Reply to all reviewers

1. Reply to Dr. Peace

Dear Dr. Peace,

Thank you very much for your input on the manuscript, it is highly appreciated. Here is our response to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

1.1. Comments from Dr. Peace

Comment 1: Wider implications of the study and comparison to other regions

The authors present an exceptionally detailed examination of geological field observations, complemented by satellite data from a relatively small, isolated region. Although the approach and topic of the manuscript seem reasonable, I found that the relevance of the study, beyond that of the local geology, was not sufficiently outlined either in the introductory sections or later in the discussion. This is not to say that the work does not have such implications but that they are not currently described adequately. As such, I think this is probably a moderately easy, yet worthwhile, aspect to resolve as the study clearly has broader implications that would increase the appeal and usefulness to a wider group.

Comment 2: Analysis of satellite imagery

The figures showing the satellite data evidently bring a lot to the study in terms of extrapolating the field-based observations to infer more regional processes, and will no doubt be useful for addressing the point outlined above. However, minimal specifics regarding the satellite data (e.g., resolution or age) are provided in the methods section. For example, does all the data presented have the same specifications? In addition, no details are provided regarding the type of analysis or criteria used to interpret features on this data. Related to the latter point, I felt that better use of the satellite data could have been made by explicitly tying individual features identified in the field-based studies to specific features on the satellite data. If this type of ground truth investigation was undertaken it should be outlined more explicitly in the manuscript. Currently, I think that the lack of the information described in this point partially undermines the findings that are derived from this analysis. As such, I suggest expanding upon these aspects in the relevant sections, but particularly in the methods section.

Comment 3: Description of the deformation - fault rock types

The paper adequately describes the orientation and distribution of deformation sufficiently, both in the outcrop observations and also on the satellite data. However, the nature and categorisation of fault rocks could be better described. This is especially important in reactivation studies as the nature of fault rocks is an important line of evidence to evaluate such aspects. As such, I suggest attempting to better categorise the fault rocks, potentially using a scheme such as those outlined in Killick (2003) or Woodcock and Mort (2008).

Comment 4: Referencing

The reference list seems up to date and extensive. However, it currently contains three ’submitted’ papers, in addition to an ‘unpublished’ internal report. I appreciate that much of this aspect is beyond the control of the authors. However, I was wondering if it is possible to cite some published work alongside these, perhaps even conference abstracts? For example, the EGU abstract Koehl et al. (2016) appears to address some of the themes in the present study. In addition, if the internal report can be made available online this would be beneficial. Hopefully during the time taken to review and revise the present paper some of the submitted papers will be accepted to alleviate this issue.

Comment 5: Abstract – Currently the abstract is quite long and the scientific aims are not easily discernible. Perhaps the abstract can be restricted to the more salient points to assist with this.

Comment 6: Line 13 – ‘central Spitsbergen’. For readers not familiar with the geography of Svalbard it might be helpful to say where this is e.g., offshore Northern Norway.

Comment 7: Lines 27-29 – What are the terms in quotes taken from and are they necessary?

Comment 8: Lines 35-39 – The last sentence of the abstract is currently very long. I suggest breaking this into smaller sentences to make it more poignant and easier to follow. This may assist with addressing the point above on the abstract length generally.

Comment 9: Line 36 – ‘mildly reactivated’. In my opinion this phrase is ambiguous as it is not clear what would entail ‘mild’ reactivation compared to an event that could be considered more extensive reactivation. I therefore suggest rewording this in addition to the variants of it that appear throughout the manuscript such as ‘partially reactivated’ (line 666) and other occurrences (lines 292, 298, 317 and 658). With respect to ‘partially reactivated’ this is particularly ambiguous as it is unclear whether this is referring to selective structures being reactivated or whether the magnitude of reactivated fault movement is minimal. Please clarify appropriately.

Comment 10: Lines 48-51 – I suggest referring to the location map (Figure 1).

Comment 11: Geological setting – This section is particularly very well written, with the information mostly confined to only the most relevant points, whilst also being generally well organised. However, the authors may want to consider numbering the sections to make this part of the manuscript easier to follow.

Comment 12: Line 145 – This sentence is currently a bit awkward to read. I suggest rewording.

Comment 13: Line 160 – ’Fourth and fifth’. This approach to denoting the points in this paragraph is difficult to follow. I suggest changing it.

Comment 14: Line 166 – Are the phrases in quotes directly from the reference in this sentence? This is currently not clear in the manuscript.

Comment 15: Line 176 – ‘thick Pennsylvanian sedimentary strata’. If possible state the thickness of these sediments.

Comment 16: Line 207 – Suggest removing the word ‘these’ to make the sentence flow better.

Comment 17: Lines 208-209 – It is not clear whether the observations are from this study or those referenced in the sentence. This should be clarified. If both this present study and the previous work make the same observation this should be made clearer.

Comment 18: Line 242 – Consider replacing ‘there’ with ‘here’.

Comment 19: Line 245 – ‘the hereby described grey sandstone’. This phrase is quite awkward to read. I suggest rewording.

Comment 20: Line 250 – Suggest removing the word ‘rather’ to make the sentence flow better.

Comment 21: Lines 267-268 – ‘we propose that the hereby-described red-bed sedimentary succession is part of the Hultberget Formation’. The readability of this sentence could be improved. I suggest something like: ‘we propose that the red-bed sedimentary succession described herein is part of the Hultberget Formation’.

Comment 22: Line 275 – ‘non-cohesive fault-rock’. In line with the second major point outlined above I suggest better characterising this the fault rock.

Comment 23: Line 285 – ‘high angle’. If possible, I suggest stating how steep the ‘high angle’ fault is.

Comment 24: Line 287 – ‘cataclasite’. Here, terminology related to fault rocks is used. I suggest doing this elsewhere in the manuscript.

Comment 25: Line 292 – ‘during Cenozoic transpression’. When reading the manuscript I did not feel that the evidence leading to this interpretation was adequately provided. Specifically, what is the time constraint leading to this interpretation?

Comment 26: Line 315 – ‘is made of’. Consider replacing with ‘comprises’ to help the sentence flow better.

Comment 27: Lines 349-350 – ‘are believed to have been eroded or never deposited’. It is not clear if this is a finding of this study or previous work. I suggest clarifying.

Comment 28: Lines 359-360 – ‘which we interpreted as steep brittle faults’. This is an example of the ambiguity outlined in 3rd main point above. In particular, was any attempt made to directly tie the interpretation of the satellite data to actual field observations such as this? If so I suggest stating it more clearly here and elsewhere in the manuscript.

Comment 29: Line 367 – ‘dolerite dykes’. Has an age of these dykes been obtained? If so it would be helpful to state it here.

Comment 30: Lines 437-432 – In these opening sentences of the section numerous lines of evidence ‘in favour of Mississippian syn-sedimentary extensional brittle faulting’ are presented as one very long sentence. It is therefore quite difficult to follow due to the large amount of information contained, and I suggest either numbering the lines of evidence or separating this into multiple sentences.

Comment 31: Line 520 – ‘c.’ not ‘ca.’ when not referring to ages or times.

Comment 32: Line 521 – As previous.

Comment 33: Lines 625-665 – The conclusions section contains many long sentences, with each concluding point comprising one such statement. I suggest shortening the sentences to make the conclusions easier to read and more poignant.

Comment 34: Line 631 – Add ‘s’ after ‘suggest’.

Comment 35: Line 634 – ‘of the Hultberget Formation, thus suggesting’. I suggest breaking this long sentence into two smaller ones by concluding the first after ‘Formation’ and replacing ‘thus’ with ‘This’. If this is accepted, then ‘suggesting’ needs to change to ‘suggests’ in the second statement.

Comment 36: Line 656 – This sentence is incomplete and ends at the word ‘which’.

Comment 37: Line 663 – 'gently dipping'. Is it possible to state which way they are dipping?

Comment 38: Line 838 – 'Geochemistry' is spelt incorrectly.

Comment 39: Figure 1A – Scale is missing.

Comment 40: Figure 1B – The white areas on the map are not on the key.

Comment 41: Figure 2 – The green and brown colours on the stratigraphic column do not appear on the key.

Comment 42: Figure 3 – Although the caption states 'The photographs are approximately one kilometer wide' I think more accurate measurement of the scale of the images is required as they are clearly not all the same dimensions.

Comment 43: Figure 4 – The dip markers on the figure are quite problematic to see and on the key a white line in a black box is shown (fault core boundary). However, this does not appear on the figure.

Comment 44: Figure 5 – the field photographs require scale and orientation.

Comment 45: Figure 6 – This figure contains two types of yellow line. Are these showing different features? If so this is not clear in the figure. Also the statement in the caption that 'The outcrop is approximately 10–15 m wide' is a bit ambiguous as it is not entirely clear which parts of the field photo are considered 'outcrop'.

Comment 46: Figure 7A – The lines marked on here are extremely thin and unlikely to be easily visible at publication scale.

Comment 47: Figure 7A-C – Scales needed.

Comment 48: Figure 8 – Scales and orientation need to be provided for all subfigures.

Comment 49: Figure 9 – Same as previous comment.

Comment 50: Figure 10 caption – 'c.' not 'ca.' when not referring to ages or times.

Comment 51: Figure 11 – The text on the figure is very small and unlikely to be easily visible at publication scale.

Comment 52: References

Killick, A.M., 2003, Fault rock classification: An aid to structural interpretation in mine and exploration geology: South African Journal of Geology, v. 106, no. 4, p. 395–402, doi: 10.2113/106.4.395.

Koehl, J., Tveranger, J., Osmundsen, P.T., Braathen, A., Taule, C., and Collombin, M., 2016, Fault-growth deposit in a Carboniferous rift-basin: the Billefjorden Trough , Svalbard: Geophysical Research Abstracts, v. 18, p. 7131.

Perron, P., Guiraud, M., Vennin, E., Moretti, I., Portier, É., Laetitia, L.P., and Konaté, M., 2018, Influence of basement heterogeneity on the architecture of low subsidence rate Paleozoic intracratonic basins (Ahnet and Mouydir basins, Central Sahara): Solid Earth Discussions, doi: 10.5194/se-2018-50.

Phillips, T.B., Jackson, C.A., Bell, R.E., and Duffy, O.B., 2018, Oblique reactivation of lithosphere-scale lineaments controls rift physiography – The upper crustal expression of the Sorgenfrei-Tornquist Zone, offshore southern Norway: Soild Earth, v. 9, p. 403–429, doi: 10.5194/se-9-403-2018.

Woodcock, N.H., and Mort, K.M., 2008, Classification of fault breccias and related fault rocks: Geological Magazine Rapid Communication, v. 145, p. 435–440, doi:10.1017/S0016756808004883.

1.2. Author’s response

Comment 1: agreed.

Comment 2: agreed.

Comment 3: agreed. We now use the classification of Woodcock and Mort (2008).

Comment 4: agreed. The internal report is already available on the main author’s ResearchGate webpage upon request. However, the suggested abstract by Koehl et al. (2016) does complement any of the submitted papers.

