Reply to Anonymous Referee #1's comments

Dear referee,

We appreciate your careful review and comments on this manuscript. We took your all comments into consideration as follows. Our replies to your main comments (MC) are listed below, followed by replies to your detailed comments (DC) in the annotated pdf.

Sincerely,
Hanaya Okuda, Ikuo Katayama, Hiroshi Sakuma, Kenji Kawai

MC 1

This manuscript reports a series of experiments on brucite at various normal stress conditions and uses the results of these experiments to make inferences on the nucleation of slow earthquakes. Specifically, the authors find a low coefficient of friction, which, together with negative values of the rate and state friction parameter (a-b) is used to claim that brucite is a key material controlling the nucleation of slow earthquakes in hydrated mantle wedges.
The data in this manuscript is of interest to the community working on fault frictional behaviour and deserves to be published. However, the manuscript needs to be improved significantly before publication. My main comments are listed below and detailed comments are given in the annotated pdf.

1. The context of the current study needs clarification. The Introduction is not written very concisely and the role of mantle wedges in explaining any type of behaviour along subduction zones is not clearly outlined. Why focus on the mantle wedge and not the subduction plate interface? In addition, the authors use the current study to make inferences on slow earthquake nucleation but slow earthquakes are not defined and the reason for attempting to explain them is not clear. I suggest significant revision and rewriting of the manuscript as a whole (see also below) but in particular of the Introduction.

Reply to MC 1

Thank you for the comment. Practically, our study is focused at the site near the plate interface. The hydrated mantle wedge materials, i.e., serpentinite minerals, compose the plate interface between the subducting oceanic crust and the mantle, and the seismic activities in this area are proposed to be controlled by serpentinite (e.g., Guillot et al., 2015; Hirt & Guillot, 2015). Therefore, we used the term "the mantle wedge" in this study. However, "the subduction plate interface in the mantle wedge" would be more accurate to describe the region of focus in this study. We modified the title as follows:

(Before) Effect of normal stress on the friction of brucite: Application to slow earthquake in the mantle wedge

(After) Effect of normal stress on the frictional behavior of brucite: Application to slow earthquakes at the subduction plate interface in the mantle wedge

Further, we added some sentences and arranged the structure of the Introduction. Serpentinite had been classically considered to be aseismic and to be an explanation for the downdip limit of the seismogenic zone. However, recent seismological observations found slow earthquakes (e.g., ETS, SSE, or LFE) at the subduction plate interface in the mantle wedge. Because slow earthquakes can trigger or be triggered by huge megathrust earthquakes, the nucleation mechanisms of those slow earthquakes are important for understanding the seismic activities at the subduction zones. Previous studies suggested that frictional characteristics of serpentinite may control the nucleation of slow earthquakes; therefore, frictional properties of serpentinite should be better understood. We rewrote the Introduction section to explain this. Please also refer to Comment 6 by referee #2.

MC 2

2. Slow earthquakes in subduction zones have been addressed before via experimental studies. These focus on the subduction interface rather than the mantle wedge, but I feel that they should be mentioned in the Discussion (e.g. Ikari et al., 2013, Nature GeoScience, DOI: 10.1038/NGEO1818; Den Hartog et al, 2012, JSG, DOI:10.1016/j.jsg.2011.12.001).

Reply to MC2

As the referee commented, other possibilities, such as the transition from negative to positive a-b or the slip-weakening behavior may generate slow earthquakes, as indicated by those studies. We added some sentences and references in the Introduction (lines 131–138 in the marked-up manuscript) and Discussion (lines 540–544 in the marked-up manuscript) that explain some of the proposed mechanisms for the occurrence of slow earthquakes.

MC 3

3. The manuscript contains a number of very bold statements which lack appropriate evidence. In particular, the interpretation of the behaviour of brucite gouge as being controlled by boundary shears is not fully justified in my view. Notably, how can the presence of Riedel shears be explained if the boundary shears would control sliding behaviour?

Reply to MC3

Riedel shear developed at the initial stage of the deformation and shortened the gouge width. However, after the peak friction coefficient, the gouge thickness was kept constant, which means that the deformation may occur parallel to the shear displacement. Moreover, we observed a clear alignment of the particle along the boundary shear but no alignment along the Riedel shear, suggesting that the deformation along the Riedel shear was not the dominant process during the steady state. Therefore, the Riedel shears were thought to be not active and just preserved after the yield point. Shear localization along the boundary shear, not along the Riedel shears, was also observed in previous studies (e.g., Haines et al., 2009). Indeed, deformation along the Riedel shear may not be completely inactive, but our microstructural observation suggests that the deformation along the boundary shear is more effective. However, as commented in DC67, we need to clearly state the evidence of the shear localization along the boundary shear. Notably, we think our original manuscript lacked the description of the variation in gouge thickness during the experiment; therefore, we updated the text as follows (line 384–386 in the marked-up manuscript):

> **(Before)** The gouge width remained almost constant following the post-yield and in the steady state.
>
> **(After)** The gouge thickness remained almost constant after the post-yield and steady state, suggesting that the deformation may localize parallel to the shear deformation, i.e., parallel to the boundary shear.

Further, our original manuscript lacked the explanation that we had not observed any alignment along Riedel shears; therefore, we added the following sentence at lines 417–419 in the marked-up manuscript:

> We did not observe any alignment along the Riedel shears, suggesting that deformation along the Riedel shears cannot be dominant at the steady state.

MC 4

4. The writing style and English of the manuscript should be revised and improved. Please see the annotated pdf for examples.

Reply to MC4

We are sorry for our poor writing and appreciate your grammatical corrections on the manuscript. We have now used an English correction service to improve the manuscript.

DC 1 in line 1

"frictional behaviour" or "friction coefficient" would be better

Reply to DC1

We modified the title as follows:

(Before) Effect of normal stress on the friction of brucite: Application to slow earthquake in the mantle wedge

(After) Effect of normal stress on the frictional behavior of brucite: Application to slow earthquakes at the subduction plate interface in the mantle wedge

DC 2 in line 2

Insert "s".

Reply to DC2

Per this comment, we modified the title as shown in the reply to DC1.

DC 3 in line 22

Replace "The microstructural observations" into "Microstructural observations".

