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Dear Dr. Randy Williams,

We have enclosed revisions to the manuscript submitted for review to **Seismica** titled: "*Influence of outer-rise faults on shallow décollement heterogeneity and sediment flux at the Japan trench*" by Schottenfels, Regalla, and Nakamura. We thank you and the two reviewers for their constructive comments. In response to these reviews, we have made three major sets of changes:

- Shortened repetitive text (reviewer A).
- Clarified our descriptions and mapping of seismic units (reviewers A and B).
- Made significant changes to our analysis of data and reporting regarding sediment thickness to fault throw ratios (reviewer B).

For the third point, we specifically thank reviewer B (Rebecca Bell) for pushing us to reconsider the ratios as it helped us see an error in how we were calculating ratios in the prior version of the manuscript. In short, we have been spatially averaging variable fault throw and sediment thickness data over long length scales (15-25+ km, across multiple horst-graben sets). However, because adjacent horsts/graben can have significantly different fault throw and, to a lesser extent, sediment thickness, this approach that would inherently cause all ratios to converge toward 1, and therefore statistically overlap regardless of deformation mode. In fact, this prior approach contracted the key findings of our work demonstrating that the short length scales (5-10 km) of heterogeneity in fault throw and sediment thickness (i.e. one horst or graben) are what really drive modes of frontal prism deformation. The recalculated data we use in the updated manuscript use measurements adjacent to the trench, and average over only one horst/graben set (5-10 km, see response to reviewers to additional information). These revised data support our original hypothesis (and our original 'point' observations along seismic lines) that areas with ratios >1 vs <1 do appear to behave differently with regard to promoting sediment accretion, subduction, erosion, or slope failure. As such, many of the interpretations and the main conclusions of the paper remain the same. We have however toned down the strength of some of our interpretations where statistics suggest uncertainty, as suggested by reviewer B.

Below we have included responses to each specific reviewer comments and line corrections, including lengthier replies as needed (responses in bold). All line numbers in the response document refer to the line numbers of the revised version of the manuscript. Upon acceptance, we will supply high resolution Adobe Illustrator (or PDF) files of all figures.

Thank you for considering the revised manuscript for publication,

Emily Schottenfels, Christine Regalla, and Yasuyuki Nakamura.
Northern Arizona University, the Japan Agency for Marine Earth Science and Technology

***AUTHOR RESPONSES IN BOLD.**

Reviewer A:
The manuscript presents a detailed and systematic analysis of a closely-spaced set of seismic reflection lines covering the Japan Trench region, including the incoming plate and outermost deformed upper plate prism and the faults that define it. While the seismic reflection imaging data itself has been presented elsewhere, the analysis is new. The work presented here has clearly been done carefully and thoroughly, and is also presented and discussed with admirable clarity in figures and text, overall.

The authors' key observation is that the work "shows that incoming plate segments with [sed thickness to normal fault throw] ratios >1 correlate to a frontal prism that predominantly experiences accretion and partial accretion, whereas incoming plate segments with ratios <1 correlate to a prism that predominantly experiences sediment subduction and frontal tectonic erosion." In their discussion, the authors draw conclusions regarding the role that this may play, or have played in 2011, in governing the likelihood of shallow large slip in megathrust earthquakes, linking ease of slip to the degree of heterogeneity in the material properties of the décollement zone.

In my opinion, the work is important, relevant to our broader understanding of shallow megathrust fault mechanics and the evolution of accretionary (or non-accretionary) prisms, as well as to the specific conditions in the Japan Trench. It absolutely merits publication in Seismica. I do have some comments that would suggest some minor to moderate revisions are in order to add to the clarity and ultimately to the impact of the work, as follows.

<u>Points of discussion:</u>

My most substantial request for clarification surrounds the identification of material as SU1 vs. SU2 and the distinction between them. It's not always clear to me what SU1 is, and why portions of the seismic interpretation are masked in brown vs. blue (SU1 and SU2 in the figures). SU2 is defined as the incoming plate sediments above the cherts (line 189). SU1 is the "older, deformed equivalent of incoming plate sediments" (line 185). But in some places, SU2 is identified in section that is deformed and above the décollement (e.g., Figs 3A and B, Fig 4A, etc.). Is the distinction simply between places where imbrication is present but stratigraphic reflector continuity is at least somewhat present (SU2) vs. where it is the same stuff but completely disrupted and chaotic in character (SU1)?

