Reply to comments of Reviewer 1

Comment: The manuscript describes modeling results and field examples of shear bands and shear zones. The results are presented in a clear, well-written, and concise text. The modeling results appear reasonable and sound. The field examples are presented at the mesoscale observation level. However, the manuscript requires some major revisions before it can be published. The first problem that I see lies in some confusion of terms that is related to nomenclature:

Response: It is nice that the reviewer has appreciated the presentation of our model results, considering them as "reasonable and sound". We thank the reviewer for providing us with insightful comments and suggestions for revising the manuscript, which have been carefully addressed in this revised version, as explained below.

Comment: For a large part of the text, especially the modelling part, the authors use a continuum mechanics rheology nomenclature, consistent with their modelling approach, which is continuum-mechanics-based. In this nomenclature "plastic" refers to "pressure-sensitive, temperature-insensitive" deformation with a yield criterion, and "viscous" refers to "temperature-sensitive and pressure-insensitive" deformation without a yield criterion. These definitions are not clear to all geologists or may be used differently by them and therefore should be defined in the introductory section.

Response: Thanks for this relevant discussion by the reviewer on our rheological considerations and the use of rheological nomenclatures: 'viscous' and 'plastic'. In the Introduction section (Ln: 132-136) we discuss the visco-plastic rheology of shear zones considered in the present modelling, where the two terms: viscous and plastic rheology are defined, as suggested by the reviewer. We also elaborate the basis of this rheological consideration in the modelling section (Ln: 226-236).

Comment: Furthermore, the term "ductile" is problematic in geology and rock mechanics. "Ductile" in rock mechanics primarily refers to brittle, distributed deformation, e.g., cataclastic flow, and in this sense, the brittle-ductile-transition is a purely confining-pressure-dependent transition from discrete fractures to zones of distributed cracking. Friction-controlled sliding may agree with the term "plastic" in the purely rheological sense defined above. However, the term "ductile shear zone" is used by most geologists as a zone where viscous deformation processes (intracrystalline plasticity or diffusion creep) dominantly accommodate the strain and thus a viscous rheology prevails. Obviously, from the short outline above, it becomes clear that the terms "ductile" and "plastic" have very different meanings in the different communities. Large parts of the discussion suffer from this confusion of terms. Again, the terms should be clearly defined and probably the terms "ductile" and "plastic" (without the prefix "crystal") should be avoided or their use should be checked for consistency in every instance.

Response: We agree with the reviewer that the terms: 'ductile' and 'plastic' are used with different meanings in different communities. We used the term- 'ductile' to mean distributed viscous deformations without macroscopic fracturing in shear zones. In fact, shear zones of our present study show viscous deformations, which is evident from extensive dynamic recrystallization on grain scales, i.e., signatures of crystal-plastic creep mechanisms, as rightly pointed out by the reviewer. The present version provides a detailed account of viscous rheological consideration in this version (Main text- Ln: 226-236, Supplementary section S3). To avoid confusion, we have now replaced the term- '*ductile*' with '*viscous*' in the entire manuscript, as suggested by the reviewer.

In the Introductory section we briefly discuss the principal rheological approaches, for example, power-law viscous and visco-plastic rheology used in previous studies for shear band localization (Ln: 84-88).

In our modelling approach we apply a yield criterion to initiate strain localization (shear band formation) within a visco-plastic macroscopic rheological framework. The plastic yield criterion is chosen based on the occurrence of localized high-strain zones, which show extreme grain size reduction and shear-parallel slip surfaces (c-surfaces) on microscales, as indicated by the reviewer. These features are described in detail in Supplementary section (S2) of the revised version. Based on the reviewer's suggestion, we now drop the term- plastic in the entire manuscript to avoid confusion, except in the expression of macroscopic model rheology (i.e., visco-plastic rheology). These issues are elaborately discussed in the Modelling method section (Ln: 226-236) and Supplementary section (S3).

Comment: The second problem of the manuscript lies in the lack of microstructural analysis in the field examples. The microstructures could provide information on the deformation mechanisms in each shear band or -zone. Once the deformation mechanism is established, rheological consequences are implied. E.g., for cataclastic-frictional microstructures (perhaps the quartzite examples?), the rheology may be "ideal-plastic" in the rheological sense or "ductile" in the rock mechanics sense, but not in the common structural geology sense. The S-foliation-dominated microstructures may indicate crystal plastic or diffusion-creep-type deformation mechanisms and therefore could imply dominantly "viscous" deformation in the rheological sense. The discussion would become much clearer, far more relevant, and less speculative with such information provided. Furthermore, rate-dependent and viscosity-related inferences are made from the mechanical modeling and discussed. Such a discussion should only use the field examples when deformation mechanisms are established for the examples – otherwise the field examples are black-box cases.

