Hercynian erosion, followed by deposition of a terrigenous *Verrucano-type* succession of Permian to Lower Triassic age, whose clasts derive from the reworked basement. The occurrence of Late Jurassic to Cretaceous deep-water sediments directly over the *Verrucano* represents a major unconformity, which can be evocative of the Briançonnais unconformity. This led former authors to interpret this type-succession as belonging to a basement high derived from a more oceanward part of the Briançonnais ribbon relative to the *external Briançonnais*, which they called the *internal Briançonnais* (e.g., [116,125]). Following this interpretation, the Acceglio and Prorel–Grand Chalvet–Rio Secco units would correspond to BB3 (Figure 1). However, comparable sequences can be found in the Tasna unit ([47]; Figure 8b), which is so far the world best example of an exposed OCT and the type locality of BB6 (Figures 1 and 7b). This observation prompts us to reconsider the interpretation of the basement–sediment contact in the Acceglio and Prorel–Grand Chalvet–Rio Secco units and explore alternative hypotheses to the classical erosional unconformity based on renewed fieldwork (see Section 5).

The succession of the Rochebrune unit [127] includes Late Triassic dolostones followed by Lower Jurassic cherty limestones (the so-called "*Lias Prepiemontais*") and Middle Jurassic calcschists made of detrital limestones with breccia horizons. The breccia clasts are mainly composed of detritus sourced from erosion of both the continental basement and its sedimentary cover [129]. Although their stratigraphic position is still a matter of debate, coeval successions locally contain mantle-derived serpentinites, prasinites and dolerite clasts (e.g., Prafauchier breccia; [127]). Radiolarian cherts were deposited over the clastic succession, followed by calcareous calcschists. They are interpreted to be Middle- to Late Jurassic in age and to predate the onset of the pelitic schists ascribed to the Early Cretaceous by regional correlation [72]. Locally, Upper Cretaceous greyish calcschists are preserved (i.e., Roche de Clots unit). The lack of a major unconformity and the presence of mantle-derived and prasinite clasts are incompatible with a Briançonnais s. str. origin of this succession, which prompted [126] to define it as the typical *Prepiemonte* sequence. That this stratigraphic succession displays thick syn-rift detrital deposits and breccia bodies with mixed continent- and mantle-derived clasts impels us to suggest that the Rochebrune unit corresponds to a BB5 and/or BB6 (cf. Figure 1).

Orogen-Related Observations

Metamorphic conditions measured in the Acceglio, Prorel–Grand Chalvet–Rio Secco and Rochebrune units are significantly higher than those in the Briançonnais s. str., reaching up to 1.2–1.5 GPa and 450–500 °C (blueschist facies; [124,130,131]). The change in the metamorphic facies is abrupt between the Briançonnais units s. str. and the Prepiemonte units, increasing by 0.7 GPa across their boundary (Figure 4). Alpine deformation is also significantly more intense in the Prepiemonte unit compared to the Briançonnais unit s. str. The classical interpretation suggesting that the Acceglio and Prorel–Grand Chalvet–Rio Secco units are part of the thick-crusted (>10 km) innermost part of the Briançonnais ribbon implies that such thick continental crust was able to subduct up to 1.2 to 1.5 GPa (>40 km) before being exhumed and emplaced in the nappe stack (e.g., [132]). Below, we question this interpretation and propose an alternative scenario.

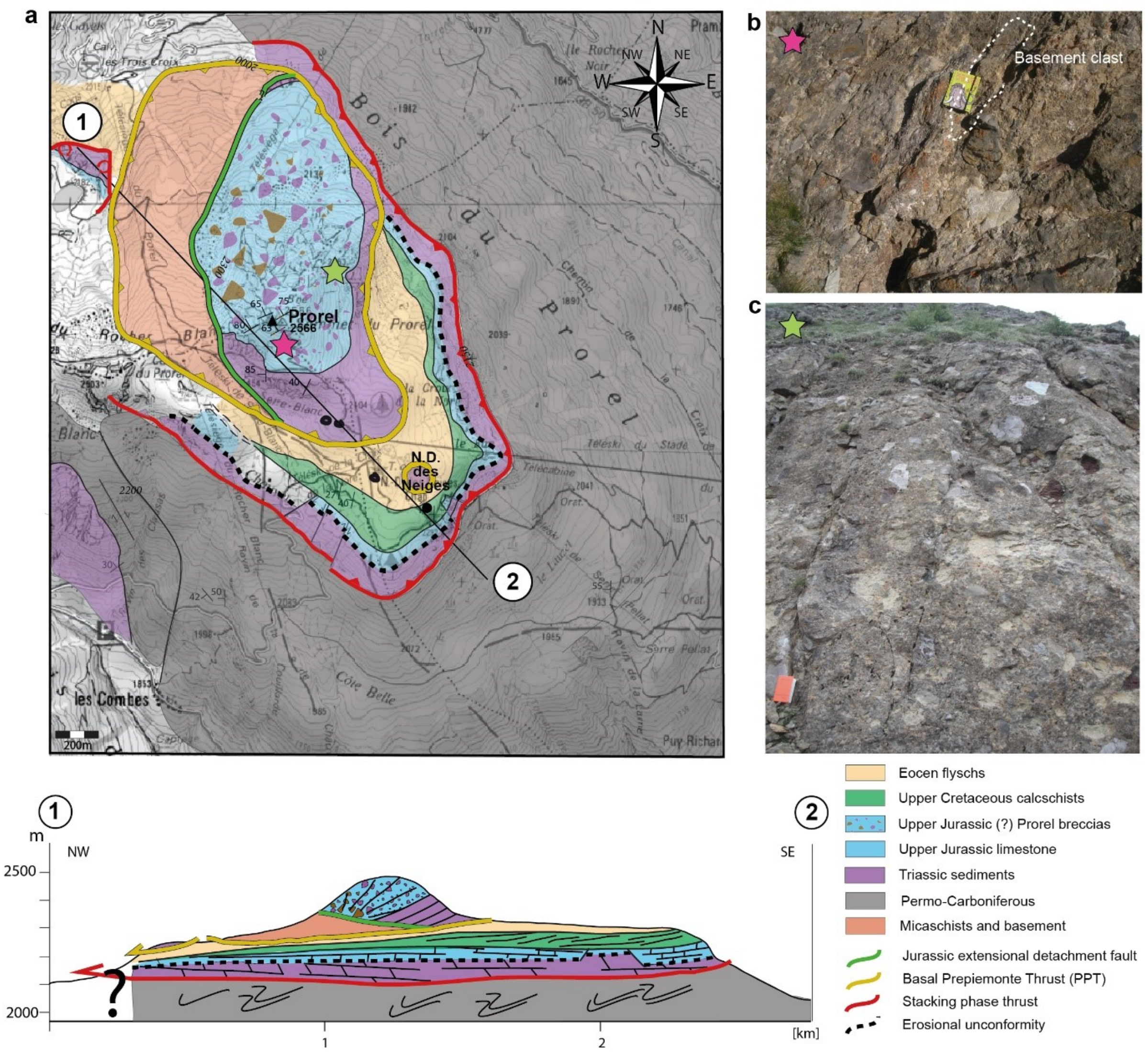

Figure 8. (**a**) Map and geological section (1)–(2) across the Prorel summit located west of Briançon. The Prorel summit is formed by breccias of supposed Jurassic age that overlie Triassic limestone/dolostone. This sedimentary sequence unconformably overlie a basement made of chlorite-rich micaschists. The contact in-between (green line in the figure) was interpreted as a reactivated Jurassic detachment fault (see text for details and discussion); (**b**) photograph of the polygenic breccias of the Prorel summit, including both pre-rift sediment- and basement clasts; (**c**) photograph of the monogenic breccias of the Prorel summit, including only pre-rift sediment clasts.

5. Reassessment of Rift Inheritance in the Prorel and Grand Chalvet–Rio Secco Units

5.1. New Field Observations

5.1.1. The Prorel Summit

The Prorel summit lies west of Briançon (Figure 5). It displays three stacked units separated by two major sub-horizontal thrust contacts (Figure 8a). The two lower units comprise Palaeozoic and Early-to-Middle Triassic rocks overlain by Late Jurassic carbonates and Eocene flysch. This stratigraphic succession is comparable to that of the Briançonnais units s. str. The uppermost unit additionally contains micaschists and sedimentary breccias of supposed Jurassic age [120,125,133]. The breccias generally dip towards the NW (Figure 8c). They contain clasts of micaschists derived from the underlying basement (Figure 8b), as well as clasts of Triassic dolostones and Permo-Triassic sandstones (Figure 8c). The size of the breccia clasts increases from SE to NW (i.e., upsection), as their composition evolves from monogenic (pre-rift sediment clasts only) to polygenic (mixed basement- and sediment clasts; [134]; Figure 8a). The breccias do not show internal deformation. They rest unconformably over Middle Triassic dolostones in the SE, while they overlie tectonized (foliated) and altered (chloritized) basements in the NW. Chloritization and foliation of the top of the basement are likely pre-Alpine, since both affect basement clasts that are reworked within the overlying undeformed sedimentary breccias. Consequently, we interpret top basement chloritization and foliation to have occurred during the Alpine Tethys rifting.

The reworking of basement clasts within the overlying, undeformed breccias implies that the basement was outcropping at the seafloor at the time of breccia deposition. This observation can best be explained by invoking an episode of basement tectonic exhumation. [125] suggested that these breccias were deposited over a steep normal fault, however, our field observations do not allow us to determine the original angle of the fault. We can only confirm that geometrical relationships indicate an extensional setting.

5.1.2. The Grand Chalvet—Rio Secco Section

In the Grand Chalvet—Rio Secco section, a Mesozoic succession lies unconformably above slivers of the poly-metamorphic basement (Figure 9). The latter is mainly composed of Palaeozoic micaschists and gneisses and displays black gouges and foliated chlorite schists (Figure 9e,f). The Mesozoic succession consists of a block of up to 800 m-thick Norian dolostones overlain by an irregular, thick bed of Rhaetian limestone that is, in turn unconformably capped by a hardground. The hardground shows a well-developed, 5–10 cm-thick brownish, iron- and manganese-rich crust containing poorly preserved fauna. [135] suggested that the hardground formed during the late Hettangian–early Sinemurian. However, this age is not supported by paleontological dating [46]. The hardground is unconformably onlapped by a monotonous succession of ca. 100–120 m of Sinemurian–Toarcian (?) calcschists [129] mainly formed by an alternation of limestones, pelites and cherts.