The distinction is not always clear to me. The "SU2" in the left half of panel 3B looks like it has similar seismic character as the "SU1" of 3D, for example. In Figure 4A, the boundary between the areas marked as SU1 vs SU2 seems like not much of a difference (referring also to the supplement fig. 3). Is the distinction a gradational one, with SU2 gradually turning into SU1 with continued deformation, or does the distinction imply a major structural or temporal break between them? I would suggest some effort to clarify the definition of these seismic units, which seem to be primarily seismic character-based structural packages. This is addressed a bit at lines

355-365, but it remained hazy to me, and the distinction could in any case better be made earlier in the text, when these observations are first introduced.

SU 2 is defined in part as having parallel reflectors, were as SU 1 is seismically chaotic. We recognize that our definitions of these units incorporated geologic interpretations (i.e., incoming plate sediments) that helped lead to this confusion. In addition, the reviewer is correct that in some cases accreted SU2 grades in to SU1, making mapping the boundary difficult.

To help clarify these points, we have done the following:

<u>Methods section 3.1.</u>
a) We have edited the description of Seismic Units to first describe seismic character, then geologic unit correlation (Lines 175-190).
b) We have added text to indicate that SU2 can be located in the overriding plate in imbricate faults, and is therefore not only on the incoming plate (Lines 180-181)
c) We have noted that the contact between SU1 and SU2 can be gradational or abrupt in the results section (Lines 328-329)

Further to that point, at lines 570-571, it says the ratio is a control on "the fate of both incoming and upper plate sediments." What are "upper plate sediments" here? Deformed lower plate material that has been incorporated into the prism (as I understand it), or something else? Note that I am not questioning the fundamental interpretation here, just asking for more clarity in how these unit assignments are made and how distinct they really are.

- **We have changed 'upper plate' to say frontal prism to be in line with word usage in other parts of the paper**

In figure 6d, the slope failure region around 39.5N is also (or is surrounded by) a region of complete accretion, placing two areas of end-member behavior in close juxtaposition. This seems interesting, but is not addressed in the manuscript, as far as I can see. Perhaps it's worth some discussion – does it imply, for example, that oversteepened slopes caused by the prism & décollement climbing up over the subducted horst leads to the slope failure?

- **We agree, but in our interpretation the oversteepened slope is a function of the subduction of a deep graben (increasing the beta angle in critical taper) rather than oversteepening due to excess sediment accretion. This idea is presented in the results section 4.1.3**

Overall, the paper while clear, seems like it could be shortened for brevity. I haven't made specific suggestions, but some of the material in the Methods (e.g., lines 25-295) seems excessively long and wordy, and elsewhere some of the points are repeated quite a bit. A pass-through with an eye toward tightening the whole thing up would be worthwhile in my view.

- **We have edited the paper to remove wordy statements and repetitive sentences.**

Having said that, I think all the figures are necessary and very well done. Also, I really appreciate having the uninterpreted seismic sections in the supplement (however, these supplement figures came through in the pdf at pretty low resolution making them hard to look at – perhaps that can be improved).

- **We have recompiled the supplemental PDF to improve seismic line image quality.**

Minor specific suggestions or requests for clarification:

Figure 1. For me (slightly red-green colorblind), the red dots and labels against the deep blue bathymetry are hard to see and read. I'd suggest a color with more contrast.

- **We have changed the red dots to yellow.**

Line 126: Does the citation format "Seno, Stein and Gripp, 1993" conform to Seismica guidelines? Or should it be "Seno et al., 1993?" Also, specify that it is P-wave velocity in the first instance, instead of later in the sentence.

- **"Seno, Stein and Gripp, 1993" has been changed to "Seno et al., 1993. P-wave now added to the first velocity instance.**

In line 130, I don't think the frontal prism should be called a sedimentary "unit" which has a different implication (i.e., a depositional unit). This goes to my discussion above about the definition of this "seismic unit." Maybe "package" is a better word here?

- **'Unit' has been changed to 'package'.**

Line 170: define mbsf.

- **These were the only two locations in the text where mbsf was used, so we wrote out 'meters below seafloor' instead of abbreviating.**

Line 174: "has" a fixed velocity.

- '**Have' changed to 'has'**

Line 308: a small grammatical thing: "Incoming plate sediment thickness varies between ~50 to 400 m" should be "between 50 and 400 m." This also applies to line 104 and other locations. Also, in other places, dashes are used for depth intervals; in general the usage is "between A and B" or "from A to B" (equivalently "from A – B").

