<u>Summary of changes to the manuscript:</u>

Lisa McNeill and Utsav Mannu provided reviews of the manuscript “Late-Quaternary Surface Displacements on Accretionary Wedge Splay Faults in the Cascadia Subduction Zone: Implications for Megathrust Rupture". The authors Anna Ledeczi, Madeleine Lucas, Harold Tobin, Janet Watt, and Nathan Miller have read the reviews and agreed to this resubmission.

The reviewers highlighted the need for more development of the wedge evolution model as well as the connection to high sedimentation rate. In response to this suggestion, we added additional context on critical wedge theory to the discussion; however, we feel that a more complete analysis and discussion of wedge evolution is a bit beyond the scope of this contribution. In fact, we plan future kinematic modelling work to pursue a full analysis of wedge evolution and the influence of high sedimentation in the framework of critical wedge theory. Accordingly, we have not modified the manuscript further on this topic. We also have added a discussion of other sediment-rich margins where the role of synkinematic sedimentation on fault activity has been investigated, mainly Makran and Sumatra, to the discussion.

The second major comment, primarily from reviewer McNeill, involved the inference in the paper that faults identified as recently active in fact are also likely to have slipped coseismically. In response, we have further developed the reasoning behind the argument for likely coseismic activation by adding an additional paragraph to the discussion concerning dynamic modeling work showing coseismic activation of splay faults. We also strengthened the discussion of seafloor scarps and their link to Holocene fault slip.

We have highlighted the fault mapping work in the abstract. We have updated all of our figures for better color schemes (Fig. 1, 4) and to include VE for sparker seismic images. Finally, we received a variety of suggestions for additional previous published work to reference in the paper, which we very much appreciate and have used to bolster our discussion and place this work more firmly in a broader context, particularly about wedge evolution and other similar margins.

<u>Line-by-line responses to reviewers:</u>

Reviewer 1 Comments

For author and editor

This paper uses two seismic reflection datasets to analyse accretionary prism fault activity and impacts on tsunami generation and prism evolution within the northern Cascadia subduction margin. As far as I can tell this is the first publication of one of these datasets and the data are of high quality. It’s particularly nice to see the high resolution images of the fault structures and stratigraphy which are well displayed. The primary aim is to assess whether these faults are likely to slip coseismically with the plate boundary thus amplifying potential tsunamis. The interpretation of the data is careful, and thorough, with a good level of detail, and is presented clearly in the figures. The paper is very nicely written and citation of references is good, although there are a few more to add. I have two main points that I feel should be addressed in revision: firstly that the paper should develop more and highlight more the history of fault activity and wedge evolution; and secondly I am not completely convinced by the conclusion that the active faults can and will slip coseismically with the plate boundary. I think the paper would be improved and have wider scope if you incorporated more of the former and remained more open on the latter. The paper is suitable for the Seismica journal and would be of interest to a wide readership as this is a “hot topic” following the 2004 and 2011 subduction zone earthquakes and tsunamis.

Modifications made based on this review are colored blue in the document.

Main comments

Coseismic slip of wedge faults:

The paper equates accretionary wedge fault activity with coseismic rupture to shallow depths (to amplify plate boundary earthquake tsunami). Alternatives are discussed in the Discussion and the conclusion is that slip is largely coseismic, but I’m not fully convinced by the arguments made. For example, these structures are in the outermost wedge – can the degree of locking here really be constrained? I also didn’t follow the conclusion that slip must be largely coseismic following the statement about afterslip (line 684). The abstract also frames this as a “done deal” in my opinion. I think the presentation should make the alternatives clearer throughout the paper and be more open.

We provide a wide range of evidence to suggest that slip on these faults is coseismic, from evidence of coseismic slip on wedge faults in other recent subduction zone earthquakes (Alaska 1964, Sumatra 2004, and Nankai 2011), to theoretical arguments about the locking, sediment consolidation, and heat flow at Cascadia. We walk through each possibility for displacement on these faults: continuous steady creep, coseismic slip, afterslip, or some combination. In the absence of seafloor geodesy, it is still likely that slip deficit is accumulating at the trench due to stress shadowing, suggested by Lindsey et al., 2021, which we discuss at line 725.