Comment 5: agreed.

Comment 6: agreed. However, “offshore northern Norway” is quite confusing for readers that are actually familiar with the study area.

Comment 7: agreed, they are not necessary in the abstract and can be described at a later stage, in the discussion.

Comment 8: agreed.

Comment 9: disagreed. The term “mildly” refers to the magnitude of movement along the reactivated structures, which is relatively small compared to km-scale offsets along large faults (e.g., the Billefjorden Fault Zone) in the study area. Furthermore, the term is clarified line 441 where it is followed by “with little or no upwards propagation”.

Comment 10: agreed.

Comment 11: agreed.

Comment 12: agreed.

Comment 13: disagreed. The introductory sentence of the paragraph stipulates that the paragraph is dealing with five different formations, and we therefore believe that the use of “first”, “second”, etc. appropriate to this paragraph.

Comment 14: yes, the phrases in between quotation marks are directly from the associated publication. The manuscript even specify in which figure of the referred publication one may find the terms in quotation marks: “Gawthorpe and Leeder, 2000, their fig. 3”.

Comment 15: agreed.

Comment 16: agreed.

Comment 17: the first sentence lines 207–208 refers to literature data, while the second sentence shows that the gneissic foliation described in the literature can be observed on satellite images.

Comment 18: agreed.

Comment 19: agreed.

Comment 20: agreed.

Comment 21: agreed.

Comment 22: agreed.

Comment 23: agreed.

Comment 24: agreed.

Comment 25: there is no major post-Mississippian contractional–transpressional tectonic event recorded in Spitsbergen other than an episode of Cenozoic transpression. Thus, it is natural to infer that any contractional structure or reactivation might have formed during Cenozoic transpression.

Comment 26: agreed.

Comment 27: agreed.

Comment 28: agreed.

Comment 29: agreed.

Comment 30: agreed.

Comment 31: agreed. However, the examples lines 520 and 521 should remain as “ca.” since they are referring to ages.

Comment 32: see response to comment 31.

Comment 33: disagreed. The present manuscript addresses a very specific issue (initiation of extension in Mississippian times, not in Early Pennsylvanian) and the authors need to be very specific in their conclusions in order to make their findings clear for all specialists and maximize the impact of the paper on future research.

Comment 34: disagreed. Two arguments “suggest” this: the extensional growth strata and the change of contact type between the two formations.

Comment 35: agreed.

Comment 36: agreed.

Comment 37: the dip of the décollements varies as that of Carboniferous strata in the area, i.e., from SW to SE and from NW to NE. The authors believe that this information is not relevant to include to the conclusion and would rather overload a conclusion already crowded with specific points.

Comment 38: agreed.

Comment 39: agreed.

Comment 40: agreed.

Comment 41: agreed.

Comment 42: agreed.

Comment 43: agreed.

Comment 44: disagreed. All four figures in figure 5 already contain scales and do not need orientation since they do not show oriented structures.

Comment 45: agreed. However, the distinction between dotted and dashed yellow lines is made in the figure caption.

Comment 46: agreed.

Comment 47: agreed.

Comment 48: agreed.

Comment 49: agreed.

Comment 50: agreed.

Comment 51: agreed.

Comment 52: agreed. However, the authors do not understand the suggestion of the work by Phillips et al. (2018) and Perron et al. (2018) to the reference list, although the authors are familiar with the suggested works. Perhaps the referee could specify the aim and the place he may find appropriate to add these references.

1.3. Changes implemented

Comment 1: addition of a sentence on the broader implications of the present study on the hydrocarbon exploration, geodynamics, and margin architecture at the end of paragraph 1 in the introduction: "The present local study has broader regional implications, especially regarding the geodynamic setting of Arctic regions in the Mississippian (contraction versus extension versus tectonic quiescence?), the architecture and geometry of the Barents Sea and west Spitsbergen margins (Mississippian basins?), and may affect our understanding of the distribution of Mississippian coal-bearing hydrocarbon source rock in the Barents Sea" lines 60–64.

Comment 2: addition of "In addition, fault surfaces and escarpments in the field were tied to map-view lineaments on satellite images that matched their trend and location (Figure 4). Critical factors used in the interpretation of geological features on satellite images in inaccessible areas include existing literature (e.g., N–S-trending gneissic foliation in basement rocks east and southeast of the field area was evidenced by multiple works, including notably Harland et al., 1966 and Witt-Nilsson et al., 1998), the geological database at svalbardkartet.npolar.no, and similarities with fault-related escarpments tied to actual brittle faults in the field area (Figure 4). Glacial features were segregated from ductile and brittle structures and fabrics using satellite images and scientific literature on recent and past glacial flow. Satellite images used in the present study are from 2011 and have a horizontal resolution of 40 cm" to the method chapter.

Comment 3: addition of "fine-grained," line 275; "i.e., fault gouge; Woodcock and Mort, 2008;" line 275; "dominantly fine-grained cohesive fault-rock (i.e., meso- to ultra-cataclasite; Woodcock and Mort, 2008)" lines 287–288; "(meso- to ultra-)" line 1064; Reference to Woodcock and Mort (2008) to the reference list.

Comment 4: Added Reference to Bergh et al. (2014), Koehl (2018), and Klitzke et al. (2018) as complements to Bergh et al. (submitted), Koehl et al. (submitted), and Klitzke et al. (submitted) respectively.

Comment 5: deletion of one sentence and several phrases.

Comment 6: added “Svalbard” line 14.

Comment 7: deleted terms in quotation marks.

Comment 8: the sentence was shortened.

Comment 9: no change.

Comment 10: added “figure 1” line 49.

Comment 11: added numbering to Geological setting sub-chapters.

Comment 12: sentence split into two and partially rewritten.

Comment 13: no change.

Comment 14: no change.

Comment 15: added “tens (hundreds?) of meters” line 181.

Comment 16: implemented suggested change.

Comment 17: no change.

Comment 18: replaced “there” by “at this location”.

Comment 19: deleted “hereby described”.

Comment 20: deleted “rather”.

Comment 21: implemented suggested change.

Comment 22: implemented suggested change. See answer to comment 3.

Comment 23: added “(> 70°)”.

Comment 24: implemented suggested change. See answer to comment 3.

Comment 25: no change.

Comment 26: implemented suggested change.

Comment 27: added reference to Harland et al. (1974).

Comment 28: see response to comment 2. Also added “based on their similarities with fault-related lineaments in the field area (Figure 4) and their obliquity to the dominant N–S-trending ductile fabrics and structures (Harland et al., 1966; Balashov et al., 1993; Witt-Nilsson et al., 1998; Johansson and Gee, 1999)” lines 377–379.

Comment 29: deletion of “in Mississippian times (Visean; Lippard and Prestvik, 1997)” line 386, and addition of “Mississippian (Visean; Lippard and Prestvik, 1997)” line 387.

Comment 30: addition of numbers ahead of each evidence.

Comment 31: replaced “ca.” by “approximately” where needed in main text.

Comment 32: none.

Comment 33: none.

Comment 34: none.

Comment 35: implemented suggested changes.

Comment 36: deletion of “which” and addition of “.”.

Comment 37: none.

Comment 38: implemented suggested change.

Comment 39: implemented suggested change.

Comment 40: addition of “Areas shaded in white represent glaciers” to the figure caption.

Comment 41: implemented suggested change.

Comment 42: addition of a common scale on figure 3a.

Comment 43: implemented suggested change.

Comment 44: none.

Comment 45: added scale to the figure.

Comment 46: implemented suggested change.

Comment 47: implemented suggested changes.

Comment 48: implemented suggested changes.

Comment 49: implemented suggested changes.

Comment 50: implemented suggested change.

Comment 51: increased the size of all text in the figure.

Comment 52: addition of the Woodcock and Mort (2008) reference to the reference list.

2. Reply to Dr. Lenhart

Dear Dr. Lenhart,

thank you very much for your input on the manuscript, it is highly appreciated. Here is our response to your comments. We hope the changes we implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact us shall this not be the case for some comments.

2.1. Comments from Dr. Lenhart

Comment 1: Throughout the manuscript, detailed descriptions of geological structures, formations etc. and the correlations of observations made in Svalbard with similar structures in e.g. the Barents Sea or northern Norway are made. However, in many cases, the location of structures, outcrops etc. is not shown on maps and it is unclear over what distances structural correlations are made. Therefore, some of the correlations and interpretations between structural trends can appear a little farfetched and undermine the good work, especially for readers who are unfamiliar with the geology and tectonic history of the wider study area. Supplementary structural element and plate-tectonic reconstruction maps may help to support the interpretations made by the authors. In general, more references to relevant figures are needed throughout the text.

Comment 2: In general, the description of field observations is very detailed and easy to follow. However, I recommend being more quantitative when it comes to extension direction, fault dip, amount of displacement, bed thickness etc. This additional information gives the reader a better idea about the size of structures and enables a better comparison with observations from other field or subsurface studies. In addition, most figures presented in the manuscript require horizontal and vertical scale bars.

Comment 3: The current manuscript is very focused on the reconstruction of the Carboniferous tectonic history of Svalbard, but wider implications of the study results are not discussed. Obvious additional discussion themes could address the role of structure reactivation and stress field perturbations in more detail. Another possibility could be the use of this study as a potential analogue to subsurface studies in the Barents Sea or a comparison of the findings to other studies (e.g. field, subsurface, or modelling studies). Addressing the wider implications of this study will increase the impact of the manuscript and make it applicable to a wider scientific audience.

Comment 4: The abstract is currently very long and contains complex sentences (e.g. the last two sentences). The rational and motivation of the study is briefly stated in the middle of the abstract (L19-20). However, to emphasize the importance of the study, I suggest moving statements about the study motivation to the first part of the abstract and to add comments on the wider implications of the study. For example: Why is this study important locally and how can the results improve our understanding of e.g. the tectono-stratigraphic evolution of Svalbard? What are the implications for studying basin evolution in the presence of pre-existing basement structures? What is the role of local stress perturbations in fault reactivation? etc.

Comment 5: L24: What is the strike of these basin-oblique, NNE-dipping faults? How do they relate to WNW-ESE-directed extension? Could it be that strike and dip got mixed up and that the faults strike NNE?

Comment 6: L32: pre-existing, not existing

Comment 7: L33: transverse faults, not fault

Comment 8: L37: add commas and write décollements with an é: : : :and shallow dipping, bedding parallel, duplex shaped décollements: : :

Comment 9: L37-38: Out of curiosity – Why would mechanically softer layers such as shales prevent further fault movement? Wouldn't thrust faults preferentially move along the shales? Please clarify your thinking here/in the main text (see later comment L571).

Comment 10: Introduction:

The rational and local importance of the study is well explained in the Introduction. A statement about the wider implications of the study would open it up to a wider audience, provided that a 'wider implications' paragraph is added to the discussion section as well.

Comment 11: L: 70: 'control' would be a better word than 'influence'

Comment 12: Geological Setting:

The geology of the study area is very well described, but the structural elements, formations, and localities that are introduced throughout this section are not shown in Figure 1 (apart from the Billefjorden Fault Zone).

