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Reply to comment on “Structural and petrological characteristics of a Jurassic detachment fault from the Mont-Blanc massif (Col du Bonhomme area, France)” (Journal of Structural Geology, 159 (2022))

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In his Comment on the paper of Dall’Asta et al. (2022), Leloup (2023) claims that our observations do not demonstrate in any way the existence of a major Jurassic extensional detachment in the Col du Bonhomme area, located in the southern Mont-Blanc Massif in France. He lists eight field arguments that allow him to question the existence of such a rift-related detachment fault, and he concludes that if rift related structures should have existed, they would be of only minor importance. In this reply, we first address the fundamental question of what geological evidence is needed to highlight the existence of a rift-related extensional detachment fault in a collisional orogen. In a second part, we reply to each of the eight points listed in Leloup (2023). In a final part, we discuss whether alternative interpretations than that of a rift related detachment fault could equally explain the observations made at the Col du Bonhomme area.

While there is little doubt that collisional orogens result from the reactivation of rifted margins (Trümpy, 1975; Bernoulli et al., 1979; Lemoine et al., 1986; Claudel and Dumont, 1999; Tavani et al., 2021), recognizing inherited rift-related structures in collisional orogens is challenging. In the Alps, the presence of inherited rift-related high-angle normal faults, such as for example the Ornon fault bounding the Bourg d’Oisans rift basin, is generally accepted (Barfety and Gidon, 1984; Lemoine et al., 1981; Chevalier et al., 2003). In contrast, examples of rift-related extensional detachment systems that are common at distal domains (e.g., Boillot et al., 1987; Manatschal et al., 2001) or necking domains (Osmundsen and Péron-Pinvidic, 2018; Muñoz-Barrera et al., 2022) of present-day magma-poor rifted margins remains scarce in fossil rifted margins preserved in orogens (Manatschal, 1999; Epin and Manatschal, 2018). The main reason is that low-angle, extensional

detachment faults are likely to be reactivated by thrust faults during convergence (Etheridge, 1986). Moreover, extensional detachment faults forming over continental crust thicker than 25 km, as is the case for crustal necking zones, can be uplifted above sea-level and getting eroded during rifting (Chenin et al., 2019). In the Alps, the preservation of such structures (e.g., Err detachment; Froitzheim and Eberli, 1990) has been favoured either by their corrugated shapes or because subsequent thrusts used other favourably oriented, weak decoupling levels such as salt or clay levels (Epin et al., 2017). Thus, neither the presence of Alpine structures nor the lack of lateral continuity of an extensional fault plane can be used as arguments definitively excluding the former presence of a rift-related detachment fault. On the opposite, three observations are absolutely mandatory to establish the presence of such structures (Epin et al., 2017): 1) a tectonically-deformed top basement on its footwall, with diagnostic cataclasites and/or gouges resulting from fluid-assisted retrograde deformation (e.g., black gouges; Epin et al., 2017), 2) undeformed syn-rift sediments on its hanging wall, sealing the tectonically-deformed top basement and/or fault zone at a low (<15°) onlap angle, and 3) reworking of the fault rocks and low-deformed footwall material in the overlying syn-rift sediments. It is important to insist on the fact that these type of extensional detachment systems are different to those of metamorphic core complexes that evolve from ductile to brittle conditions and exhume greenschist basement (Davis and Coney, 1979; Brun et al., 2018). In the paper of Dall’Asta et al. (2022), we present evidence for all three critical observations, which led us to conclude that a Jurassic extensional detachment fault has been locally preserved in the Col du Bonhomme area. This interpretation is also in line with the observations presented in

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Ribes et al. (2020) and with additional observations and data presented in Dall'Asta (2022). It is important to stress that our interpretation is not based solely on field observations and measurements, but also on petrological, microstructural, and geochemical arguments, as well as on detrital zircon U–Pb LA-ICP-MS ages presented in Ribes et al. (2020).