- **grammar changes made throughout**

Figure 4A: where does SU3 go at the leftmost normal fault? –there seems to be a space/volume problem in the interpretation as shown.

- **As stated in lines 299-301 of the revised text, the reduction in resolution of the seismic reflection data under the frontal prism often precludes definitive mapping of SU3 >~5km down dip of the trench. However, based on your comments, we now recognize that not mapping the unit all may cause confusing for the reader. As such, we have added dashed lines to approximate the inferred location of SU3 at depth, and label it "SU3?" in Figure 4.**

Figure 4C: If it is complete sediment subduction, then what is the portion of SU2 in the thrust sheet above the dashed line linked to the deformation front? That seems to be frontally accreted material, and therefore part of the prism, according to the definitions in the manuscript.

- **We think this question arises in our prior definition of SU2 as "incoming plate sediments" rather than as those having parallel reflectors.**
- **We changed "upper plate" to say "frontal prism" to be consistent with language in rest of manuscript, and edited figure 4 to more clearly indicate the differences in SU 1 vs SU2 and where transitional/ gradational contacts are present.**

Line 341 (and elsewhere): I don't think "along-strike" needs to be hyphenated unless used as a modifier (e.g., "in the along-strike direction"). Similarly at line 78, no hyphen needed in "type location."

- **Hyphens removed.**

Line 350: Greater average throw on normal faults under the prism "implies that there is a continued accumulation of slip on normal faults following subduction under the frontal prism." This is interesting, as it implies that the decollement geometry could be modified by this continued subsidence after (or concurrent with) deformation. What are the implications for decollement and prism geometry? This is not really discussed but maybe should be expanded on.

- **Yes, we agree that this is a likely scenario, and are trying to test this idea with additional data collection (linking seismic and bathymetric data sets). But, that data is beyond the scope of this paper. We considered adding a discussion of this point to the decollement heterogeneity section, but given that we do not present the data to fully back up these interpretations in this paper, we felt it was too speculative. As such we ultimately decided to refrain from speculating on its implications in the discussion section.**

Line 595: Starting at "Whereas," this is an incomplete sentence.

- **'Whereas' changed to 'in contrast'**

Reviewer B:

This paper uses an impressive suite of 44 2D seismic reflection profiles to explore the role that sediment thickness and outer-rise fault offset play in controlling the mode of frontal prism deformation. It has long been known that parts of the Japan Trench are characterised by tectonic erosion, sediment subduction and others sediment accretion. This paper proposes a relationship between the ratio of the sediment thickness of a unit known as seismic facies 2 (SU2) and the maximum outer-rise fault throw. The authors propose that where the ratio is greater than 1, sediment accretion occurs, and when it is less than 1 sediment erosion and slope failures to occur (and in line 35 they also suggest that sediment subduction occurs when the ratio is <1).

The idea that sediment thickness and fault throw influence prism deformation style makes intuitive sense- and the models shown in Fig 7 look very sensible and plausible. There is quite a lot of repetition in the paper of the main conclusion that <1 ratio leads to tectonic erosion and slope failure and > 1 ratio leads to accretion (and sometimes the text says sediment subduction is seen in areas where fault throw is greater than sediment thickness).

- **We reduced a lot of this repetition in the revisions**

Given the strength of these repeated statements I was expecting to see a clear, statistically significant relationship between the sediment thickness/fault offset ratio and the different deformation styles in Fig. 6. While Fig. 6 does show a convincing relationship between <1 values of the ratio and slope failure, the ratios for total accretion, partial accretion, sediment subduction and tectonic erosion are all very similar and within error. The authors need to be a lot more nuanced in their text to explain that although the weighted averages are slightly different between complete accretion and tectonic erosion, for example- the uncertainty range overlaps significantly. The authors can make strong statements about the relationship between thin sediment thickness and high offset faults in relation to slope failure… but relationships with other prism deformation styles are much more tenuous

We thank reviewer B for bringing up this point. In considering their comments, and our history of thinking through our data and observations, we realized that the approach we had been using to calculate the ratio data was inadequate. Our initial observations of individual seismic lines led us to hypothesize that the ratio of sediment thickness to fault throw at the trench, at the time of sediment subduction or accretion, may be a fundamental control on which processes occurred. However, in an attempt to increase the number of data points that we could use to test this idea, we included fault throw and sediment thickness data from the entire incoming plate, and matched all modes of deformation in graben at the trench and at depth. This is not what we should have done, because sediment thickness and fault throw can vary a lot over short spatial scales, and averaging data over long spatial scales smooths over this variability. Therefore, if we average data that varies a lot spatially we will always end up ratios that approach 1. This explains the significant overlap in the ratio data presented in the prior version of the manuscript.