Comment 13: I suggest adding a figure that shows the location and geometry of the geology and structural elements present in the study area in more detail. This will also provide a bit more context and spatial reference to the outcrop photographs shown in later sections of the manuscript. In addition, a regional cross-section across the area may help to illustrate the deformational history and vertical and horizontal relationship between formations better.

Comment 14: In general, more references to figures are needed to better guide readers who are unfamiliar with the area. As a suggestion, the authors could include a couple of plate-tectonic reconstructions and structural elements maps in the supplementary material to illustrate the Paleozoic plate configuration of Svalbard, Greenland and Norway, as well as major extensional and compressional events.

Comment 15: L83: Neoproterozoic as one word

Comment 16: L140-141: What was the direction of contraction/plate movement during the Ellesmerian Orogeny? Was it SW?

Comment 17: L145: successions in the footwall and hanging wall of faults?

Comment 18: L168. kilometer-scale

Comment 19: Methods:

The description of the methodology is rather short. The resolution, age, and workflow to interpret the satellite images is not provided.

Comment 20: L201: rephrase; e.g. In areas that are difficult to access, satellite images of exposed basement rocks were used to identify brittle faults in exposed Proterozoic basement rocks: : :.

Comment 21: Results:

Basement rocks: L219-221: Can you indicate the faults that cross-cut the Atomfjella on a map? Where is Ny-Friesland?

Comment 22: L224-225: See previous comment. Please indicate the mentioned localities on a map, otherwise the reader has no idea about the location and distance between areas with WNW-ESE-trending faults and basement structures. A map will help to support your interpretation.

Comment 23: Sedimentary rocks: L234: south-to-southwestward

Comment 24: L241: How thin are these beds? Be quantitative.

Comment 25: L244: ‘: : :previous descriptions. Plural.

Comment 26: L248: Remove ‘However’. Start sentence with: Iron nodules found in the upper part: : :

Comment 27: L250: Replace ‘On the contrary’ with ‘However’,

Comment 28: L259 and throughout this paragraph: How thick are the described sandstone and shale beds? There is no scale in the photograph in Figure 7.

Comment 29: Brittle faults: L276: You state the amount of displacement along these faults in the figure caption, can you also add it in the text?

Comment 30: L278: Can you quantify the amount of thickening?

Comment 31: L288: décollements

Comment 32: L292: décollements

Comment 33: L307: cross-cut

Comment 34: L301 & 303: cross-cutting

Comment 35: L315: cross-cut

Comment 36: L320: Is it possible to estimate the amount of displacement across the Overgangshytta Fault? e.g. order of magnitude. I see that you provided an estimate on L355, but it would be nice to also have this in the results section.

Comment 37: Discussion:

The discussion section represents a very thorough examination and discussion of possible interpretations for the observed structures. Parts of the discussion/interpretation can be supported by additional figures to support the author's arguments and to better guide the reader. The current manuscript does not include a section on the wider implications of the results of this study. I suggest to add a paragraph on this at the end of the discussion section.

Comment 38: L325: The first sentence of the Discussion section repeats the last sentence of the previous paragraph (L318-321). I suggest rephrasing these sentences to avoid too much repetition.

Comment 39: L328-330: This sentence suggests that, based on the fault core width and amount of deformation, the Overgangshytta Fault does not terminate nearby. Can you support this interpretation with a reference to studies that investigated the relationship between fault length/displacement and deformation zone size?

Comment 40: L345: kilometer-thick

Comment 41: L348: meter-to-kilometer-scale, down-to-NNE

Comment 42: L360-381: It is difficult to believe how basement structures in Spitsbergen correlate to fault zones in northern Norway without showing plate-tectonic reconstructions (see earlier comments on the lack of supporting figures). The Timanian Orogeny has not been introduced at the beginning of the manuscript. At the moment, the interpretation of the WNW-ESE-striking faults appears to be based on long-distance, map-view correlations and may seem a little farfetched. However, additional figures illustrating the geometrical and plate-tectonic relationship between the correlates basement structures in Spitsbergen, the Barents Sea, and northern Norway may support and clarify the presented interpretation.

Comment 43: L410-411: Can you quantify the amount of reverse displacement along the fault? e.g. meter-scale or tens-of-meter?

Comment 44: L412: décollement

Comment 45: L416: What is the scale of these 'minor thrust faults'?

Comment 46: scale of these 'minor thrust faults'?

Comment 47: L435 and following paragraph: What is the dominant extension direction during the Mississippian? How does it relate to the N-S, NE-SW, and WNW-ESE-striking faults observed in the area? Was there a preferential reactivation of faults oriented perpendicular to the extension direction? Or may local strain perturbations be responsible for the activation of basin-oblique faults?

Comment 48: L439: Can you quantify the amount of thickening? It looks very minor on the outcrop photograph in Figure 8. Please add vertical and horizontal scales to every figure.

Comment 49: L440: cross-cutting

Comment 50: L447: is believed

Comment 51: L450: paleo-current data

Comment 52: L465-469: This sentence is very long and complex. Please rephrase. Add commas between shallow-dipping, bedding-parallel, duplex-shaped décollements.

Comment 53: L470-476: See previous comment above. It is difficult to picture the spatial and geometrical relationship between WNW-ESE-striking faults in Spitsbergen, northern Norway and Greenland without any maps. These seem to be very long-distance correlations unless you show that these faults originate from the same locality during Late Devonian-Carboniferous.

Comment 54: L491: Again, what is the Mississippian extension direction? How does the stress field look like?

Comment 55: L493: cross-cutting

Comment 56: L497: Please quantify the dip angle of the Billefjorden Group

Comment 57: L508: (b) not (a)

Comment 58: L512: Where is Kongsfjorden and the Brøggerhalvøya located? Please indicate on a map.

Comment 59: L523: local absence of the Late Mississippian unconformity

Comment 60: L533: What is the direction of compression/transpression?

Comment 61: L540: How far away is the Finnmark Platform from the study area? This seems to be a very long/distance correlation.

Comment 62: L546 and following paragraph: What was the extension direction? Was it stable or did it change? Can the activity of faults that are not preferentially aligned towards the extension direction be explained by local, potentially basement fabric-controlled, stress/strain perturbations? It would be nice to illustrate fault activity (e.g. initiation phase, interaction and linkage phase etc.) and extension direction through time on map-view sketches.

Comment 63: L571: décollements; How thick are the shale beds? Are they thick enough to decouple faulting on N-S faults fromWNW-ESE faults? It would be good to support this statement with a literature reference, e.g. studies on mechanical stratigraphy (Wilkins, S. J., & Gross, M. R. (2002). Normal fault growth in layered rocks at Split Mountain, Utah: influence of mechanical stratigraphy on dip linkage, fault restriction and fault scaling. Journal of Structural Geology, 24(9), 1413-1429.)

Comment 64: L577: cross-cut

Comment 65: L578: Please quantify the amount of offset

Comment 66: L582: small amounts: plural

Comment 67: Conclusions:

Each conclusion point consists of a single, very long and complex sentence. Please consider breaking them up into multiple sentences to make it easier to follow them. Consider adding a conclusion point that illustrates the wider implications of your study results.

Comment 68: L650: pre-existing Neoproterozoic faults; remove 'which' at the end of the sentence.

Comment 69: L663: décollements

Comment 70: L666: décollements

Comment 71: Figure 1B: The map doesn't show many localities and formations that are mentioned in the text. Please add them. It would also be useful to have a structural elements map for the Late Devonian-Carboniferous covering Svalbard, the Barents Sea, northern Norway and Greenland (see comments above). A map like this would make it easier to follow your thinking and interpretations.

Comment 72: Figure 2: The orange and green colours shown in the stratigraphic chart are not explained in the legend. Please add them.

Comment 73: Figure 3: Although you stated an approximate scale of each satellite image at the end of the figure caption, please add a scale bar in every image. The interpreted foliation and lineaments are actually difficult to see on the dark rocks. Is there any change to improve the image quality?

Comment 74: Figure 4: What do the pink and blue arrows indicate? Not all brittle faults have a dip direction indicator? Is the dip of these faults unknown?

Comment 75: Figure 5: Please add vertical and horizontal scales to photograph A. The label ‘Fig. 4b’ in photograph A seems to be wrong.
Comment 76: Figure 6: Please add horizontal and particularly, vertical scale bars. An approximate outcrop size is not enough.
Comment 77: Figure 7: Please add horizontal and vertical scale bars. Location of 7A is not indicated in Figure 4.
Comment 78: Figure 8: Please add horizontal and particularly, vertical scale bars – at least in B and C. An approximate outcrop size is not enough. Indicate the location of these outcrops on Figure 4.
Comment 79: Figure 9: Please add horizontal and particularly, vertical scale bars. An approximate outcrop size is not enough. Indicate the location of these outcrops on Figure 4.
Comment 80: Figure 10: Please add horizontal and particularly, vertical scale bars. An approximate outcrop size is not enough. Indicate the location of these outcrops on Figure 4. Add ‘southeastward view of the Overgangshytta Fault’ for the description of A in Figure caption. Location of 10D is not shown in 10A.
Comment 81: Figure 11: Please indicate profile location in Figure 4 and add approximate horizontal and vertical scales. Profiles like this greatly help the reader to follow the description of your observations and interpretations. It might be useful to refer to this figure earlier in the manuscript, e.g. in the results section.
Comment 82: Figure captions: - Replace crosscut with cross-cut where applicable

2.2. Author’s response

Comment 1: structural element and plate-tectonic reconstruction maps are probably not appropriate in such a short study with a relatively small study area. However, we believe that the comment of the reviewer is highly relevant to the next publication the main author is currently writing, which deals with the regional geology of Spitsbergen in the Mississippian and regional Cenozoic reactivation of Mississippian faults. In the study area, structural correlations are made over a maximum distance of 1 km in the field (Figure 4), 10–12 km for satellite images (Figure 1 and 3), and up to ca. 1000 km in the discussion when the findings of the present study is compared to recent findings in the NW Barents Sea (Anell et al., 2016) and in the SW Barents Sea (Koehl et al., 2018a).

Comment 2: agreed. The size of scales and outcrops were added in figure captions were missing. However, the short duration of the fieldwork period in the area, and the number and quality of accessible outcrops did not always allow for quantitative measurements (only a few fault surfaces accessible for measurement; see stereonets in fig. 4).