Reply to DC3

Per this comment, we removed "The" from the text (line 24 in the marked-up manuscript).

DC 4 in line 23

Replace "the" into "a".

Reply to DC4

Per this comment, we modified the article (line 25 in the marked-up manuscript).

DC5 in lines 25-27

This is confusing. It suggests that other minerals are considered, but these are not mentioned. This statement misses context.

Reply to DC5

We have reviewed the frictional characteristics of other serpentinite minerals in the Discussion; therefore, we modified the text (lines 26–28 in the marked-up manuscript) as follows:

(Before) Brucite is found to be the only mineral that has a low friction coefficient and exhibits unstable frictional behavior under hydrated mantle wedge conditions, explaining the occurrence of slow earthquakes in the mantle wedge.

(After) Among serpentinite-related minerals, weak and unstable frictional behavior of brucite under the hydrated mantle wedge conditions may play a role in slow earthquakes at the subduction plate interface in the mantle wedge.

DC6 in line 36

Remove "due".

Reply to DC6

Per this comment, we removed "due" (line 40 in the marked-up manuscript).

DC7 in lines 42-44

This needs some clarification. Presumably, a different mineral composition of serpentinite means that the related mineral will have a different composition (to have the same overall chemical make up)?

Reply to DC7

Mineral compositions of serpentinite vary depending on pressure and temperature conditions. In this sentence, we would like to explain that because each mineral has a different frictional characteristic, it is important to consider frictional properties of all serpentinite-related minerals in order to understand the frictional behavior of bulk serpentinite. To make it clear, we modified this sentence (lines 86–89 in the marked-up manuscript) as follows:

(Before) The mineral composition of serpentinite has a strong effect on the mechanical behavior of bulk serpentinite because each serpentinite-related mineral, such as antigorite, brucite, and talc, has a different frictional behavior.

(After) Serpentinite is made up of serpentinite-related minerals, such as antigorite, brucite, and talc, and as those minerals show different frictional behavior, the frictional properties of each mineral should be understood to interpret the mechanical behavior of bulk serpentinite.

DC8 in line 48

Remove "compared with other serpentinite-related minerals."

Reply to DC8

Per this comment, we removed this part from the sentence. In addition, we separated this sentence into two parts according to referee #2 Comment 2 (lines 89–93 in the marked-up manuscript).

(Before) Despite a variety of previous experimental investigations of the frictional properties of antigorite and talc (Hirauchi et al., 2013; Moore et al., 1997; Moore and

Lockner, 2007, 2008; Okazaki and Katayama, 2015; Reinen et al., 1994; Sánchez-Roa et al., 2017; Takahashi et al., 2007; Tesei et al., 2018), brucite has rarely been considered in previous studies compared with other serpentinite-related minerals, which might be due to the fact that it is difficult to detect brucite under natural conditions because of its fine-grained nature (Hostetler et al., 1966).

(After) Many previous experimental studies investigated the frictional properties of antigorite and talc (Hirauchi et al., 2013; Moore et al., 1997; Moore and Lockner, 2007, 2008; Okazaki and Katayama, 2015; Reinen et al., 1994; Sánchez-Roa et al., 2017; Takahashi et al., 2007; Tesei et al., 2018). However, brucite has rarely been considered in previous studies, as it is challenging to detect brucite under natural conditions because of its fine-grained nature (Hostetler et al., 1966).

DC9 in lines 50-51

Please clarify why this is and the relevance of this.

Reply to DC9

We understand that the metasomatic reaction between serpentinite and meta-sedimentary rock occurs at the subduction plate interface as observed in geological studies. Deformation within such a metasomatic layer was observed (e.g., Tarling et al., 2019) and reacted minerals like talc are weak and deform easily (e.g., Hirauchi et al., 2013); therefore, the Si metamorphism does affect on the deformation property of serpentinite layer at the interface. However, the metamorphic layer is often narrow, and Si is effectively consumed according to both geological and hydrothermal experiments (e.g., Kawahara et al., 2016; Mizukami et al., 2014; Oyanagi et al., 2015, 2020). Therefore, we expect that the serpentinite layer, which is often several hundred of meters to kilometers wide, possibly contains brucite. Practically, brucite was found from shallow mantle wedge conditions (e.g., Kawahara et al., 2016; Mizukami et al., 2014). Indeed, we have to assess the frictional properties of metamorphic zones like talc within the serpentinite layer to understand the deformation at the subduction plate interface. But we still need to understand the deformation properties of the matrix part of serpentinite layer, which may contain brucite. We added some sentences, in lines 99–113 in the marked-up manuscript, to describe them.

DC10 in line 59

Replace "stick-slip behavior is significant" into "significant stick-slip behavior has been observed."

Reply to DC10

Per this comment, we modified this sentence (lines 123–124 in the marked-up manuscript).

DC11 in line 60

Insert "behavior."

Reply to DC11

Per this comment, we inserted "behavior" (line 125 in the marked-up manuscript).

DC12 in line 62

Replace "the" into "a."

Reply to DC12

Per this comment, we replaced the article (line 127 in the marked-up manuscript).

DC13 in lines 70-71

This seems too much generalized. Please underpin this strong statement with evidence.

Reply to DC13

Per this comment, we modified the text (lines 68–79 in the marked-up manuscript) as follows:

(Before) The effective normal stress is an important parameter that constrains the frictional behavior because the apparent frictional strength of a material decreases with decreasing effective normal stress. Near lithostatic pore pressure conditions, which lead to low effective normal stress conditions, have been inferred based on seismic velocity structures at the plate interfaces of several subduction zones where slow earthquakes coincidentally occur such as Cascadia, SW Japan, Central Mexico, and Hikurangi (Audet et al., 2009; Audet and Kim, 2016; Eberhart-Phillips and Reyners, 2012; Matsubara et al., 2009; Shelly et al., 2006; Song and Kim, 2012). Importantly, low effective normal stress seems favorable for the nucleation of slow earthquakes (Liu and Rice, 2007, 2009; Rubin, 2008; Segall et al., 2010).

