Dear Editor,

Please find below our replies (marked in light blue) to the referees' comments (marked in grey) and a copy of the manuscript that highlights the incorporated changes based on the feedback of the referees.

Best wishes,

James Gilgannon

Referee 1: Alberto Ceccato

I reviewed a previous version of the manuscript, and I am glad to see that the Authors answered in an exhaustive and very detailed way to the concerns of both Reviewers. The Authors' modification to the previous version of the manuscript effectively improved both the readability and the scientific content and structure of the paper. The overall length of the paper is right at the word count limit for a Short Communication. I wish to see these data and discussions published as soon as possible. Unfortunately, I still have some minor comments which the Authors may want to consider. The manuscript already fulfil the high-quality standards of Solid Earth and it deserves to be published after some very minor corrections. I provide below some comments and suggestions which I hope might help the Authors in shortening the text and clarify even more its content.

General comments:
1) Title: as it is now, the title is rather inconsistent with the whole bulk of topics discussed in the manuscript. I am referring to "focus mass transport", which subject is rather limited in the Discussion section. This comment relates also to the General comment 3) about Section 3.1.
Perhaps a slight rewording of the title would make it effectively reflect the content of the whole manuscript (e.g.: "Experimental evidence that viscous shear zones generate periodic pore sheets: effects on fluid redistribution and mechanical behaviour"; something that include both topics. By the way, this is only a suggestion.)

We agree that changing the title slightly would better serve the manuscript. It is now "Experimental evidence that viscous shear zones generate periodic pore sheets".

2) Introduction and Discussions: there are two seminal papers, in my opinion, from Neil Mancktelow (2002, "How ductile are ductile shear zones?" Geology https://doi.org/10.1130/G22260.1; and 2008 Lithos https://doi.org/10.1016/j.lithos.2007.09.013) which must be discussed (or at least cited) in your manuscript. Both papers cover exactly the topics and paradigms you wish to discuss, and thus I am quite surprised in not seeing them even cited in your manuscript.

Briefly, Mancktelow (2002) shows that there is the necessity of a "pressure-sensitive plastic deformation" component during viscous deformation of ductile shear zones to explain melt–fluid flow within ductile shear zones from a continuum mechanics point-of-view.
Indeed, including this point-of-view in the Introduction (Lines 20-32) would strengthen and support your claim for the necessity of a "reappraisal of the community's perception of how viscous deformation in rocks proceeds with time", alongside with natural and experimental results. It would also support your discussion in Sections 3.1 and 3.2.3 (Lines 225-227).

We agree and have exchanged some emails with Neil Mancktelow discussing this. Our initial exclusion came from citation limits imposed by other journals that we submitted the manuscript to prior to SE. We have now included citation of Mancktelow (2006) (https://doi.org/10.1130/G22260.1) and another important early work on creep cavities by Mancktelow et al. (1997) (https://doi.org/10.1007/s004100050379).

3) "How mylonites could focus mass transport". I would like to see a clear discussion and separation between what is observed and inferred from the experimental data and microstructures and what is then extrapolated to occur in natural shear zones. I'll explain myself. The presented experimental data and microstructures show that there is the formation of a systematic, periodic and anisotropic pore network which allows for the mass redistribution within your sample, rather than an effective mass transport. The deforming sample in conjunction with the deformation apparatus cell constitute a "closed" chemical system.

Given that the "system definition" is a matter of scale, if one considers the deforming sample and the confining medium as two separate entities, the ingress of Ar from the confining medium is a clear evidence for the occurrence of an effective mass transport between two media. However, this cannot be demonstrated with the presented data and I completely understand that demonstrating Ar mobility is far beyond the scope of the present manuscript.
By contrast, mass transport in natural shear zones implies either gain or loss of chemical components in an "open" chemical system, which commonly includes two media: the shear zone and the some other rock (host rock, subducted or nearby tectonic units, e.g. Selverstone et al., 1991 JMG; Barnes et al., 2004 JMG) which act as either source or sink of the transported mass.
Therefore, I would suggest the Authors to clearly state that in the experimental case the porosity allows for a mass redistribution within the sample, which sample can be probably treated as a closed system. Then, if this process is extrapolated and adapted to the natural "open system" shear zones, where the deforming dynamic-porosity-bearing medium communicates with another medium, it can effectively promote mass transport. This can be easily addressed by the Authors with some rewording of the paragraph.

We can see why this would be useful to clarify and have amended the text.

We have changed:
"While it is unclear what the exact composition of the fluid was, the presence of many newly precipitated minerals in pores, and across pore clusters, is evidence that mass was mobile in porous domains during the deformation."

to read on lines 114-117:
"While it is unclear what the exact composition of the fluid was, the presence of many newly precipitated minerals in pores, and across pore clusters, is evidence that mass was mobile and redistributed during the deformation. Thus if extrapolated to a natural deformation where the chemical system may be more open, mass transport through this porous network could lead to mass gain or loss in the mylonite rather than just redistribution."

4) In my opinion, it would be better to present first the comparison with other experiments and then discuss how the porous anisotropy may affect the mechanics of such experiments (swop the order between section 3.2.1 and 3.2.2). This would also allow to extend the discussion about the Generalised Thermodynamic model to the other experiments and thus discuss the differences between the experimental results. Indeed, when reading the section comparing experimental results one question comes up: what about the boundary conditions (constant force vs. constant velocity) in these different experiments? Does it relates to the mechanics? This is only a personal suggestion, but it would probably ease the reading of the manuscript and its logical structure.

Otherwise, the Authors need to consider the boundary conditions as one of the "difference and similarities" between experiments (Lines 183-197), given that they show the important role of boundary conditions on the mechanics and microstructure of experiments in the previous section (3.2.1).

We favour the current order of the sections but thank the author for his suggestion. We have added a clarification that the experiments we compare were also run at constant twist rates, like our own.

5) Section 3.3: I really like the discussion about veining and fluid flux, which perfectly fits with the above-discussed "mass transfer" capability of shear zones related to creep cavitation and the dynamic fluid pump model. The reference to "recent experiments on calcite gouges" fits perfectly with the "earthquakes and tremors" topic discussed at the end of the paragraph and the discussion of experimental mechanics above. However, the discussions concerning dyking and frictional melting seem a bit out of place, they are still speculative (as stated by the Authors) and a bit disconnected to the rest of the paper in my opinion (Delete Lines 230-233; 236-240). Therefore, I would suggest the Authors to limit the discussion about "speculative" topics, also in order to shorten the main text. A rapid rewording and swop of sentences within the paragraph will easily satisfy this suggestion, if the Authors agree on that.

We thank the referee for their suggestion but we wish to retain the inclusion of dyking and frictional melt. Firstly, this is because we have now linked this more clearly to melt segregation and flow, in line with the comments of Referee 2. Secondly, we feel that in such a discussion section about further consequences both the topics fit well.

As referee 2 rightly pointed out to us, our results are likely important for partially molten systems and while we are reluctant to focus the paper around this point we wished to include some mention of it in the more speculative aspects of our discussion. Additionally, in the case of frictional melting, and more broadly earthquake nucleation, it is clearly an important revelation if a mylonite is much more granular. It also fits perfectly with the sentiments of the citation (Mancktelow (2006)) the referee suggested we include about the modelling of mylonites as pressure-dependent rocks. We have changed this section now to link this discussion to the work of Mancktelow (2006). On lines 257-260 it now reads as:

"This is relevant for observations of deep seated frictional melting where the presence of a porous anisotropy in mylonites may facilitate changes to some kind of granular or frictional mechanical mode that is otherwise unexpected. This would compliment earlier work that suggested that the mechanical behaviour of mylonites may be more pressure dependent than generally assumed (Mancktelow, 2006) and the emergence of creep cavities with high strains would facilitate this."

Detailed comments:
Line 80: If you are not considering the mineral-filled pores in your quantification, then specify that these values are minimum estimates.

We thank the reviewer for the point they raise but we do not wish to make this change as it is much more complicated than simply saying there is a minimum due to some pores being filled.

Firstly, if the porosity is dynamic, as the model we test aspects of suggests, then we do not know if what we measure is a minimum, maximum, minima, maxima or any other position in the distribution of measurable values that could be occurring as pores open and close. It is likely that there is a very complicated competition of chemical and mechanical rates for pore opening and closing that determine how much pore space is open at any one moment (cf. the supp for Fusseis et a. 2009). Additionally, we would claim that regardless of whether the porosity was time-dependent, we would also need to know the porosity values of all other possible slices through the rock to know where our measurement sits in terms of a minimum value. We may in fact be observing a plane that gives porosity values much closer to a maximum. Moreover, the model of Fusseis et al. (2009) states that the opening of creep cavities would be proportional (in some way that is not clearly defined) to the strain rate, and as there is a rather large strain rate gradient through the samples, with the max strain rate occurring within the window we sample, then we would in fact be much closer to a maximum for the sample. The comparison between the porosity values of our samples in our study is only really valid because the strain rates applied during the constant twist rates are broadly similar between experiments. Thus we compare very loosely 'constant strain rate windows' that vary with strain. We have included these porosity values only after the first round of referee's comments lead us towards this. There is a limit to how useful these values are and we do not wish to make that harder to evaluate by guessing at if they are close to a minimum or maximum value.

Line 165: Please specify what is the related boundary conditions in the Generalised Thermodynamic model (i.e. constant velocity = constant thermodynamic flux; constant force = ?).

We have amended the text accordingly.

Referee 1: Lars Hansen

The revised manuscript is greatly improved, and I thank the authors for taking the time to consider my previous comments. The introduction and discussion are much clearer in the revised version, and I find the inclusion of the absolute porosity changes to be intriguing. There are a couple of primary points I'd like to raise related to the revised text and to the response to my initial comments. I still think the content of the article is timely and worth publishing. My comments relate to the fact that I'm having trouble making some logical connections among different parts of the paper, and therefore some clarification would be welcome in a revision.