Comment 3: agreed. The present manuscript represents a relatively local study with greater implications than simply the geology of central Spitsbergen. However, the authors are aware of existing models (Braathen et al., 2011; Smyrak-Sikora et al., submitted) conflicting with their interpretation and would rather not extrapolate the results of such a small study area to the whole margin. Multiple disagreement in interpretation with initial co-authors of the manuscript (notably Prof. Olaussen, Dr. Smyrak-Sikora, and Dr. Johannessen – University Centre in Svalbard – and Prof. Stemmerik – Natural History Museum Copenhagen) incites the authors of the present manuscript to cautiousness. Nevertheless, the main author is currently writing another manuscript focused on the regional geology of Spitsbergen in the Mississippian, using the findings of the present manuscript as supporting evidence to further argue for a regional model for the northern Barents Sea and west Spitsbergen margins. Regarding the use of field examples shown in the present study as analogues to subsurface studies in the Barents Sea, it is partly addressed in chapter 5.2, sub-chapter 3, paragraphs 3–5, in which reference to offshore studies is made (e.g., Anell et al., 2016; Phillips et al., 2016; Fazlikhani et al., 2017; Koehl et al., 2018a). Paragraph 3 compares an offshore study of the Gullfaks–Visund Fault (Cowie et al., 2005) to the Billefjorden Fault Zone, while paragraph 4 insists on the importance of Mississippian growth strata onshore Spitsbergen for seismic studies in the Barents Sea, notably building on the results of Anell et al. (2016) in the northwestern Barents Sea and their interpretation of thickened strata between basement and Permian strata. Paragraph 5 further compares offshore studies in Lofoten–Vesterålen (Bergh et al., 2007) and western Troms (Indrevær et al., 2013) to infer the extension direction.

Comment 4: agreed. However, the brief introduction of the succession of tectonic events at the beginning of the abstract is crucial for the reader to grasp the ambiguity of the scientific problem dealt with in the present manuscript (tectonic setting during the deposition of sedimentary rocks of the Billefjorden Group). Regional implications are not directly relevant to the present manuscript, although mentioned in the introduction chapter as suggested by the reviewer in subsequent comments, and will be dealt with in three upcoming manuscripts investigating contractional structures in sedimentary rocks of the Billefjorden Group in adjacent areas in central Spitsbergen

(Koehl, in prep. b), and regional oblique-slip margin-oblique faults throughout Spitsbergen (Koehl et al., in prep) and Bjørnøya (Koehl, in prep. a).

Comment 5: the term “NNE-dipping” gives both the dip (to the NNE) and implies the strike (WNW–ESE) of the fault(s). This type of writing aims at keeping the manuscript relatively short (although it is already long for the type of study and size of the study area). We hope it is alright to keep it this way throughout the whole manuscript.

Comment 6: agreed.

Comment 7: agreed.

Comment 8: agreed.

Comment 9: shale décollements decoupled deformation between lower basement faults and Pennsylvanian (to Cenozoic) sedimentary cover, and, thus, prevented further vertical movement along basement-seated faults.

Comment 10: agreed.

Comment 11: agreed.

Comment 12: agreed.

Comment 13: agreed. However, the use of a regional cross-section might not be this useful for such a local study. Nevertheless, the first author of the present manuscript is currently writing another manuscript on the same topic at a regional scale in Spitsbergen and will use the suggestion of the Dr. Lenhart in this future manuscript.

Comment 14: disagreed. Again, this manuscript is a very local study and crowding an already quite long manuscript with regional maps an tectonic reconstructions might not be appropriate, but it may be relevant for the first author’s upcoming regional manuscript.

Comment 15: agreed.

Comment 16: agreed. Very good point, the manuscript is not clear enough.

Comment 17: agreed.

Comment 18: agreed.

Comment 19: agreed.

Comment 20: disagreed. The current sentence illustrates better our point in that the satellite images where carefully selected because of the relevance of the area they cover, not because the area was difficult to access.

Comment 21: agreed. However, the faults crosscutting the Atomfjella Antiform mentioned in this sentence are located north of the area shown in figure 1b (see Witt-Nilsson et al., 1998) and can therefore not be included on the map.

Comment 22: agreed for Ny-Friesland and the Atomfjella Antiform (now shown in figure 1a and 1b respectively). However, smaller localities like Mittag-Lefflerbreen are already mentioned in figure 3 and would rather overcrowd figure 1.

Comment 23: agreed.

Comment 24: agreed.

Comment 25: agreed.

Comment 26: agreed.

Comment 27: disagreed. “On the contrary” better illustrate our point.

Comment 28: agreed.

Comment 29: agreed.

Comment 30: agreed.

Comment 31: agreed.

Comment 32: agreed.

Comment 33: agreed.

Comment 34: agreed.

Comment 35: agreed.

Comment 36: agreed. However, this topic cannot be addressed in the result chapter and the comment was implemented in the first subchapter of the discussion.

Comment 37: agreed. However, as mentioned in our response to previous comments, the present manuscript is a local study that will represent the corner stone of a regional study in Spitsbergen. The wider implications will be addressed in this next manuscript.

Comment 38: agreed.

Comment 39: agreed. Highly relevant comment, which led to a reorganization of sub-chapter 5.1 and to a significant improvement of the manuscript.

Comment 40: agreed.

Comment 41: agreed. However, the denomination “down-NNE” is often used in similar scientific articles and the authors would therefore prefer to keep the formulation this way.

Comment 42: agreed. The manuscript currently lacks reference to relevant paleo-tectonic reconstructions. However, the authors would prefer not to include any plate tectonic reconstruction map to the manuscript because it is nor the aim neither part of the results of the manuscript.

Comment 43: agreed.

Comment 44: agreed.

Comment 45: agreed.

Comment 46: agreed.

Comment 47: this topic is addressed in paragraph number 5 of the last sub-chapter of the discussion (“Switch from widespread to localized extension”).

Comment 48: agreed.

Comment 49: agreed.

Comment 50: agreed.

Comment 51: agreed.

Comment 52: agreed.

Comment 53: comment addressed in our response to comment 42.

Comment 54: comment addressed in our response to comment 47.

Comment 55: agreed.

Comment 56: agreed.

Comment 57: the authors used “(a)” and “(s)” to show that the observed tilting might results from displacement along one or several faults. However, this formulation does not seem to be clear enough and the authors addressed the issue.

Comment 58: agreed.

Comment 59: agreed.

Comment 60: agreed.

Comment 61: the Finnmark Platform is located some 800 km away from the study area, i.e., the study area and the Finnmark Platform and closer to each other than the Caledonides of northern Norway and the Caledonides of Svalbard. Although our correlation might seem farfetched right now, the correlation of the Caledonides across the North Atlantic Ocean and the Barents Sea might have been farfetched too a few decades ago. Moreover, multiple studies tend to suggest such Timanian affinity is possible (see Mazur et al., 2009; Majka et al., 2010; Klitzke et al., 2018, submitted; Koehl, in prep.).

Comment 62: the authors believe that the extension direction was constant (see Bergh et al., 2007; Eig and Bergh, 2011; Hansen and Bergh, 2012; Koehl et al., 2018) and, alone, may explain all the observed fault patterns and kinematics.

Comment 63: agreed. However, the thickness of the coaly beds in the Billefjorden Group is already extensively mentioned in the result chapter, section 4.2, paragraph 1.

Comment 64: agreed.

Comment 65: agreed.

Comment 66: agreed.

Comment 67: disagreed. Again, the present manuscript is a local study with regional implications. However, the regional implications would be too farfetched if the authors were to propose a regional model for Spitsbergen and the Barents Sea only based on a local field and remote sensing study. Regarding the "complexity" of the conclusion points, these will be the foundations of two upcoming manuscript and, thus, need to be very specific and detailed in order for the reader to link the present manuscript to upcoming work.

Comment 68: agreed.

Comment 69: agreed.

Comment 70: agreed.

Comment 71: agreed. However, the present manuscript is a local study targeting a small audience of (geo-) scientists working with Svalbard and the Arctic. Thus, the authors argue that a regional map with structural lineaments may not be appropriate to include. Such maps may be found in Bergh et al. (2007), Indrevær et al. (2013), Anell et al. (2016), Koehl (2018) and Koehl et al. (2018a, 2018b).

Comment 72: agreed.

Comment 73: agreed. However, it is not possible to improve the quality of the satellite images.

Comment 74: yes, the dip of some of the faults interpreted from the satellite images is unknown. Pink and blue double-arrows indicate outcrop exposures of the Hultberget Formation and Billefjorden Group respectively, as indicated in the caption of figure 4.

Comment 75: disagreed. The person in the lower right corner is the scale. In addition, the label "figure 5b" in figure 5a correctly indicates the location of figure 5b.

Comment 76: agreed. However, vertical and horizontal scale being the same, there is no need to add both.

Comment 77: agreed. However, vertical and horizontal scale being the same, there is no need to add both.

Comment 78: agreed.

Comment 79: agreed.

Comment 80: agreed.

Comment 81: agreed. However, figure 11 is a schematic N–S profile across the study area shown in figure 4. Adding a line to show the approximate location of the profile would crowd figure 4 too much. Figure 11 is the proposed model for the study area and is quite interpretative and sometimes speculative. Thus, it might not be judicious to mention it in the result chapter.

Comment 82: agreed.

2.3. Changes implemented

Comment 1: added references to figures throughout the main text.

Comment 2: added “Person as scale in the lower right corner” in the caption of fig. 2a; “Rifle orange cover as scale (ca. 1.20 m-long)” in the caption of fig. 2c; “Camera cover (15x10 cm) as scale” in the caption of fig. 2d; “and 2–2.5 m high” in the caption of fig. 6; “The outcrop is approximately 10 m high” in the caption of fig. 7a; “The outcrop is ca. two meters high” in the caption of fig. 7b; “The outcrop is ca. three meters high” in the caption of fig. 7c; “shows the width of the core” in the caption of fig. 10a; “The fault core is limited by the dashed white and dashed red lines and is ca. 3 meters wide” in the caption of fig. 10e; “Ca. one km-long” in the caption of fig. 11.

Comment 3: no change.

Comment 4: shortening of the last two sentences of the abstract: deletion of “, thus suggesting that normal faulting along this major fault initiated as early as the Mississippian” lines 36–37, and of “Mississippian margin-oblique” line 40.

Comment 5: no change.

Comment 6: implemented suggested change.

Comment 7: implemented suggested change.

Comment 8: implemented suggested changes.

Comment 9: no change.

Comment 10: addition of a few lines on regional implications lines 60–70.

Comment 11: implemented suggested change.

Comment 12: addition of the Atomfjella Antiform, Odellfjellet Fault, Balliolbreen Fault, and Løvehovden Fault to figure 1b.

Comment 13: addition of a few key structural elements to figure 1b (see response to comment 12), and addition of all the outcrop photograph location on figure 4.

Comment 14: no change.

Comment 15: implemented suggested change.

Comment 16: addition of "west-directed thrusting" lines 150–151.

Comment 17: implemented suggested change.

Comment 18: implemented suggested change.

Comment 19: addition of 10 lines (lines 215–224) on the satellite photograph resolution and on the interpretation methodology with regards to field outcrops.

Comment 20: no change.

Comment 21: addition of the location of "Ny-Friesland" in figure 1a

Comment 22: Ny-Friesland and the Atomfjella Antiform are now shown in figure 1a and 1b respectively.

Comment 23: implemented suggested change.

Comment 24: added thickness of beds.

Comment 25: implemented suggested change.

Comment 26: implemented suggested change.

Comment 27: no change.

Comment 28: addition of a scale in figure 7 and of the bed thickness in the relevant paragraph.