In his comment, Leloup (2023) focuses on eight field and structural arguments to refute our interpretation of a Jurassic extensional detachment system in the Col du Bonhomme area. The eight points are: 1) the lacking lateral extend of gouges (they seem to occur only at some few locations), 2) the lack of high strain deformation observed at the top of the basement, 3) the lack of good strain markers and the inaccurate sense of shear reported in the paper, 4) the observation that black coloured rocks are not always gouges, 5) the observation that contacts between Triassic sandstones and rhyolites are not deformed, suggesting a primary stratigraphic contact rather than a tectonic contact, 6) the observation that secondary faults offset the basal Triassic-basement contact but not the top of the Triassic suggesting a Triassic age for these faults, 7) a more complex geometry observed at Nan des Lotharets with kinematics incompatible with those presented in Dall'Asta et al. (2022), and 8) the occurrence of brecciated dolostones, interpreted as possible seismites, possibly formed prior to lithification during the Triassic (Egli et al., 2013). These eight observations lead Leloup (2023) to conclude that there is no evidence for the existence of a Jurassic extensional detachment fault in the Col du Bonhomme area. He argues that some of the observed deformations (high-angle faults) are likely of Triassic age so that if rift-related structures should have existed, they would be of minor importance.

Points 1 and 4: We consider the local absence of gouges (point 1) and the fact that not all rocks that are black are gouges (point 4) are not arguments against the existence of a rift-related detachment fault. Indeed, we found indurated gouges and footwall material reworked in the syn-rift Grès Singuliers, as indicated by field, thin section (Fig. 3 in Dall'Asta et al. (2022) and detrital U–Pb zircon ages (Ribes et al., 2020) showing reworking of the Mont-Blanc granite (303 Ma) in the Grès Singuliers but not in the Triassic sandstones. At least 25% of the crystalline pebbles (forming 90% of the basal conglomerates (Eltchaninoff, 1980)) correspond to cataclasites. This indicates that parts of the detachment fault were eroded prior to Alpine convergence, as already suggested by Ribes et al. (2020). Moreover, we do not characterize fault rocks based on their colour, but on their macro and microscale fabric. There is absolutely no doubt that cataclasites and black gouges do occur

in the Col du Bonhomme area (Fig. 1A and B and Fig. 8 and 9 in Dall'Asta et al., 2022).

Point 2: We agree with Leloup (2023) that there are no high-strain rocks such as mylonites observed at the top of the basement in the Col du Bonhomme area. The presence of brittle, fluid-assisted retrograde deformation and the lack of mylonites clearly show that deformation did not occur in the ductile field. This is compatible with the PT conditions at which deformation occurred (below greenschist facies; Dall'Asta et al., 2022) and is also similar to observations made at other rift-related necking detachment systems in the Alps (e.g., Grosina; Mohn et al., 2012 or Gorzano/Invorio; Decarlis et al., 2017).

Point 3: The rareness of stretching lineations is an observation that we share with Leloup (2023). We would like to emphasise that stretching lineations are commonly less well developed in cataclasites than in mylonites. However, stretching lineations in phyllosilicate-rich cataclasites, gouges and pre-rift sedimentary rocks occur in the deformed basement-cover interface of the Col du Bonhomme area, an observation we also shared with the author of the comment during a joint field trip in 2021. To support the existence of these structures, we added in this reply (Figs. 1B and 2A and B) an illustration of the kinematic record of the deformed basement-cover interface with data from the gouges and cataclasites of the Nan de Lotharets outcrop. Although such data exist, we concur that kinematic markers are scarce at the outcrop-scale. Studies of metamorphic core complexes in the Whipple mountains (SW United States; Yin and Dunn, 1992) showed that formation and kinematics of detachment systems are complex. Detachment faults cannot be considered as continuous structures, and often they are segmented (e.g., Early Cretaceous detachments faults in the hyper-extended Mauléon Basin, Western Pyrenees; Masini et al., 2014). Such segmentation can result in variable fault and fracture orientations (Muñoz-Barrera et al., 2020), which may explain the ill-defined kinematic observations. Regarding the Col du Bonhomme area, Dall'Asta et al. (2022) suggested the presence of a right stepping segment boundary at the southern termination of the Mont Blanc Massif, which could have added structural complexity to the detachment kinematics explaining the N–S stretching directions observed oblique to the main extension direction. The former presence of Triassic evaporites, also indicated by inclusions of anhydrite in quartz, is an additional complexity that may account for the lack of a well-defined kinematic transport directions. Finally, although we do not have a direct answer for why the kinematic framework remains ill defined, we point out that