I admit that I did find the expanded discussion on the thermodynamics of creep to be difficult to follow at times. I appreciate the emphasis on the boundary conditions, and the possibility for constant velocity boundary conditions to prevent localization. However, I'm not sure I understand why a macroscopic response related to the porosity evolution must be linked to localization. There should still be some effect on the mechanical response associated with a 1% increase in the pore fraction, even if there isn't localization. This effect is well documented in the literature on partially molten rocks (e.g., see part 1 and part 2 of Hirth and Kohlstedt, 1995). Because of the reduction in grain-grain contact area, the local stresses are higher, and therefore higher strain rates are generated for the same macroscopic stress. The details of this reduction in apparent viscosity clearly depend on the specific microstructure, but for the basalt-olivine system in dislocation creep, you'd expect a reduction in viscosity of about 10% (factor of 1.5 increase in strain rate at constant stress, or a factor of 1.1 decrease in stress at constant strain rate, for a stress exponent of 3.5). Some of the experiments in Barnhoorn et al. (2004) may have weakening of this amount at strains >5, but the majority seem pretty stable.

We would contest that it is not immediately clear if the explanation given for why a partial molten system had a certain response during an experiment would directly apply to a sub-solidus deformation. That being said we agree that it is very surprising that the emergence of the porosity did not have any overall mechanical effect (like the referee described for partially molten systems). Possibly one of the most interesting implied results of our investigation is the apparent reinforcement of the sentiment of Dimanov et al. (2007) about the decoupling of the microstructure and the mechanics. In this sense, it points to a need to better understand the tension, noted in material sciences (cf. Rudnicki and Rice (1975) (https://doi.org/10.1016/0022-5096(75)90001-0) and Rice (1976) (https://www.osti.gov/biblio/7343664)), between material instabilities (where localisation arises due to macroscopic properties and processes) and geometric instabilities driven by material heterogeneities (imperfections, cracks, clusters of pores or a domain of finer grain size) in rocks. We hope that our results will spark future work in this direction.

I find it particularly interesting that the porosity doesn't increase until after gamma = 5. Considering that you are only counting open pores (as documented in the revised manuscript), this must mean the sample has increase in volume by 1% between a gamma of 5 and a gamma of 10. I understand the hypothesis that porosity is generated by recrystallization, but there is still plenty of recrystallization (perhaps even more) at low strains. So it remains unclear to me why there is a porosity increase only after very large strains (and as noted above, in association with essentially no change in flow stress). I think it would be useful to include some explanation, even if speculative, for this phenomenon.

Thank you for drawing attention to this interesting point. We too agree that it is something worth understanding but we cannot speak any more than we have already in the manuscript to the trajectory of porosity change with strain.

Unfortunately, there are far too many aspects of the experiments that are unconstrained to speculate in any way that would be meaningful or helpful for the reader. The main reason for why the porosity increases in such jumps is simply down to the resolution of our sampling. We chose samples that represented stages of the deformation and transformation and as such we cannot speak to the intermediate stages of porosity change as we do not have the data. From the data at hand we do not know, microstructurally, when the onset of significant dynamic recrystallisation was and can only assume that it must be close to peak stress. This, combined with the fact that the other samples arrested below peak stress show no to less than a few percent of recrystallisation (see fig. 6b in Barnhoorn et al. (2004)), suggests that our low strain sample must have had little to no recrystallisation occur. We would claim that this makes the comparison of the pore populations from before and after peak stress, from a process perceptive, limited.

Moreover, we agree that there are many interesting questions about what happens to the porosity values during the strains intermediate to peak stress and gamma 5. We would suppose to find creep cavities emerging and inherited porosity becoming overprinted with the new syn-kinematic porosity, but whether or not this means that there would be a transiently high, lower or similar porosity as the two pore population transitioned we cannot say. In the case of relating the post peak stress samples (gamma 5 sample to the gamma 10.6), this 1% porosity increase is achieved during a roughly 20-25% change in recrystallisation (see fig. 6b in Barnhoorn et al. (2004)). This is therefore not such a large jump in porosity value with strain/transformation by recrystallisation. While we too would like to know the details of this intermediate trajectory, it is beyond the scope of our current work and hope that future work will establish how these changes occur.

Regarding the link to partially molten rocks, I understand the authors' point that to properly treat that connection is a major undertaking. And I understand that this comparison has been made already by Spiess et al. (2012). However, I still feel that something needs to be said in this manuscript, even if it is just a single sentence referring the reader to Spiess et al. I should also note that the authors' second reason for not including this topic (that these experiments represent single phase aggregates) does not sound quite right to me. If there is a fluid phase in the pores (as the authors suggest there is in the revised version), then this is a multiphase system. Much of the relevant literature on partially molten rocks focuses on a single solid phase and a single fluid phase.

We completely agree with the referee that our work seems to lead to the conclusion that some single phase rocks may be more akin to those in multiphase systems. This was one of the major personal conclusions of the first author when writing up their PhD thesis, from which this work comes. However, we would claim that in the eyes of the community the experiments of Barnhoorn et al. (2004) are classical examples of how high homologous temperature deformation proceeds in monominerialic rocks and we would prefer to discuss our results with this in mind. As we have chosen a shorter communication, and because our actual results are purely those relating to pores and their distribution, we would rather keep to our current discussion where we guide the reader towards what it may mean for creep cavities and fluid to be present, be it melt or other liquids. In light of this, and because we agree with the referee, we have tried to accommodate a more direct link to the consequences of partially molten rocks. We hope that this draws the reader closer to the link that the referee hoped to establish.

The second paragraph of section 3.3 (Lines 245-252) now reads:

"In the case of dyke intrusion at high grade conditions, the work of Weinberg and Regenauer-Lieb (2010) infact already invoked creep cavities and their coalescence into creep fractures as the responsible mechanism for allowing dyking to occur. While our results do not show the development of creep

fractures, they forward the speculative argument of Weinberg and Regenauer-Lieb (2010) that creep cavities will occur during ductile shearing in rocks and could be interpreted to add weight to the discussion of Spiess et al. (2012) about the grain-scale role of creep cavities in promoting melt segregation and flow. When this is considered alongside the body other seminal experimental work on partially molten rocks (e.g. Kohlstedt and Holtzman, 2009), it becomes clear that tests need to be devised to distinguish between the different theories of melt segregation and migration (e.g. compaction length vs. sheets of creep cavities)."

I also appreciate the expanded discussion on how failure associated with cavity formation is not easily predicted in existing experiments in rocks. My comment here is intended to point out that there is an extensive literature on failure by cavity formation in metals, and the time to failure is a primary concern for engineering applications. Correspondingly, there are a variety of efforts to establish constitutive equations that predict the time to failure, which is exactly what the authors seem to be advocating for. Some well cited examples include Ashby and Dyson (1984, https://doi.org/10.1016/B978-1-4832-8440-8.50017-X) and Kowalewski et al. (1994, https://doi.org/10.1243/03093247V294309). As with the discussion of partially molten rocks, it seems unfortunate to not, at least, acknowledge that significant effort has already been made on this front outside the geological literature and refer the reader to this vast resource.

We have now amended the text to include reference to time to failure models. We thank the referee for raising their concern because it drew attention to nuance of our point that had been hidden in implication. The first paragraph of section 3.2.3 (Lines 212-221) now reads:

"Our results, and those of the four other experiments described above, suggest that mylonites of various compositions develop complicated microstructures that for an unknown set of critical conditions can facilitate a spontaneous mechanical change from flow to fracture. While there are many ways to incorporate history-dependence into flow laws that account for some microstructural change (cf. Renner and Evans, 2002; Barnhoorn et al., 2004; Evans, 2005) it does not seem that this kind of rate equation would capture the differences between ours and the four other experiments described. For example, a flow law that integrated strain (e.g. Hansen et al., 2012) would not be able to account for why some of the five experiments fractured at shear strains below 5 (e.g. Dimanov et al., 2007; Rybacki et al., 2008, 2010) with others flowing up to a shear strain of 50 with no fractures developing (Barnhoorn et al., 2004). This observation also seems to highlight a limitation to the use of empirical relationships that link strain or time to failure by creep fracture (e.g. Rybacki et al., 2008). Taken together, we suggest that this potential disconnection between the microstructure and mechanics of a mylonite places a need for the use of more complex physics to describe how a shear zone may deform with time."

The observation that some experiments fail and others do not seems to suggest that a damage mechanics approach to time to failure may overlook the dissipative competition of processes or misses some aspect about spatial distribution of damage. Even in the case of more complex “two damage state variable” approaches, like that of Kowalewski et al. (1994), they would likely not be able to reconcile the differences between the four torsion experiments we cited in our work. This is largely because they are not considering the energetic competition of processes, only the mechanical coupling of two linked damage variables. In the case of our experiments one could say that grain size change was some kind of damage with time and the creep cavities another coupled damage process. If one applied the assumptions of Kowalewski et al. (1994) our experiments should have failed at some point due the accumulation of damage. As they did not it seems to suggest that the steady state attained in our experiments must result from some more complex coupling of physics.

We have now highlighted our position more directly in the text and cite the geological work of Rybacki et al. (2008) as it also fits a time to failure curve. We would rather not include the mention of damage here as it has a rather vast literature base and one of the purposes of our short communication was to engage with parts of the tectonics community that may not have a clear background in rock mechanics. A reader interested in creep cavities would quickly find the damage mechanics literature and we do not think excluding citation to the material sciences here will be an impediment to the curious.

Minor comments:

Line 29: Why capitalize “Generalized Thermodynamic”? This can’t be the only generalized thermodynamic model.

We have capitalised this because there are several schools of non-equilibrium thermodynamic frameworks and one of them is referred to formally as Generalised Thermodynamics. We have added a citation now to draw any curious reader to a review article in which this is defined.

Lines 29 to 30: Is it really a paradigm if much remains to be tested? I guess it sounds more like a hypothesis to me.

We would disagree because a paradigm more completely captures both a distinct set of ideas and the surrounding philosophy in which those ideas are pursued and tested. Contained within the paradigm is the notion of which data or observation is good or bad. In this sense it is as much about the perspective as it is the detail of the hypothesis. For example the microstructures of the experiments we revisit were originally investigated with a particular paradigm in mind which included assumptions about pores not opening at high confining pressure. We do not use the word paradigm to be superfluous but to convey holistically the nature of the dynamic granular fluid pump model which is about more than an esoteric porosity.

Lines 54 to 55: I'm not sure I fully understand this statement. Indeed, the energetics are critical to consider, but they are, to some extent, already included in the mechanics. For example, the typical quantities to measure in tests of viscous materials are stress and strain rate. The product of these two quantities is the total energy dissipation (in Watts per unit volume). Therefore, the energetics of the system are generally being measured and considered in traditional treatments of these data. Perhaps some additional clarification is necessary here.