Comment 29: addition of "and offsets are generally decimeter- to meter-scale (Figure 8)" line 307.

Comment 30: addition of "tens-of-centimeter-thick" lines 311–312.

Comment 31: implemented suggested change.

Comment 32: implemented suggested change.

Comment 33: implemented suggested change.

Comment 34: implemented suggested change.

Comment 35: implemented suggested change.

Comment 36: addition of "comprised between a few meters and" line 391.

Comment 37: no change.

Comment 38: deletion of “made of sedimentary strata of the Hultberget, Ebbadalen and Minkinfjellet formations” lines 359–360, and changed “thus suggesting” into “which suggests” line 361.

Comment 39: The third paragraph of sub-chapter 5.1 was moved to the beginning of the sub-chapter. The authors also added reference to quantitative studies to the main text lines 371–375 “This is supported by quantitative studies on the width of fault cores (e.g., Forslund and Gudmundsson, 1992; Childs et al., 2009; Bastesen and Braathen, 2010; Johannessen, 2017), which indicate that faults with 2–3 meters wide core zones (like the Overgangshytta fault; Figure 10a) generally accommodate vertical displacement ranging from a few meters to several hundreds of meters”, lines 383–386 “Notably, quantitative studies discussing potential relationships between fault length and displacement show that a fault like the Overgangshytta fault is likely to be several hundred to a few thousand meters long (Watterson, 1986; Nicol et al., 1995; Schlische et al., 1996; Gudmundsson, 2000; Kolyukhin and Torabi, 2012)”, and to the reference list.

Comment 40: implemented suggested change.

Comment 41: changed “km-thick” into “kilometer-thick” line 360.

Comment 42: addition of “Although not always reconstructed in paleo-tectonic reconstructions, in the early Neoproterozoic, the position of Svalbard was probably close to the Timanian margin of northern Baltica prior to the opening of the Asgard Sea and Iapetus Ocean/Ægir Sea (Torsvik et al., 1996; Cawood et al., 2001, 2010; Cawood and Pisarevsky, 2017), and prior to the Timanian Orogeny in the late Neoproterozoic (Roberts and Siedlecka, 2002; Roberts and Olovyanishnikov, 2004)” lines 420–426 and to the reference list. In addition, the authors added a sentence about the Timanian Orogeny in the introduction lines 84–87.

Comment 43: addition of “, potentially accommodating a few meters to several tens of meters of reverse displacement” lines 482–483.

Comment 44: implemented suggested change.

Comment 45: replacement “small” by “meter” line 484.

Comment 46: addition of “(centimeter- to decimeter-scale)” line 484.

Comment 47: no change.

Comment 48: addition of “thickened by several tens of centimeters” line 514.

Comment 49: implemented suggested change.

Comment 50: implemented suggested change.

Comment 51: implemented suggested change.

Comment 52: implemented suggested change.

Comment 53: see response to comment 42.

Comment 54: see response to comment 47.

Comment 55: implemented suggested change.

Comment 56: addition of “gentle (10–30°)” to the result chapter line 263 and to the discussion chapter lines 580–581.

Comment 57: replacement of “(a)” line 591 (two occurrences) by “one or several”. Deletion of “(s)” lines 591 and 592.

Comment 58: addition of “B” and “K” in figure 1a to locate Brøggerhalvøya (B) and Kongfjorden (K).

Comment 59: implemented suggested change.

Comment 60: addition of “ENE–WSW-oriented” line 203 in the geological setting chapter and line 617 in the discussion chapter, and of “west-directed” and “thrusting” in the discussion chapter lines 616 and 617.

Comment 61: no change.

Comment 62: no change.

Comment 63: added the suggested reference to the reference list and to the main text lines 488–497.

Comment 64: implemented suggested change.

Comment 65: addition of “(< 1 km)” line 664.

Comment 66: implemented suggested change.

Comment 67: no change.

Comment 68: implemented suggested changes.

Comment 69: implemented suggested change.

Comment 70: implemented suggested change.

Comment 71: addition of multiple localities to figures 1a and 1b.

Comment 72: implemented suggested change.

Comment 73: implemented suggested change.

Comment 74: no change.

Comment 75: no change.

Comment 76: implemented suggested change.

Comment 77: implemented suggested changes.

Comment 78: implemented suggested changes.

Comment 79: implemented suggested changes.

Comment 80: replacement of “Outcrop photograph showing the geometry” by “Eastward view” line 1231.

Comment 81: addition of a scale bar to figure 11.

Comment 82: implemented suggested changes.

From widespread Mississippian to localized Pennsylvanian extension in central Spitsbergen, Svalbard

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Abstract

In the Devonian–Carboniferous, a rapid succession of clustered extensional and contractional tectonic events is thought to have affected sedimentary rocks in central Spitsbergen, Svalbard. These events include Caledonian post-orogenic extensional collapse associated with the formation of thick Early–Middle Devonian basins, Late Devonian–Mississippian Ellesmerian contraction, and Early–Middle Pennsylvanian rifting, which resulted in the deposition of thick sedimentary units in Carboniferous basins like the Billefjorden Trough. The clustering of these varied tectonic settings makes it sometimes difficult to resolve the tectono-sedimentary history of individual stratigraphic units. Notably, the context of deposition of Mississippian clastic and coal-bearing sedimentary rocks of the Billefjorden Group is still debated, especially in central Spitsbergen. We present field evidence (e.g., growth strata and slickensides) from the northern part of the Billefjorden Trough, in Odellfjellet ~~(Austfjorden)~~, suggesting that tilted Mississippian sedimentary strata of the Billefjorden Group deposited during active (Late/latest?) Mississippian extension. ~~Evidence include slickenside lineations and growth strata in the hanging wall of basin-oblique NNE-dipping faults, such as the Overgangshytta fault. These~~ WNW–ESE-striking basin-oblique faults showing Mississippian growth strata systematically die out upwards within Mississippian to lowermost Pennsylvanian strata, thus ~~and~~ suggesting a period of widespread WNW–ESE-directed extension in the Mississippian ~~(rift "initiation" phase)~~, ~~followed by~~and an episode of ~~more~~ localized extension in Early–Middle Pennsylvanian times ~~("interaction and~~

~~linkage" and "through-going fault" phases)~~. In addition, the presence of abundant basin-oblique faults ~~parallel to the Overgangshytta fault~~ in basement rocks adjacent to the Billefjorden Trough suggests that the formation of Mississippian normal faults was partly controlled by reactivation of preexisting Neoproterozoic (Timanian?) basement-seated fault zones. We propose that these preexisting faults reactivated as transverse ~~fault~~ or accommodation cross faults in or near the crest of transverse folds reflecting differential displacement along the Billefjorden Fault Zone~~, thus suggesting that normal faulting along this major fault initiated as early as the Mississippian~~. In Cenozoic times, a few margin-oblique faults (e.g., the Overgangshytta fault) may have mildly reactivated as ~~an~~ oblique thrusts during transpression–contraction, ~~and~~ but shallow_-dipping, bedding_-parallel, duplex_-shaped déecollements in shales of the Billefjorden Group possibly prevented ~~further~~ substantial movement along ~~Mississippian margin-oblique~~these faults.

1. Introduction

At the end of the Caledonian Orogeny in late Paleozoic times, Norway (Séranne et al., 1989; Osmundsen and Andersen, 2001; Gudlaugsson et al., 1998; Koehl et al., 2018a), Greenland (Hartz et al., 1997; Sartini-Rideout et al., 2006; Hallett et al., 2014; McClelland et al., 2016) and Svalbard (Manby and Lyberis, 1992; Braathen et al., 2018) were part of a large E–W trending intra-cratonic basin (Ziegler et al., 2002) that was subjected to a major episode of gravitational collapse, resulting in the formation of thick, Early to Middle Devonian sedimentary basins that evolved into rift basins in Late Devonian (?) to Carboniferous times (Figure 1). In Spitsbergen, however, Late Devonian–Mississippian times recorded a short-lived period of contraction related to the Ellesmerian Orogeny, inverting Devonian collapse basins and associated basin-bounding faults (Piepjohn, 2000; Bergh et al., 2011; Piepjohn et al., 2015). Further transpression related to the opening of the Northeast Atlantic Ocean and the formation of a major fold-and-thrust belt in Cenozoic times complicates the study of Mississippian sedimentary rocks, making it difficult to identify and resolve Mississippian fault movements.

-Although the sedimentology and stratigraphy of Mississippian sedimentary rocks are well studied in Spitsbergen (Gjelberg and Steel, 1981; Gjelberg, 1984; McCann and Dallmann, 1996; Maher, 1996), Bjørnøya (Gjelberg, 1981; Gjelberg and Steel, 1983; Worsley et al., 2001) and the SW Barents Sea (Bugge et al., 1995; Larssen et al., 2002; Samuelsberg et al., 2003; Koehl et al., 2018a), little is known about the tectonic setting in which they were deposited, i.e., during

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Ellesmerian contraction–transpression in, e.g., foreland basins (Piepjohn, 2000; Bergh et al., 2011; Piepjohn et al., 2015), or during a continuous episode of extensional collapse in spoon-shaped basins (e.g., Séranne et al., 1989; Osmundsen and Andersen, 2001; Koehl et al., 2018) and/or during rifting (Gjelberg and Steel, 1981; Gjelberg, 1984), or during a period of tectonic quiescence (e.g., Johannessen and Steel, 1992; Braathen et al., 2011). Thus, the present local study has broad regional implications, especially regarding the geodynamic setting of Arctic regions in the Mississippian (contraction, extension, tectonic quiescence, transitional?), the architecture and geometry of the Barents Sea and west Spitsbergen margins (Mississippian basins?), and the distribution of Mississippian coal-bearing hydrocarbon source rock around Svalbard and in the Barents Sea.

~~Particularly i~~Currently, ~~n central Spitsbergen,~~ in the Billefjorden Trough in central Spitsbergen (Braathen et al., 2011), Mississippian sedimentary rocks are believed to represent pre-rift sedimentary rocks deposited prior to the main phase of extension in the Pennsylvanian (Johannessen and Steel, 1992; Braathen et al., 2011). However, new field observations in Mississippian strata in Austfjorden, in the northern part of the Billefjorden Trough (Figure 1~~Figure 1Figure 1~~), challenge this model.

The present study provides new insights in the Mississippian tectonic history of central Spitsbergen, Svalbard, using field structural analysis of newly exposed Mississippian sedimentary deposits in Odellfjellet, Austfjorden (Figure 1~~Figure 1Figure 1~~). These sedimentary rocks are mildly reworked by Cenozoic transpression, and show preserved Mississippian primary faults and offsets, thus representing an excellent opportunity to resolve the tectonic history of this period. We emphasize the ~~influence~~ control of NW–SE-striking faults, like the Overgangshytta fault, on the deposition of Mississippian–Lower Pennsylvanian sedimentary strata and use adjacent and/or overlying Lower–Late Pennsylvanian sedimentary rocks as a comparison. We compare basement-seated NW–SE-striking faults in central Spitsbergen with similar faults in northern Norway, which possibly formed during to the late Neoproterozoic Timamian Orogeny (Roberts and Siedlecka, 2002; Roberts and Olovyanishnikov, 2004). Finally, we discuss potential controlling factors that may have influenced Mississippian faulting.