Fig. 1. A- Cross section view of the basement -cover interface (Col des Fours) showing a top tectonized basement composed of cataclasite and gouges overlaid by a pre-rift allochthonous block composed of Triassic dolostones and lenses of basal arkoses. The base of the cover is characterized by the occurrence of tectonic breccias as well as foliated limestones. B- View of the fault-core (Nant des Lotharets, 45° 43' 47.30"N/6° 43' 54.16"E) overlaid by calcite rich sandstones composed of clasts of anhydrite-bearing quartz. The gouges and cataclasites show mostly N–S stretching lineations (dark green points) and some E–W slickenfibers (light green points). The detachment fault and high-angle normal faults are highlighted by the green and red line on the stereogram. The orange planes correspond to the bedding on the pre-rift dolostones C- View of the first sediments overlying the exhumed basement (site: Nant des Lotharets (45° 43' 36.74N/6° 42' 40.39E)) composed of crinoid-rich mud filling fractures in the basement. D- Stratigraphic contact between the Grès Singuliers and the tectonized top basement (site: Plan des Tufts (45° 43' 55.15"N/6° 44' 15.21"E)). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

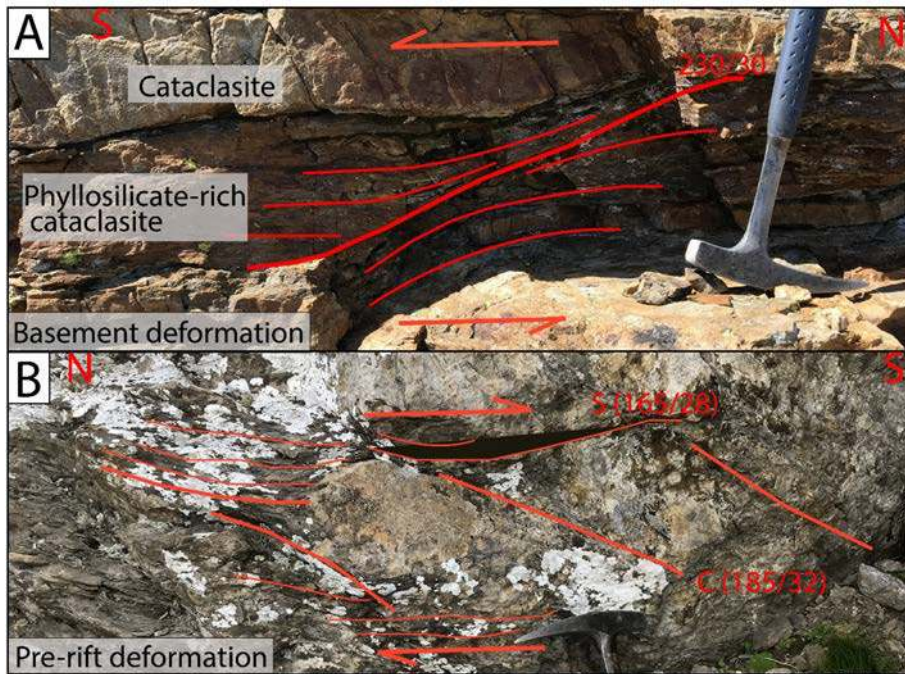


Fig. 2. A- Phyllosilicate-rich cataclasite in the Tête Nord des Fours showing E-W top to the south sense of shear (45°46'13.36''N/6°43'46.17''E). B- S/C deformation in the pre-rift sediments (Rhetian) from the Rocher du Bonhomme showing a top to the south sense of shear.

this is also observed at other detachment systems dominated by brittle deformation mechanisms (Froitzheim and Eberli, 1990).