At the saddle between the Grand Chalvet and the Tête des Fournéous (Figure 9a), some thicker beds of coarse-grained, recrystallized limestones are visible. These limestones are overlain by a detritic, up to 60 m-thick succession composed of coarse breccia layers and calcarenitic beds. Near the base of this detritic formation, the breccias are monogenic and predominantly made of Upper Triassic dolostones. Upsection, the breccias becomes polygenic and additionally include basement-derived clasts. This section ressembles the "*Complexe détritique*" of [136], which additionally includes blocks of serpentinites. Although we did not observe serpentinite clasts, we found some dark greenish, strongly chloritized metasediments likely derived from the dismantling of the underlying basement, as interpreted for the Rio Secco and Prorel areas (see the previous section).

Further north, in the Vallon de la Ruine, a continuous and well-bedded Jurassic sequence directly overlies the basement. The top of the basement is strongly chloritized and made of foliated cataclasites, like the top basement observed in the Prorel (see the previous section). [137] analysed these rocks and highlighted striking chemical similarities with fault rocks from a well-preserved Jurassic detachment exposed in the Err nappe (Central Alps). The observations made in the Vallon de la Ruine are also similar to those reported from Piz Alv (Bernina Nappe) in the Central Alps by [46] (see their Figure 8): both sites display Jurassic sediments directly overlying a tectonically exhumed basement. Thus, in analogy with [46], we interpret the outcrop of the Vallon de la Ruine as an extensional allochthon overlying a former rift-related detachment fault (Figure 9c). We interpret the outcrop of the Vallon de la Ruine to be in lateral continuity with the block made of pre-rift Triassic dolostones observed in the Grand Chalvet–Rio Secco section (see the first paragraph of the current section).

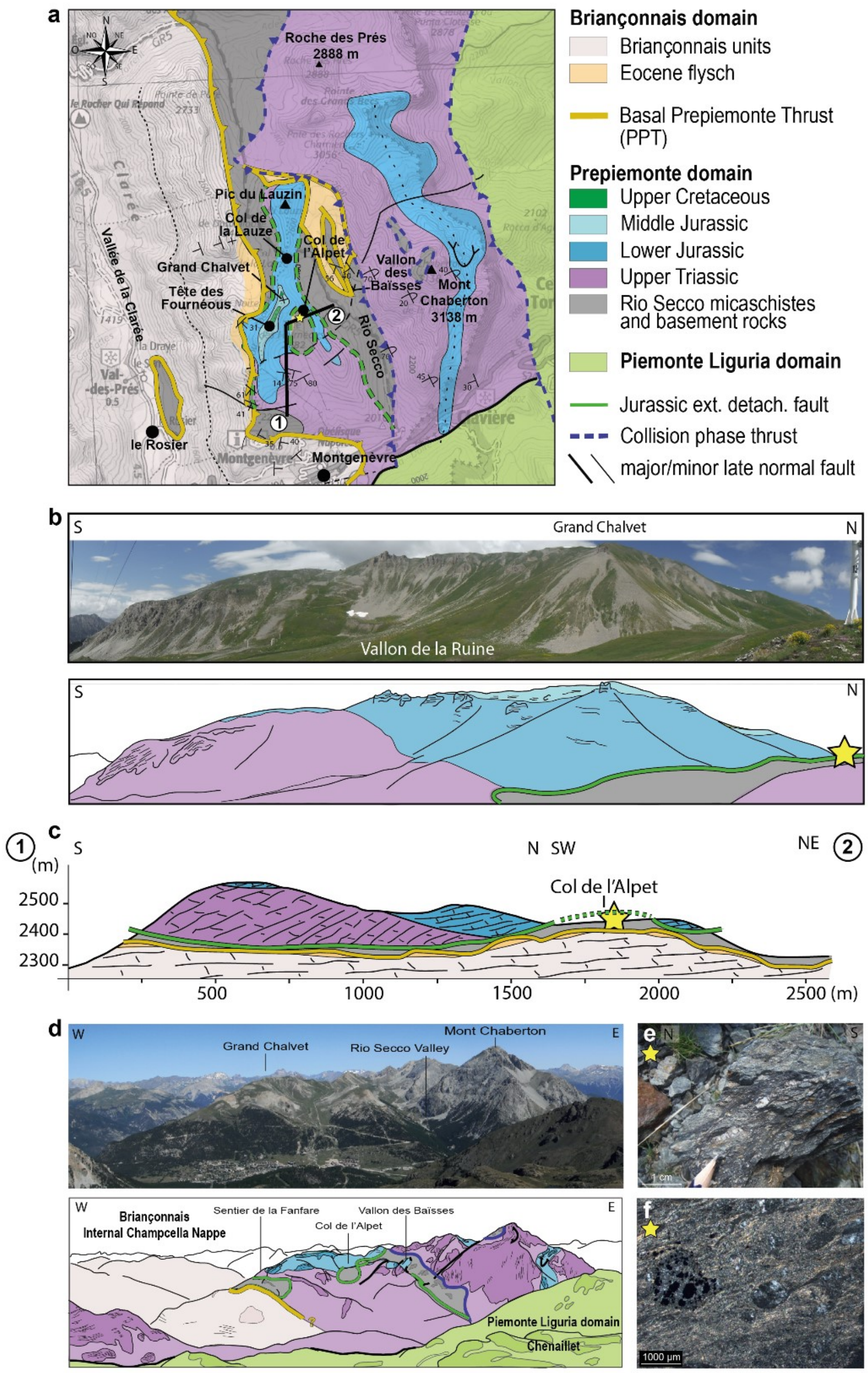

Figure 9. (**a**) map of the Grand Chalvet area showing the location of section (1)–(2) shown in panel (**c**) and the location of the black gouges (yellow star) shown in panels (**e**,**f**); (**b**) Panoramic view across the "Crête du Grand Chalvet" and the "Col de l'Alpet" and (**c**) its geological interpretation showing the relationship between the Briançonnais and Prepiemonte units. The zone containing slivers of basement with black gouges (green line) is interpreted as a reactivated Jurassic extensional detachment fault. It truncates internal structures of the Grand Chalvet; (**d**) Panoramic view of the Grand Chalvet Mont Chaberton area showing the Prepiemonte domain and the Basal Prepiemonte Thrust (PPT). The green line traces remnants of basement containing gouges, which are interpreted as relics of a reactivated Jurassic detachment system; (**e**,**f**): macroscopic and microscopic view of the black gouge within the basement at Col de l'Alpet.

Further east, in the Rio Secco Valley, widespread Triassic evaporites and coarse sandstones that alternate with recrystallized limestones of Dogger(?)–Malm(?) age occur at the contact between the basement and the overlying Jurassic sediments [136]. Despite significant Alpine overprint, this succession displays striking similarities with those observed at the Vallon de la Ruine, the Prorel summit and the Acceglio unit, which prompt us to suggest that this succession is primarily inherited from the Jurassic rifting.

5.2. From Outcrop Observations to Paleogeographic Interpretations

Because of the pervasive sedimentary gap and karstification over large areas of the Briançonnais domain s. str. and their sealing by Late Jurassic deep-water post-rift sediments, this domain was consensually interpreted as having undergone significant syn-rift uplift and erosion followed by fast drowning (e.g., [71,109,116]). As the Acceglio, Prorel and Grand Chalvet–Rio Secco units locally show deep-water Jurassic sediments directly over the basement; the intervening unconformity was interpreted to have resulted from the same uplift and erosional event. Hence, these units were assumed to derive from the same (Briançonnais) high and were referred to as "Internal Briançonnais" (see [71,116,125]). To account for the lack of the thick Triassic dolostones in the "Internal Briançonnais", while they are present in the "External Briançonnais", this interpretation implies that uplift and karstification were respectively higher and more pervasive in the most distal/internal part of the Briançonnais. Besides, to account for the up to 1.2–1.5 GPa reported in the Acceglio unit, this model requires that the thick continental crust of the Briançonnais was able to penetrate the subduction trench and was subsequently exhumed.

Based on our observations from the Prorel and Grand Chalvet–Rio Secco units, we question this interpretation and suggest that the unconformity between the basement and the overlying Late Jurassic sediments is the expression of basement exhumation along detachment faults during Jurassic rift-related hyperextension, rather than the result of uplift and erosion. This new interpretation for the Western Alps is comparable to that already accepted for the Tasna Unit and for the Err and Bernina nappes preserving remnants of the distal Adriatic margin in the Central Alps in SE Switzerland [8,47]. Our new interpretation has major implications on the paleogeographic and paleo-topographic position of the so-called "Internal Briançonnais units", which may be better interpreted as Prepiemonte units. Indeed, if the top of the basement is interpreted as an exhumation fault, the Prorel and Grand Chalvet–Rio Secco units are more likely derived from a BB6 than from a BB3 (Figure 1). Following this hypothesis, the basement–sediment unconformities did not form on a topographic high but may rather represent a tectonic exhumation surface located at a topographic low. Here we interpret the Prorel, and Grand Chalvet–Rio Secco units as analogues of the Tasna unit, i.e., as units derived from the most distal European–Briançonnais margin. Thus, we suggest including in the *Prepiemonte domain* the "Ecailles Intermédiaires" of [120], the "Ultrabriançonnais" domain of [138], and the "Internal Briançonnais" of [71] and [125].

The reinterpretation of some internal units of the Western Alps as deriving from a paleo topographic low (Prepiemonte) rather than a paleo high (Briançonnais s. str.) is of major importance for the restoration of the rift architecture. In the following, we show which diagnostic field observations can be used to distinguish between highs and lows and to identify major fault scarps in fossil-rifted margins, and we evaluate the nature and origin of unconformities for the former distal European–Briançonnais margin.