2. Geological setting

2.1. Precambrian geology

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The study area, the Billefjorden Trough, is located at the boundary of two major structural domains, the northwestern and eastern terranes of Svalbard (Harland and Wright, 1979; Ohta et al., 1989; Labrousse et al., 2008), previously named the Nordfjorden and Ny-Friesland blocks respectively (Cutbill and Challinor, 1965; Harland et al., 1974). East of the trough, the Ny-Friesland block is composed of basement rocks with well developed, variably dipping, N–S-trending foliation, dominated by biotite-amphibolite gneisses of the Eskolabreen Complex (Balashov et al., 1993; Johansson and Gee, 1999) and Meso- to Neo-proterozoic metasedimentary rocks of the Smutsbreen and Polhem formations (Harland et al., 1966). These rocks are involved in a large-scale, N–S-trending, gently north-plunging fold structure, the Atomfjella Antiform (Witt-Nilsson et al., 1998). In addition, Paleoproterozoic granitic and granodioritic basement gneisses (Harland et al., 1974) crop out in the hanging wall of the Balliolbreen fault and in the footwall of the Odellfjellet fault, two major segments of a regional east- to ENE-dipping fault complex, the Billefjorden Fault Zone (BFZ; Harland et al., 1974; McCann and Dallmann, 1996; Braathen et al., 2011; Figure 1Figure 1Figure 1).

2.2. Late Paleozoic post-Caledonian basins and faults

Devonian sedimentary basins

Post-Caledonian "Old Red" collapse basins formed along inverted Caledonian thrusts in the Early to Late Devonian and are bounded by major N–S- to NNW–SSE-striking faults (Harland et al., 1974; Manby and Lyberis, 1992; Manby et al., 1994). Large portions (> 6 km-thick) of these basins are preserved west of a west-dipping segment of the BFZ, although they were probably deposited east of the fault as well (McCann and Dallmann, 1996). Devonian collapse sediments were possibly reworked by contraction related to the Late Devonian–Mississippian Svalbardian Phase (McCann, 2000; Piepjohn, 2000; Bergh et al., 2011; Piepjohn et al., 2015). Notably, in Billefjorden and Austfjorden (Figure 1Figure 1Figure 1), positive tectonic inversion of the Balliolbreen segment of the BFZ resulted in over-thrusting and juxtaposition of Paleoproterozoic, granitic and granodioritic basement gneisses to the east with Devonian clastic sedimentary deposits to the west (Figure 1Figure 1Figure 1; McCann, 2000). However, this short-lived episode of contraction is challenged by new evidence of basement exhumation, possibly as core complexes along inverted Caledonian shear zones in Early to Late Devonian times in northwestern Spitsbergen (Braathen et al., 2018), in Early Devonian to Mississippian times in the SW Barents Sea (Klein and

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Steltenpohl, 1999; Klein et al., 1999; Steltenpohl et al., 2011; Koehl et al., 2018a), and in the Late Devonian–Mississippian in northeastern Greenland (Sartini-Rideout et al., 2006; Hallett et al., 2014; McClelland et al., 2016).

Carboniferous sedimentary basins

During post-Caledonian, Carboniferous, ENE–WSW-directed extension/sinistral transtension, multiple sedimentary troughs formed throughout the Svalbard archipelago, e.g., the Billefjorden, Lomfjorden, St Jonsfjorden and Inner Hornsund troughs (Maher, 1996; McCann and Dallmann, 1996), while major sedimentary basins, such as the Sørkapp, Nordkapp and Hammerfest basins, developed in the Barents Sea (Gabrielsen et al., 1990; Gudlaugsson et al., 1998; Anell et al., 2016; Koehl et al., 2018a). These basins and troughs were filled with thick Carboniferous sediments deposited along (reactivated) high-angle normal faults, like the east-dipping Balliolbreen and Odellfjellet segments of the BFZ in central Spitsbergen (Harland et al., 1974; McCann and Dallmann, 1996).

Mississippian sedimentary strata are up to 2.5 km in cumulative thickness, and are easily recognizable at outcrop scale because they commonly comprise coal seams and coaly shales interbedded with dominant clastic deposits, both in the Barents Sea (Bugge et al., 1995; Larssen et al., 2002; Samuelsberg et al., 2003), on Bjørnøya (Gjelberg and Steel, 1983; Gjelberg, 1984) and in Spitsbergen (Cutbill and Challinor, 1965; Cutbill et al., 1976; Gjelberg, 1981, 1984; Gjelberg and Steel, 1981). In central Spitsbergen (e.g., in Billefjorden), preserved Mississippian strata are relatively thin (< 300 m; Cutbill et al., 1976) and are divided into two formations, the Hørbyebreen Formation composed of the Triungen and Hoelbreen members, and the Mumien Formation including the Sporehøgda and Birger Johnsonfjellet members (Figure 2Figure 2Figure 2). The Hoelbreen and Birger Johnsonfjellet members show abundant, characteristic coal seams and coaly shales, whereas the Triungen and Sporehøgda members are dominantly composed of clastic sedimentary deposits (Cutbill and Challinor, 1965; Cutbill et al., 1976; Gjelberg and Steel, 1981; Gjelberg, 1984; Figure 2Figure 2Figure 2).

Mississippian sedimentary rocks of the Billefjorden Group are generally believed to represent pre-rift units (Johannessen and Steel, 1992; Braathen et al., 2011), though an early syn-rift origin is considered possible (Steel and Worsley, 1984; Nøttvedt et al., 1993; McCann and Dallmann, 1996). The pre-rift interpretation is largely based on the presence of Mississippian rocks

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on both sides of the BFZ. Moreover, Mississippian sedimentary strata display NW-plunging folds (e.g., in western Spitsbergen), suggesting that they might have (partly) deposited during west-directed thrusting ~~contraction~~ related to the Svalbardian phase (Bergh et al., 2011) of the Late Devonian–Mississippian Ellesmerian Orogeny (McCann, 2000; Piepjohn, 2000). During this contractional event, the BFZ might have acted as a transpressional fault, possibly accommodating left-lateral displacement > 200 km (Harland et al., 1974). In addition, contraction-related uplift may be responsible for extensive erosion of Mississippian rocks.~~,~~ ~~t~~Thus, it is commonly difficult to~~preventing direct~~ compar~~e~~ison ~~of~~ sedimentary successions in the ~~faults~~ footwall and hanging wall of faults and to ~~impeding the~~ identif~~y~~ication ~~of~~ potential growth strata (McCann and Dallmann, 1996).

Pennsylvanian sedimentary rocks in central Spitsbergen represent the thickest, preserved sedimentary deposits recorded in the Billefjorden Trough. These are divided into five formations belonging to the Gipsdalen Group (Figure 2~~Figure 2Figure 2~~). First, the late Serpukhovian Hultberget Formation is composed of characteristic red and subsidiary grey sandstones, conglomerates and shales (Cutbill and Challinor, 1965; Cutbill et al., 1976; Johannessen, 1980; Gjelberg and Steel, 1981; Johannessen and Steel, 1992; Figure 2~~Figure 2Figure 2~~). Second, the Bashkirian Ebbadalen Formation is made of highly variable lithologies, including interbedded grey–yellow sandstones and grey–green shales (Ebbaelva Member), and red and yellow sandstones and conglomerates interbedded with red shales (Odellfjellet Member) interfingering with gypsum–anhydrite and dark limestones and dolomites (Trikolorfjellet Member; Holliday and Cutbill, 1972; Johannessen, 1980; Johannessen and Steel, 1992; Braathen et al., 2011; Figure 2~~Figure 2Figure 2~~). Third, the Moscovian Minkinfjellet Formation is dominated by limestone and dolomite with minor evaporites (Carronelva and Terrierfjellet members), and carbonate karst breccias (Fortet Member; McWhae, 1953; Cutbill and Challinor, 1965; Lønøy, 1995; Figure 2~~Figure 2Figure 2~~). Fourth and fifth, the Wördiekammen and Gipshuken formations mainly consist of dolomite and limestone interbedded with evaporites and cross-cut by dissolution breccias in the latter (Gee et al., 1952; Cutbill and Challinor, 1965).

By contrast to the pre-rift origin inferred for Mississippian sedimentary units, Pennsylvanian rocks of the Hultberget, Ebbadalen and Minkinfjellet formations are thought to represent respectively the early, main and late syn-rift sedimentation episodes (Prosser, 1993) or the “initiation”, “interaction and linkage”, and “through-going fault” stages (Gawthorpe and

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Leeder, 2000, their fig. 3) in the Billefjorden Trough (Johannessen and Steel, 1992; Braathen et al., 2011). Pennsylvanian syn-rift sedimentation was accompanied by significant kilometer-scale downthrowing to the east along the BFZ, and tilting of SW-dipping Carboniferous normal faults and related fault-propagation folds into a subvertical/east-dipping position in the eastern part of the Billefjorden Trough (e.g., the Løvehovden fault; Maher and Braathen, 2011; Braathen et al., 2011). Middle Pennsylvanian–Cisuralian sedimentary strata of the Wördiekammen and Gipshuken formations are largely accepted as late syn-rift to post-rift sedimentary units (Braathen et al., 2011), in other words as part of the "through-going fault" stage of Gawthorpe and Leeder (2000). In Odellfjellet (Austfjorden; Figure 1~~Figure 1Figure 1~~), newly exposed strata investigated in the present contribution crop out near cliffs of tens (hundreds?) of meters thick Pennsylvanian sedimentary strata of the Hultberget, Ebbadalen and Minkinfjellet formations (Johannessen and Steel, 1992; Lamar and Douglaass, 1995).

2.3. Cenozoic fold and thrust belt

Apart from a few minor tectonic episodes, e.g., in the Permian–Triassic (Worsley and Mørk, 1978; Mørk et al., 1982; Steel and Worsley, 1984; Osmundsen et al., 2014) and potentially in the Cretaceous (Nemec et al., 1988; Prestholm and Walderhaug, 2000; Onderdonk and Midtkandal, 2010), the Svalbard Archipelago is believed to have remained relatively quiet tectonically from the end of the Pennsylvanian to the end of the Mesozoic. In mid-Cenozoic times, ENE–WSW-oriented contractional–transpressional deformation related to continental break-up and subsequent opening of the Northeast Atlantic Ocean formed sub-horizontal NW- to NNW-trending folds (Bergh et al., 1997; Bergh and Grogan, 2003), and inverted major normal faults, resulting in the formation of the West Spitsbergen fold-and-thrust belt (Harland, 1969; Lowell, 1972; Harland et al., 1974; Haremo et al., 1990; Dallmann et al., 1993; Dißmann and Grewing, 1997). Cenozoic dextral transpression and contraction reactivated preexisting, margin-parallel, N–S-trending Caledonian and margin-oblique NW–SE- to NNW–SSE-trending Svalbardian (Ellesmerian) folds and thrusts (Bergh et al., 1997; Blinova et al., 2012, 2013), and inverted Devonian–Carboniferous normal faults such as the BFZ, making fault offsets difficult to resolve.