Point 5: The most critical point raised by Leloup (2023) is the observation that contacts between Triassic sandstones and rhyolites are not deformed, suggesting a primary stratigraphic contact rather than a tectonic contact between the pre-rift Triassic sandstones and the

rhyolites. First, we did not find rhyolites in the Col du Bonhomme area. Such rocks rather occur in the northern Mont Blanc Massif (Val Ferret and Catogne; for a detailed description of the outcrops see Dall'Asta, 2022). At these locations the Triassic sandstones are indeed in stratigraphic contact with the rhyolites. However, the rhyolites are in tectonic contact with the underlying polymetamorphic basement, and we

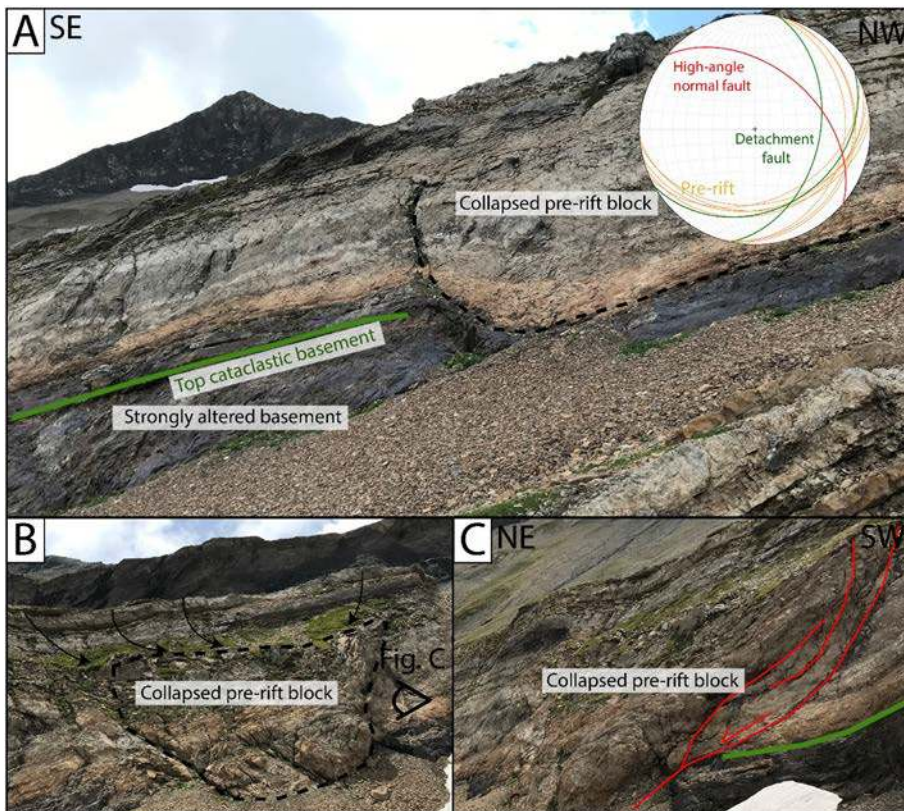


Fig. 3. A- View of the E-W Faille des Fours showing olistolith of Triassic cover (45°43'49.51''N/6°43'47.85''E). B- Close view of an olistolith showing associated to E-W minor fault plane. C- Associated to the collapse of the block in the half-graben. The orange planes on the stereogram correspond to the pre-rift bedding, the green line shows the location of the detachment fault and the red lines the Faille des Fours. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interpret that the rhyolites and Triassic sandstones could be part of an extensional allochthon overlying the rift-related extensional detachment. In the Col du Bonhomme area, the contact between the Triassic cover and the basement corresponds in our interpretation to a tectonic contact. This is evidenced by: 1) the reworking of dolostone clasts in the gouge, 2) the development of an important foliation in the limestones, 3) the formation of breccias (composed of clasts of foliated limestones and clasts of Triassic seismites (point 8) see Figs. 1A), and 3) the development of sheared boudins. The occurrence of anhydrite-bearing quartz in the pre-rift limestones, the lenses of sandstones at the base of the Triassic cover, and the occurrence of anhydrite might represent the vestiges of an evaporite-rich layers acting as a decoupling level between the cover and the basement.

Point 6: We do not exclude the existence of Triassic deformation, however, as mentioned by [Leloup \(2023\)](#), locally the Triassic sediments form primary stratigraphic contacts to rhyolites further north in the Mont-Blanc massif (e.g., Catogne Mt.) but not in the area of the Col du Bonhomme (point 5 and see comment below). A careful examination of the N-S trending Triassic fault described by [Leloup \(2023\)](#) in the Col des Fours shows that they actually correspond to a Triassic olistolith or later collapse of the pre-rift along the fault (Fig. 3) along an E-W striking, possibly Jurassic high-angle normal fault described in [Dall'Asta et al. \(2022\)](#).