We agree that the product of the stress and strain rate tensors will give a mechanical dissipation term, and the point we are making is that this term (along with other potential dissipation terms) must be included in the energy conservation equation for the corresponding coupled feedbacks to be accounted for.

Answering your question succinctly is best achieved by referring to fig. 4 in Herwegh et al. (2014) (From transient to steady state deformation and grain size: A thermodynamic approach using elasto–visco–plastic numerical modeling - https://doi.org/10.1002/2013JB010701). Here the referee will see that the rheological flow law is a mechanical rate that feeds into the energetic balance of the system but does not itself define the stability of the system. In more complex formulations of what is expressed in Herwegh et al. (2014) many dissipative processes can compete at several dissipative length scales (cf. Hobbs et al. 2011 (https://doi.org/10.1016/j.jsg.2011.01.013)). That is to say that when one considers the energy equation as the governing equation then rate equations (like flow laws (several may act together to dissipate energy) or reaction rates) feed into how temperature changes with time. Another key difference is that one also considers the stored energy of the system when placing the energetics first. Which, in an isothermal case you described, would recast your W/t = (sigma/t * epsilon) + (sigma * epsilon/t) to become W/t = F/t + Phi/t, where F is the Helmholtz free energy and Phi entropy production. Here the dissipation through a flow law would be captured in Phi/t. By considering these variables one is considering far more than one can in a rheological equation and places mechanical dissipation as one among many factors that govern the stability of a reacting and deforming system.

This information is readily available in the work we cite and we would rather not add more information within the manuscript to make the case for the details of this Generalised Thermodynamic framework. We hope that the referee finds this agreeable and agrees with us that we have provided enough choice citations for a curious reader to dive further into the topic.

Lines 58 to 59: T should be italicized.

The text has been changed accordingly.

Line 75: I think a slight rewording is needed to clarify that it is the clusters (rather than the pores) that are systematically oriented.

We have changed the text to:

"The pore density map of this experiment highlights that pores appear in clusters and that these clusters repeat across a large area with a systematic orientation (fig. 1d)."

Line 120: This statement caught me off guard a bit. I suppose my instinct is that the evolution of the porosity and porosity distribution will depend large on the nature of the pore fluid and the pore-fluid pressure. I think the only way to say that these features of the porosity depend on bulk material properties like the elastic modulus is to demonstrate that the porosity is different for different materials, rather than the suggestion that the porosity reaches steady state, as is implied here.

We have amended the text with an explanation and citation to address the referee's concerns. The text now reads:

"Curiously, our results also seem to suggest that porous domains develop within zones of stable orientation and, possibly, wavelength (approx. 15° from the shear zone boundary with a wavelength of 400 μm). This is consequential because it implies that the emergence of porous sheets is determined by some bulk material characteristic (for example, like the elastic moduli) and not by the positions of any initial heterogeneities hosted within the starting material (akin to grain-size variations). This speculation about the role a bulk material characteristic controlling the location of pore sheet formation is possibly supported by other experimental observations that the regular spacing of creep fractures from the coalescence of pore sheets changed with temperature (see fig. 16 in Dimanov et al. (2007))."

We agree with the referee that our contribution's results do not let us discriminate between which bulk characteristic could play a role but we now draw on the observation of Dimanov et al. (2007) that creep fracture spacing changed with temperature. This bulk change in microstructure across millimetres with a state variable further suggests that it is likely some kind of material scale control that governs the location and orientation of the pore sheets. It would be interesting to see if future studies can show for more than the two temperatures that Dimanov et al. (2007) did, if the change in spacing is linear or non-linear with temperature as this might illuminate if it is the elastic properties or not that are driving these changes.

Line 129: "affected" → "affect"

The text has been changed accordingly

Line 131: Remove “concerning” or “of”

The text has been changed accordingly

Line 148: Is “flux” the right word here? What is there a flux of? This discussion is about the boundary conditions, but flux refers to some sort of transport. Is this the flux of energy into the system? Some clarification would be useful.

As we draw on an existing definition we have now included citation for the reader to pursue further if they so desire.

Line 195: “evolved”→ “evolve”

The text has been changed accordingly

Line 198: Again, shouldn’t the pore-fluid pressure factor into this discussion?

This is a good point and we have now amended the text to reflect the referee’s comment. The text now reads:

“It is not clear what critical condition leads some to fracture and others to not: for example, is it the local pore density, differences in pore fluid pressure or the widths of the porous domains that controls if a fracture develops?”

Line 200: Remove “a” prior to “fracture”

The text has been changed accordingly

Line 230: An “e.g.” makes sense before the citation to Hobbs since there are many documented observations of frictional melting in the geological record.

The text has been changed accordingly

Experimental evidence that viscous shear zones generate periodic pore sheets~~that focus mass transport~~

James Gilgannon[1], Marius Waldvogel[1], Thomas Poulet[2], Florian Fusseis[3], Alfons Berger[1], Auke Barnhoorn[4], and Marco Herwegh[1]

[1]Institute of Geological Sciences, University of Bern, 3012 Bern, Switzerland
[2]CSIRO Mineral Resources, Kensington, WA 6151, Australia
[3]School of Geosciences, The University of Edinburgh, Edinburgh EH9 3JW, UK
[4]Department of Geoscience and Engineering, Delft University of Technology, Delft, The Netherlands

Correspondence: James Gilgannon (james.gilgannon@geo.unibe.ch)

Abstract.

In experiments designed to understand deep shear zones, we show that periodic porous sheets emerge spontaneously during viscous creep and that they facilitate mass transfer. These findings challenge conventional expectations of how viscosity in solid rocks operates and provide quantitative data in favour of an alternative paradigm, that of the dynamic granular fluid pump model. On this basis, we argue that our results warrant a reappraisal of the community's perception of how viscous deformation in rocks proceeds with time and suggest that the general model for deep shear zones should be updated to include creep cavitation. Through our discussion we highlight how the integration of creep cavitation, and its Generalised Thermodynamic paradigm, would be consequential for a range of important solid Earth topics that involve viscosity in Earth materials, like slow earthquakes, the flow of glacial ice and the tectonics of exoplanets.

1 Introduction

Our existing models for mantle convection, the advance of glaciers and even the dynamics of the seismic cycle all include, and rely on, the concept that solids can be viscous and flow with time. In this sense, the fluid mechanical concept of viscosity is a cornerstone of Geoscience and our view of a dynamic Earth is built around it. In rocks, a record of this viscosity is found in mylonitic shear zones, the largest of which are the deep boundaries of tectonic plates that can reach into the asthenospheric upper mantle (Vauchez et al., 2012). Consequentially, mylonites represent important interfaces in the lithosphere that crosscut different geochemical, geophysical and hydrological domains. This role places them at the centre of discussions on slow earthquakes and the hydrochemical exchange of deep and shallow reservoirs (e.g. Beach, 1976; Fusseis et al., 2009; Bürgmann, 2018). In this context, it is critical to have a robust and complete model of deep shear zones and the viscous rocks in them.

The accepted conceptual model for lithospheric shear zones supposes that there is a mechanical stratification with depth from an upper frictional to lower viscous domain (Sibson, 1977; Schmid and Handy, 1991; Handy et al., 2007). In this model, viscous creep is a continuous slow background deformation and, at certain conditions, is punctuated by fracturing. It is this fracturing, which can have physical (e.g. Beall et al., 2019) or chemical (e.g. Alevizos et al., 2014) driving forces, that creates seismicity and mass transport pathways through the deep Earth (Sibson, 1994). Two core assumptions of this conceptual model are that creep in polycrystalline aggregates mainly contributes to distorting the deforming mass (e.g. Poirier, 1985; Hobbs and Ord, 2015) and the large confining pressures of the viscous domain reduce porosity and permeability with compaction (Edmond and Paterson, 1972; Xiao et al., 2006). In contrast, there is a newer paradigm ~~which argues that~~ that argues viscous creep in mylonitic rocks can intrinsically produce a dynamic permeability, called creep cavitation ~~(Dimanov et al., 2007; Fusseis et al., 2009)~~(cf. Mancktelow et al., 1998; Herwegh and Jenni, 2001; Dimanov et al., 2007; Fusseis et al., 20 . The most well known formulation of this paradigm is the Generalised Thermodynamic model (cf. Hobbs et al., 2011)known as the dynamic granular fluid pump (Fusseis et al., 2009). While much of this paradigm remains to be tested, the notion that mylonites generate self sustaining and dynamic pathways for mass transport is radical and consequential for the interpretation of how deep shear zones behave during deformation.

The dynamic permeability is proposed to be created and sustained through the opening and closure of syn-kinematic pores, called creep cavities, by viscous grain boundary sliding during creep (e.g. Herwegh and Jenni, 2001; Dimanov et al., 2007; Fusseis et al., 2009). In recent years the paradigm has gained traction with many more contributions interpreting the presence of, or appealing to creep cavities in natural samples (e.g. Gilgannon et al., 2017; Précigout et al., 2017; Lopez-Sanchez and Llana-Fúnez, 2018; Giuntoli et al., 2020). With the most notable claims involving creep cavities being that in polymineralic viscous shear zones their formation establishes an advective mass transport pump (Fusseis et al., 2009; Menegon et al., 2015; Précigout et al., 2019), it aids melt migration (Závada et al., 2007; Spiess et al., 2012) and has even been speculated to nucleate earthquakes (Shigematsu et al., 2004; Dimanov et al., 2007; Rybacki et al., 2008; Verberne et al., 2017; Chen et al., 2020). However, much of the most convincing supporting evidence currently available is limited to deformation experiments on fabricated geo-materials and is generally restricted to grain-scale observations. Hence it has been difficult to evaluate if this phenomenon is extensive and relevant at the material scale for natural samples and, moreover, if it is applicable to natural deformations in deep shear zones.

In this contribution we provide unambiguous experimental evidence in a natural starting material that supports, and extends, the paradigm concerning the role of creep cavities in shear zones. We present quantitative results showing that creep cavities are a spatially significant feature of viscous deformation, being generated in periodic sheets throughout the samples. Our analyses are intentionally made over large areas of the experimentally deformed samples in order to contextualise and understand the role of creep cavities at a scale more comparable to those where macroscopic material descriptions are unusually made. We argue that our results warrant a reappraisal of the community's perception of how viscous deformation proceeds with time in rocks and suggest that the general model for viscous shear zones should be updated to include creep cavitation. A key consequence of this would be that the energetics of the deforming system become the keystone of our perspective rather than the mechanics.