5.2.1. Criteria to Discriminate between Topographic Highs and Lows

Relying on isostatic considerations, topographic highs necessarily display higher crustal thicknesses than topographic lows. Diagnostic features expected to be observed at topographic highs include minor accommodation and, when the high is subaerial, the presence of erosional truncations and the possible occurrence of a karst in the case of carbonates. The occurrence of pelagic facies over an erosional truncation does not necessarily indicate a deep-water depositional environment but requires deposition below the wave base in a setting protected from currents. The occurrence of a karst overlain by pelagic sediments, as observed in the Briançonnais s. str., can be explained by the emergence and subsequent drowning of an isolated topographic high (here also referred to as a *continental ribbon*), for instance, due to syn-rift uplift followed by post-rift thermal subsidence [38,41]. All observations made at the Briançonnais s. str. are compatible with the hypothesis that this domain represented an isolated ribbon of relatively thick continental crust within the distal European–Briançonnais margin.

Conversely, topographic lows are expected to display significant accommodation and deep-water sedimentary facies. Field observations from the Prorel and the Grand Chalvet-Rio Secco (this study), as well as from the Acceglio zone [125] indicate: (1) a lack of erosional unconformity, as proven by the locally complete stratigraphic record of the pre-rift Triassic to early Jurassic strata; (2) significant accommodation, as indicated by the large thickness and/or deep-water facies of the Late Jurassic to Cretaceous deposits intercalated with pelagic depositional environments (radiolarian cherts); and (3) the presence of gravity-driven sedimentation, as proven by the presence of breccias and turbidites. All these fingerprints are consistent with the position of the Prorel and Grand Chalvet–Rio Secco units at a topographic low with respect to the Briançonnais units s. str.

5.2.2. Criteria to Distinguish between Erosional and Tectonic Exhumation Surfaces

Sub-aerial erosional unconformities are necessarily associated with either tectonic uplift and/or global sea level changes (eustatism) and must occur on a relatively thick crust (>25 km). In carbonate environments, sub-aerial erosion is typically marked by karst. In contrast, extensional detachment faults can exhume deep-seated rocks from their footwall at the surface/seafloor independent of uplift and/or sea-level changes, and hence can occur in deep-water environments/over thin crust. Diagnostic fingerprints of extensional detachment fault systems have been discussed by [8] and include: (1) gouges, foliated cataclasites and cemented cataclasites in the core- and damage zone of extensional detachment faults [33,89,139]; (2) tectono-sedimentary breccias reworking the underlying basement directly over the detachment surface [140,141]; and (3) discontinuous pre- and early syn-tectonic sedimentary deposits whose base is truncated by extensional faults, and whose top is onlapped by continuous post-tectonic deposits ([142] and references therein).

The basement/sediment contacts in the Prorel and Grand Chalvet–Rio Secco units are unlikely to be Alpine tectonic surfaces since compressional structures (e.g., thrusts) do not generate tectonic exhumation of basement, and thus cannot account for the deposition of syn-tectonic sediments directly over a tectonized top basement surface. Besides, the reworking of deformed basement clasts into the sedimentary breccias sealing a tectonized top basement testifies for a pre-sedimentation deformation (i.e., pre-orogenic in the present example). Thus, the hypothesis that breccias are derived from a "*schistes à blocs*" (wildflysch) olistostrome shed from the advancing thrust sheets (e.g., [120,143]) does not hold.

The basement/sediment contacts in the Prorel and Grand Chalvet–Rio Secco units are also unlikely to be uplifted and/or eroded surfaces since, on the one hand, erosion does neither produce gouges nor cataclasites. On the other hand, basement clasts should occur in the first breccias overlying the basement; and yet the first breccias overlying basement display monogenic, sediment-derived clasts, which turn only later into polygenic, sediment- and basement-derived clasts. Note that a comparable evolution from monogenic- to polygenic- breccias was reported from the Err Nappe of the former distal Adriatic margin and was linked to the long-lived activity of an extensional detachment fault [141]. A similar evolution from monogenic- to polygenic breccias was also found at ODP Site 1068 in the distal Iberia margin [144], which is now consensually regarded as displaying low-angle detachment faults (e.g., [145]).

In the Acceglio zone, Refs. [121,125] noticed that the nature of the breccia clasts was almost always intimately linked to that of the underlying substratum (Figure 7a). A sub-aerial, continental origin of the Acceglio zone breccias is unlikely and would be paradoxical, as recognized by [125], who invoked a submarine off-scarping of unknown origin to explain the denudation of large portions of pre-rift basement and sediments. The Acceglio breccia are also strikingly similar, both in composition and facies distribution, to the so-called Bardella- and Saluver breccias from the distal part of the conjugate Adriatic margin. [43] and [141] interpreted the latter to have formed during the Middle Jurassic extension along long-offset detachment faults (i.e., the Err detachment system). The Acceglio–Col du Longet breccias can be compared to the Falknis Breccia Fm adjacent to the Tasna Nappe, which was interpreted to have formed at the toe of a mega-fault scarp, just inboard of the Tasna OCT [45,47]. The Acceglio–Col du Longet breccias are also comparable to the Monte Galero Breccias (Arnasco–Castelbianco unit in northwestern Italy), which were interpreted to have formed at the toe of a major topographic ramp controlled by a large fault [46]. All these settings correspond to BB5 (Figures 1 and 10).

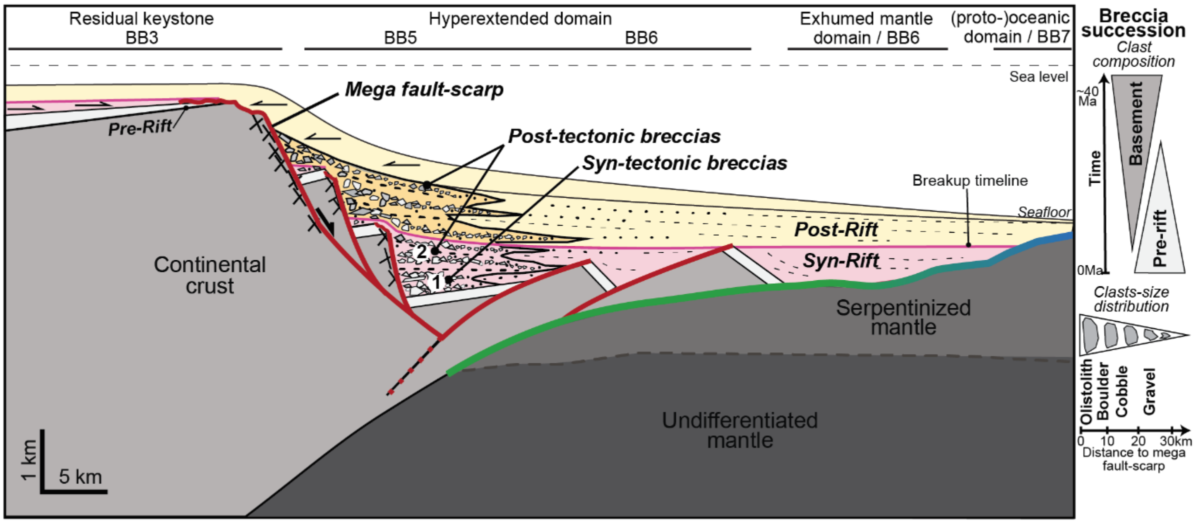

Figure 10. Schematic diagram summarizing the major structural and stratigraphic characteristics across a mega-fault scarp at distal magma-poor rifted margins (modified from [45]). Note the presence of syn- and post-rift mega-breccias at the toe of the fault scarp. In the present study, we interpret the Briançonnais s. str. units to have belonged to the distal high to the left of the figure, which represents a residual keystone/BB3; and we interpret the Prepiemonte units (including the so-called "Internal Briançonnais" of [126]) to have belonged to an extensional detachment system at a topographic low/BB5–BB6, as illustrated in the center of the figure. (1) syn-tectonic strata; (2) post-tectonic strata.

Here we propose a new interpretation for the basement/sediment contact in the Acceglio, Prorel and Grand-Chalvet–Rio Secco regions, namely that the top basement in these units is a Jurassic tectonic exhumation surface. This hypothesis relies on three main observations: (1) the tectonized and hydrated nature of the top basement; (2) the reworking of this tectonized/hydrated basement within the overlying breccias; and (3) the (unconformable) tectonic juxtaposition of blocks of pre- and early syn-rift sediments against basement (i.e., extensional allochthons) and their sealing by little deformed late syn-rift to post-rift sediments. Although these interpretations are new for the studied sites in the Western Alps, similar interpretations have been proposed for outcrops in the Central Alps (e.g., Punta Rossa unit (Valais domain); [140]), which show a much stronger Alpine overprint, based on the diagnostic fingerprints mentioned above. Our observations from the Prorel and Grand Chalvet–Rio Secco areas compare well with those reported by [47] from the Tasna OCT (Figure 7b). Indeed, the Tasna region is consensually regarded as displaying tectonic exhumation surfaces overlain by either extensional allochthons made of pre-rift material, or by syn-rift sediments [47,111,146]. We stress that our new interpretation of the unconformity between basement and overlying Late Jurassic sediments in the Prepiemonte units can solve the apparent paradoxes reported by [125].

5.2.3. Criteria to Discriminate between a Sharp vs. a Progressive Topographic Slope

Considering the Prepiemonte units as deriving from a topographic low and the Briançonnais units s. str. from a topographic high, leads to the question of whether the slope in-between was sharp (i.e., achieved over a short distance by one steeply dipping major fault, e.g., Figure 10) or progressive (i.e., achieved over a large distance by several minor normal faults). Abrupt topographic steps usually provide a long-lived detrital source for (coarse-grained) sediment and significant accommodation. Thus, they often display massive breccia bodies with large clasts and olistoliths directly at their toe, and clasts of decreasing size as moving away from the scarp ([45]; BB5 in Figures 1 and 10). Conversely, long-lived mega-breccia deposition is not expected along and ahead of a gentle slope with multiple fault-controlled depocenters. In such settings, breccia bodies are limited to the syn-rift sequence and confined to the fault-bounded depocenters (e.g., Figure 2 in [45]).