Moreover, neither the Alpine nor the Triassic deformation can account for the three main observations that led us to propose the presence of a rift-related extensional detachment fault at the Col du Bonhomme (see 3 key observations listed in the 2nd paragraph and discussion of alternative interpretations in the last paragraph). [Leloup \(2023\)](#) suggests that not all deformation observed in the Bonhomme area is linked to Jurassic rifting (points 6, 7 and 8), a point that we of course share. Petrographical observation of the basal sandstones indicates no Alpine deformation and only significant compaction and pressure-dissolution (e.g., Fig. 3B in [Dall'Asta et al., 2022](#)). Alpine deformation was observed only on the top part of the Grès Singuliers below the Aalenian shales.

Point 7: local complexities as observed at the Nant des Lotharets.

The best outcrop of gouge, although not the only one, was described in the Nant des Lotharets area. The gouge horizon is dipping gently toward the W-NW and is conform to the overlying sediments (Fig. 1B). This area is also affected by a series of NW-SE normal faults affecting the basement and the Triassic cover associated to few meters of offset (Fig. 1B). These faults do not seem to affect the syn-rift cover and might indeed be sealed by these sandstones. On the opposite, in the Col des Fours area, the sediments are dipping toward the E-SE, as confirmed on the 1:50'000 BRGM geological map ([Mennessier et al., 1977](#)). This indeed tends to show that a large-scale antiform is present, deforming the pre-Alpine tectonized top basement (Figs. 1B and 3A). The hinge of the folds is located in-between the Tête Sud des Fours and the Rocher du Bonhomme. This further confirms the pre-Alpine age of this tectonic contact. Besides, the connection between the gouge and the Bonhomme fault, which passes further north of the Rocher du Bonhomme, cannot be seen in the field.

Point 8: Indeed, syn-sedimentary breccias interpreted as seismite or widespread in the Triassic dolostones in the Western Alps ([Loup, 1992](#)) and also in the Col du Bonhomme. However, in the Col du Bonhomme, these breccias are overprinted by later tectonic breccias at the base of the Triassic cover (Fig. 1A). In fact, these tectonic breccias contains clasts of the seismite deposits indicating that they are posterior and therefore unrelated to the Triassic seismite deposits.