2 New results from classical experiments

To make this argument, we have revisited the microstructures of a set of classical shear zone formation experiments performed on Carrara marble (Barnhoorn et al., 2004). The torsion experiments were run at a high homologous temperature (~~T~~ T = 1000 K, ~~T_h~~ T_h = 0.6) with confining pressure (~~P~~ p = 300 MPa) at constant twist rates. Samples were deformed to large shear strains and recorded the dynamic transformation of undeformed, homogeneous, coarse-grained marbles into fine-grained ultramylonites. The experiments demonstrated that microstructural change by dynamic recrystallisation was concurrent with mechanical weakening and the development of a strong crystallographic preferred orientation. More recently, it was shown that these experiments contain creep cavities and that the pores emerged with, and because of, grain-size reduction by sub-grain rotation recrystallisation (Gilgannon et al., 2020). In this contribution we expand on these observations and present new results that quantify and contextualise the development of porosity inside of an evolving viscous shear zone.

Please refer to the appendix for details of the methods used in the following results.

2.1 Porosity evolution with mylonitisation

At very low shear strains, and before any dynamic recrystallisation, pores decorate grain boundaries and appear as trails through large grains (d $\approx$ 200 μm, fig. 1a). These pores are likely fluid inclusions trapped in and around the original grains (Covey-crump, 1997) (the pore density map in fig. 1b reflects this by highlighting the outlines of the initial grain-size). In the experiment run to a shear strain of 5, which is in the midst of significant microstructural adjustment, the porosity has a clearly different character. The pores appear at the triple junctions of small recrystallised grains (d $\approx$ 10 μm) and in some cases are filled with new precipitates (fig. 1c). The pore density map of this experiment highlights that pores appear in clusters ~~that~~ and that these clusters repeat across a large area ~~and are systematically oriented~~ with a systematic orientation (fig. 1d). Once the microstructure is fully recrystallised (γ = 10.6), and has reached a microstructural steady state, the porosity forms elongated sheets (fig. 1e). The density map of this experiment reveals that this porosity has become more spatially extensive and also shows a systematic orientation (fig. 1f). These pore sheets contain new precipitates of mica, Mg-calcite and pyrite, implying that the sheets are permeable and act as mass transfer pathways (fig. 2). When quantified, it appears that the porosity values before and after dynamic recrystallisation are similar but as strain increases the porosity increases by an order of magnitude (table 1).

Table 1. Sample porosity

Sample	γ_{max}	Porosity (%)
PO344	0.4	0.29
PO422	5.0	0.20
PO265	10.6	1.15

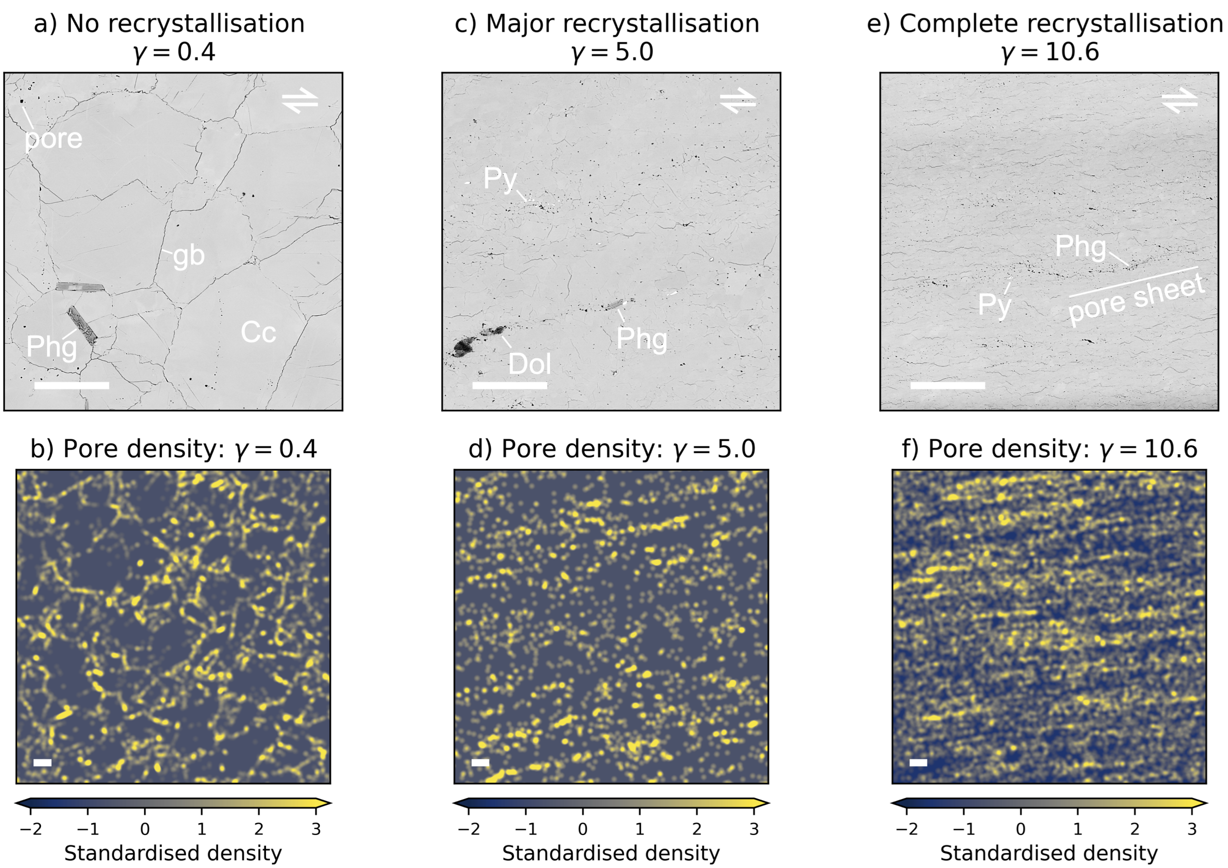

Figure 1. Microstructure and pore density in samples with increasing strain. The samples document the production of a mylonite through dynamic recrystallisation. Panels a,c and e are backscatter electron images while b, d and f are pore density maps. In all images the white scale bar is 100 μm. The pointed ends of the colour bars refer to the fact that some data values are larger than the max and min of the colour map. (Py = pyrite, Dol = dolomite, Phg = phengite, Cc = calcite, gb = grain boundary).

2.2 2D continuous wavelet analysis of pore sheets

We quantify the spatial extent and character of these permeable pore sheets with 2D continuous wavelet analysis. In particular, we use the fully-anisotropic 2D Morlet wavelet (Neupauer and Powell, 2005) to identify features in the pore density maps and expand a 1D scheme of feature significance testing used in climate sciences (Torrence and Compo, 1998) to 2D to filter for noise in the data. Furthermore, by implementing a 2D (pseudo) cone of influence we exclude boundary effects of the analysis at large wavelengths. For details of the wavelet analysis see the Methods section. Fundamentally, wavelet analysis can be thought of as a filter that highlights where the analysed data interacts with the wavelet most strongly. By varying the size and orientation (λ and θ in fig. 3a) of the Morlet wavelet one can isolate significant features in the data and gain quantitative information about

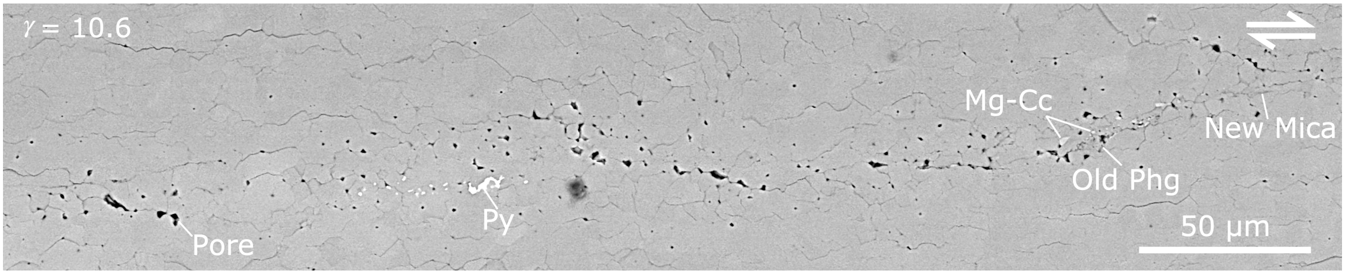

Figure 2. A more detailed view of the pore sheet labelled in figure 1e. Please find supporting spectra from Energy Dispersive Spectroscopy (EDS) in the appendix for the small precipitates. (Py = pyrite, Phg = phengite, Mg-Cc = magnesium calcite).

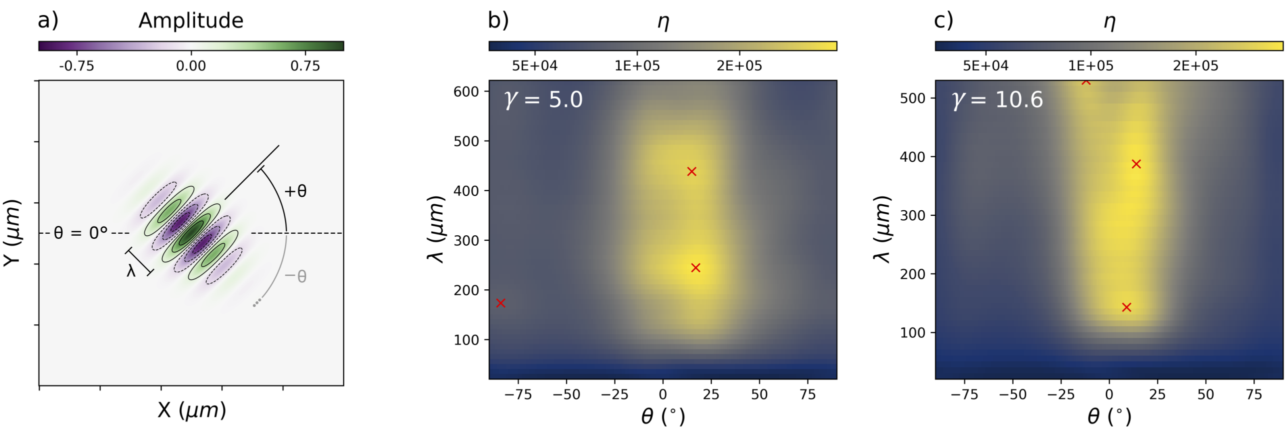

Figure 3. Wavelet analysis of partly (γ = 5.0) and fully (γ = 10.6) recrystallised samples. Fig. 3a show's a generic 2D Morlet wavelet. The wavelet analysis is conducted by considering the wavelet's interaction with the porosity density maps at each spatial position. This is repeated for different orientations (θ) and wavelengths (λ). Figures 2b and c visualises the wavelet analysis results for the two samples. Peaks in η represent the largest interaction with the wavelet (see section A7 for details). Peaks are identified by local extremes in η and marked with red crosses. We note that two local extremes are not discussed in the text. This is because one was very close to the *sensible limit* of the analysis (θ = -12°, λ = 530 μm) defined in appendix section A6 and the other did not correlate with any microstructural features (θ = -84°, λ = 173 μm).

them, including orientation, dimension and any spatial frequency.