The presence of mega-breccia bodies with large clasts all along the inner part of the Prepiemonte domain is compatible with an abrupt topographic step, as [125] suggested when pointing out the large clasts in the Acceglio–Col du Longet breccias. [45,47] proposed a comparable interpretation for the Falknis Breccia and the Nappe de la Brèche Fms, and [46] for the Monte Galero breccias. The presence of a major and steep topographic ramp in the distal part of the Briançonnais ribbon (Figure 11c) would compare with the mega-fault scarps observed along the distal part of the East India, Newfoundland and Socotra magma-poor upper-plate margins [41,45]. Thus, based on the occurrence of massive mega-breccia bodies along the southeastern side of the Briançonnais ribbon, we suggest the existence of an abrupt topographic step, presumably owing to a mega-fault scarp between the Briançonnais and Prepiemonte domains. This step would correspond to a BB5 and would testify to the upper-plate margin affinity of the European–Briançonnais margin (Figures 1 and 11c).

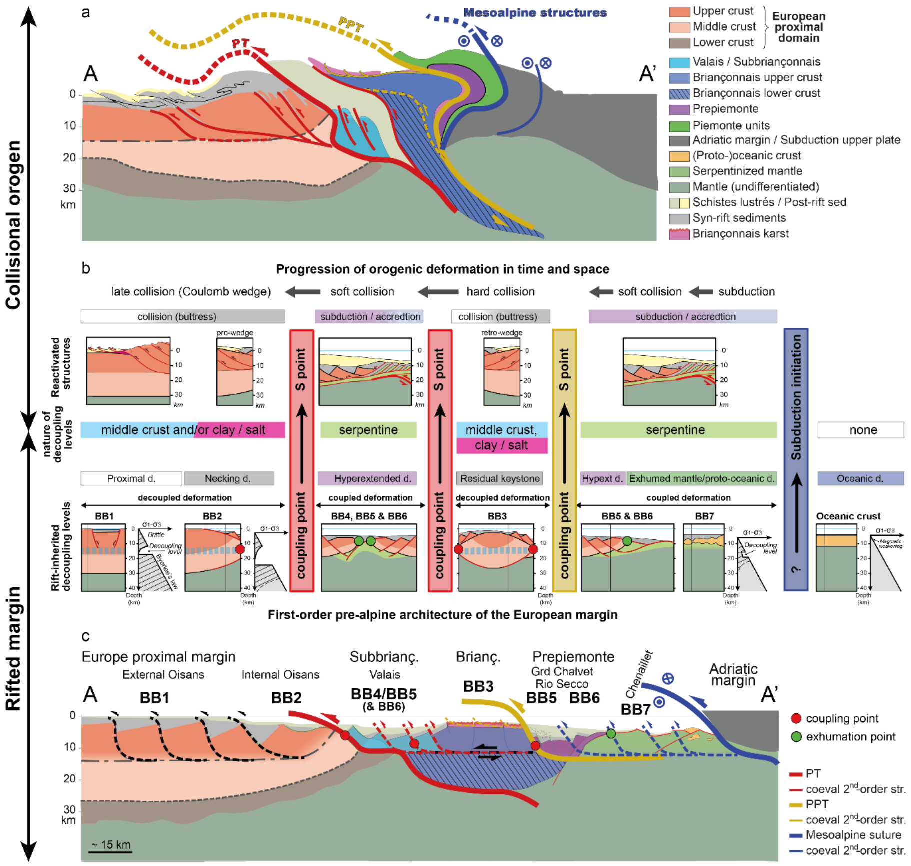

Figure 11. (**a**) Interpretation of the ECORS-CROP seismic profile (modified from [24]) showing the location of the main Alpine units described in the text (see Figure 12 for present and paleogeographic

location); (**b**) Conceptual model (modified from [12]) illustrating (top panel): the in-sequence reactivation of coupling points and rift-inherited decoupling levels from subduction to soft collision, to hard collision, and to late collision in the European–Briançonnais margin; (bottom panel): first-order original architecture of the European–Briançonnais margin, which was characterized by the occurrence of a ribbon of relatively thick continental crust (Briançonnais domain; 15–25 km) between two hyperextended domains (the Valais and Piemonte domains). The schematic sections also display the distribution of the Coupling Points (CPs) and main decoupling layers. (**c**) Schematic section across the European–Briançonnais margin (modified from [19]) showing the location of the future main Alpine units described in the text (see Figure 12 for present and paleogeographic location). Note that the rift section in panel (**c**) and the orogenic section in panel (**a**) are displayed on same scale and that the surface of the Subbriançonnais, Briançonnais upper crust, Briançonnais lower crust and Prepiemonte domains are equivalent between the two panels. Abbreviations: d.: domain; PT: Basal Penninic Thrust; PPT: Basal Prepiemonte Thrust; str.: structure; σ_1–σ_3: deviatoric stress.

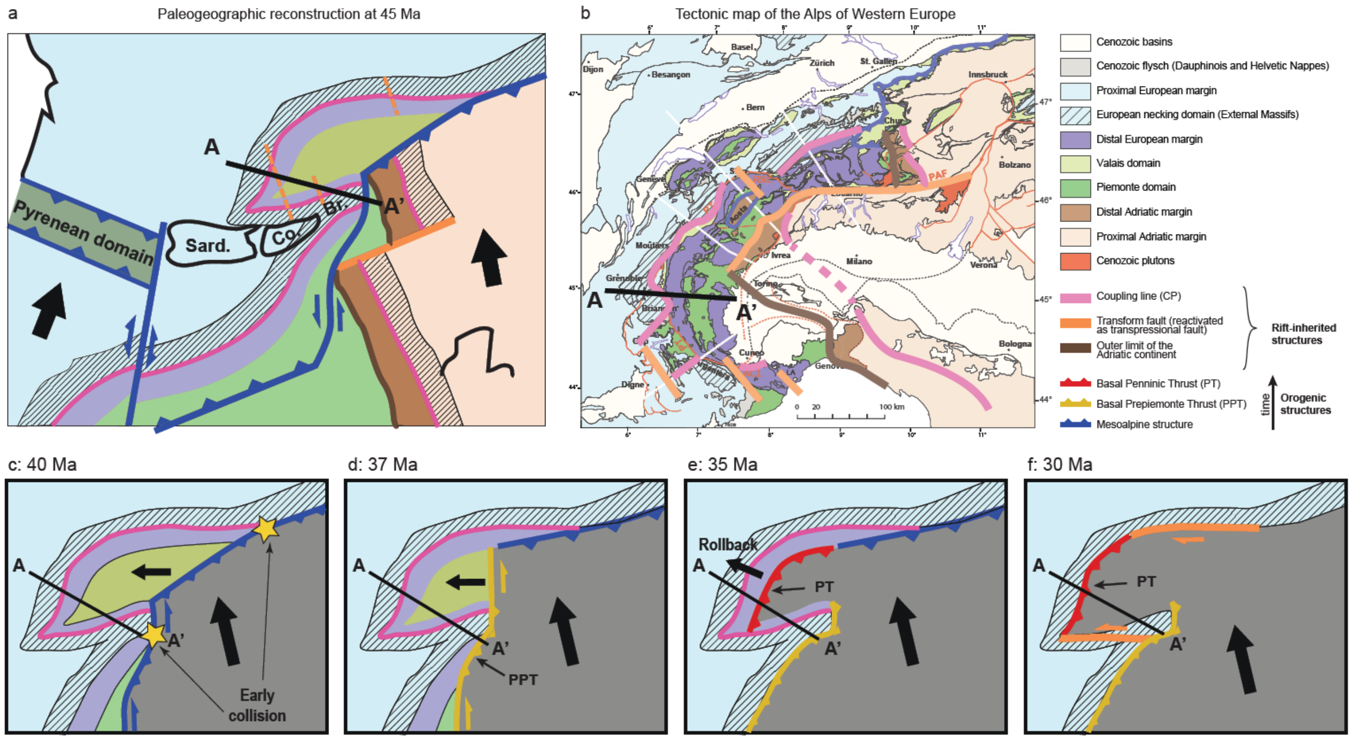

Figure 12. (**a**) Schematic paleogeographic restoration of the Alpine Tethys realm at 45 Ma based on (**b**) a present-day tectonic map of the Alps of Western Europe (modified from [24]; see text for details); (**c**–**f**) Schematic paleogeographic restorations of the Briançonnais region showing the successive phases of continental collision, Basal Prepiemonte Thrust (PPT) and Basal Penninic Thrust (PT) activity, as well as the local vs. regional kinematic directions (see text for details and discussion). Abbreviations: Br.: Briançonnais; Co.: Corsica; Sard.: Sardinia.

6. The Alpine Stack and Related Major Structures in the Western Alps

The Western Alps are made of a stack of nappes derived from the former distal European–Briançonnais margin, squeezed between the European and Adriatic proximal margins, which acted as buttresses. The first-order crustal structure of the orogen is well-constrained thanks to numerous geophysical datasets [70,147–149]. Examples are the ECORS-CROP section ([81]; Figure 3a) and the tomographic section published by [74] (Figure 3b). These two sections show that the orogen is framed by a tabular, ca. 30 km-thick crust underlain by a fairly well-imaged Moho interface. The limit between the Adriatic plate and the internal parts of the belt is not precisely resolved on the seismic image. In contrast, the termination of the European proximal margin (i.e., the external domain of the

Alpine orogen) is relatively well-defined by converging reflections in the internal part of the external massifs (e.g., internal Oisans; Section 4.1.1). The tomographic section (Figure 3b) displays an east-dipping European Moho down to ca. 80 km. Noteworthy, the first-order crustal template in this section is very similar to the crustal structure imaged in the Western Pyrenees ([150,151], and references therein).

The intra-orogenic structure is less well resolved in the geophysical data. In the following, we address the questions of how to reconcile the relatively simple orogenic crustal template with: (1) the much more complex superficial geological observations; and (2) the inherited rift template and its kinematic evolution. We are aware that attempting to unravel the detailed structure and evolution of the arcuate Western Alps in 2D is hampered by the fact that the structure of the belt is 3D and non-cylindrical. Therefore, we only focus on the structures bounding the main tectonic units forming the Alpine stack. Following [8], we define first-order orogenic structures as structures juxtaposing different rift domains, which we identify relying on the BB approach described above. In this view, three main structures can be defined: (1) the Penninic Basal Thrust (PT) between the European proximal margin and the Briançonnais domain s. str.; (2) the Prepiemonte Basal Thrust (PPT) between the Briançonnais domain s. str. and the Prepiemonte domain as defined herein (see Section 4.3); and (3) the limit between the Prepiemonte and Piemonte domains.