(After) In addition, near lithostatic pore pressure conditions, which lead to low effective normal stress conditions, have been inferred based on seismic velocity structures at the plate interfaces of several subduction zones where slow earthquakes coincidently occur in the regions such as Cascadia, SW Japan, Central Mexico, and Hikurangi (Audet et al., 2009; Audet and Kim, 2016; Eberhart-Phillips and Reyners, 2012; Matsubara et al., 2009; Shelly et al., 2006; Song and Kim, 2012). This low effective normal stress condition may be correlated to the occurrence of slow earthquakes because frictional deformation becomes dominant, rather than viscous deformation, in terms of shear strength (French and Condit, 2019; Gao and Wang, 2017). Furthermore, the low effective normal stress condition seems favorable for the nucleation of slow earthquakes (Liu and Rice, 2007, 2009; Rubin, 2008; Segall et al., 2010) and is also consistent with smaller stress drops than regular earthquakes (Ide et al., 2007; Rubinstein et al., 2007, 2008; Schmidt and Gao, 2010). Thus, frictional properties of serpentinite under the low effective normal stress condition likely play an important role in the occurrence of slow earthquakes at the subduction plate interface near the mantle wedge.

Please note that these sentences were moved to the third paragraph according to comment 7 from referee #2.

DC14 in line 72

Remove "s."

Reply to DC14

Per this comment, we removed "s" (line 68 in the marked-up manuscript)

DC15 in line 76

This is probably a too strong statement. "seems" would be better here.

Reply to DC15

Per this comment, we modified "is" into "seems" (line 75 in the marked-up manuscript)

DC16 in line 78

Insert "s."

Reply to DC16

This sentence was removed during the revision.

DC17 in line 83

Remove "a."

Reply to DC17

Per this comment, we removed this sentence according to DC18 (please see below).

DC18 in lines 83-85

This is only true if fault motion localizes in brucite-rich layers, which I think would be very speculative.

Reply to DC18

Based on previous geological studies on the paleo-mantle wedge that showed brucite can stably exist in serpentinite, we think that brucite is one of the important phases controlling frictional behavior at the subduction plate interface in the hydrated mantle wedge. Moreover, based on our microstructural observations, we noted that a small volume of brucite can weaken the serpentinite bulk strength. According to the information above, we think that the weak, unstable frictional behavior of brucite may play a key role in the nucleation of slow earthquakes. In the Introduction, however, readers cannot access enough information to reach this conclusion; therefore, we removed this sentence from the manuscript.

DC19 in line 96

Insert "s."

Reply to DC19

Per this comment, we inserted "s" (line 175 in the marked-up manuscript)

DC20 in lines 98-99

In my understanding, the brucite is the gouge, so please reformulate.

Reply to DC20

Per this comment, we modified the text (lines 178–179 in the marked-up manuscript) to make it clear as follows:

(Before) the brucite powder was quickly placed in each of the two gouges

(After) the brucite powder was quickly sandwiched between the blocks to form the gouge

DC21 in line 109

I do not think that you can call this saturated as no vacuum was applied so the gouge likely still contained some air. "Water-wet" would be more accurate.

Reply to DC21

Per this comment, we replaced "water-saturated" with "water-wet" (line 190 in the marked-up manuscript)

DC22 in line 116 (Figure 1)

The "Stainless spacer" should probably be "Stainless steel spacer".

Reply to DC22

Per this comment, we corrected it to "stainless steel spacer." Please refer to the comment below.

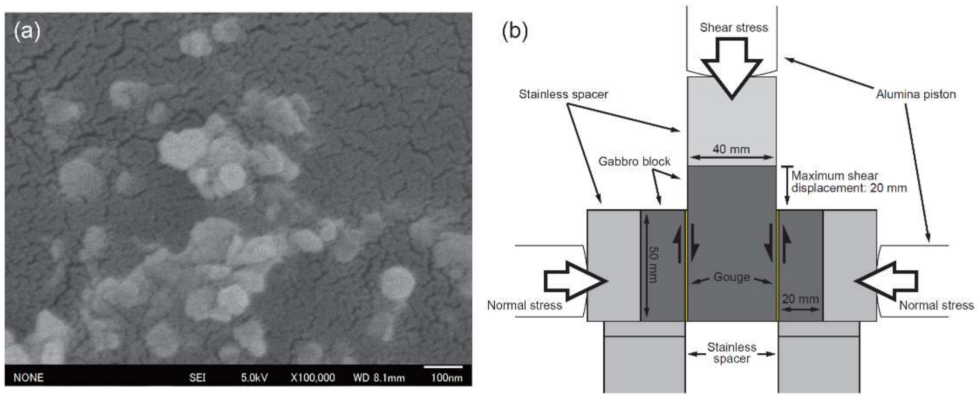
DC23 in line 118 (Figure 1)

The text in this figure is very small and hard to read (this includes the scale bar in a). I would suggest increasing the size of the text.

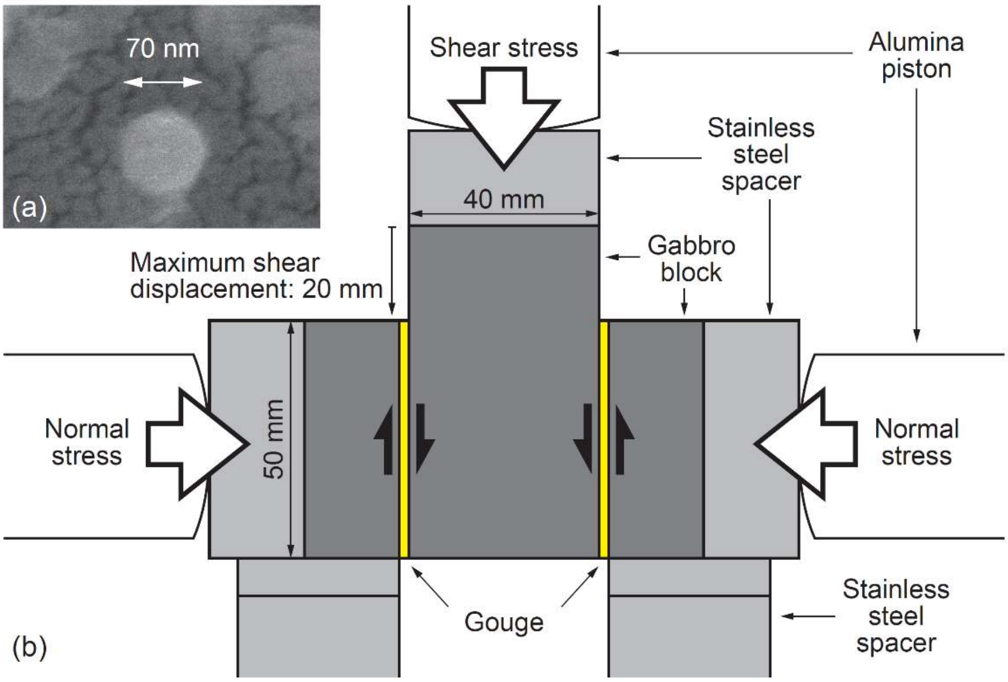
Reply to DC23

Per this comment, we modified Figure 1 as follows:

(Before)



(After)



<u>DC24 in line 126</u>

The cohesion should be compared to the shear strength of the samples, not the normal stress.