In our revisions, we returned to our initial observations in seismic lines that suggested it is the ratio of sediment thickness to fault throw <u>at the time of subduction</u> that controls the deformational process at the trench, not a spatially averaged value averaged over the entire incoming plate. Therefore, in this revised version of the manuscript, we modified our data analysis to calculate ratios using only data at the trench (See lines 475- 525 for further explanation). This data set does show that accretion is correlated to ratios >1 and erosion and slope failure correlate to ratios <1, and the ratios for each mode do not overlap within 1 sigma. These data do more closely agree with our qualitative observations of mapping seismic lines, which after all is what prompted us to calculate ratios in the first place.

We now focus or results and discussion on the new ratio calculations using data at the trench (lines 475- 510, Figure 6), and also discuss the limitations of averaging over longer spatial scales (lines 511-525, Figure S9), that was our approach in the prior manuscript draft.

We do still think that the ratio of 1 may be an important delimiter separating different deformation modes and different decollement properties (and the "at the trench" ratios support this), and therefore have left much of the text explaining these points. However, we recognize there is still variability and even overlap (at the 2 sigma and 3 sigma uncertainty ranges) in some of our results, so we have softened the discussion of the ratios a bit. Instead, we try to emphasize the dominant patterns (i.e. high ratios tend to lead to process X whereas low ratios lead to process Y). These changes appear in Results section and throughout the Discussion.

In Fig 6 the margin has been divided up into segments showing >1 and <1 sediment thickness/fault throw ratios, however these zones often combine more than one type of deformation style (e.g. the most southern segment which includes the 2011 Tohoku earthquake slip area includes total accretion and sediment subduction (I think anyway. The green colours used for partial accretion and sediment subducting are similar)). Given the extensive dataset presented in Fig 5, I wonder why margin segments haven't been chosen to correlate more closely with each style of deformation seen at today's deformation front? Fig 5 suggests the data exists to do this correlation- which may be more meaningful.

Thank you again for pushing us on this point. We have significantly modified Figure 6d in the following ways:
1) We have changed the modes map on the upper plate to not combine multiple related modes. We now show both the original line mapping as well as the shaded polygon area interpretation.
2) We have removed the dashed regions with ratios >1 or < 1 (which again were based on while-line averages) and replaced this with in interpolated grid of ratios on the incoming plate, using sediment thickness and fault throw data interpolated to a 1km grid

I agree completely with the conclusion that the variation in sediment thickness and fault throw is leading to geometrical and compositional heterogeneity on the decollement over length scales of 5-10 km. The correlation of individual deformation styles to magnitudes of slip in the 2011 Tohoku earthquake seems a bit a stretch, though. Although the maximum fault slip did occur in a region interpreted as complete accretion, areas which slipped by a still very large 30-40 m occurred in a region with three different deformation modes (red, green and blue in Fig 6).

We feel that our discussion of these points in the prior version of the text did not clearly articulate our thinking here. We realize that the text made it appear that we thought there was a major change in mode of decollement properties at the northern boundary of the Tohoku rupture that "blocked" propagation, but that it not what we intended. It also seemed to convey that we thought an individual mode correlates to a specific style of slip.

Instead we wanted to compare the relative levels of heterogeneity in the shallow subduction interface between the region that did slip to the trench (which is mostly experiencing sediment accretion or partial accretion and likely has a relatively compositionally

homogenous decollement) versus the region north of the rupture (~39.1-39.7 degrees north) that has much more heterogeneous modes, and likely much more heterogeneous decollement properties. There are several lines of emerging evidence that these two portions of the margin behave differently, and other authors have also suggested a correlation to the presence or lack of accretion. Our intent was to say our data support these ideas. We have edited the text in the abstract and in lines 654-690 to better convey these ideas.

Overall, this is a nice piece of seismic interpretation work putting forward an interesting hypothesis to test. However, the conclusions are somewhat simplified and over-stated in the text. Only the relationship between low sediment thickness/fault throw ratio with slope failure is convincing. All the other deformation modes appear to show the same sediment thickness/fault throw ratio within error. I would suggest a major revision of the text to be a bit more detailed and nuanced in terms of how the results are described. It is ok if there is not a clear relationship between sediment thickness/fault throw ratio and accretion/subduction/tectonic erosion, but that needs to be described in detail. From reading the abstract/conclusions alone I think you get a very different impression of the key findings than when you look at Fig 6.