We believe the evidence presented here suggests these fault most likely slip coseismically during large megathrust events; however, this has not been the prevailing concept for wedge faults at subduction zones; however, this may be more due to historical bias than reality. Our point is to emphasize the coseismic potential of these faults in light of these recent large megathrust events and the hazard of a future event at Cascadia.

That being said, we have made some changes throughout this manuscript to be more open to the possibility that slip on wedge faults is not coseismic. See below for more specifics, but most of the changes are to the discussion.

Our comment about afterslip is a citation that afterslip may amount to a maximum of 20-50% of total observed slip on a fault, but that the remainder of that portion is coseismic. Therefore, this would imply that even if some of the offset visible on seismic data is due to afterslip, at least a portion to a majority of the accumulated slip is coseismic in nature. This statement was confusing so we clarified it at line 730.

You mention the mechanics of landward-vergent faults slipping accompanying megathrust movement (line 688) – I would recommend looking at Henstock et al (2006), Geology for commentary on this issue from the Sumatra 2004 earthquake. Here the faults are also landward vergent but we identified scarps related to the backthrusts/antithetics which we felt was mechanically more easily activated than the contrasting dip direction seaward-dipping (landward vergent) faults. I do think you should explore this further – the opposing fault geometries are quite evident in figure 10.

The Henstock et al. (2006) paper provides a valuable argument for an alternative mode of slip on wedge faults, where the authors suggest that seaward-vergent antithetic faults to the dominant landward-vergent faults slipped in the Sumatra 2004 event. However, as this is based solely on geomorphic evidence of scarps in this region, and does not show any seismic data, either crustal-scale or high-resolution, in this region, we do not necessarily think the same scenario must be true for the LVZ at Cascadia. None of the figures we show in this paper that include CASIE21 lines have large offset seaward-vergent faults. Minor seaward-vergent faults are visible, for example, in Figures 6c and 6g; however, our stratigraphic evidence from the high-resolution data, as well as our thorough search for bathymetric scarps, suggests that these are not active. It is hard to compare our results to the above paper, therefore, because the arguments in Henstock et al. (2006) are not bolstered by seismic data. However, based on the comparison of geomorphic evidence alone between the papers, we can say confidently that seaward-vergent thrusts in the LVZ at Cascadia are not active, as we are not seeing scarps such as those cited in Henstock et al. (2006).

We added a paragraph discussing the mechanics of landward-vergent thrusting in the discussion that highlights the probability for dynamic rupture propagation at like 760. We added additional references to Xu et al., 2015 and van Zelst et al., 2022 which use dynamic modelling to show that both seaward and landward-vergent wedge splay faults are readily dynamically triggered by slip on the megathrust.

You note in section 3.2 the fault parameters that are being recorded, but don't mention dip (other than very broadly around line 725). Because the faults are likely listric it is difficult to comprehensively comment here, but it might be useful to document some fault dip information. A subsequent study may wish to use these results to model a hypothetical fault and tsunami, as you suggest on Line 740.

Dips are not recorded in this work because it is based on interpretation in the time domain, but we record length, strike, and vergence (noted around line 300 and 310). Quantifying fault dips is outside the scope of this work but will be incorporated into a future study in which we will analyze depth-converted sparker data and apply kinematic modelling to wedge evolution to derive specific fault slip rates and per-event displacements. Fault dips and geometries from the CASIE21 team are being fully analyzed by others in a different manuscript and will be published soon. Fault geometries and mapping done in our work will be made available in a future USGS *data release for use in modelling initiatives such as CRESCENT, and our group is already working directly with modelers to provide splay fault geometries through collaborations like the CoPes Hub.*

Wider significance of the results (making more of the fault activity, strain distribution and prism evolution story):

From the early parts of the paper, it feels that it's focused on fault coseismic slip and tsunami generation, when there is an excellent story here on structure, evolution of the wedge and fault activity history. Certainly the abstract and introduction give this impression. There is some good discussion (Lines 560-665) on these other topics but it's actually relatively brief. I think you should make this a stronger part of the paper, and of the abstract, and develop this aspect more in the discussion. I would also strongly recommend comparing with studies on other subduction zones where the distribution of activity of thrust faults has been presented, e.g., Smith et al (2012), JGR for the Makran. This would widen the significance of the paper.