<u>Reply to DC24</u>

We modified the sentence (lines 208–210 in the marked-up manuscript) as follows:

<u>(Before)</u> Note that cohesion was not considered because the cohesion stresses were 0.36 and 0.47 MPa for the dry and wet cases, respectively, which are much smaller than the tested normal stress conditions.

<u>(After)</u> Note that cohesion stresses were 0.36 and 0.47 MPa for dry and wet cases, respectively, calculated by linear regression of shear stress and normal stress of all the experiments. Because the obtained cohesion stresses were too small to affect the friction coefficients, the cohesion stress was not considered in this study.

<u>DC25 in lines 129-130</u>

This sentence needs rewriting and clarification:

- "the latter part of each velocity step" needs to be clarified.

- "detrending" a "slip dependency" (grammar of the sentence) is incorrect and needs correction.

- "The slip dependency" needs clarification itself.

<u>Reply to DC25</u>

We rewrote the sentence (lines 215–217 in the marked-up manuscript) as follows:

<u>(Before)</u> The slip dependency, which was calculated from the later part of each velocity step test with a shear displacement of 500 μm, was detrended before conducting the following analyses.

<u>(After)</u> Before conducting the following analyses, the friction coefficient versus the displacement curve was detrended for the slip-weakening trend, which was obtained from the friction data in the second half of each velocity step of 500 μm shear displacement.

<u>DC26 in line 135</u>

Please clarify what is meant here.

<u>Reply to DC26</u>

We modified the text (lines 223–224 in the marked-up manuscript) as follows:

<u>(Before)</u> The transition of V was calculated by the following relationship:

<u>(After)</u> We estimated the effect of elastic interaction due to the machine stiffness on V using the following relationship:

DC27 in line 148-149

Pleases clarify "downsteps" and "upsteps".

Reply to DC27

We modified the text (lines 237–239 in the marked-up manuscript) as follows:

(Before) Note that d_c for the downsteps is larger than that for the upsteps.

(After) Note that d_c values for the velocity steps whose velocities decreased from 33 to 3 μm s^{-1} (downsteps) are larger than those for the velocity steps whose velocities increased from 3 to 33 μm s^{-1} (upsteps).

DC28 in line 150

Please clarify.

Reply to DC28

To make the word "asperity contact" clear, we modified the text (lines 240–241 in the marked-up manuscript) as follows:

(Before) d_c reflects the contact diameter of the asperity contact

(After) d_c reflects the diameter of the contact area between grains

DC29 in line 151

Replace "becomes" into "is."

Reply to DC29

Per this comment, we modified it (line 243 in the marked-up manuscript).

DC30 in line 152

Replace "becomes" into "is."

Reply to DC30

Per this comment, we modified it (line 244 in the marked-up manuscript).

DC31 in lines153-154

Please clarify. Presumably you are referring here to solving for a and b separately vs. for a-b?

Reply to DC31

We calculated a and b separately at first, then obtained $a - b$ from the calculated a and b. To describe this more clearly, we modified the text (244–252 in the marked-up manuscript) as follows:

> **<u>(Before)</u>** Although there are still debates on the choice of constitutive laws (Bhattacharya et al., 2015, 2017; Marone, 1998), the value of $a - b$ is more critical for seismic activities.
>
> **<u>(After)</u>** Although there are still debates on the choice of constitutive laws (Bhattacharya et al., 2015, 2017; Marone, 1998), as all constitutive laws give the same result on $a - b$, we calculated the value of $a - b$ by using separately obtained a and b with the aging law. The focus of this study will be the $a - b$ value because it plays an essential role in the nucleation process of earthquakes. However, other parameters like d_c and stiffness are also important to the nucleation process, and therefore, those parameters should be assessed in future studies.

Please note that this modification includes Comment 14 by the referee #2.

<u>DC32 in line 156</u>

Replace "the" into "a."

<u>Reply to DC32</u>

Per this comment, we modified the article (line 256 in the marked-up manuscript).

<u>DC33 in line 157</u>

Replace "the" into "a."

<u>Reply to DC33</u>

Per this comment, we modified the article (line 257 in the marked-up manuscript).

<u>DC34 in line 165 (about chapter 2.2.2)</u>

The fact that brucite is a sheet-structure mineral should be mentioned in the Introduction.

<u>Reply to DC34</u>

Per this comment, we added the sentence which explains that brucite is a sheet-structure mineral in lines 116–118 in the marked-up manuscript as follows:

> Furthermore, as brucite is a sheet-structure mineral, which often shows a low friction coefficient due to weak interlayer bonding, its frictional behavior may play a role in earthquakes at the serpentinite layer (Moore et al., 2001; Moore and Lockner, 2004).

<u>DC35 in line 167</u>

Please correct. Do you mean "composed of"?

<u>Reply to DC35</u>

Per this comment, we corrected it to “composed of” (line 273 in the marked-up manuscript).

<u>DC36 in line 169</u>

Insert “the.”

<u>Reply to DC36</u>

Per this comment, we inserted “the” (line 275 in the marked-up manuscript).

<u>DC37 in line 170</u>

Remove “the.”

<u>Reply to DC37</u>

Per this comment, we removed it (line 275 in the marked-up manuscript).

<u>DC38 in line 170</u>

Insert “s.”

<u>Reply to DC38</u>

Per this comment, we inserted “s” (line 275 in the marked-up manuscript).

<u>DC39 in lines 170-173</u>

Please be explicit what is meant here.