Response: We greatly appreciate this insightful comment and discussion by the reviewer, indicating the need of a microstructural support to justify the choice of rheology in the shear zone modelling. This revised version provides a new section to describe deformation-associated microstructures of shear zone rocks. As rightly pointed by the reviewer, we find extensive grain size reduction by dynamic recrystallization (crystal-plastic mechanism). This allows us to consider an overall viscous rheology of the shear zones, which is clarified in this version (Ln: 226-236, see also Supplementary S3). Microstructural studies also reveal sharp variations in recrystallized grain sizes, delineating zones of strain-rate enhancement due to commencement of yielding in shear zone rocks. These high-strain zones often contain grain scale shear-parallel slip surfaces, often filled with secondary minerals, such as biotite, chlorite and oxides. Based on these microstructural characteristics, we consider a yield criterion to develop macroscale strain localization in a viscously deforming system, as described in a visco-plastic rheological model. The revised version includes a set of microstructural analyses to support our rheological considerations for shear zone modelling. These new additions are, however, placed in the supplementary section (S2) to maintain the manuscript length. We sincerely thank the reviewer for this excellent suggestion.

Detailed comments:

Comment: Line 21: omit “intense”

Response: Corrected, as suggested. (Ln: 21)

Comment: Lines 83-107: The discussion should include the possibility that the S- and C- fabric elements may not develop simultaneously as poposed by Berthe et al. 1979. Recent studies by Bukovska et al. 2013, 2016 indicate a different origin and should be mentioned and discussed here.

Response: We thank the reviewer for this important suggestion. We have now included these studies in both the Introduction and Discussion sections of the updated version (Ln: 109-112 and 460-461).

Comment: Line 86-87: there is important experimental evidence for the formation of shear bands in the semi-brittle deformation regime, and this should be considered here, too: Pec et al. 2016, Marti et al. 2017, 2018, 2020, Schmocker et al. 2003.

Response: The reviewer has rightly noted that shear bands can form in a semi-brittle deformation regime. A brief statement on this point is included in the Introduction. We have cited the relevant works provided by the reviewer. Thanks for this suggestion (Ln: 81-84).

Comment: Line 95: definition of terms "viscous" and "plastic", see introductory comments above. It will not be clear to most geologists how or why the terms viscous and plastic are used in a distinguishing of differing sense here. Furthermore, it is not clear why the strain accommodating processes in S and C bands have to be different.

Response: Based on the introductory comment by the reviewer, we have used the term: 'viscous' in place of 'ductile'. The basis of viscous rheological consideration has also been explained (Ln: 132-136 and 226-236). We used the term: 'plastic' only in the expression of visco-plastic rheology, where a yield criterion is coupled, which is explained in the preceding response.

It is to be noted that we use the nomenclature: C-Bands to mean macroscale bands of strain localization parallel to the shear direction, surrounded by regions of distributed viscous deformations, where shear bands are absent on macroscopic scales.

In our model strain localization results from a yielding process, involving weakening and reduction in the effective viscosity (Eq. 7) that in turn enhances the shear rates. C-bands accommodate strain at much higher shear rates, as reflected from dramatic decrease in recrystallized grain sizes. In addition, shear-parallel slip surfaces are found to localize more preferentially in them. These aspects are described in the revised version (Ln: 226-237) and Supplementary section (S3).

We appreciate this nice point noted by the reviewer.

Comment: Line 99: "accommodates" instead of "accommodate"

Response: This is corrected. Thanks. (Ln: 114)

Comment: Line 100: how is it determined that the deformation in the localized zones is not viscous?

Response: The text is modified to clarify the reviewer's comment. We describe C bands as localized zones of high strain, where viscous deformation can occur, as rightly commented by the reviewer. In fact, the revised version shows microstructural evidence (extreme grain size reduction by crystal-plastic creep and recrystallization), implying that a shear band also takes part in intense viscous deformations. This context is discussed in different parts of this version (Ln: 170-175 and 226-236). Thanks for raising this important point.

Comment: Fig. 1: please give scales in km, not just in degrees of latitude and longitude. CGGC does not appear in the maps but in the text – please indicate the abbreviation in the maps or refer to other units (NPSZ?)

Response: Corrected. The scales are provided in km, as suggested by the reviewer. Thanks.

Comment: Lines 158-162: by foliation you refer to a S-foliation? Please specify.

Response: Yes, it refers to a S-foliation, which is now specified (Ln: 185).

Comment: Fig. 3: the C-bands show a coarse grain and have a melt-like appearance within the feldspar-biotite matrix. Such melt segregations will have a different mechanical property compared to the matrix. Please comment on this aspect, especially with respect to the relevance to modeling and in terms of rheological development.

Response: In places, the shear zones had emplacement of quartzo-feldspathic materials along C-bands. This feature is now mentioned in the revised figure caption. The bands localized under the influence of the pre-emplacement rheological condition in the shear zone, and they later controlled the emplacement process in the course of shearing. However, the associated fluid activities might have acted as rheological weakening factor to facilitate the process of shear localization, as considered in our numerical modelling formulation (Eq. 7). This issue is briefly addressed in the discussion (Ln: 387-394).