Wavelet analysis reveals that, in both the partly and fully recrystallised samples, porosity is highly ordered with a strong periodicity and anisotropy. Both samples show two dominant modes of porosity distribution (fig. 3b and c). While the sample is only partly recrystallised, porosity is preferentially oriented at 17 and 15 degrees (measured antithetically in relation to the shear plane, see fig. 3a) with wavelengths of $\sim$ 240 and $\sim$ 440 μm respectively (fig. 3b and fig. 4a, b and c). This is both contrasted and complemented by the modes found in the fully recrystallised experiment, where the anisotropy is oriented at 9

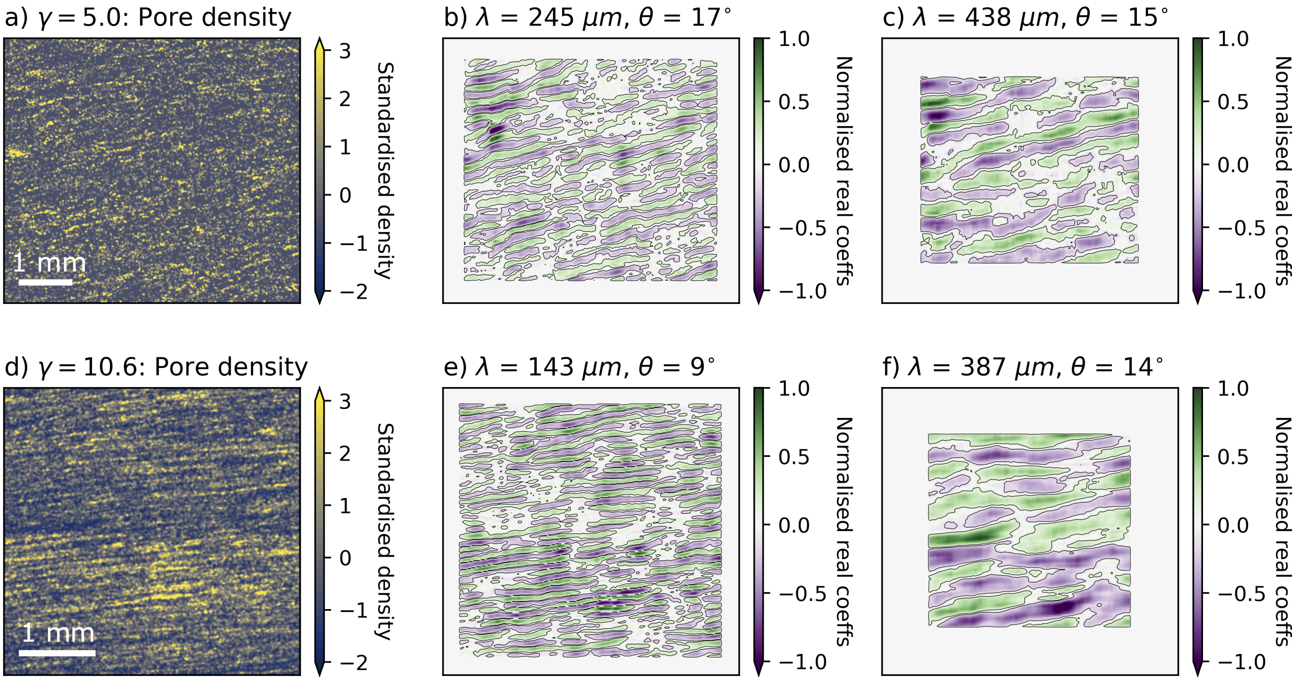

Figure 4. Visualisation of the results of the wavelet convolution with the pore density maps. The anisotropy identified by the dominant peaks in fig. 3 are shown for the partly (figs. 4a-c) and fully (figs. 4d-f) recrystallised samples. For each convolution at each wavelength analysed areas are defined for where edge effects may occur and data here is removed, this results in the white areas in the edge of figs. 4b-c and e-f (see section A6 for details). As before, the pointed ends of the colour bars refer to the fact that some data values are larger than the max and min of the colour map.

and 14 degrees with wavelengths of $\sim$ 140 and $\sim$ 390 μm, respectively (fig. 3c and fig. 4d, e and f). Interestingly the longer wavelength porosity features in both samples share similar orientations and spacing (Δ 1°, Δ 50 μm). As wavelet analysis does not require features to be periodic to be identified, the periodicity is a result and not an artefact of the analysis.

3 Discussion

These results provide an unambiguous foundation for discussing the community's perception of how viscous deformation proceeds with time and more generally the role of viscous deformation in the conceptual shear zone model. We claim this because our results show that a mylonitic shear zone deforming viscously can spontaneously develop highly anisotropic and periodic porous domains. This is not something that is expected within the prevailing paradigm for the deformation of rocks at high temperatures and pressures. For this reason it is important for us to reconsider the role of mylonites during geochemical, geophysical and hydrological processes in the lithosphere.

3.1 How mylonites could focus mass transport

Firstly, we suggest that the presence of periodic, porous sheets in natural shear zones would act to focus fluid during active deformation. Geochemical studies have proposed that the enrichment or depletion of elements in purely viscous shear zones must reflect syn-deformational fluid migration (e.g. Carter and Dworkin, 1990; Selverstone et al., 1991). Our results provide an experimental insight into aspects of the syn-kinematic pore network that likely facilitates this fluid transport in natural mylonites. The fluid phase in our experiments is not constrained but likely some mix of CO_2, H_2O and Ar that is both inherited from fluid inclusions of unknown compositions in the starting material, from decarbonation of the dolomite present (cf. Delle Piane et al., 2008), the breakdown of some, but not all, phengite minerals (cf. Mariani et al., 2006) and Ar that has likely diffused into the sample from the confining medium. While it is unclear what the exact composition of the fluid was, the presence of many newly precipitated minerals in pores, and across pore clusters, is evidence that mass was mobile ~~in porous domains~~ and redistributed during the deformation. Thus if extrapolated to a natural deformation where the chemical system may be more open, mass transport through this porous network could lead to mass gain or loss in the mylonite rather than just redistribution. Additionally, our results validate the prediction of pore sheets in the dynamic granular fluid pump model (Fusseis et al., 2009) and extend it to show that pore sheets can develop spontaneously in homogenous rocks, with a periodic and oriented character. Curiously, our results also seem to suggest that porous domains develop within zones of stable orientation and, possibly, wavelength (approx. 15° from the shear zone boundary with a wavelength of 400 μm). This is consequential because it implies that the emergence of porous sheets is determined by some bulk material characteristic (for example, like the elastic moduli) and not by the positions of any initial heterogeneities hosted within the starting material (akin to grain-size variations). This speculation about the role a bulk material characteristic controlling the location of pore sheet formation is possibly supported by other experimental observations that the regular spacing of creep fractures from the coalescence of pore sheets changed with temperature (see fig. 16 in Dimanov et al. (2007)). What exactly governs the appearance and location of these apparently stably oriented and spaced microstructural adjustments is a clear candidate for important future research as it hints at a challenge to the widely cited role of material inhomogeneity in determining the location of deformationally induced transformations and fluid pathways often cited in geological studies (e.g. Goncalves et al., 2016; Fossen and Cavalcante, 2017; Giuntoli et al., 2020).

3.2 Does a porous anisotropy affect the mechanics of a mylonite?

Two questions naturally arise from our results: (1) how could the presence of periodic porous sheets affect the mechanical behaviour of mylonites in the deep lithosphere?; and (2) why did the emergence of a spatially extensive and anisotropic porosity not ~~affected~~ affect the viscous mechanical state recorded in the original experiments of Barnhoorn et al. (2004)? Answering these questions is not trivial but there is some ground to be gained by considering the broader Generalised Thermodynamic literature behind the paradigm ~~of~~ concerning creep cavities and contrasting our results to other experiments where creep cavities have been observed to have an mechanical impact.

3.2.1 What effect are creep cavities expected to have in a Generalised Thermodynamic model?

In the dynamic granular fluid pump model, creep cavities are predicted to emerge as one of several dissipative processes that act to bring the reacting and deforming rock mass into a thermodynamic stationary state (Fusseis et al., 2009). That is to say that the chief concern of the model is that of the energetics of the system with a focus on the rate of entropy production. Theoretically this means no process is a priori excluded from activating and the most efficient combination of processes that use and store energy act in congress to produce a thermodynamic stationary state (Fusseis et al., 2009; Regenauer-Lieb et al., 2009, 2015): the system is neither accelerating or decelerating in a dissipative sense but is in some kind of steady state. In this model, many factors play a role in determining whether or not creep cavities will affect the mechanical state of the deforming body.