3. Methods

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The present work is a compilation of satellite images from toposvalbard.npolar.no covering areas in the eastern part of the Billefjorden Trough (Figure 3~~Figure 3Figure 3~~), and of field structural observations in Carboniferous sedimentary rocks in Odellfjellet (Figure 1~~Figure 1Figure 1~~) collected during a field excursion in summer 2016 (Figure 4~~Figure 4Figure 4~~). Structural data are plotted in lower-hemisphere, equal-area Schmidt stereonets as great circles. Satellite images of exposed basement rocks were used to identify brittle faults in exposed but difficultly accessible Proterozoic basement rocks adjacent to Carboniferous sedimentary deposits in the Billefjorden Trough. In addition, fault surfaces and escarpments in the field were tied to map-view lineaments on satellite images that matched their trend and location (Figure 4). Critical factors used in the interpretation of geological features on satellite images in inaccessible areas include existing literature (e.g., N–S-trending gneissic foliation in basement rocks east and southeast of the field area was evidenced by multiple works, including notably Harland et al., 1966 and Witt-Nilsson et al., 1998), the geological database at svalbardkartet.npolar.no, and similarities with fault-related escarpments tied to actual brittle faults in the field area (Figure 4). Glacial features were segregated from ductile and brittle structures and fabrics using satellite images and scientific literature on recent and past glacial flow. Satellite images used in the present study are from 2011 and have a horizontal resolution of 40 cm.

4. Results

4.1. Basement rocks

East and southeast of the investigated outcrops by a riverbed in Odellfjellet (Figure 1~~Figure 1Figure 1~~), Mesoproterozoic to earliest Neoproterozoic basement rocks crop out~~,~~ and ~~these~~ display a well-developed N–S-trending gneissic foliation (Harland et al., 1966; Balashov et al., 1993; Witt-Nilsson et al., 1998; Johansson and Gee, 1999). This prominent ductile fabric is visible on satellite images where it defines series of clustered, (sub-) parallel, linear to arcuate lineaments following the topography of ridges exposed within Mittag–Lefflerbreen, e.g., Framstakken (Figure 3~~Figure 3Figure 3~~a), Heclastakken (Figure 3~~Figure 3Figure 3~~b) and Furystakken (Figure 3~~Figure 3Figure 3~~c), and on mountain flanks, e.g., southernmost tip of Sederholmfjellet (Figure 3~~Figure 3Figure 3~~d). In these outcrops, basement rocks are glaciated (Marks and Wysokinski, 1986) and glacial lineations and features are easily differentiated from basement ductile fabrics, and correlated with ongoing ice flow (Figure 3~~Figure 3Figure 3~~; Marks and Wysokinski, 1986).

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Discrete, steep, WNW–ESE-trending escarpments occur and trend oblique (sub-orthogonal) to the prominent N–S-trending foliation in Mesoproterozoic to Neoproterozoic basement rocks (Figure 3~~Figure 3Figure 3~~; Harland et al., 1966; Balashov et al., 1993; Witt-Nilsson et al., 1998; Johansson and Gee, 1999). Further, these escarpments are parallel to steeply dipping strike-slip to normal brittle faults that cross-cut the Atomfjella Antiform in northern Ny-Friesland, e.g., the Mosseldalen fault (Witt-Nilsson et al., 1998). Thus, we interpret the abundant WNW–ESE-trending escarpments in basement rocks in southernmost Sederholmfjellet and in basement ridges in Mittag–Lefflerbreen to represent steep, inherited, Neoproterozoic to early/mid-Paleozoic, WNW–ESE-striking brittle faults. This is supported by outcrop occurrences of similarly striking basin-oblique brittle faults in Ebbadalen (in Billefjorden; Christophersen, 2015) and Biscahalvøya (in northwestern Spitsbergen; Gee, 1972; Labrousse et al., 2008), which cross-cut Mesoproterozoic to earliest Neoproterozoic basement rocks and terminate below unconformably overlying Devonian–Carboniferous sedimentary deposits.

4.2. Sedimentary rocks

Dark grey sandstones and coaly shales

In Odellfjellet (Figure 1~~Figure 1Figure 1~~ and Figure 4~~Figure 4Figure 4~~), we evidenced the presence of a several tens of meter thick succession made of meter-thick beds of grey sandstones and dark coaly shales showing a gentle (10–30°) south-to-southwest-wards dip (Figure 5~~Figure 5Figure 5~~a). The lower part of this succession crops out at the river mouth and is dominated by interbedded, meter-thick beds of coal-bearing shale and grey sandstone (Figure 5~~Figure 5Figure 5~~a). Coal-bearing shales showed sparse plant fossils, including Stigmaria ficoides (Figure 5~~Figure 5Figure 5~~b; Playford, 1962; Birkenmayer and Turnau 1962). The upper part of the succession crops out hundreds of meters south- and south-westwards along the riverbed. There, the succession includes in addition beds of grey claystone with iron nodules (Figure 5~~Figure 5Figure 5~~c) and soil profiles with polygonal fractures (Figure 5~~Figure 5Figure 5~~d). One kilometer southwards along the riverbed, the upper part of the succession of grey sandstone–coaly shale crops out again and is interbedded with thin decimeter- to meter-thick beds of yellow sandstone in the hanging wall of a major fault, the Overgangshytta fault. ~~There~~At this location, the succession forms a 10–20 meter-wide, E–W- to WNW–ESE-trending, open and upright anticline (Figure 6~~Figure 6Figure 6~~).

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Based on previous descriptions of the Billefjorden Group and Hultberget Formation in Billefjorden (Cutbill et al., 1976; Gjelberg, 1984), the ~~hereby described~~ grey sandstone and coaly shale sedimentary strata observed at the river mouth and in the hanging wall of the Overgangshytta fault may either belong to the upper part of the Billefjorden Group or represent the base of the Hultberget Formation. ~~However, i~~Iron nodules similar to those found in the upper part of the grey sandstone–coaly shale succession (Figure 5c) have not been described in the lower part of the Hultberget Formation and are rather typical of the upper part of this Formation (Cutbill et al., 1976). On the contrary, iron nodules are fairly common within the upper part of the Sporehøgda and Birger Johnsonfjellet members of the Mississippian Mumien Formation (Cutbill et al., 1976; Gjelberg, 1984; Figure 2~~Figure 2Figure 2~~). In addition, the presence of soil profiles (Figure 5~~Figure 5Figure 5~~d) and Stigmaria ficoides (Figure 5~~Figure 5Figure 5~~b), a plant fossil abundantly found in the Billefjorden Group (Playford, 1962; Birkenmayer and Turnau 1962; Gjelberg, 1984), respectively near the top and base of the described outcrops rather suggests that the grey sandstone and coaly shale strata in Odellfjellet are part of the Billefjorden Group.

Red sandstones and shales

At the river mouth, tilted beds of grey sandstones and coal-bearing shales are in angular unconformity contact with flat-lying decimeter to meter-thick beds of red to yellow sandstones partly covered by Quaternary glacial deposits (Figure 7~~Figure 7Figure 7~~a). Hundreds of meters southwards along the riverbed, grey sandstones and dark coaly shales are interbedded with thin, tens of centimeter-thick beds of yellow sandstone (Figure 7~~Figure 7Figure 7~~b), which proportion gradually increases southwards. Farther south, coaly shales eventually disappear and are replaced by abundant meter-thick red sandstone and shale interbedded with subsidiary decimeter-thick grey to yellow sandstone (Figure 7~~Figure 7Figure 7~~c). Based on the typical red coloration of the dominant sandstone and shale beds and on the presence of thin beds of yellow sandstone and subsidiary grey sandstone (Cutbill et al. 1976; Gjelberg, 1984), we propose that the ~~hereby described~~ red-bed sedimentary succession described herein is part of the Hultberget Formation (Figure 2~~Figure 2Figure 2~~).

4.3. Brittle faults

Faults within the Billefjorden Group

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In Odellfjellet (Figure 1~~Figure 1Figure 1~~ and Figure 4~~Figure 4Figure 4~~), sedimentary rocks of the Billefjorden Group are cross-cut by steep NE–SW- to ENE–WSW-, NW–SE- to WNW–ESE-, and subsidiary NNE–SSW- to N–S-striking faults (Figure 4~~Figure 4Figure 4~~). Brittle faults display abundant, centimeter- to decimeter-thick lenses of fine-grained, light-colored, non-cohesive fault-rock (i.e., fault gouge; Woodcock and Mort, 2008; Figure 8~~Figure 8Figure 8~~a). Slickensides (grooves) along these faults indicate dominant normal dip-slip and subordinate normal oblique-slip movements (Figure 4~~Figure 4Figure 4~~) and offsets are generally decimeter- to meter-scale (Figure 8). WNW–ESE- to NW–SE-striking faults generally die out within grey sandstones and coaly shales of the Billefjorden Group and often display thickened sandstone beds in the hanging wall, which do not appear to continue into the faults footwall (Figure 8~~Figure 8Figure 8~~b–c). Based on the dominant normal sense of shear of these fault, we argue that thickened sedimentary strata in the hanging wall represent potential tens-of-centimeter-thick growth strata reflecting syn-tectonic sedimentation. Notably, Figure 8~~Figure 8Figure 8~~c shows that, in places, interpreted syn-tectonic growth strata along NNE-dipping faults are composed of two discrete sedimentary units, including proximal sandy wedges and distal prograding to sheet-like sand bodies eroded upwards, which are separated from each other by an angular unconformity.

In places, high-angle (> 70°) brittle faults appear to flatten and sole into shale-dominated beds of the Billefjorden Group, forming duplex-like geometries that incorporate lenses of squeezed shale and dominantly fine-grained cohesive fault-rock (i.e., meso- to ultra-cataclasite; Woodcock and Mort, 2008) with clasts of partially preserved coaly shale, as well as possible shallow ~~-~~dipping, bedding ~~-~~parallel déecollements (Figure 8~~Figure 8Figure 8~~d–e). In cross-section, these flattening brittle faults display normal sense of shear (red line in Figure 8~~Figure 8Figure 8~~d–e), while smaller faults within duplex-like structures show minor centimeter-scale reverse offsets of host-rock clasts (dashed red lines in Figure 8~~Figure 8Figure 8~~d–e). We tentatively interpret these as Carboniferous normal faults and duplexes soling downwards into shale-dominated déecollements, which were subsequently partly reactivated as reverse faults, possibly during Cenozoic transpression.