Comment: Fig. 4: the shear zones are considerably coarser grained than what is termed "wall-rock" here and appear to have a melt-origin, while the wall rock does not show clear evidence for melt. Again, as in Fig. 3, a considerably weaker rheology is expected for these shear domains. Modeling such structures appears difficult: have the melt segregations formed first, so that they localize the deformation? In such a case, a homogeneous matrix cannot be assumed for modeling. Or has melt material filled pre-existing shear bands? If this is the case, why are such bands so dilatant?

Response: This shear zone has actually developed in a pegmatitic body, which initially consisted of very large crystals that underwent size reduction during shear deformation. However, their grain size still remained coarser than the gneissic host rock. We have replaced this panel with another example to maintain consistency in the presentation.

Comment: Lines 178-180: C-band formation appears to be in contrast with viscous deformation here – why? Please define or describe the difference between viscous deformation and localized shear band formation. Why should localized deformation not be viscous? Commonly, shear bands can be considered localized zones of viscous deformation.

Response: Yes, the reviewer has rightly suggested that shear bands can also undergo intense viscous deformations, as revealed from grain size contrasts. In addition, shear bands contain sporadic microscale slip surfaces, which are generally absent in the domain of distributed viscous deformations. The updated version presents detailed description of microstructural evidence in supplementary section (S2) to show the distributed and localized viscous deformation. This issue is also clarified in the main text (Ln: 170-175, 188-194 and 202-206).

Comment: Line 276: "accommodates" instead of "accommodate"

Response: Corrected. Thanks. (Ln: 332)

Comment: Lines 276-278: this statement implies that plastic yield will produce some strain localization. In principle, plastic deformation may produce homogeneous strain – depending, in part, on the definition of "plastic". That is why it is important to define the terms, see introductory comments

Response: The term 'plastic' was used to model the yielding phenomenon in the shear zone materials, accompanying synkinematic weakening and reduction of effective viscosity, as explained in the preceding response. This sentence is modified to avoid confusion in our expression (Ln: 333).

Comment: Lines 318-322: the terms viscous and plastic appear to be used in a strictly continuum mechanics rheological sense here. As many geologists may have a somewhat different understanding of these terms, it is important to explain them in the introductory part. Furthermore, the difference in plastic and viscous strain accommodation mechanisms may follow from the modeling, but the mechanisms are not demonstrated for the field examples. For a complete discussion, this aspect of the analysis needs to be performed or at least some evidence for supporting an interpretation of different deformation processes needs to be given.

Response: The reviewer has correctly noted that the present model uses the terms: viscous and plastic, in a rheological sense within a framework of continuum mechanics. This point is now clearly stated in this version (Ln: 132-136). Based on the reviewer's suggestion, we now include microstructural descriptions (main text, Ln: 170-175, 188-194 and 202-206; supplementary section S2) to show the rheological basis of shear zone deformations, as addressed in our preceding responses.

Comment: Lines 323-329: these few lines discuss very important aspects of definitions and identification of deformation mechanisms in conjunction with rheology. The identification of viscous deformation mechanisms is fairly straightforward from thin sections. As for "plastic" deformation in the rheological sense, this can manifest itself in cataclastic deformation processes, because these are pressure-sensitive. Such processes can also be identified from thin sections. The term "ductile" in some rock mechanics literature (e.g. Byerlee) can include distributed brittle deformation (e.g. cataclasis). Geological literature often refers to ductile as a viscous deformation. See general introductory remarks above.

Response: We greatly appreciate the suggestion for providing grain scale characteristics as a support for rheological considerations. The revised version includes microstructural description of C-bands and the bulk regions, i.e., outside the bands. They allow us to account for viscous rheology with a plastic yield criterion in our shear zone model (Ln: 226-236). The microstructural descriptions are placed in the Supplementary section (S2) to maintain the main manuscript length. Many thanks for this constructive suggestion.

Comment: Lines 330-344: the occurrence of different types of shear zones is less dependent on the tectonic setting but, instead, strictly temperature- and strain rate-dependent. Of course, higher temperatures and lower strain rate favor viscous deformation, whereas cataclastic deformation processes dominate in lower temperature regimes and at higher strain rate.

Response: The reviewer has correctly pointed out that the shear zone type is less dependent on the tectonic settings. We actually meant that the tectonic setting can largely control strain rates, which in turn determine the type of shear zone. This part has been modified to clarify our expression (Ln: 295-417). We appreciate this discussion by the reviewer.

Comment: Line 351: "ductile shear zones" – see general comments above. Probably, this term should be avoided altogether.

Response: We have dropped the term- ductile in this version of the manuscript.