One of these factors that may be pertinent to our experiments is the boundary conditions for deformation. It is known from various types of modelling that different boundary conditions, i.e. constant force vs constant velocity, can promote or inhibit material instability and localisation (e.g. Fressengeas and Molinari, 1987; Cherukuri and Shawki, 1995; Paterson, 2007). In the case of constant velocity boundary conditions, like those applied in our torsion experiments, localisation is not expected to occur (e.g. Fressengeas and Molinari, 1987; Paterson, 2007). Indeed, from a Generalised Thermodynamic perspective, when the boundary conditions are set to a constant thermodynamic flux, i.e. a constant velocity (like the experiments we revisit) (cf. Regenauer-Lieb et al., 2014), the dissipative conditions are fixed and the material is forced to meet them through the activation of as many dissipative micro-mechanisms, at as many positions in the rock, as necessary (cf. Veveakis and Regenauer-Lieb, 2015; Guével et al., 2019). Conducting a deformation experiment in this fashion means that the onset of a localising instability can be missed because the rock is not allowed to incrementally adjust to an incrementally applied energy input (e.g. Peters et al., 2016). This does not prohibit the possibility of local microstructural differences developing but it does mean that, at the scale of the material a distributed deformation can remain favourable despite a heterogeneous microstructure. This observation of a stable but heterogeneous microstructure suggests that the size of the heterogeneities produced are not sufficiently large to impose further localisation. In the work of Shawki (1994) it was shown that thermal perturbations below a critical wavelength would not impose localisation during constant velocity boundary conditions. If the variation in creep cavity domains reflect different amounts of work being dissipated locally, and hence heat being produced, then one can see that the shorter wavelength porous domains, which reflects the size of actual pore sheets (fig. 2), are below the size of the thermal heterogeneities that were found to impose localisation in the constant velocity models (see fig. 5 in Shawki, 1994). Thus, from a Generalised Thermodynamic perspective, the boundary conditions of our experiments may, in part, explain why we do not see an obvious mechanical effect of the porosity with ongoing straining: once the steady state microstructure is attained, the sample is in a thermodynamic stationary state for the imposed boundary velocity that favours a distributed deformation.

A constant force boundary condition (also known as a constant thermodynamic force boundary condition (cf. Regenauer-Lieb et al., 2014)) is predicted to produce instability and localisation in rock deformation at high homologous temperatures (e.g. Fressengeas and Molinari, 1987; Paterson, 2007). It is often assumed that plate boundaries in nature will be under such a boundary condition (cf. Alevizos et al., 2014) and in this instance the presence of anisotropic domains of porosity may have a different impact than in our experiments. For example in experiments, not dissimilar in geometry to our own, run on olivine, it was found that localisation did indeed occur at constant force conditions and not for constant velocity (Hansen et al., 2012). At a constant force this localisation was expressed both in the microstructural adjustments (with the development of an oriented foliation and domains of varying grain-size) and in the mechanical behaviour of the olivine aggregates (noted by a continual weakening of the samples beyond a shear strain of 0.5). If we for a moment speculate on how our experiments may have proceeded under constant force boundary conditions it could be that porous domains emerge with some similar modes of periodicity to those observed under a constant velocity but in this case they might provide the sites for some kind of instability. For example, in our hypothetical case, pore sheets may aid in establishing features like the high frequency foliation and lower frequency domains of grain-size variation observed by Hansen et al. (2012) (e.g. figs. 5c and d and fig. 9a in Hansen et al. (2012)). Of course our speculation is only that and this line of argument requires new experimental testing that is beyond the scope of our revisiting of the classical experiments of Barnhoorn et al. (2004). What it does highlight is that viscous deformation in mylonites requires more research to understand exactly when and where a periodic occurrence of creep cavities could have a mechanical impact.

3.2.2 A comparison to other experiments that developed domains of creep cavities

In this context, there are four other experimental works in which creep cavities were documented to develop that are worth comparing to our results. All of these experiments were run in torsion with constant twist rates (constant thermodynamic flux boundary conditions) at high confining pressures and homologous temperatures on synthetic dolomite (Delle Piane et al., 2008), synthetic gabbro (Dimanov et al., 2007) and synthetic anorthite aggregates (Rybacki et al., 2008, 2010). All experiments developed creep cavities in oriented and spaced domains during linear viscous flow. In the gabbroic and some of the anorthitic samples, these porous domains became sites for the generation of instabilities known as creep fractures (Dimanov et al., 2007; Rybacki et al., 2008, 2010). When one compares the four experimental sets to our samples and one another, it is clear there are many differences and similarities. Firstly, the starting materials are all compositionally different and have various initial mean grain sizes, grain shapes and grain size distributions. Secondly, all four of these experiments use fabricated samples in comparison to our natural Carrara marble samples. Thirdly, when domains of creep cavities did emerge in the four experiments, some produced bands that were broadly a mirrored orientation to our results around the shear plane (see fig. 14 and 16 in Dimanov et al. (2007); fig. 1 in Rybacki et al. (2008); fig. 6 in Rybacki et al. (2010); and fig. 2 in Spiess et al. (2012)) with others being similarly oriented to our results (see fig. 8a in Delle Piane et al. (2008) and fig. 5 in Rybacki et al. (2010)). Lastly, for the gabbroic and anorthitic experiments these oppositely oriented porous domains were reported to ~~evolved~~ evolve into fractures while those domains of a similar orientation to our results did so less or not at all (Dimanov et al., 2007; Rybacki et al., 2008, 2010), and never in the dolomite experiments where linear viscous flow was maintained (Delle Piane et al., 2008). It is not clear what critical condition leads some to fracture and others to not: for example, is it the local pore density, differences in pore fluid pressure or the widths of the porous domains that controls if a fracture develops? While it is hard to draw any categorical conclusions from the comparison of these experiments, it is noteworthy that in each experimental case the mechanical data recorded a viscous deformation, regardless of whether ~~a~~ fracture instabilities occurred or not. This point draws attention to a conclusion already made in the seminal work of Dimanov et al. (2007), " *[c]learly, the 'microstructural state' is not obviously representative of the 'mechanical state'...* ". If this holds true for mylonites in nature then it opens an ambiguity over how the deformation of a mylonite will proceed with time: will it fracture, or will it flow?

3.2.3 Is a flow law enough to describe a mylonite?

Our results, and those of the four other experiments described above, suggest that mylonites of various compositions develop complicated microstructures that for an unknown set of critical conditions can facilitate a spontaneous mechanical change from flow to fracture. While there are many ways to incorporate history-dependence into flow laws that account for some microstructural change (cf. Renner and Evans, 2002; Barnhoorn et al., 2004; Evans, 2005) it does not seem that this kind of rate equation would capture the differences between ours and the four other experiments described. For example, a flow law that integrated strain (e.g. Hansen et al., 2012) would not be able to account for why some of the five experiments fractured at shear strains below 5 (e.g. Dimanov et al., 2007; Rybacki et al., 2008, 2010) with others flowing up to a shear strain of 50 with no fractures developing (Barnhoorn et al., 2004). ~~We~~ This observation also seems to highlight a limitation to the use of empirical relationships that link strain or time to failure by creep fracture (e.g. Rybacki et al., 2008). Taken together, we suggest that this potential disconnection between the microstructure and mechanics of a mylonite ~~makes it impossible to use only one rate equation~~ places a need for the use of more complex physics to describe how a shear zone may deform with time.

This point complements the fact that the dynamic granular fluid pump model (Fusseis et al., 2009), which our work tests aspects of, requires the consideration of energy, mass and momentum balance alongside rate equations for irreversible physical deformation (like plastic or viscous flow laws) and both reversible and irreversible chemical processes (Fusseis et al., 2009; Regenauer-Lieb et al., 2009, 2015). These different dissipative processes act at different diffusive length scales and are predicted to account for the geometry and temporal variation of several phenomena that all act synchronously during a deformation (cf. Regenauer-Lieb et al., 2015). In this perspective a flow law(s) is necessary but not sufficient to fully describe a deformation, with the balancing of the energy equation being of chief importance. Said another way, many thermally activated rate equations for physical processes may compete to dissipate energy and collectively produce a bulk mechanical diffusivity (Veveakis and Regenauer-Lieb, 2015). While our results cannot speak to all of these claims, they do show that there is some validity to the predictions of this newer paradigm, namely the emergence of pore sheets. This generally adds weight to older discussions about the possible need for a more complex view of deformation in mylonites ~~(Evans, 2005; Dimanov et al., 2007)~~ (Evans, 2005; Mancktelow, 2006; Dimanov et al., 2007) and suggests further testing is needed of the Generalised Thermodynamic ideas behind the paradigm concerning creep cavities.

3.3 Some consequences of incorporating creep cavities into the conceptual shear zone model

There are several enigmatic observations that are not well accounted for in the current conceptual model for lithospheric shear zones. To name a few: there is field evidence of frictional melting in the deep crust ~~(Hobbs et al., 1986)~~(e.g. Hobbs et al., 1986)

; the intrusion of dykes during upper amphibolite facies conditions (Weinberg and Regenauer-Lieb, 2010) and the fact that some geophysical data suggest that slow earthquake phenomena can occur at depths below the seismogenic zone (Wang and Tréhu, 2016). If the new evidence that we present, that mylonites can develop periodic porous domains during a viscous deformation, is incorporated into our conceptual model for lithospheric shear zones many new possible explanations emerge for otherwise hard to explain observations.

In the case of dyke intrusion at high grade conditions, the work of Weinberg and Regenauer-Lieb (2010) infact already invoked creep cavities and their coalescence into creep fractures as the responsible mechanism for allowing dyking to occur. While our results do not show the development of creep fractures, they forward the speculative argument of Weinberg and Regenauer-Lieb (2010) that creep cavities will occur during ductile shearing in rocks ~~.~~ and could be interpreted to add weight to the discussion of Spiess et al. (2012) about the grain-scale role of creep cavities in promoting melt segregation and flow. When this is considered alongside the body other seminal experimental work on partially molten rocks (e.g. Kohlstedt and Holtzman, 2009) , it becomes clear that tests need to be devised to distinguish between the different theories of melt segregation and migration (e.g. compaction length vs. sheets of creep cavities).

Additionally, recent experiments on calcite gouges made observations of creep cavities and argued that their formation allowed the gouge to transition from flow to friction (Chen et al., 2020). While these were lower temperature experiments than our own, they reinforce the notion that rocks could spontaneously transition from a viscous rheology to another mechanical state. This is relevant for observations of deep seated frictional melting where the presence of a porous anisotropy in mylonites may facilitate changes to some kind of granular or frictional mechanical ~~state~~ mode that is otherwise unexpected. ~~Also in the~~ This would compliment earlier work that suggested that the mechanical behaviour of mylonites may be more pressure dependent that generally assumed (Mancktelow, 2006) and the emergence of creep cavities with high strains would facilitate this.