- **Our updated calculations of ratios using data adjacent to the trench do show a much larger spread in data, and a clear distinction between rations >1 and <1. As such, while we have toned down how strongly we hang our hat on this ratio split, our main conclusions have largely remained the same. We hope that the points are similarly convincing to you as a reader.**

Hope these comments are helpful, and the authors are very welcome to contact me if anything is unclear.

Best wishes,
Rebecca Bell, Imperial College London

Specific comments:

Line 35: You say here that sediment subduction is observed in areas where fault throw is greater than sediment thickness. Is this correct? Fig 6 shows sediment subduction occurs when the sediment thickness/fault offset ratio is 1.06. Need to be a bit careful in your statements throughout. I agree that the slope failure regions clearly correlate with a ratio <1, but the relationship with sediment subduction and tectonic erosion is not that clear in Fig 6.

- **As discussed above, we have revised our calculations of ratios presented in Figure 6 and have updated the text accordingly throughout. We hope this has resolved this particular issue.**

Line 110 "Our results show that a fault throw threshold may control" – shouldn't this say that the ratio of sediment thickness and fault throw control (rather than just fault throw itself)?

- **Edited text to say: "Our results show that the relative magnitudes of fault throw and sediment thickness together control modes of prism deformation, sediment flux, and shallow décollement heterogeneity"**

Line 200 -210- Can you refer to figures which show these three categories of fault? That would help the reader understand these text descriptions.

- **Figure 3 now cited here.**

Line 251- Again, can you provide references to some figures that show examples of the poorly defined faults you describe in this paragraph?

- **We now cite Supplemental Figures S3-S7.**

Fig 3D- shouldn't some component of the subducted "SU1+SU2" unit be coloured blue? I think this would help to get the point across visually that there has been subduction of SU2 here.

- **In response to both reviewer comments about SU1 vs SU2 labeling on Figure 4 we have modified Fig 3D to show the area that we interpret to be SU2. This area includes a portion of the graben where faint parallel reflectors, likely within SU2, can be seen on the seismic line.**

This study measures the ratio between sediment thickness and fault throw in the trench region of the Japan Trench and argues that ratios >1 promote sediment accretion and that ratios <1 promote erosion and slope failure. In my previous review I noted that although this conclusion makes intuitive sense and the model presented in Fig 7 looks sensible, I was surprised that the statistics shown in Fig 6 did not really support this conclusion. Previously the ratios for all deformation modes (apart from slope failure) were close to 1. I am pleased that this comment prompted the authors to look at their calculations again and they recognised an issue. Previously the authors were averaging the sediment thickness and fault throw measurements over multiple horsts and grabens, averaging over features that are not necessary controlling the deformation style at the trench today. In this revision they now present sediment thickness : fault throw ratios for only the horst/graben feature currently at the trench- therefore they capture the ratio for the feature which is responsible for the current deformation mode. The numbers they show in Fig 6 now show much greater spread supporting more strongly their original conclusion. Ratios for both slope failure and tectonic erosion and now more convincingly below 1.

I am pleased to see that the authors have also removed a lot of the previous repetition (particularly the repetition in continually stating the conclusions of the study) and they are a bit softer in the language they use around their findings and recognise the potential uncertainty.

I believe this study is now ready for publication and I look forward to seeing it in print.

Rebecca Bell, Imperial College London

Dear Emily Schottenfels, Christine Regalla, Yasuyuki Nakamura:

I hope this email finds you well. I have reached a decision regarding your submission, "Influence of outer-rise faults on sediment flux and décollement heterogeneity at the Japan trench". Following the most recent round of reviews, we would like to accept your manuscript for publication at Seismica.

The second reviewer (Rebecca Bell) has now had time to fully assess your revised manuscript. As you can see, they are pleased with the changes that were made, and recommend publication in current form. Before that can happen though, we will need you to upload all of the production ready files. This will need to include an editable manuscript file using one of the Seismica templates (tex+bib, docx, or odt) in addition to high-resolution versions of each figure (.png or .pdf).

Please note that our tentative acceptance of your manuscript is based on its current form. If you identify anything that you would like to or need to change as you are preparing the production ready files, please get in touch with me before doing so.

Thank you for chosing Seismica for your work. I look forward to seeing this submission through the copy-editing process and on to publication.

Kind regards,

Randolph Williams