<u>Reply to DC39</u>

The sentence “Under natural conditions, the aligned platy particles of interconnected talc were reported to contribute to the low friction coefficient of low angle normal faults (Collettini et al., 2009).” represents the importance of the crystal orientation of platy particles within the gouge. What we wanted to express in the sentence “The experimentally determined friction coefficients of single-crystalline muscovite and chlorite are much smaller than those of powdered polycrystalline samples (Horn and Deere, 1962; Kawai et al., 2015; Niemeijer, 2018; Okamoto et al., 2019).” was that the alignment of sheet-structure minerals has a significant effect on frictional strength. However, those studies mainly compared single-crystalline and powdered polycrystalline sheet-structure minerals. Therefore, considering the next comment, we removed the sentence from the manuscript because those references do not directly show the effect of the alignment of sheet-structure minerals on friction.

DC40 in lines 173-174

This conclusion does not follow from the foregoing text.

Reply to DC40

As we modified the texts in reply to DC39, we think the problem is now solved. Please see the above.

DC41 in line 176

Remove "s."

Reply to DC41

Per this comment, we removed "s" (line 282 in the marked-up manuscript).

DC42 in lines 176-177

Please add some details on how these were prepared.

Reply to DC42

To explain the procedures for the preparation of thin sections, we modified the text (lines 282–285 in the marked-up manuscript) as follows:

> **(Before)** Thin sections parallel to the shear direction and normal to the gouges with a thickness of 30 μm were prepared.
>
> **(After)** After the experiment, we impregnated the gouge and the blocks with epoxy resin to keep the deformation structures within the gouge. Thin sections parallel to the shear direction and normal to the gouges with a thickness of 30 μm were prepared from the impregnated samples.

DC43 in lines 186-187

Please be more specific in this definition of the peak friction coefficient - "initially" is too vague and would best be replaced by a quantification of the displacement range.

Reply to DC43

We added the quantitative description of the displacement for the peak friction coefficient (lines

294–295 in the marked-up manuscript) as follows:

> **(Before)** In general, both dry and wet experiments initially show high friction coefficients
>
> **(After)** In general, both dry and wet experiments show high friction coefficients at a shear displacement of 1.5–2 mm

DC44 in line 187

Replace "lasting about 10 mm shear displacement" into "with a shear displacement of about 10 mm."

Reply to DC44

Per this comment, we replaced the text (line 296 in the marked-up manuscript).

DC45 in line 187

Insert "s."

Reply to DC45

Per this comment, we inserted "s" (line 296 in the marked-up manuscript).

DC46 in line 188

Remove "the."

Reply to DC46

Per this comment, we removed it (line 297 in the marked-up manuscript).

DC47 in line 188 (about the description of "steady state")

It does not seem like a true steady state is reached, so it would be better to use the term "final friction coefficients" rather than "steady state" friction coefficients.

Reply to DC47

According to the comment we modified the description of "steady state friction coefficient" into "final friction coefficient." In the microstructural analyses, we still use the term "steady state" because the microstructure of the gouge at the 10 mm shear displacement is consistent with the microstructure at the "steady state," and the friction coefficient and gouge thickness were almost constant. We added some sentences in lines 370–373 in the marked-up manuscript as follows:

> Note that the steady state may not be achieved at a shear displacement of 10 mm, but as the final friction coefficients were similar to the friction coefficients at 10 mm shear displacement, here we used the term "steady state" and considered that the microstructure

at 10 mm shear displacement might be consistent with the steady state.

<u>DC48 in line 189</u>

What are the numbers between brackets? This is confusing. If it is extra precision - please decide on only one level of precision for reporting.

<u>Reply to DC48</u>

The brackets meant the standard deviation of multiple experiments. To avoid confusion, we fixed the descriptions as follows:

<u>(Before)</u> 0.40(4) and 0.26(3)

<u>(After)</u> 0.40±0.04 and 0.26±0.03

We also modified other parts, including Table 1.

<u>DC49 in line 193</u>

Insert "s."

<u>Reply to DC49</u>

Per this comment, we inserted "s" (line 302 in the marked-up manuscript)

<u>DC50 in line 206 (Figure 3)</u>

"Previous" contains a typo

<u>Reply to DC50</u>

We are sorry for the typo; we corrected it.

<u>DC51 in line 210 (Caption for Figure 3)</u>

Replace "insignificantly depend on" into "do not show a clear trend with normal stress."

<u>Reply to DC51</u>

Per this comment, we corrected it (line 318 in the marked-up manuscript).

<u>DC52 in lines 213-214 (Caption for Figure 3)</u>

This looks like an experimental artifact rather than the inherent frictional behaviour of brucite. How reliable is this data?

<u>Reply to DC52</u>

We do not exactly understand what caused this sudden stress drop; therefore, we did not discuss the peak value of wet brucite for 60 MPa normal stress. To make this point clear, we added the sentence in the figure caption as follows:

(Before) Note that the peak friction coefficient of wet brucite at an effective normal stress of 60 MPa is high because of sudden stress drops in the initial stage of the shear displacement (Fig. S1).

(After) Note that the peak friction coefficient of wet brucite at an effective normal stress of 60 MPa is high because of sudden stress drops in the initial stage of the shear displacement (Fig. S1). As this data may include some experimental artifacts, we do not use this peak value in this study.

We also added the sentence in the main text in lines 303–306 in the marked-up manuscript as follows:

(Before) Note that the peak friction coefficient of wet brucite at an effective normal stress of 60 MPa is high because of sudden stress drops in the initial stage of the shear displacement (Fig. S1).

(After) Note that the peak friction coefficient of wet brucite at an effective normal stress of 60 MPa is high because of sudden stress drops in the initial stage of the shear displacement (Fig. S1). As this data may include some experimental artifacts, we do not use this peak value for 60 MPa normal stress in this study.

DC53 in lines 222-223

I suggest leaving this out as the current experiments do not give information on effects of numerous other variables, such as temperature, grain size, etc.

Reply to DC53

We agree with the referee. Per this comment and Comment 15 by referee #2, we deleted the sentence and just stated that the $a-b$ values do not differ between upsteps and downsteps (lines 329–331 in the marked-up manuscript) as follows:

(Before) The $a-b$ values obtained for the upsteps and downsteps insignificantly differ (Figs. 4a and b), which implies that the normal stress condition mainly controls the $a-b$ values.