In conclusion, we agree with some of the observations reported by [Leloup \(2023\)](#). However, in our opinion none of the eight points listed by [Leloup \(2023\)](#) refutes the existence of a major Jurassic extensional detachment fault in the Col du Bonhomme area. Nonetheless, looking at the problem from another angle, it is also interesting to explore whether the hypotheses of a Permo-Triassic exhumation of the basement (e.g., Aiguilles-Rouges exhumation ([Vanardois et al., 2022](#))) or simply an

Alpine deformation ([Egli and Mancktelow, 2013](#)) is compatible with the key observations summarized in the 2nd paragraph of this reply, and detailed in [Dall'Asta \(2022\)](#), [Dall'Asta et al. \(2022\)](#) and [Ribes et al. \(2020\)](#). Although a Permo(?)Triassic exhumation, either transtensive to transpressive ([Ballèvre et al., 2018](#); [Vanardois et al., 2022](#)), cannot be excluded, it cannot explain the Jurassic isostatic rift evolution of the proximal European margin (uplift of the Mont-Blanc massif and Aiguilles-Rouges massif), nor the reworking of basement, gouges and Triassic sandstones in the Grès Singuliers sandstone ([Ribes et al., 2020](#)), both of which are dated as Early Jurassic ([Ribes et al., 2020](#)). This spatially localized, and timely restricted detritic pulse during a regional transgressive stage ([Roux et al., 1988](#)), highlights a sudden uplift of the basement in the area. An interpretation of the deformed basement as the result of an older Permian or Variscan tectonic event is also not compatible with the observation that Triassic rocks are locally deformed along the contact. Similarly, an Alpine age for the detachment can be excluded, since it cannot explain the reworking of fault rocks in the pre-Alpine Grès Singuliers ([Ribes et al., 2020](#); [Dall'Asta 2022](#)). Moreover, the reworking of vein fragments in the sediments similar to the quartz-hyalophane veins found in the gouge is another important argument to favour a pre-Alpine age of the deformation. However, it is possible that elsewhere, the Jurassic detachment was reactivated during Alpine convergence. In his comment, [Leloup \(2023\)](#) states that if rift-related structures should have existed, they would be of minor importance, i.e., linked to some minor Jurassic high-angle faults. This interpretation can, however, neither explain the observed stratigraphic contact between the Grès Singuliers and the fault plane, which is at a low angle (<15°), nor the occurrence of a deformed top basement with diagnostic cataclastites and/or gouges, and their reworking in the overlying syn-rift Grès Singuliers. Moreover, local complexities and variations of local thickness of the syn-rift cover might be associated to corrugations of the detachment fault as observed in other extensional detachment faults (e.g., Mykonos detachment fault ([Lecomte et al., 2010](#))).

The question remains, whether the interpretation of a Jurassic extensional detachment is violating existing knowledge concerning the Mont-Blanc massif and if such an interpretation is incompatible with what we know from present-day rifted margins. First, it is important to mention that similar interpretations have already been proposed for the internal Pelvoux ([Gillcrust, 1988](#)). Moreover, it is generally accepted that the continental crust was thinned and extended during Jurassic rifting, as indicated by Jurassic mantle exhumation in the Valais basin ([Beltrando et al., 2012](#); [Ribes et al., 2019](#)). Although most models, even recent ones, prefer to explain crustal thinning during rifting in the Alps only by brittle high-angle faulting (see [Michard et al., 2022](#)), we remind that observations made at present-day rifted margins undoubtedly show the existence of extensional detachment faults from the necking domain to the distal domains of rifted margins (e.g., [Reston and McDermott, 2011](#)). Therefore, and supported by field, structural, petrological, mineralogical, geochemical and sedimentological observations, as well as on detrital zircon U-Pb LA-ICP-MS ages documented in [Ribes et al. \(2020\)](#), [Dall'Asta et al. \(2022\)](#) and in the PhD of [Dall'Asta \(2022\)](#), we consider that the interpretation of a rift-related, Early Jurassic extensional detachment fault in the Col du Bonhomme area in the Mont Blanc Massif is justified and supported by data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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