We added a sentence to the abstract to foreground the fault activity mapping story. We added a paragraph comparing Cascadia to other sediment rich subduction zones (Makran and Sumatra) to line 690 in the wedge evolution section of the discussion, and added two additional sources: Smith et al., 2012 and McNeill & Henstock, 2014.

In addition your work has produced a new accurate fault map, with some newly identified faults, which should be highlighted more.

We add a sentence to the abstract highlighting the new fault map.

In your wedge evolution model (Fig 9), do you envision vergence changing as structures become inactive or further back in the wedge? Or is the LVZ an early Pleistocene phenomenon and these structures will persist? This wasn't very clear.

We prefer the latter explanation, as put forth by others on this topic (e.g., Adam et al., 2004). We add a clarification in section 5.3 at line 665. While both landward and seaward conjugate faults may form, landward-vergent structures dominate in both the inactive and active portions of the outer wedge. Vergence could not change once faults are inactive because there is no displacement.

Determining relative fault activity from basin stratigraphy:

With your high resolution dataset, are you able to identify any distinctive reflectors which may be correlatable along (or even across) the margin, particularly for continuous basins if your profiles are sufficiently close together? Figure 2 shows some clear reflectors and even potential cyclicity in the basin sediments (maybe some climatic signature that would be widespread?) so the possibility of correlation. Can this be looked at? I take the point that sediments may be very locally derived (from adjacent anticlines) but you may have a widespread signature nonetheless.

While we explored this possibility at depth during the early parts of this work, we were not able to identify such reflectors which correlate between basins due to the high proportion of locally-derived sedimentation. We added a sentence at like 640 to clarify this.

I also suspect there are other more recent core records and late Quaternary sedimentation rates than Barnard, 1978. It would be good to cite a range of studies here if you can (Line 260).

Barnard (1978) is the most widely-cited sedimentation source at Cascadia because of the sparse work that has been done on this topic. It is cited as the main source in recent studies which discuss sedimentation rate in this region such as Adam et al., 2004 and Goldfinger et al., 2017. However, we found one additional obscure but more recent paper: Caulet (1995) which reports results from IODP Leg 146 and gives a sedimentation rate of 9 cm/kyr. We added this to the paper.

In Section 3.2, you need to add some sentences that explicitly describe whether the thrusts are typically blind or surface breaking (I think there are examples of both), and how thrusts (blind or not) deform the basin sediments. And then how you define a fault to be inactive, ie what constitutes deformation ("true surface deformation") – presumably all you need is tilt of the seafloor. See also the note below about how the height of an anticline is defined/measured.

We clarified this and added a new paragraph and a few extra sentences around line 245 in section 3.2.

<u>Other margins and other references:</u>

For Sumatra 2004 and evidence for shallow coseismic slip I would add the following references if possible: Henstock, McNeill, Tappin, 2006, Geology – this is the first paper to make this suggestion following the first bathymetric survey. Importantly this paper also examines how landward vergent faults might behave during plate boundary slip, relevant to your paper's discussion (see above); Huepers et al., 2017, Science – drilling data used to identify temperature-driven diagenesis; and Stevens et al., 2021, G3 – new thermal modelling supporting the idea. My apologies for the self citation!

We added citations for Henstock et al. (2006), Hupers et al. (2017), and Stevens et al. (2021), as all these studies are extremely relevant to this work!

For the Nankai example, maybe it should state "probably" propagated to the toe/megasplay as there is some uncertainty here (in introduction and also line 704).

We made this modification at line 95 and 755.

Do tsunamis with added upper plate fault slip really create an earlier arriving tsunami (shorter warning times – line 101)? I feel it would make minimal difference but has this scenario been modelled for Cascadia?