(After) The $a-b$ values obtained for the upsteps and downsteps insignificantly differ (Figs. 4a and b).

DC54 in lines 223-224

Please be more accurate in this description - this is not quite what can be seen in Figure 4.

Reply to DC54

To describe the results more in detail, we modified the sentence (lines 333–337 in the marked-up manuscript) as follows:

(Before) The constitutive parameter a insignificantly depends on the applied normal stress, whereas b decreases as the normal stress increases, leading to the transition from negative to positive $a - b$ values (Figs. 4e and f).

(After) In the experiments with normal stress conditions of 20, 40, and 60 MPa, the constitutive parameter a is almost constant with 0.0054 for both upsteps and downsteps, whereas b decreases from 0.0064 to 0.0042 and from 0.0076 to 0.0040 for upsteps and downsteps, respectively, as the normal stress increases (Figs. 4e and f). Accordingly, we concluded that the decrease in b induces the transition from negative to positive $a - b$.

DC55 in lines 228-229

Presumably, (a-b) was not determined for experiments that showed stick-slip. Please mention this explicitly (according to Figure 4 this should be stated in the text). It would be good if (a-b) values could be determined for these experiments too, which can be done without modelling the steps.

Reply to DC55

According to this comment, we determined the $a - b$ value by simply comparing the averaged friction coefficients for two velocities for dry experiments under normal stress conditions of 40 and 60 MPa. We added sentences that explain how we determined $a - b$ value for stick-slip behavior in the Method section (lines 262–267 in the marked-up manuscript). Texts in the Result and the caption for Fig. 4 were also modified (lines 343–344 and 361–362 in the marked-up manuscript). Results were also added into Fig. 4 as shown in the next comment.

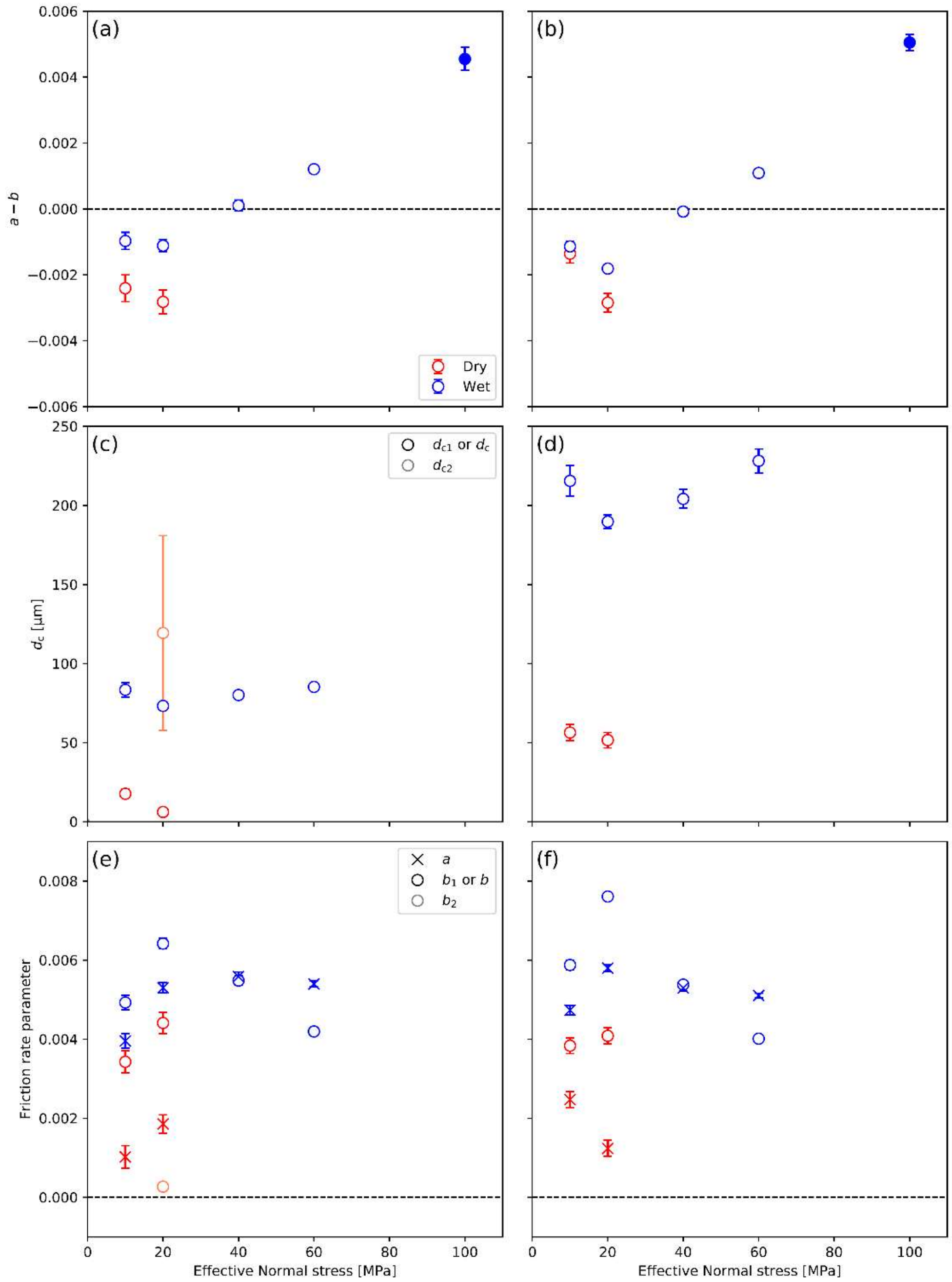
DC56 in line 242 (Caption for Figure 4)

Please add the "upsteps" vs. "downsteps" in each panel for clarification.