6.1. The Basal Penninic Thrust (PT)

The present-day limit between the external European units (i.e., the Dauphinois, including the ECM) and the internal Penninic (Briançonnais) units corresponds to the Basal Penninic Thrust (PT; [152]). On an E-W-directed transect across the Western Alps (Figure 11c), the PT is often a relatively simple, east-dipping, crustal-scale structure (Figure 3a). When looking at the PT, the following key observations stand out: (1) in the northern Western Alps, the PT seeded in a hyperextended domain, as indicated by the occurrence of deep-water facies in the ultra-dauphinois units in its footwall, and of the Subbriançonnais units in its hanging-wall; (2) the youngest sediments in the footwall of the PT are late Eocene in age ("Priabonian Trilogy"; [153]), which implies a coeval or younger activation of the corresponding thrust; and (3) the rocks of the footwall generally display similar metamorphic degrees to those of the hanging-wall [28], except in the domain east of Moûtier/Petit Saint Bernard (Figure 4). These observations suggest that the PT nucleated in the Subbriançonnais/Valais domain and reactivated the European necking domain (Figure 11a,c). The kinematic transport direction along the PT was WNW-directed in the study area but may have changed from N-directed to W-directed through time, as discussed in Section 7.6. The main movement along the PT occurred during the late Eocene, post-dating the stacking of more internal units [154]) and predating the emplacement of the ECM and Miocene formation of the fold-and-thrust belt in the more external parts of the orogen [83]. In map view (Figure 4), between the west of Briançon and the southwest of Sion, the PT follows the internal limit of the Pelvoux, Belledonne and Mont Blanc ECM. Northeast of Sion and between the southwest of Briançon and the east of Argentera, the PT is less well defined, and it is noteworthy that, in these regions, no ECM is exposed. These two areas correspond respectively to the Rawil and Vocontien depressions. The origin of the Rawil depression has been explained in [155] as inherited from the pre-Alpine left stepping of the Mont Blanc–Aiguilles Rouges and Aar basement highs. In contrast, the Vocontian depression sits on thinner continental crust, as recently imaged by [148], and hence can be regarded as the lateral termination of the Subbriançonnais domain (e.g., Valais Basin).

In the Central Alps, the PT was uplifted during a late phase of crustal doming [156], which led to the tectonic exhumation of deeper parts of the PT footwall (i.e., the so-called North Penninic units derived from the northern margin of the Valais Basin (see [60,155]). In the southwest, the PT is difficult to map but seems to lie on the internal flank of the Mercantour–Argentera Massif that is in a more internal position compared to the rest of the Western Alps [157]. These observations highlight that, despite some local complexities discussed below (Section 7), a first-order link between the location of the PT and crustal thinning/limits of rift domains can be established.

6.2. The Basal Prepiemonte Thrust (PPT)

The Basal Prepiemonte Thrust (PPT) is here defined as the limit between a hanging-wall comprised of units derived from the most distal (hyperextended domain) of the European–Briançonnais margin and a footwall comprised of more external units (e.g., Dauphinois and Briançonnais s. str.). While the units in the hanging-wall of the PPT typically display high-P rocks (apart from local exceptions such as the Chenaillet Ophiolite), and deep-water post-rift sediments, those in the footwall lack high-P rocks (Figure 4). Note that our definition of the PPT differs from that of previous publications since we include the "internal Briançonnais units" of [71] into the Prepiemonte units (see Section 5).

Five key observations stand out from the PPT: (1) the PPT separates units derived from two different rift domains, namely a topographic high (Briançonnais ribbon) in the footwall and a topographic low (Prepiemonte hyperextended domain) in the hanging-wall; (2) the PPT partly reactivated a former mega-fault scarp at the internal/distal edge of the Briançonnais ribbon (cf. Section 5.2); (3) the youngest sediments in the footwall of the PPT are late Eocene in age [85], implying coeval or younger age for this structure; (4) rocks in the footwall and hanging-wall of the PPT display markedly different metamorphic degrees, namely low- to moderate-pressure facies in the footwall and high-pressure facies in the hanging-wall ([124]; Figure 4); and (5) remnants of basement rocks found along the PPT display diagnostic features of former Jurassic detachment systems (see Section 5).

The PPT is well exposed and mapped in the Grand Chalvet area (Figure 9 and top cross sections in Figure 5), where it juxtaposes the Grand Chalvet unit (Prepiemonte) on top of the Champcella unit (Briançonnais s. str.) along a sub-horizontal tectonic contact. This contact is localized along an Upper Triassic evaporite-rich decoupling level. The PPT is also exposed in the tectonic window of the Vallon des Baïsses (Figure 9b,d), where a sub-horizontal succession of Briançonnais affinity (Middle Triassic dolostones directly overlain by Upper Jurassic limestones) is truncated by a steep fault and overlain by rocks and deposits of Prepiemonte affinity (Rio Secco micaschists and basement rocks; Figure 9d). In this area, the PPT forms a ramp that coincides with the eastern termination of the Grand Chalvet area. It juxtaposes the high-P-bearing Rio Secco unit against the Briançonnais Champcella unit that experienced only low-grade metamorphism. A similar N-S-trending ramp structure that juxtaposes high-P and steeply dipping Prepiemonte units over low-P rocks belonging to the Briançonnais unit can also be found in the Rochebrune area further south ([127]; bottom cross-section in Figure 5).

In the Mont Chaberton and Rochebrune areas (see cross-sections in Figure 5), we interpret the complex, discontinuous and locally little deformed Mesozoic sequences in the hanging-wall of the PPT as former extensional allochthons floored by a Jurassic extensional detachment, as indicated by the occurrence of fault rocks (see discussion in Section 5). We assume that these Jurassic detachment faults were reactivated as thrusts during Alpine convergence, which would explain their poor preservation. This interpretation relies on the fact that structures like those exposed at the Grand Chalvet (Figure 9, see description in Section 5) have been described in the Central Alps, where they were interpreted as thrust faults reactivating former extensional detachment faults (e.g., Punta Rossa unit; Figure 9 in Beltrando et al., 2014).

In the footwall of the PPT, the Champcella nappe system exposed between Grand Chalvet and Prorel (Figure 5) displays a top-to-the-west stacking of Triassic dolostone-bearing units along evaporite-bearing shear zones. South of the Durance valley, the Champcella nappe is overthrust by the Peyre Haute nappe, which preserves the Briançonnais unconformity. The thin-skinned nappe stack observed in the Briançonnais s. str. may have formed simultaneously with the emplacement of the PPT in its footwall. Out-of-sequence back-thrusts (in dark blue in Figure 5) locally cut these thrusts, largely complexifying the local geology. As a result, the external parts of the Briançonnais s. str. lie at present on top of the internal parts of the Champcella unit (e.g., northern section in Figure 5; see also [158]). This complex structure resulted from the interference between a rift-inherited, north-south tending, topographic step and polyphase Alpine E-W-directed shortening. N-directed thrusting, as proposed by [57], is observed in the high-P-bearing units in the hanging-wall of the PPT, but we cannot confirm its occurrence in the footwall of the PPT.

Based on our observations, we conclude that the PPT reactivated former detachment systems in the most distal parts of the European–Briançonnais margin hyperextended domain, here referred to as the Prepiemonte domain. We suggest that the PPT seeded at an inherited topographic ramp that is used to separate the Briançonnais ribbon from the Prepiemonte hyperextended domain (see Section 5.2). This ramp was reactivated as a WNW-directed thrust to accommodate Alpine deformation. Thrusting along the PPT occurred after the deposition of the (Eocene) Nummulitic limestone [154], and pre-dated both the stacking of the more external parts of the belt and the phase of back-thrusting. The PPT, as defined herein, is a new structural element of the Western Alps; therefore further studies will be necessary to determine its extent and unravel its detailed kinematics.

6.3. Internal and External Limits of the (Proto-)Oceanic Piemonte Domain

When looking at the limit between the Piemonte and the Prepiemonte units, i.e., the boundary between the European–Briançonnais margin and the (proto-)oceanic domain, five key observations stand out: (1) the basement of these units are made of different rock types, namely continent-derived in the Prepiemonte units, and serpentinized mantle and/or (scarce) gabbros in the Piemonte units; (2) the sedimentary cover is similar in both units, predominantly made of Schistes Lustrés; however, basalts are lacking or very rare over continental basement (Prepiemonte unit); (3) the youngest sediments are Cretaceous flysch-type deposits in both units [107]; (4) both units display similar high-P metamorphic degrees; and (5) the contractional kinematic history is similar in both units, including polyphase north- and west-vergent movements ([57], and references therein).

Based on these observations, it is difficult to distinguish between the Prepiemonte and Piemonte domains, particularly where continent-derived extensional allochthons overlie mantle rocks (see discussion in Section 7.2.4). The main thrusts appear to have reactivated rift-inherited detachment faults in both the exhumed mantle- and hyperextended domains, or to have nucleated along decoupling levels within the overlying sedimentary sequence.

7. Discussion

7.1. Determining the Rift Template of the Western Alps: Why Is It Important?

Unraveling the link between the orogenic architecture and the initial rift template is necessarily an iterative process because the orogenic architecture cannot be understood without taking the rift-inherited architecture into account, and the rift structure cannot be restored without understanding the orogenic architecture. Although we are still far from understanding the details of both the Alpine orogenic- and rift system, the use of the BBs/rift domains approach described above (Section 2) is a significant step toward comprehending how rift inheritance controls the subsequent orogenic evolution on a first order.

In the last decades, the increasing number of geophysical studies and drill holes at magma-poor rifted margins enabled the identification of their primary morphological, structural and compositional characteristics. Relying on such diagnostic criteria to interpret field observations from the Grischun region in the Swiss Alps enabled [42,48] to propose 3D restorations of parts of the distal Adriatic margin. Despite the pervasive Alpine overprint of the former distal European–Briançonnais margin, several authors proposed restorations of its initial architecture (e.g., [72]; for a review, see [71]). Since then, numerous studies have improved our knowledge of the European–Briançonnais margin: Ref. [159] refined the age of rifting in the proximal margin. Ref. [78] described long offset low-angle faults in the internal Oisans Massif, consistent with more recent studies on the internal Mont Blanc massif by [33,34], who linked these structures to thinning along the European necking zone. Ref. [38,41,160] reexamined the main unconformities in the Briançonnais unit s. str. and discussed their implications on the sedimentary, tectonic and isostatic evolution of the distal domains of the European margin. New studies on the most internal parts of the Alps highlighted core complex structures in the (proto-)oceanic Chenaillet unit [49], as well as in the blueschist-facies ophiolites of the Queyras area [93]. These findings support the similarity between the fossil European–Briançonnais margin and present-day magma-poor rifted margins. However, much uncertainty remains on the three-dimensional architecture and the origin of the Briançonnais continental ribbon and surrounding Valais and Piemonte basins. Besides, the nature, origin and age of unconformities and breccias overlying crustal and mantle rocks in the most internal domains of the Alps remains a matter of lively debate. In this contribution, we propose some first-order answers to these questions.