In the case of quartz and calcite-dominated crustal-scale shear zones there often exists a peculiar relationship between viscous strain localization in ultramylonites, fracturing and precipitation of synkinematic veins/fluid flux within these ultramylonites (e.g. Badertscher and Burkhard, 2000; Herwegh and Kunze, 2002; Herwegh et al., 2005; Haertel et al., 2013; Poulet et al., 2014; Tannock et al., 2020) . In the wake of our results, it is tempting to propose that this syn-kinematic veining may be related to an interplay of fluid transport and the instability of the anisotropic porous domains. This is especially so for cases like the deeper portions of the basal shear zones of the nappes of the Helevtic Alps, where veining is observed to broadly increase with proximity to ultramylonitic shear zones (cf. Herwegh and Kunze, 2002) that are expected to be purely viscous in our current mechanical paradigm of the crust.

Moreover, any instability of pore sheets in natural plate boundaries may factor into explaining how both ambient and teleseismically triggered tremors can occur at depths below the seismogenic zone (Wang and Tréhu, 2016). This could place sheets of creep cavities alongside brittle fracturing and non-isochoric chemical reactions as the potential nuclei of slow earthquake phenomena. As the emergence of creep cavities was linked to dynamic recrystallisation (Gilgannon et al., 2020), a process expected throughout the lithosphere, the porous anisotropy presented here would allow slow earthquake phenomena to occur across a range of metamorphic conditions and mineralogical compositions (Peacock, 2009).

4 Conclusions

In summary, the current paradigm of viscosity that is borrowed from fluids is not a completely adequate analogy for solid geomaterials. We claim this because we observe that during the formation of a mylonite, that was recorded to possess viscous mechanical properties, a heterogeneous microstructure of periodic porous domains emerged. The current paradigm of viscosity in rocks does not expect this to occur and we have discussed how this observation of pore sheet formation during viscous deformation is seen in at least four other experiments of differing compositions. The porous anisotropy we observe likely has a role to play in both the transport of mass and the mechanics of the lithosphere. On this basis, we advocate for an update to the current concept of viscosity at high temperatures and pressures in rocks to include the periodic porous anisotropy we have presented. Our discussion has explored some of the possible consequences of changing our paradigm and moving forward these speculations should be further tested. As the viscosity of solids is a cornerstone of Geoscience, our results have farther reaching implications than the conceptual shear zone model and may even be relevant for other scenarios where solid state deformation is modelled with viscous rheologies, like glacial flow (e.g. Egholm et al., 2011) and tectonics on exoplanets (e.g. Noack and Breuer, 2014).

References

Alevizos, S., Poulet, T., and Veveakis, E.: Thermo-poro-mechanics of chemically active creeping faults. 1: Theory and steady state considerations, Journal of Geophysical Research: Solid Earth, 119, 4558–4582, https://doi.org/10.1002/2013JB010070, 2014.

Badertscher, N. and Burkhard, M.: Brittle–ductile deformation in the Glarus thrust Lochseiten (LK) calc-mylonite, Terra Nova, 12, 281–288, https://doi.org/10.1046/j.1365-3121.2000.00310.x, 2000.

Barnhoorn, A., Bystricky, M., Burlini, L., and Kunze, K.: The role of recrystallisation on the deformation behaviour of calcite rocks: large strain torsion experiments on Carrara marble, Journal of Structural Geology, 26, 885–903, https://doi.org/10.1016/j.jsg.2003.11.024, 2004.

Beach, A.: The Interrelations of Fluid Transport, Deformation, Geochemistry and Heat Flow in Early Proterozoic Shear Zones in the Lewisian Complex, Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 280, 569–604, 1976.

Beall, A., Fagereng, Å., and Ellis, S.: Fracture and Weakening of Jammed Subduction Shear Zones, Leading to the Generation of Slow Slip Events, Geochemistry, Geophysics, Geosystems, 20, 4869–4884, https://doi.org/10.1029/2019GC008481, 2019.

Bürgmann, R.: The geophysics, geology and mechanics of slow fault slip, Earth and Planetary Science Letters, 495, 112–134, https://doi.org/10.1016/j.epsl.2018.04.062, 2018.

Carter, K. and Dworkin, S.: Channelized fluid flow through shear zones during fluid-enhanced dynamic recrystallization, Northern Apennines, Italy, Geology, 18, 720–723, https://doi.org/10.1130/0091-7613(1990)018<0720:CFFTSZ>2.3.CO;2, 1990.

Chen, J., Verberne, B., and Niemeijer, A.: Flow-to-Friction Transition in Simulated Calcite Gouge: Experiments and Microphysical Modelling, Journal of Geophysical Research: Solid Earth, p. e2020JB019970, https://doi.org/10.1029/2020JB019970, 2020.

Cherukuri, H. and Shawki, T.: An energy-based localization theory: I. Basic framework, International Journal of Plasticity, 11, 15–40, https://doi.org/10.1016/0749-6419(94)00037-9, 1995.

Covey-crump, S.: The high temperature static recovery and recrystallization behaviour of cold-worked Carrara marble, Journal of Structural Geology, 19, 225–241, https://doi.org/10.1016/S0191-8141(96)00088-0, 1997.

Delle Piane, C., Burlini, L., Kunze, K., Brack, P., and Burg, J.-P.: Rheology of dolomite: Large strain torsion experiments and natural examples, Journal of Structural Geology, 30, 767–776, https://doi.org/10.1016/j.jsg.2008.02.018, 2008.

Dimanov, A., Rybacki, E., Wirth, R., and Dresen, G.: Creep and strain-dependent microstructures of synthetic anorthite-diopside aggregates, Journal of Structural Geology, 29, 1049–1069, https://doi.org/10.1016/j.jsg.2007.02.010, 2007.

Edmond, J. and Paterson, M.: Volume changes during the deformation of rocks at high pressures, International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 9, 161–182, https://doi.org/10.1016/0148-9062(72)90019-8, 1972.

Egholm, D., Knudsen, M., Clark, C., and Lesemann, J.: Modeling the flow of glaciers in steep terrains: The integrated second-order shallow ice approximation (iSOSIA), Journal of Geophysical Research: Earth Surface, 116, https://doi.org/10.1029/2010JF001900, 2011.

Evans, B.: Creep constitutive laws for rocks with evolving structure, Geological Society, London, Special Publications, 245, 329–346, https://doi.org/10.1144/GSL.SP.2005.245.01.16, 2005.

Fossen, H. and Cavalcante, G.: Shear zones - A review, Earth-Science Reviews, 171, 434–455, https://doi.org/10.1016/j.earscirev.2017.05.002, 2017.

Fressengeas, C. and Molinari, A.: Instability and localization of plastic flow in shear at high strain rates, Journal of the Mechanics and Physics of Solids, 35, 185–211, https://doi.org/10.1016/0022-5096(87)90035-4, 1987.

Fusseis, F., Regenauer-Lieb, K., Liu, J., Hough, R., and De Carlo, F.: Creep cavitation can establish a dynamic granular fluid pump in ductile shear zones, Nature, 459, 974–977, https://doi.org/10.1038/nature08051, 2009.

Gilgannon, J., Fusseis, F., Menegon, L., Regenauer-Lieb, K., and Buckman, J.: Hierarchical creep cavity formation in an ultramylonite and implications for phase mixing, Solid Earth, 8, 1193–1209, https://doi.org/10.5194/se-8-1193-2017, 2017.

Gilgannon, J., Poulet, T., Berger, A., Barnhoorn, A., and Herwegh, M.: Dynamic recrystallisation can produce porosity in shear zones, Geophysical Research Letters, 47, e2019GL086 172, https://doi.org/10.1029/2019GL086172, 2020.

Giuntoli, F., Brovarone, A., and Menegon, L.: Feedback between high-pressure genesis of abiotic methane and strain localization in subducted carbonate rocks, Scientific reports, 10, 1–15, https://doi.org/10.1038/s41598-020-66640-3, 2020.

Goncalves, P., Poilvet, J.-C., Oliot, E., Trap, P., and Marquer, D.: How does shear zone nucleate? An example from the Suretta nappe (Swiss Eastern Alps), Journal of Structural Geology, 86, 166–180, https://doi.org/10.1016/j.jsg.2016.02.015, 2016.

Guével, A., Rattez, H., Alevizos, S., and Veveakis, M.: Contact phase-field modeling for chemo-mechanical degradation processes. Part I: Theoretical foundations, 2019.

Haertel, M., Herwegh, M., and Pettke, T.: Titanium-in-quartz thermometry on synkinematic quartz veins in a retrograde crustal-scale normal fault zone, Tectonophysics, 608, 468–481, https://doi.org/10.1016/j.tecto.2013.08.042, 2013.

Handy, H., Hirth, G., and Bürgmann, R.: Continental Fault Structure and Rheology from the Frictional-to-Viscous Transition Downward, chap. 6, pp. 139–182, MIT Press, 2007.

Hansen, L., Zimmerman, M., Dillman, A., and Kohlstedt, D.: Strain localization in olivine aggregates at high temperature: A laboratory comparison of constant-strain-rate and constant-stress boundary conditions, Earth and Planetary Science Letters, 333-334, 134–145, https://doi.org/10.1016/j.epsl.2012.04.016, 2012.

Herwegh, M. and Jenni, A.: Granular flow in polymineralic rocks bearing sheet silicates: new evidence from natural examples, Tectonophysics, 332, 309 – 320, https://doi.org/10.1016/S0040-1951(00)00288-2, 2001.

Herwegh, M. and Kunze, K.: The influence of nano-scale second-phase particles on deformation of fine grained calcite mylonites, Journal of Structural Geology, 24, 1463–1478, https://doi.org/10.1016/S0191-8141(01)00144-4, 2002.

Herwegh, M., de Bresser, J., and ter Heege, J.: Combining natural microstructures with composite flow laws: an improved approach for the extrapolation of lab data to nature, Journal of Structural Geology, 27, 503–521, https://doi.org/10.1016/j.jsg.2004.10.010, 2005.

Hobbs, B. and Ord, A.: Structural Geology: The Mechanics of Deforming Metamorphic Rocks, Elsevier, Netherlands, 2015.