We removed this implication as we couldn't find the original source. We added a reference to van Zelst et al. 2022, which shows that splay fault induced tsunamis can have multiple flooding episodes compared to megathrust-only fault ruptures.

To what extent does the exposure of fault scarps at the seafloor (or their surface expression) depend on fault activity rather than sedimentation rates in specific locations (which might be variable)? This is an area of active submarine canyons and varying slope gradients and therefore presumably quite complex variations in sediment deposition.

We discuss this in depth in the first paragraph of section 5.2., at line 625. Sedimentation has a large effect on seafloor deformation, including other factors like slip rate and fault dip (Chiama et al., 2023).

Minor points:

Line 168 - Check Grays is not spelt Greys (just the once I think, line 168)

We fixed this error.

Line 124 – this is an important place to discuss other margins and distribution of strain and fault activity in prisms more widely.

We added a paragraph about fault activity in other margins to the discussion (section 5.3), but we feel it doesn't belong at this point of the introduction.

Line 162 – These faults were primarily mapped from sidescan sonar data.

We added "sidescan sonar data" into this sentence.

Line 240 – I feel you're missing mention of unconformities here. You could also refer to other studies that have taken similar approaches here eg Smith et al. (2012 – Makran).

We modified this to mention unconformities here as well as adding a citation to McNeill et al., 2000, which documents a large unconformity in this region. We added the Smith et al. (2012) reference to line 690, section 5.3 instead of this paragraph as that is where we discuss similar work at other margins.

Line 305 – For definition and mapping of the inner-outer wedge or "active" wedge, some work was done on this in the 90's by Goldfinger, McNeill et al. Some of it is unpublished, but a change in fault orientation was noted as you cross the wedge in OR and this can be seen (the dashed line) on figure 3 of McNeill et al (2000, GSAB) – although I'm unsure if this is mapped correctly here! An outer-arc high is also mapped there marking the rear of the "modern" wedge which could be equivalent to your inner-outer wedge boundary. I noticed on your Fig 4 your active/inactive boundary is at the position in Northern OR of the change in fault/fold orientation. This was hypothesised before as the onset of locking and faults then form parallel to convergence further landward rather than parallel to the deformation front in the outermost wedge. You have described the fault strike ranges for the regions of activity and inactivity (and they do seem slightly different) but it would be worth looking more closely at this and commenting. The earlier suggestion (Goldfinger et al) that this transition marked the seaward extent of locking would clash your suggestion that the wedge faults even further seaward would move coseismically with the plate boundary, and might make after slip a more likely scenario.

Our inner-outer wedge transition is defined by Lucas et al. based on new CASIE21 data and is not equivalent to the outer arc high as it defines a material change in wedge properties without the influence of wedge morphology. We do not mention the locking suggestion from Goldfinger et al. based on the morphology of the wedge given the much newer geodetic data which suggests the shallow wedge is either frictionally locked or stress shadowed (see earlier explanation). We added the citation of McNeill et al. (2000).

Line 378 – When mentioning the strike-slip faults, be sure to say they're strike-slip, otherwise they might be confused with the thrust faults for unfamiliar readers.

We made this clarification here and in other places throughout the paper.

Line 485 – How is the height of the anticline defined here? If it's above the basin then to what extent does it reflect activity vs fault geometry?

Yes, above the basin – we added this clarification. For a complete discussion of how seafloor signature is influenced by fault geometry and other factors, see section 5.2.

Line 710 – Whilst these examples all have some relevance, it would be good to comment on other subduction accretionary wedge examples where there are some observations. Eg remind us what happened in Alaska 1964 – I think this was rather simpler based on the known fault ruptures?

We added a paragraph to remind readers about recent megathrust events under section 5.4 at line 705.

Figure 4 – some lines are not clear here, I think because there are too many coloured lines, some of which are quite similar in colour. Can you use dashed or thinner lines or black lines in places eg for tracklines? For example I couldn't easily identify the inner-outer wedge boundary from this figure.