7.2. First-Order Architecture of the European–Briançonnais Margin

In this section, we propose a first-order restoration of the European–Briançonnais margin (Figure 11c). To achieve this, we relied on the following methodology: (1) we used regional field observations on the nature of the top basement, sedimentary facies, amount of accommodation, the occurrence of erosional- or tectonic unconformities and/or magmatic additions to identify BBs and the rift domains they derive from [19]; and (2) we provided a first-order estimate of the width of each rift domain based on published tectonic restorations and/or width ranges observed at modern rifted margins (e.g., [5]). In contrast to classical first-order margin templates (e.g., Figure 1), the European–Briançonnais margin shows a complexity owing to the occurrence of a continental ribbon in the outer part of the margin (i.e., the Briançonnais domain; Figure 11c). Below, we describe and discuss the characteristics of the different domains we identified. Note that this simple-looking approach is hampered by the pervasive Alpine overprint of the internal units, the oblique trend of the rift domain boundaries relative to the shortening direction, and the possible occurrence of strike-slip movements during convergence. How much of the former margin has been lost during subduction is also poorly constrained. However, that all distal BBs (BB5, BB6 and BB7) can be identified in the internal units of the Western Alps implies that orogeny may well have sampled the whole former distal margin, including the OCT and (proto-)oceanic domains.

7.2.1. The Proximal European Margin

The crustal structure of the former proximal margin is well-imaged until the internal part of the ECM. On reflection- and tomographic seismic sections (Figure 3), the lower parts of the crust do not display major deformation structures, despite the presence of rift basins and thrust faults. This suggests that most rift- and orogenic structures in the external/proximal domain are only local and do not affect the whole crust. The nature of the transition between the external- (former proximal margin) and internal parts of the orogen (former distal margin) is more debated. On the ECORS-CROP section [81], as well as in the recent CIFALPS seismic data [161], the ca. 30 km-thick crust terminates beneath the internal Oisans, as marked by two converging reflections (Figure 3a). In classical interpretations, the upper reflection is defined as the PT and corresponds to a major Alpine thrust. However, such a pair of converging reflections are unlikely to be linked to orogenic shortening only [15]. Noteworthy, similar pairs of converging reflections are fingerprints of necking domains in seismic images of modern rifted margins, where they are interpreted as conjugate extensional shear zones accommodating crustal tapering ([162,163] and references therein). However, other interpretations exist to explain the deeper reflections (see Figure 2 in [15] and references therein).

The observation that the PT juxtaposes deep-water post-rift sediments in its hanging-wall over a ca. 30 km-thick basement with shallow-water post-rift sediments in its footwall supports the hypothesis that the crust in the hanging-wall of the PT was thinner than that in its footwall before Alpine shortening. Therefore, we suggest that the PT thrust seeded within the Valais hyperextended domain and reactivated the necking domain of the European margin, and that the latter is marked by a pair of converging reflections. This interpretation is consistent with seismic observations at modern margins, where the necking domain is defined as the domain where the top basement and Moho start converging (e.g., [32]). This interpretation is further supported by the occurrence of long-offset low-angle detachment faults in the internal part of the Oisans Massif ([78]; cf. Section 4.1.2) and is consistent with the interpretation of [34] that the former European necking domain in the Western Alps coincides with the inner part of the ECM. Thus, we are confident that the proximal European margin (BB1) and the necking domain (BB2) are well preserved in the Western Alps and that the latter can be mapped along the internal parts of the ECM.

7.2.2. The Valais Basin

Although there is a consensus that the Valais Basin is located between the European shelf and the Briançonnais ribbon, its age, extent, and width are highly debated. In our study area, we only have access to the Subbriançonnais units, which are interpreted to sample the northwestern slope of the Briançonnais ribbon. The observations made in the Argentière half-window do not allow us to confidently assign a BB affinity to this domain, although it is proven that the Valais Basin locally reached mantle exhumation (BB6; cf. Section 4.3.1). Remnants of the Valais Basin are sandwiched between the European and Briançonnais domains and extend from east of the Tasna Nappe exposed in the Engadine valley in SE Switzerland [47] towards the west, including the Petit Saint Bernard/Versoyen unit [110]. This hypothesis is well supported by sediment dispersal (see [47,164]). The southwestern tip of the Valais Basin is unknown, but it may be represented by the Vocontian Basin, which lies in the foreland of the Western Alps. Refs. [165,166] suggested that the Valais Basin was linked to the Atlantic Ocean through the Pyrenean–Biscay system and thus assigned an Early Cretaceous age to the formation of this basin. Despite the lack of age data confirming this model, many Alpine geologists relied on it (for references, see [22]). More recent studies question the Cretaceous Valais Ocean model because (1) reliable age data from exhumed mantle rocks and magmatic additions flooring the Valais Basin, as well as directly overlying sediments, point to a Jurassic origin (e.g., [47,110,167], and references therein); (2) a link between the Valais Basin and the Pyrenean domain is neither documented in the Provence–Corsica domain, nor in the Sardinia–Languedoc domain (e.g., [168,169]); and (3) recent plate kinematic models show that the Early Cretaceous Iberia/Europe plate boundary is strongly segmented but does not display any opening of a new oceanic basin in the Alpine domain [21,50], conversely to older kinematic models (e.g., [170]), in which the M0 magnetic anomaly was incorrectly used as an isochron [171].

Based on existing data, the most likely scenario is that the Valais Basin formed during the Jurassic as a V-shaped basin that was floored in the east by mantle rocks (e.g., Petit Saint Bernard area (Figure 4) [110]; and Tasna Nappe [47]) and terminated westwards in the Vocontian Basin. In the Vocontian, outside the domain affected by major Alpine shortening, the crust is at present only ca. 15 km thick [148], implying that extension in the Valais Basin reached the necking stage therein. Further northeast, in the present study area, the Valais Basin reached the hyperextension stage as it displayed exhumed mantle domains [110]. The size of the Briançonnais ribbon may have decreased towards the northeast until it disappeared where the Valais and Piemonte basins merged, east of the Tasna Unit/Engadine window in the Central Alps (Figure 2d).

7.2.3. The Briançonnais Ribbon

The characteristic fingerprint of the Briançonnais ribbon is its stratigraphic record, in particular, its diagnostic syn- and post-rift unconformities. The paleogeographic position of this ribbon, its crustal thickness and width are poorly constrained and most likely varied along strike (Figure 2d).

Former studies assumed that the Briançonnais represented a terrane [166] and that it formed the continuation of the Iberian plate in the Alpine domain [172]. This model assumed that the European–Iberia plate boundary corresponded to an (oceanic) basin linking the Pyrenean and Valais domains, a model that is increasingly questioned by recent studies (see discussion in the previous section). In the alternative V-shaped Valais model, the Briançonnais represents a V-shaped continental ribbon terminating northeastwards, where the Valais Basin merged with the Piemonte (proto-)oceanic domain of the Alpine Tethys (Figure 2d). This is in line with the decreasing volume of Briançonnais-derived units going eastwards and the lack of these units in the Tauern window. Although further work is needed to confirm our interpretation, at present, we are not aware of any data disproving it.

The restoration of the Briançonnais nappes s. str. near Briançon (i.e., the restoration of the Champcella and Peyre Haute nappes), assuming an E–W shortening, provides a pre-shortening width estimate of the order of 60 km for the Briançonnais ribbon in this region [173]. Ref. [174] reckoned a width $\geq$20 km for the only Champcella Nappe in the Briançonnais.

The stratigraphic record and isostatic evolution of the Briançonnais domain imply that this ribbon was floored by a moderately thinned crust. However, precise values are difficult to determine. Conflicting interpretations exist for the uplift and erosion history of this domain. While older studies assumed an uplift of more than 1 km to account for the complete removal of the Triassic in the "Internal Briançonnais" in our interpretation, where the "Internal Briançonnais" units rather correspond to Prepiemontais units (see Section 5), we estimate the uplift of the Briançonnais s. str. to be only a few hundreds of meters and to decrease towards the more internal units (i.e., towards the former distal margin). This interpretation is based on the fact the Peyre Haute Nappe, which forms the highest nappe in the Briançonnais s. str. stack, and hence the most internal Briançonnais s. str. unit, locally preserves Liassic limestones below the unconformity.

In their recent review of the Briançonnais isostatic history, [38] showed that the timing of uplift and erosion was closely linked to that of crustal necking. The later unconformity between the Late Jurassic pelagic limestones and the Late Cretaceous was interpreted as the result of passive infill, as expected for gravity-driven sedimentation filling a residual rift topography (Figure 11c; [41]).

7.2.4. The Hyperextended and (Proto-)Oceanic Domain of the Piemonte Basin

Here we discuss the Prepiemonte and Piemonte units as belonging to the same paleogeographic entity. Although these units show major differences, such as the presence or absence of serpentinized mantle rocks, they also share many similarities, namely (1) the presence of both radiolarian cherts and Schistes Lustrés over the basement (crust and/or mantle); and (2) a similar high-P metamorphic overprint. Studies of well-preserved OCTs such as the Tasna OCT [47] or the Err–Platta OCT [175] showed a gradual transition from a wedging continental crust to a domain of exhumed subcontinental mantle and finally to a magma-dominated proto-oceanic domain. Despite obvious differences between hyperextended- (BB4 and BB5) and exhumed mantle/(proto-) oceanic domains (BB6 and BB7), the transition between them does not correspond to a sharp boundary and hence is challenging to define. This is especially true in the internal units of the Western Alps, where a pervasive Alpine overprint decoupled the sediments from their original underlying basement (thin-skinned deformation). Some authors argue that the contacts between the basement and tectono-sedimentary breccias overlain by deep-water sediments result from Alpine reactivation (e.g., Wildflysch-type sequence; [57]). However, we disagree that all breccia–basement contacts should be exclusively interpreted as Alpine thrusts. The main arguments against an Alpine origin for some breccias are that convergent settings cannot account for: (1) the reworking of top-basement-derived fault rocks in pre-Alpine sedimentary breccias; (2) the existence of primary contacts between breccias and basement, as observed in the Prorel and Grand Chalvet (see previous sections) and in the Chenaillet [49]; and (3) the occurrence of little- or not deformed sediments over highly deformed and altered top basement. Moreover, many breccias in the Western Alps are clearly pre-Alpine, as indicated by their stratigraphic position.