Hobbs, B., Ord, A., and Teyssier, C.: Earthquakes in the ductile regime?, Pure and Applied Geophysics, 124, 309–336, https://doi.org/10.1007/BF00875730, 1986.

Hobbs, B., Ord, A., and Regenauer-Lieb, K.: The thermodynamics of deformed metamorphic rocks: A review, Journal of Structural Geology, 33, 758–818, https://doi.org/10.1016/j.jsg.2011.01.013, 2011.

Kohlstedt, D. and Holtzman, B.: Shearing Melt Out of the Earth: An Experimentalist's Perspective on the Influence of Deformation on Melt Extraction, Annual Review of Earth and Planetary Sciences, 37, 561–593, https://doi.org/10.1146/annurev.earth.031208.100104, 2009.

Lopez-Sanchez, M. A. and Llana-Fúnez, S.: A cavitation-seal mechanism for ultramylonite formation in quartzofeldspathic rocks within the semi-brittle field (Vivero fault, NW Spain), Tectonophysics, 745, 132–153, https://doi.org/10.1016/j.tecto.2018.07.026, 2018.

Mancktelow, N.: How ductile are ductile shear zones?, Geology, 34, 345–348, https://doi.org/10.1130/G22260.1, 2006.

Mancktelow, N., Grujic, D., and Johnson, E.: An SEM study of porosity and grain boundary microstructure in quartz mylonites, Simplon Fault Zone, Central Alps, Contributions to Mineralogy and Petrology, 131, 71–85, https://doi.org/10.1007/s004100050379, 1998.

Mariani, E., Brodie, K., and Rutter, E.: Experimental deformation of muscovite shear zones at high temperatures under hydrothermal conditions and the strength of phyllosilicate-bearing faults in nature, Journal of Structural Geology, 28, 1569–1587, https://doi.org/10.1016/j.jsg.2006.06.009, 2006.

Menegon, L., Fusseis, F., Stünitz, H., and Xiao, X.: Creep cavitation bands control porosity and fluid flow in lower crustal shear zones, Geology, 43, 227–230, https://doi.org/10.1130/G36307.1, 2015.

Neupauer, R. and Powell, K.: A fully-anisotropic Morlet wavelet to identify dominant orientations in a porous medium, Computers & Geosciences, 31, 465–471, https://doi.org/10.1016/j.cageo.2004.10.014, 2005.

Noack, L. and Breuer, D.: Plate tectonics on rocky exoplanets: Influence of initial conditions and mantle rheology, Planetary and Space Science, 98, 41–49, https://doi.org/10.1016/j.pss.2013.06.020, 2014.

Paterson, M.: Localization in rate-dependent shearing deformation, with application to torsion testing, Tectonophysics, 445, 273–280, https://doi.org/10.1016/j.tecto.2007.08.015, 2007.

Peacock, S.: Thermal and metamorphic environment of subduction zone episodic tremor and slip, Journal of Geophysical Research: Solid Earth, 114, https://doi.org/10.1029/2008JB005978, 2009.

Peters, M., Herwegh, M., Paesold, M., Poulet, T., Regenauer-Lieb, K., and Veveakis, M.: Boudinage and folding as an energy instability in ductile deformation, Journal of Geophysical Research: Solid Earth, 121, 3996–4013, https://doi.org/10.1002/2016JB012801, 2016.

Poirier, J.-P.: Creep of Crystals: High-Temperature Deformation Processes in Metals, Ceramics and Minerals, Cambridge Earth Science Series, Cambridge University Press, https://doi.org/10.1017/CBO9780511564451, 1985.

Poulet, T., Veveakis, M., Herwegh, M., Buckingham, T., and Regenauer-Lieb, K.: Modeling episodic fluid-release events in the ductile carbonates of the Glarus thrust, Geophysical Research Letters, 41, 7121–7128, https://doi.org/10.1002/2014GL061715, 2014.

Précigout, J., Prigent, C., Palasse, L., and Pochon, A.: Water pumping in mantle shear zones, Nature Communications, 8, 15 736, https://doi.org/10.1038/ncomms15736, 2017.

Précigout, J., Stünitz, H., and Villeneuve, J.: Excess water storage induced by viscous strain localization during high-pressure shear experiment, Scientific Reports, 9, 3463, https://doi.org/10.1038/s41598-019-40020-y, 2019.

Regenauer-Lieb, K., Yuen, D., and Fusseis, F.: Landslides, Ice Quakes, Earthquakes: A Thermodynamic Approach to Surface Instabilities, pp. 1885–1908, https://doi.org/10.1007/978-3-0346-0138-2_15, 2009.

Regenauer-Lieb, K., Karrech, A., Chua, H., Poulet, T., Veveakis, M., Wellmann, F., Liu, J., Schrank, C., Gaede, O., Trefry, M., Ord, A., Hobbs, B., Metcalfe, G., and Lester, D.: Entropic Bounds for Multi-Scale and Multi-Physics Coupling in Earth Sciences, pp. 323–335, Springer Berlin Heidelberg, Berlin, Heidelberg, https://doi.org/https://doi.org/10.1007/978-3-642-40154-1_17, 2014.

Regenauer-Lieb, K., Veveakis, M., Poulet, T., Paesold, M., Rosenbaum, G., Weinberg, R., and Karrech, A.: Multiscale, multiphysics geomechanics for geodynamics applied to buckling instabilities in the middle of the Australian craton, Philosophical Magazine, 95, 3055–3077, https://doi.org/10.1080/14786435.2015.1066517, 2015.

Renner, J. and Evans, B.: Do calcite rocks obey the power-law creep equation?, Geological Society, London, Special Publications, 200, 293–307, https://doi.org/10.1144/GSL.SP.2001.200.01.17, 2002.

Rybacki, E., Wirth, R., and Dresen, G.: High-strain creep of feldspar rocks: Implications for cavitation and ductile failure in the lower crust, Geophysical Research Letters, 35, https://doi.org/10.1029/2007GL032478, 2008.

Rybacki, E., Wirth, R., and Dresen, G.: Superplasticity and ductile fracture of synthetic feldspar deformed to large strain, Journal of Geophysical Research: Solid Earth, 115, https://doi.org/10.1029/2009JB007203, 2010.

Schmid, S. and Handy, M.: Towards a genetic classification of fault rocks - geological usage and tectonophysical implications, chap. 16, pp. 339–361, Academic Press, New York, 1991.

Selverstone, J., Morteani, G., and Staude, J.-M.: Fluid channelling during ductile shearing: transformation of granodiorite into aluminous schist in the Tauern Window, Eastern Alps, Journal of Metamorphic Geology, 9, 419–431, https://doi.org/10.1111/j.1525-1314.1991.tb00536.x, 1991.

Shawki, T.: An Energy Criterion for the Onset of Shear Localization in Thermal Viscoplastic Materials, Part II: Applications and Implications., Journal of Applied Mechanics, 61, 538–547, https://doi.org/10.1115/1.2901493, 1994.

Shigematsu, N., Fujimoto, K., Ohtani, T., and Goto, K.: Ductile fracture of fine-grained plagioclase in the brittle-plastic transition regime: implication for earthquake source nucleation, Earth and Planetary Science Letters, 222, 1007–1022, https://doi.org/10.1016/j.epsl.2004.04.001, 2004.

Sibson, R.: Fault rocks and fault mechanisms, Journal of the Geological Society, 133, 191–213, https://doi.org/10.1144/gsjgs.133.3.0191, 1977.

Sibson, R.: Crustal stress, faulting and fluid flow, Geological Society, London, Special Publications, 78, 69–84, https://doi.org/10.1144/GSL.SP.1994.078.01.07, 1994.

Spiess, R., Dibona, R., Rybacki, E., Wirth, R., and Dresen, G.: Depressurized Cavities within High-strain Shear Zones: their Role in the Segregation and Flow of SiO2-rich Melt in Feldspar-dominated Rocks, Journal of Petrology, 53, 1767–1776, https://doi.org/10.1093/petrology/egs032, 2012.

Tannock, L., Herwegh, M., Berger, A., Liu, J., and Regenauer-Lieb, K.: The effects of a tectonic stress regime change on crustal-scale fluid flow at the Heyuan geothermal fault system, South China, Tectonophysics, 781, 228 399, https://doi.org/10.1016/j.tecto.2020.228399, 2020.

Torrence, C. and Compo, G.: A Practical Guide to Wavelet Analysis, Bulletin of the American Meteorological Society, 79, 61–78, https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2, 1998.

Vauchez, A., Tommasi, A., and Mainprice, D.: Faults (shear zones) in the Earth's mantle, Tectonophysics, 558-559, 1–27, https://doi.org/10.1016/j.tecto.2012.06.006, 2012.

Verberne, B., Chen, J., Niemeijer, A., de Bresser, J., Pennock, G., Drury, M., and Spiers, C.: Microscale cavitation as a mechanism for nucleating earthquakes at the base of the seismogenic zone, Nature Communications, 8, 1645, https://doi.org/10.1038/s41467-017-01843-3, 2017.

Veveakis, E. and Regenauer-Lieb, K.: Review of extremum postulates, Current Opinion in Chemical Engineering, 7, 40–46, https://doi.org/10.1016/j.coche.2014.10.006, 2015.

Wang, K. and Tréhu, A.: Invited review paper: Some outstanding issues in the study of great megathrust earthquakes - The Cascadia example, Journal of Geodynamics, 98, 1–18, https://doi.org/10.1016/j.jog.2016.03.010, 2016.

Weinberg, R. and Regenauer-Lieb, K.: Ductile fractures and magma migration from source, Geology, 38, 363–366, https://doi.org/10.1130/G30482.1, 2010.

Xiao, X., Evans, B., and Bernabé, Y.: Permeability Evolution During Non-linear Viscous Creep of Calcite Rocks, pp. 2071–2102, Birkhäuser Basel, Basel, https://doi.org/10.1007/978-3-7643-8124-0_3, 2006.

Závada, P., Schulmann, K., Konopásek, J., Stanislav, U., and Ondrej, L.: Extreme ductility of feldspar aggregates - Melt-enhanced grain boundary sliding and creep failure: Rheological implications for felsic lower crust, Journal of Geophysical Research: Solid Earth, 112, https://doi.org/10.1029/2006JB004820, 2007.