Reply to DC56

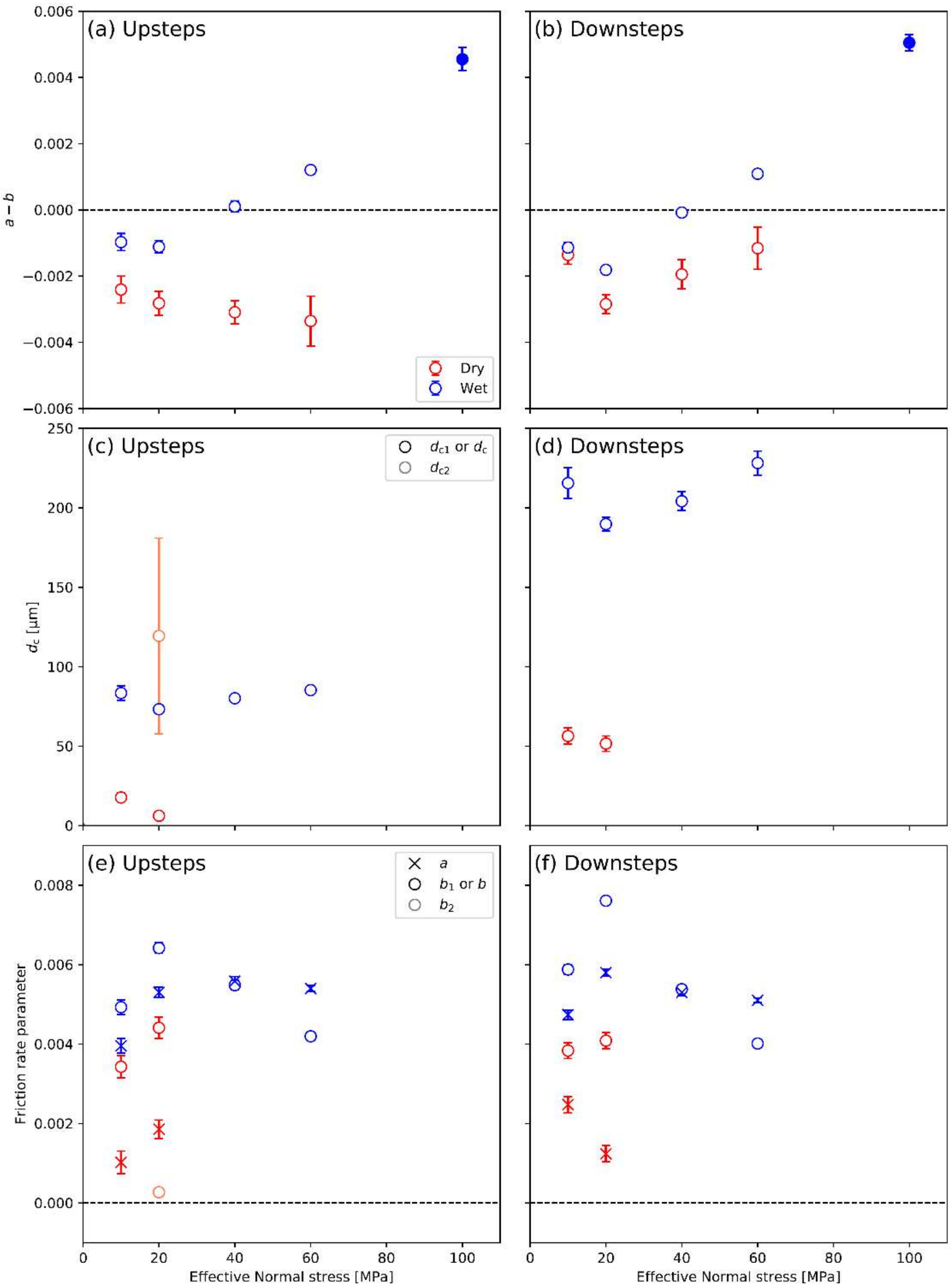
According to this comment and Comment 17 by referee #2, we added “upsteps” and “downsteps” in the figure as follows:

(Before)



(a)
(b)
(c)
(d)
(e)
(f)
$a-b$
Dry
Wet
d_c [μm]
d_{c1} or d_c
d_{c2}
Friction rate parameter
a
b_1 or b
b_2
Effective Normal stress [MPa]
Effective Normal stress [MPa]

(After)



DC57 in line 258

Replace "gouge width shortened" into "gouge thickness decreased."

Reply to DC57

Per this comment, we replaced this phrase with "gouge thickness decreased" and modified all "gouge/shear band width" into "gouge/shear band thickness."

DC58 in lines 267-268

The microstructures do not provide enough evidence to conclude this. In fact, these very low resolution micrographs provide very little information on the deformation processes as individual grains cannot be observed.

Reply to DC58

Both dry and wet cases showed the propagation of Riedel shear, followed by the boundary shear. Plus, as the deformation localized along the boundary shear according to the crystal orientation, we expect that the difference in the entire gouge thicknesses will not affect the overall frictional characteristics. However, as the referee commented, microstructural analyses with higher resolution is needed for clarification. Unfortunately, individual grains could not be observed by polarized or scanning electron microscopes because the grains were very small (70 nm in diameter). Therefore, we modified this sentence to explain the limitation of this study (lines 388–393 in the marked-up manuscript) as follows:

(Before) The narrow width of the gouge in the wet case may be the result of the leaking the sample during the experiment, although the deformation processes of the dry and wet cases do not differ, as shown above.

(After) The narrow thickness of the gouge in the wet case may result from the leakage of the sample during the experiment, but we did not have any mechanism to prevent the gouge from leaking out. The difference in the entire gouge thickness may not affect the overall frictional characteristics because both dry and wet cases showed the Riedel shear development at first, followed by the boundary shear development. Observation of grain contact is needed for clarification, but it was not possible in this study because the grains were very small (70 nm in diameter).

DC59 in line 285

Please clarify.

Reply to DC59

Per this comment, we modified the text (lines 410–411 in the marked-up manuscript) as follows:

(Before) Because the elongation of brucite is length fast (Berman, 1932) and its birefringence is 0.014–0.020 (Deer et al., 2013),

(After) Because brucite has a negative elongation (Berman, 1932) and its birefringence is 0.014–0.020 (Deer et al., 2013),

DC60 in line 295

I do not think that this is true - 10 micron for the dry case vs. 20 micron for the wet case.

Reply to DC60

Per this comment, we modified that description as follows (lines 422–423 in the marked-up manuscript):

(Before) The width of the shear band is 20 μm (Fig. 7d), that is, the same as in the dry case.

(After) The thickness of the shear band is 20 μm (Fig. 7d), which is a little wider than the dry experiments.