Many studies consider the Alpine Tethys, including the Valais Basin, to be floored by Penrose-type oceanic crust (e.g., [22]), and yet evidence supporting this hypothesis is still missing [20,101]. Indeed, all mantle rocks found in ophiolites show a subcontinental origin [101], and all basalts display a subcontinental mantle contamination signature; [176,177]). Besides, the applicability of slab models to the Alpine system, as proposed by [22] (and references therein), has recently been questioned by [20] (and references therein). Therefore, we argue that using the term *proto-oceanic* is more appropriate to refer to the crust flooring of the Piemonte Basin.

7.3. Rift-Inherited Structures and Decoupling Levels: Role in Controlling Reactivation

Inherited rift structures and decoupling levels are often reactivated during convergence, and thus, they may be challenging to identify in the final orogen. In the Western Alps, well-preserved rift structures can be found in the little overprinted external domain (e.g., Ornon fault; Figure 6) and more rarely in the internal domain (e.g., normal- and detachment faults at the Chenaillet ophiolite). However, most rift-inherited structures and decoupling levels may simply be either not exposed or misinterpreted. The study of the Pyrenean–Biscay system [12] allowed us to identify well-preserved remnants of rifted margins that were previously interpreted as collisional structures. It also allowed to development of concepts on the fate of rift-inherited decoupling levels during convergence [14]. Here we aim to test these concepts in the Western Alps. The schematic European–Briançonnais margin section in Figure 11b shows the distribution of rift domains, main rift structures and potential decoupling levels.

Among the first-order characteristics of rifted margins, the location of the coupling point (CP; i.e., where the continental crust becomes fully brittle; see Section 2) is of major importance for understanding their inversion. Indeed, the CP (or "Coupling line" when the CPs are mapped along strike) separates the thin-crusted hyperextended, exhumed mantle and/or (proto-) oceanic domains with an overall low buoyancy ("negative floatability") oceanward from the thick-crusted necking and proximal domains with a high buoyancy ("positive floatability") continentward (see the pink "Coupling line" in Figure 12). This concept was used to explain why the wedging crust of the Alpine necking zones (BB2)/external domains failed to enter subduction, acted as buttresses, and hence remained in the orogenic wedge (e.g., [15]). Here we go further by suggesting that the border between the Briançonnais s. str. and Prepiemonte units was also a CP and that the Briançonnais continental ribbon (BB3) acted as a buttress in the Western Alps, in a comparable way as the European necking domain/External Massifs (BB2). This model would account for the relatively good preservation of the Briançonnais domain in the present-day orogen.

Considering the CP as a "floatability threshold" as described above, only rocks derived from BB4, BB5, BB6 and BB7 (i.e., oceanward from CP) should be able to enter the subduction channel, and hence to reach high-P metamorphic conditions, conversely to rocks derived from BB1, BB2 and BB3. In this perspective, the reassessment of Lemoine's so-called "internal Briançonnais", which displays a high-P overprint but was assumed to belong to BB3, is critical (cf. Sections 4.3.3 and 5). Note that this hypothesis may only be true for "immature/Ampferer-type subduction systems" such as the Alpine Tethys ([5,20] and references therein), in which the relatively short slab (<few 100′s km) does not generate a significant subduction pull-force. However, thick-crusted domains may enter subduction in "mature/Benioff-type subductions", in which a long and dense slab may generate a significant subduction pullforce, as exemplified in the Caledonides [178].

The CP also separates crusts with different rheological properties and potential decoupling levels (Figures 1 and 11b), which may explain the difference in the reactivation style on either side. For instance, in distal parts of rifted margins (crustal thickness < 10 km), decoupling levels typically lie within the serpentinized mantle, along low-angle detachment systems and/or within pre-rift salt levels or clay-rich post-rift sediments. Yet, in the Alpine nappe stack, the base of the Piemonte and Prepiemonte units is either a serpentinized mantle, a former rift-related detachment, or a decoupling level in the sedimentary cover. A comparable reactivation may have occurred in the Valais Basin of our study area, where the crust was presumably thinned to less than 10 km. There, the Subbriançonnais units appear to have been detached along a shallow decoupling level within the sediments and/or upper serpentinized mantle. Note that the preservation of detachment surfaces or their footwall rocks is rare and often linked to basement singularities. For instance, mantle or crustal rocks preserved at the Prorel and Grand Chalvet–Rio Secco are generally linked to basement rugosity, corrugated surfaces and/or local offsets along late-rift high-angle faults, as discussed by [8].

In domains where the crust is thicker than 10 km, such as the Briançonnais s. str. (BB3) or the ECM (BB1/BB2), decoupling levels usually occur in the sedimentary cover as well as in the ductile middle crust (for examples see [155,179]). In our study area, decoupling levels continentward of the CP often lie within Triassic evaporites in the Briançonnais units, leading to thin-skinned-dominated deformation. The reactivation of the European necking zone is very similar to that observed in the Pyrenees, considering that the so-called "Axial Zone" of the Pyrenees is the genetic equivalent of the ECM: thick-skinned deformation occurred where weak sediments (e.g., evaporites) were absent, while deformation remained thin-skinned-dominated where Triassic evaporites were present (e.g., [14]). That necking domains often lack pre-rift sediments due to significant basement tectonic exhumation/new real estate creation [34,142] would explain why Alpine thrusts rooted in the ductile middle crust in these domains, as supported by crustal-scale seismic imaging (e.g., ECORS-CROP). Besides, as only such thick-skinned deformation associated with crustal ramps can build significant topography, this would also explain why the highest mountains of the Western Alps lie in the footwall of a former necking domain.

By analyzing the Alpine stack, we can see that the two major structures that are the PT and PPT, initiated oceanward of a CP and seeded at inherited topographic ramps (necking zones) that used to separate thick-crusted/buoyant proximal and necking domains from thinner and "subductable" hyperextended-, exhumed mantle- and (proto-)oceanic domains (Figure 11b,c). Geological maps at the scale of the Western Alps confirm that the PT and the PPT generally (but not exhaustively) followed rift domain boundaries and juxtaposed former deep-water domains over shallow-water domains (Figure 4).

7.4. Timing of Convergence, in-Sequence Faulting, and Strain Partitioning

The Mesoalpine phase is generally accepted to have consisted of N-S directed shortening that initiated at magnetic anomaly 34 (84 Ma, Santonian/Campanian). It is interpreted to mark the onset of the Africa–Europe convergence ([22,23]; Figure 12c). Related deformation is documented as early as the Late Cretaceous (e.g., Provençal phase) and was initially diffuse in the European–Briançonnais margin, as recorded in the Alpine foreland in SE France (e.g., Massif du Dévoluy, [180]; and S^{te} Victoire or S^{te} Baume) and, according to [57], in the realm that later became the Western Alps. Early, N-S-directed shortening is also documented in the (proto-)oceanic domain, as indicated by high-P mineral ages [181]. Note that the youngest high-P ages available from the Western Alps are ca. 35 Ma, and their exhumation is dated 32 to 31 Ma [67], showing that high-P rocks were about to be exhumed back to the seafloor shortly after 35 Ma. This implies that subduction and exhumation of high-P rocks occurred before 31 Ma. The shift to E-W-directed shortening occurred after 35 Ma, as documented by the sediments of the Priabonian Trilogy. Thus, the final emplacement of high-P rocks in the present nappe stack occurred coeval to the transition from N–S- to E–W-directed shorting in the Western Alps.

Dating of sediments and minerals shows that the stacking of the Alpine nappes occurred in sequence toward the continent, initiating with the PPT, continuing with the PT and ending in the external domain. Nappe stacking initiated in deep-water conditions, as indicated by flysch-type deposits. Later/more inboard, it involved shallower conditions, as indicated by first shallow-marine nummulitic limestones and then by shallow-marine to subaerial Molasse-type sediments. This succession is interpreted to reflect the progressive involvement of thicker crust with higher buoyancy in the collision (Figure 11b). The final collision stage involved the proximal margin with mid-crustal decoupling levels in the footwall of the former necking domain (cf. previous section).

In summary, deformation related to Alpine convergence in the Western Alps realm initiated with local distributed events (Provençal phase; [180]). Nappe stacking started only in the late Eocene and migrated in sequence from internal to external. Note, however, that the timing of collision may have changed along the strike of the Alpine arc, and strain may have been partitioned between thrusting and strike-slip faulting within a complex kinematic framework (see Figure 12 and discussion in Sections 7.5 and 7.6).

7.5. From Late Subduction to Collision in the Western Alps

The spatio-temporal evolution from late subduction (i.e., thin-skinned orogenic wedge accretion) to early collision (i.e., nappe stacking involving the PPT and PT in the distal margin) to mature collision (i.e., nappe stacking involving the proximal margin) is schematically shown in the map and section views in Figures 11 and 12.

The late subduction stage in the Alpine Tethys: Little is known about this stage, apart from the well-constrained N-S-directed movement of Africa/Adria relative to Europe. However, the width of the intervening (proto-)oceanic domain remains ill-constrained. While older models assumed wide oceans [22], more recent models suggest that this domain was less than 250 km wide [52]. The narrow ocean solution can explain the lack of back-arcs in the Alpine domain (a narrow ocean implies a short slab; [5,20]). An important observation is that the hyperextended domain entered the subduction, as indicated by the (ultra-)high-P rocks derived from this domain (e.g., Dora Maira, Acceglio). Continental collision first occurred in the north (Central Alps; Figure 12a) before the onset of collision in the west (Western Alps; Figure 12c), as shown by the ages of high-P rocks derived from both regions [182–184]. Thus, we suggest that hard collision initiated in the northeast and locally also in the southwest, while most of the future Western Alps still underwent strike-slip-dominated subduction within a (proto-)oceanic or hyperextended domain (Figure 12a). We postulate that the onset of hard collision (i.e., when the necking domain reached the subduction trench) triggered "slab" rollback in the remaining (proto-)oceanic domain, and hence the shift from regional N–S- to E–W-directed shortening in the early stages of continental collision (Figure 12c; [66]).