We modified this figure to make the tracklines much thinner. We changed the inner-outer wedge boundary color to white. We made this modifications in each figure that uses this map as a panel.

For all seismic figures it would be clearer if the vertical exaggeration was put on each image (VE=X).

We added the VE to each sparker image used in the paper.

Reviewer 2 Comments

For author and editor

Review of "Late-Quaternary Surface Displacements on Accretionary Wedge Splay Faults in the Cascadia Subduction Zone: Implications for Megathrust Rupture"

Summary:

This paper presents a valuable investigation into the role of splay faults in the Cascadia subduction zone, with a focus on the landward vergence zone (LVZ). The use of high-resolution seismic data to identify and map active splay faults in great detail, allowing for detailed analysis of fault distribution and potential slip. The authors convincingly argue for the potential of these faults to contribute to large earthquakes and tsunamis. This paper will significantly contribute in solidifying the understanding of splay fault behavior in Cascadia's megathrust zone and improve seismic and tsunami hazard mitigation strategies. While the paper could benefit from certain refinements, it remains a significant contribution likely to interest a broad readership.

Modifications based on this review are colored orange in the document.

General Comments:

1. **More details on wedge evolution taking critical wedge theory into account:** The paper skillfully uses the theoretical understanding of interaction between the wedge evolution and sedimentation, to explain the observation and formulate wedge evolution. However, several of those assumptions are generally true for a critical wedge. However, if the wedge is far from criticality (either stable or non-critical), sedimentation will have a different impact. As detailed information about the rheology and architecture of sediments and decollement are known, one can investigate how close these wedges or different parts of it are to criticality.

We agree there are very interesting things to say about the influence of wedge top sedimentation on the overall wedge mechanics. However, a full analysis of fault activation and wedge evolution of the landward vergence zone using critical wedge theory is outside the observational scope of this paper; planned future work will apply kinematic modelling to this issue to derive specific fault slip rates and per-event displacements. We don't fully analyze the taper of the wedge in this work, which would be needed to understand the results in the context of critical wedge theory. However, we add a few sentences commenting on the role of critical wedge theory in explaining our wedge evolution model in section 5.3.

2. **More proxies on activity of faults in different regions:** Most comments on activity of faults are based on deformational patterns seen in shallow seismic profiles. Can this be also reconciled with the shallow earthquake activity in both the regions active and inactive regions. A small discussion on seismic activity can make this paper even more impactful.

Seismicity between 46˚ and 48˚N latitude at Cascadia is extremely rare, low in magnitude, and poorly located (e.g., Stone et al., 2018; Morton et al., 2023); therefore, it does not shed any light on splay fault activity. Such events are almost exclusively <Mw 3.5 and can only be located with precision while ocean bottom seismometers are deployed, which is rarely. Most of these events are too small to allow derivation of focal mechanisms. Only few of these events occur within the bounds of the accretionary wedge, and almost none of them in the shallow portion. We added a sentence clarifying the microseismicity data available at Cascadia in addition these sources to line 110 and 770.

Minor Comments:

L 245: How was the angle of each basinal unit computed?

We add a clarification to line 255.

L 267: "Conservatively to approximately" please choose only one qualification?

We removed "approximately".

L 580: Is the outer wedge gradient same as the outer wedge slope?

Yes, but we changed gradient to slope.

L585: There are multiple references to Lucas et. al.(in prep), as this text is not accessible to anyone, it would be better to either put the in prep manuscript of Lucas et. all in preprint or provided some supplementary figures to back these statements

We altered this citation to:

Lucas, M. C., Tobin, H. J., Carbotte, S. M., Han, S., Boston, B., & Watt, J. T. (2022). *Mapping Potentially Active Cascadia Splay Faults using CASIE21 Seismic Reflection Imaging*. *2022*, T53B-04.

This is an AGU abstract from 2022. If such a citation is not allowed, we are happy to cite as a personal communication from Madeleine Lucas. We expect Lucas et al. to be submitted to Seismica within the next few months. A preprint is not allowed due to USGS coauthors.