DC61 in line 312

Replace "indicating" into "suggesting."

Reply to DC61

Per this comment, we replaced it with "suggesting" (line 443 in the marked-up manuscript).

DC62 in lines 313-314

I believe that this observation was not reported in the Results section?

Reply to DC62

We reported this observation as "The gouge width remained almost constant following the post-yield and in the steady state." in line 384 in the marked-up manuscript, Result section 3.2.1. However, to make it clearer, we rewrite this sentence a follows:

(Before) The gouge width remained almost constant following the post-yield and in the steady state.

(After) The gouge thickness remained almost constant after the post-yield and in the steady state, suggesting that the deformation may localize parallel to the shear deformation, i.e., parallel to the boundary shear.

DC63 in line 315

Replace "confirming that the shear deformation within the gouge occurs" into "consistent with shear deformation localized."

Reply to DC63

Per this comment, we replaced it with "consistent with shear deformation localized" (line 446 in the marked-up manuscript).

DC64 in lines 316-317

This does not make sense - please correct.

Reply to DC64

Per this comment, we rewrote this sentence (lines 448–449 in the marked-up manuscript) as follows:

(Before) friction with a smooth slip surface reduces the friction coefficients

(After) a smooth slip surface reduces the friction coefficient compared to a roughened slip surface

DC65 in line 317

Insert "development of the."

Reply to DC65

Per this comment, we inserted it (line 450 in the marked-up manuscript).

DC66 in line 324

Why is this indirectly?

Reply to DC66

As previous studies suggested that the usage of the nanoparticles could induce the preferred orientation of particles, we would like to express the possibility that the nanoparticle could enhance the observed slip-weakening behavior. However, as we did not test with larger grains, we cannot clarify this. Based on the reason above, we used the word "indirectly" here, but we think using "indirectly" could cause misunderstanding to readers; therefore, we removed this word from the manuscript.

DC67 in line 326 (a comment on discussion)

The microstructures showed Riedel shear as well as boundary shears. How can the Riedel shears be explained if everything would be controlled by the boundary shears as suggested here?

Reply to DC67

As shown in microstructural observations with different shear displacements, the Riedel shear developed at the first stage of the experiment. During the activation of the Riedel shear, the gouge thickness shortened. During the steady state, however, the boundary shear developed, and the gouge thickness remained constant. This sequence implies that the Riedel shear was no longer active during the steady state. In addition, according to the observation of crystal orientation, we observed the clear alignment of the particle along the boundary shear, but not along the Riedel shear. This observation also supports that the shear deformation localized along the boundary shear. Based on the results described above, we concluded that the boundary shear controls the entire shear deformation in the steady state. We consider that the presence of Riedel shears at the steady state could be remnants of previous deformation structures, which are not active at steady state. Please also refer to the reply to MC3. We expect that arrows along Riedel shears in Figs. 5d and 6e may cause some ambiguities (Comment 19 of referee #2); therefore, we removed those arrows.

DC68 in line 326

Insert "likely."

Reply to DC68

Per this comment, we inserted it (line 459 in the marked-up manuscript).

DC69 in line 337

Replace "weaken" into "decrease."

Reply to DC69

Per this comment, we changed it to "decrease" (line 471 in the marked-up manuscript).

DC70 in line 345 (section title)

Insert "s."

Reply to DC70

Per this comment, we inserted it.

DC71 in line 348

Insert "on brucite."

Reply to DC71

Per this comment, we inserted it (line 483 in the marked-up manuscript).

DC72 in line 349

Insert "and."

<u>Reply to DC72</u>

Per this comment, we inserted "and" (line 484 in the marked-up manuscript).

<u>DC73 in line 351</u>

Remove "an."

<u>Reply to DC73</u>

Per this comment, we removed it (line 487 in the marked-up manuscript).

<u>DC74 in line 363</u>

Remove "an."

<u>Reply to DC74</u>

Per this comment, we removed it (line 500 in the marked-up manuscript).

<u>DC75 in lines 365-366</u>

This is only true if brucite is present in continuous fault strands in which the deformation localizes. I suggest modifying this statement accordingly.

<u>Reply to DC75</u>

According to this comment, we modified the text (lines 502–503 in the marked-up manuscript) as follows:

<u>(Before)</u> Therefore, antigorite and lizardite are not preferably deformed if other weaker minerals, such as brucite, are present.

<u>(After)</u> Therefore, antigorite and lizardite are not preferably deformed if other weaker minerals, such as brucite, are present in continuous fault strands in which the deformation localizes.

<u>DC76 in line 372</u>

Remove "when."

<u>Reply to DC76</u>

Per this comment, we removed it.

DC77 in line 375

Replace "with" into "at."

Reply to DC77

Per this comment, we replaced it into "at" (line 514 in the marked-up manuscript).

DC78 in lines 380-384

Please shorten this sentence.

In addition, the last part of this statement is too strong ("brucite is the only mineral that has weak, unstable frictional characteristics"). This is statement is based on laboratory studies, which are not perfect, so weak, unstable frictional characteristics of other minerals cannot be excluded.

Reply to DC78

To shorten this sentence and weaken the statement, we modified it (lines 519–522 in the marked-up manuscript) as follows:

(Before) The distribution of brucite is associated with deformation and the brucite volume is high enough to weaken the bulk strength as discussed in Sect. 4.1; therefore, brucite might be a key mineral controlling the seismic activities in the shallow hydrated mantle wedge because brucite is the only mineral that has weak, unstable frictional characteristics under a wide range of temperature–pressure conditions (Fig. 8).

(After) Although talc is still significantly important for the deformation at the subduction plate interface (Hirauchi et al., 2013), the possible occurrence of brucite and its weak and unstable frictional characteristics implies that brucite might be one of the possibilities to control the seismic activities at the subduction plate interface in the shallow hydrated mantle wedge.

DC79 in line 385

Remove "the."

Reply to DC79

Per this comment, we removed it (line 527 in the marked-up manuscript).

DC80 in line 423

Insert "range of."

Reply to DC80

Per this comment, we inserted it (line 571 in the marked-up manuscript).

DC81 in line 424

Insert "s."

Reply to DC81

Per this comment, we inserted it (line 571 in the marked-up manuscript).