From early to final collision in the Western Alps: At this stage, the previously subducted and exhumed high-P rocks of the Piemonte and Prepiemonte domains were thrust along the PPT over the Briançonnais (Figure 12d). Although the latter was pulled into the subduction zone, it could not subduct because of its thick and thus buoyant continental crust. This may explain why shortening between Europe and Adria stepped into the Valais domain leading to the formation of the PT (Figure 12e). At this stage, the Briançonnais domain was thrust over the proximal margin along the PT. In other words, the Briançonnais changed from a footwall position relative to the PPT into a hanging-wall position relative to the PT. "Slab" breakoff presumably occurred when the thick, buoyant crust of the European necking domain tried to enter the subduction. It presumably triggered the pulse of magmatic activity along the Periadriatic system observed at 30 Ma [68]. From this time onward, the pulling force driving the Alpine Tethys subduction had ceased, and convergence started to be accommodated by subduction in the Ligurian and Ionian domains, resulting in the rotation of the Adriatic plate relative to Europe and in the collision between the Adriatic and European–Briançonnais margins [185]). This final collision was expressed by the uplift of the ECM and by the formation of both a fold-and-thrust belt and a flexural basin over the proximal margin (e.g., [186]). This history is well recorded in the central and northern parts of the Western Alps. However, the convergence history of the southern Western Alps may have been completely different as this domain never recorded a proper continental collision between Europe and Adria.

7.6. The Change in Kinematics from Subduction to Early Collision: Global vs. Regional

It is generally accepted that the kinematics during the subduction of the Alpine Tethys (proto-)oceanic domain is related to N-S convergence between Africa and Europe. However, a transition from N–S to E–W-directed convergence has been documented from the time continental collision started in the north. Whether this shift was related to a global-scale change in the kinematics of the major tectonic plates (Africa, N-America and Europe) or was controlled by the regional-scale rotation of Adria as a result of "slab" rollback (cf. previous section) is still unclear. As plate kinematic data (e.g., [22]) indicates that the African plate did not significantly shift during Alpine convergence, we assume that the kinematic shift was linked to the regional "slab" rollback and subduction initiation. In this perspective, one can expect a gradual change in the shortening direction together with a younging of the onset of hard collision from the N to the SW along the Western Alps. Such a regionally-controlled kinematic reorganization may be further complexified by strain partitioning between shortening perpendicular to the kinematic direction and strike-slip faulting along the Adria-Europe plate boundary (Figure 12a). In our first-order E-W directed restoration (schematic cross-sections in Figure 11a,c), we consider that strike-slip and subduction only affected the most distal, hyperextended and (proto-)oceanic parts of the section (i.e., the Prepiemonte and Piemonte units), and that the main collision occurred during the E–W-directed phase of shortening post-dating 35 Ma (Figure 12e–f).

7.7. The Three-Dimensional Distribution of Rift Coupling Points (CPs): Its Impact on the Orogenic Architecture and Evolution of the Western Alps

As described above, the CP is likely to become the "singularity point" or "S-point" of the convergent system, i.e., the tip of the buttress ([187]; Figure 11b). Although mapping the CP is challenging, in the Western Alps, it should follow the Briançonnais ribbon (Figure 11c and pink line in Figure 12). At the margin scale and accepting the V-shape geometry of the Briançonnais ribbon (Figure 2d; see discussion in Sections 7.2.2 and 7.2.3), three segments with different CP distributions can be identified along the European–Briançonnais margin (Figure 12a). In the northeastern segment, where the Briançonnais ribbon is less than 10 km thick, the unique CP lies within the distal European margin, inboard of the Briançonnais domain. In the southwestern segment, where there is no major crustal thinning between the European and Briançonnais domains (i.e., no Valais/Subbriançonnais domain), the unique CP lies within the distal Briançonnais domain. In contrast, in the intervening segment, where our study area lies, up to three CP can be expected in a section view because of the presence of a continental ribbon between two overstepping hyperextended rift basins (e.g., Figures 11b,c and 12a). A first CP occurs at the European margin necking domain, a second one at the western necking domain of the Briançonnais domain (facing the Valais Basin) and a third one at the eastern necking domain of the Briançonnais domain (facing the Piemonte Basin).

Although sections in the northeast and southwest segments only have one CP (Figure 12a) and display similar orogenic structures, some significant differences can be noted and/or should be expected. The proportion of Briançonnais- vs. Europe-derived material in the northern segment is lower compared to the central and southern segments. The CP of the northern segment lies at the PT, while the PPT is not a prominent structure. The continental collision started earlier in the northern segment, and there was no complex strain partitioning. In contrast, in the southwest segment, the CP corresponds to the PPT, while the PT is not a prominent structure. Pre-35 Ma N–S convergence is expected to have mainly been accommodated by strike-slip deformation in the central segment of the Western Alps, and final shortening to have culminated in a minor continental collision compared to further north.

In the central segment, both the PT and PPT correspond to major structures. They presumably nucleated at the abrupt topographic steps/CPs framing the thick-crusted Briançonnais s. str. continental ribbon within the Valais and Prepiemonte hyperextended and/or exhumed mantle domains. The early collision started at the PPT (i.e., the most distal CP) and was responsible for the thrusting of the internal high-P bearing units over the Briançonnais ribbon. The main thrust faults used evaporite-bearing decollement levels in the Mesozoic cover. During this early stage of collision, the Briançonnais basement may have been pulled underneath the orogenic upper plate; however, the significant buoyancy of the Briançonnais crust on the one hand and the existence of “subductable” material in the Valais Basin further inboard on the other may be the reason of the subsequent PT activation.

Consequently, the internal Briançonnais–Piemonte units became part of the hanging-wall and were thrust westwards over the former European proximal domain. During the final collision phase, the Adriatic indenter collided with the European buttress. At this stage, the deformation style at the orogen scale changed from fundamentally asymmetrical-(W-directed stacking phase, including the PPT and PT) to symmetrical (E-directed back-thrusting phase; [77]). During this late stage, the previously stacked units were pushed underneath the necking zone, leading to the thickening of the distal European crust, which contributed to the formation of topography in the Alpine belt. This went along with the localization of new thrusts in the footwall of the PT, which contributed to the uplift of the ECM and to the formation of the fold-and-thrust belt in the external part of the Alps. In the internal parts, remnants of the former distal margins were thrust backward onto the Adriatic indenter. The overprint of the initially west-directed PPT ramp by east-directed back-thrusting structures may explain the steep and locally inverted position of the Prepiemonte unit along the sections shown in Figure 11a.

8. Conclusions

In this contribution, we used diagnostic petrologic, stratigraphic and structural criteria to replace the main Alpine units of the Western Alps into a synthetic rifted margin template (so-called Building Block (BB) approach). We found that some units previously attributed to the internal part of the thick-crusted Briançonnais continental ribbon (BB3) may rather derive from the thin-crusted Prepiemonte hyperextended domain (BB5 and BB6). We argue that the Briançonnais and Prepiemonte domains were separated by a significant topographic step, presumably owing to a mega-fault scarp, which significantly controlled subsequent Alpine reactivation. We also reassessed the paleogeography of the Alpine Tethys rift system, the kinematic history of the Alpine orogeny, as well as the architecture of the Western Alps. We suggested that the Briançonnais domain was a ribbon of little rifted continental crust between two overstepping en-échelon rift basins, namely the Valais domain to the northwest and the Piemonte domain to the southeast. We argue that the resulting uneven architecture of the European–Briançonnais margin can explain most of the Western Alps’ complexity. Indeed, while classical margins display one single coupling point (CP) along the dip, which corresponds to the location of full crustal embrittlement, the European–Briançonnais margin displayed coupling points on either side of the Briançonnais ribbon: two located in the Subbriançonnais/Valais domain, and another at the mega-fault scarp separating the Briançonnais and Prepiemonte domains. During Alpine convergence, the main shortening seeded at these coupling points: the first structure to be reactivated was the limit between the Prepiemonte and Briançonnais domains, which now corresponds to the Basal Prepiemonte Thrust (PPT); the second was the Subbriançonnais/Valais domain, which now corresponds to the Basal Penninic Thrust (PT). In our kinematic model, N–S convergence between Adria and Europe during the Mesoalpine orogenic phase resulted in continental collision and N–S shortening in the Central Alps, while shortening was mainly accommodated by strike-slip movements in the Western Alps. From the late Eocene onward, the onset of hard collision in the northern Western Alps (i.e., when the necking zones reached the subduction trench) led to subduction rollback and a shift from N–S to E–W contraction in the Western Alps. This shortening was first accommodated along the PPT, and once the Briançonnais reached the subduction trench, shortening stepped into the "easier-to-subduct" Subbriançonnais/Valais hyperextended domain further inboard, along the PT. Although further work is needed to confirm our interpretation, at present, we are not aware of any data disproving it.

Author Contributions: Conceptualization, G.M., P.C., I.H. and E.M. investigation, G.M., I.H., E.M., G.F. and A.D.; writing—original draft preparation, G.M., P.C. and I.H.; writing—review and editing, E.M., G.F. and A.D.; supervision, G.M.; project administration, G.M.; funding acquisition, G.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Margin 6 consortium.

Data Availability Statement: Data is contained within the article and within the Ph.D. thesis of Haupert (2015) ([173] in the reference list).

Acknowledgments: The authors are grateful to A. Pfiffner, T. B. Andersen and an anonymous reviewer for thorough and very constructive reviews. Moreover, we would like to thank Marie-Eva Epin, Pietro Mosca and Nicolò Incerpi for discussions in the field, as well as all Ph.D. students, Post-Docs and colleagues, too numerous to name all, for the discussions and debates throughout the last years on the Alps and its pre-Alpine evolution. We would also like to thank the consortium M6 for financing this work.

Conflicts of Interest: The authors declare no conflict of interest.

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