Faults within the Hultberget Formation

Sedimentary rocks of the Hultberget Formation are cross-cut by steep NNE–SSW- to N–S-, NE–SW- to ENE–WSW-, and subsidiary low-angle WNW–ESE-striking faults (Figure 4~~Figure 4Figure 4~~). Fault-cores include centimeter- to decimeter-thick lenses of ~~non-cohesive~~ light-colored fault-~~rock~~ gouge (Figure 9~~Figure 9Figure 9~~a). Displacement along these faults is in the order of a few decimeters to 1–2 meters, as shown by normal offsets of red and grey sedimentary beds (Figure 9~~Figure 9Figure 9~~b–d). A major difference between faults cross-cutting the Billefjorden Group and those truncating red and grey strata of the Hultberget Formation is that we did not identify any growth strata in the latter, therefore suggesting that movement along brittle faults cross-cutting the Hultberget Formation occurred after sediment deposition.

The Overgangshytta fault

The southernmost outcrops along the riverbed are cross-cut by a major NNE-dipping fault that we name the Overgangshytta fault (Figure 4~~Figure 4Figure 4~~ and Figure 10~~Figure 10Figure 10~~a). In the hanging wall, this fault is characterized by a decametric/mesoscale anticline incorporating beds of grey sandstones and coaly shales of the Billefjorden Group interbedded with thin beds of yellow sandstone more typical of the Hultberget Formation (Figure 6~~Figure 6Figure 6~~). The footwall of the fault is dominated by red sandstones and shales interbedded with grey to yellow sandstones (Figure 10~~Figure 10Figure 10~~a). These rocks are similar to those of the Hultberget Formation farther north along the riverbed (Figure 7~~Figure 7Figure 7~~c) and to red Devonian sandstones also observed in the area, west of the BFZ (McCann and Dallmann, 1996). The 2–3 meter-thick fault-core ~~is made of~~comprises steeply SSW-tilted strata (Figure 10~~Figure 10Figure 10~~a) cross-cut by abundant fractures comprising centimeter- to decimeter-scale lenses of yellow (Figure 10~~Figure 10Figure 10~~b) and light-colored ~~non-cohesive~~ fault-~~rocks~~ gouges (Figure 10~~Figure 10Figure 10~~c). The fault shows slickenside lineations indicating dip-slip normal movements (Figure 10~~Figure 10Figure 10~~d). The Overgangshytta fault was not observed in adjacent cliffs to the WNW, where sedimentary strata of the Hultberget, Ebbadalen and Minkinfjellet formations crop out, possibly suggesting that the fault dies out laterally and/or vertically (Figure 10~~Figure 10Figure 10~~e and supplements).

5. Discussion

5.1. Origin of the Overgangshytta fault

The red sandstones and shales interbedded with grey to yellow sandstones in the footwall of the Overgangshytta fault (Figure 10~~Figure 10~~a, d and e) are similar to kilometer-thick Devonian sedimentary deposits observed west of the BFZ in adjacent onshore areas in André Land (Manby and Lyberis, 1992), and their presence in the footwall of the Overgangshytta fault may indicate hundreds of meter- to kilometer-scale, down-NNE, normal displacement along this fault. However, such Devonian deposits have never been observed east of the BFZ and are believed to have been eroded or never deposited (Harland et al., 1974). Thus, sedimentary strata in the footwall of the Overgangshytta fault (Figure 10~~Figure 10~~a and e) are more likely to represent uppermost Mississippian–lowermost Pennsylvanian strata of the Hultberget Formation, analog to those observed in the hanging wall of the fault (Figure 7~~Figure 7~~a–b). Isopach maps from Cutbill et al. (1976) suggest that the Hultberget Formation is no thicker 80 m in Odellfjellet, and, therefore, the presence of sedimentary strata of the Hultberget Formation on both sides of the Overgangshytta fault may indicate vertical displacement comprised between a few meters and 80 m along the fault. This is supported by quantitative studies on the width of fault cores (e.g., Forslund and Gudmundsson, 1992; Childs et al., 2009; Bastesen and Braathen, 2010; Johannessen, 2017), which indicate that faults with 2–3 meters wide core zones (like the Overgangshytta fault; Figure 10a) generally accommodate vertical displacement ranging from a few meters to several hundreds of meters.

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The Overgangshytta fault was not observed in adjacent cliff-outcrops ~~made of sedimentary strata of the Hultberget, Ebbadalen and Minkinfjellet formations~~ (Figure 4~~Figure 4Figure 4~~, Figure 10~~Figure 10Figure 10~~e, and supplements), ~~thus~~ which suggest~~sing~~ that the fault dies out laterally approximately ~~ca.~~ 300 meters to the west-northwest and/or upwards within the Hultberget Formation. However, ~~T~~the width of the fault-core (2–3 meters), the suggested displacement along the fault (a few meters to several tens of meters), and the intensity of deformation in the hanging wall of the fault along the riverbed (Figure 6~~Figure 6Figure 6~~ and Figure 10~~Figure 10Figure 10~~a–c) do not support a nearby lateral termination of the fault. Notably, quantitative studies discussing potential relationships between fault length and displacement show that a fault like the Overgangshytta fault is likely to be several hundred to a few thousand meters long (Watterson, 1986; Nicol et al., 1995; Schlische et al., 1996; Gudmundsson, 2000; Kolyukhin and Torabi, 2012).

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~~However~~By contrast, northwards, along the riverbed, NNE-dipping faults striking parallel to the Overgangshytta fault die out upwards in coal-bearing sedimentary rocks of the Billefjorden Group (Figure 8~~Figure 8Figure 8~~b–c). We therefore propose that the Overgangshytta fault also dies out upwards within uppermost Mississippian–Lower Pennsylvanian strata of the Hultberget or Ebbadalen Formation. Such upwards dying-out geometry was also observed for similarly striking,

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steep, SW- to SSW-dipping faults in Billefjorden, the Kampesteindalen fault and Ebbabreen faults. The former dies out within the Ebbadalen Formation and juxtaposes sedimentary strata of the Hultberget Formation in the footwall with rocks of the Ebbadalen Formation in the hanging wall (Braathen et al., 2011; Smyrak-Sikora pers. comm., 2016), whereas the latter downthrow thickened Mississippian rocks of the Billefjorden Group to the southwest and die out upwards within the Hultberget Formation (McCann and Dallmann, 1996). Thus, the steep and upwards dying-out geometry of the Overgangshytta fault (Figure 10Figure 10Figure 10e) together with slickengrooves indicating normal dip-slip movement (Figure 10Figure 10Figure 10d) suggest that this fault formed as an extensional normal fault in the Mississippian to earliest Pennsylvanian.

The red sandstones and shales interbedded with grey to yellow sandstones in the footwall of the Overgangshytta fault (Figure 10a, d and e) are similar to km-thick Devonian sedimentary deposits observed west of the BFZ in adjacent onshore areas in André Land (Manby and Lyberis, 1992), and their presence in the footwall of the Overgangshytta fault may indicate hundreds of meter- to km-scale, down-NNE, normal displacement along this fault. However, such Devonian deposits have never been observed east of the BFZ and are believed to have been eroded or never deposited (Harland et al., 1974). Thus, sedimentary strata in the footwall of the Overgangshytta fault (Figure 10a and e) are more likely to represent uppermost Mississippian–lowermost Pennsylvanian strata of the Hultberget Formation, analog to those observed in the hanging wall of the fault (Figure 7a–b). Isopach maps from Cutbill et al. (1976) suggest that the Hultberget Formation is no thicker 80 m in Odellfjellet, and, therefore, the presence of sedimentary strata of the Hultberget Formation on both sides of the Overgangshytta fault may indicate overall vertical displacement < 80 m along the fault.

East and southeast of the studied outcrops in Odellfjellet (Figure 1Figure 1Figure 1), satellite images show numerous WNW–ESE-trending escarpments in Paleoproterozoic to earliest Neoproterozoic basement rocks in Sederholmfjellet and Mittag–Lefflerbreen (Figure 3Figure 3Figure 3), which we interpreted as steep brittle faults based on their similarities with fault-related lineaments in the field area (Figure 4Figure 4) and their obliquity to the dominant N–S-trending ductile fabrics and structures (Harland et al., 1966; Balashov et al., 1993; Witt-Nilsson et al., 1998; Johansson and Gee, 1999). Although not always reconstructed in paleo-tectonic reconstructions, in the early Neoproterozoic, the position of Svalbard was probably close to the Timanian margin of northern Baltica prior to the opening of the Asgard Sea and Iapetus Ocean/Ægir Sea (Torsvik et

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al., 1996; Cawood et al., 2001, 2010; Cawood and Pisarevsky, 2017), and prior to the Timanian Orogeny in the late Neoproterozoic (Roberts and Siedlecka, 2002; Roberts and Olovyanishnikov, 2004). In northern Baltica, Ssimilar, steep, and abundant, WNW–ESE-striking, margin-oblique (i.e., oblique to the Atlantic margin) brittle faults were mapped on the Varanger Peninsula (Siedlecka and Siedlecki, 1967; Siedlecki, 1975, 1980) and Magerøya (Koehl, 2018; Koehl et al., submitted) in northern Norway, and represent fault segments of a major, inherited, Neoproterozoic subvertical fault, the Trollfjorden–Komagelva Fault Zone, which formed during the Timanian Orogeny and is thought to have accommodated hundreds of kilometers of lateral displacement (Rice, 2013). This fault experienced multiple episodes of reactivation and was last reactivated under transtension in Mississippian times (Visean; Lippard and Prestvik, 1997), shortly before it was intruded by Mississippian (Visean; Lippard and Prestvik, 1997) dolerite dykes that seal the fault (Roberts et al., 1991; Nasuti et al., 2015). Hence, we propose that the WNW–ESE-trending fault-related escarpments observed in Paleoproterozoic to earliest Neoproterozoic basement rocks in Sederholmfjellet and Mittag–Lefflerbreen (Figure 3Figure 3Figure 3) correspond to inherited Neoproterozoic (Timanian?) strike-slip faults. Possible inherited Timanian fabrics also exist in southern Spitsbergen and include steep WNW–ESE- to NW–SE-striking Neoproterozoic faults and shear zones that show affinities with the Timanides of northern Norway (Mazur et al., 2009; Majka et al., 2010), thus supporting our interpretation. Moreover, a recent seismic study suggests a Timanian origin for the WNW–ESE-trending Olga Basin in the northern Barents Sea (Klitzke et al., 2018, submitted). We propose that steep basement-seated margin-oblique faults in central Spitsbergen were partly reactivated as normal faults during post-Caledonian extension and may have localized the formation of Mississippian–earliest Pennsylvanian basin-oblique WNW–ESE-striking normal faults like the Overgangshytta fault in Odellfjellet. Such interpretation accounts both for the strike-slip (inherited?) and normal (post-Caledonian reactivation?) shear senses inferred for WNW–ESE-striking faults in northern Ny-Friesland (Witt-Nilsson et al., 1998).

In the hanging wall of the Overgangshytta fault, the anticline involving sedimentary rocks of the Hultberget Formation and Billefjorden Group (Figure 6Figure 6Figure 6) may represent a normal fault-related fold (Schlische, 1995), e.g. a rollover anticline formed as a response to large extensional displacement along a listric fault, or a growth anticline formed during the propagation of the fault into overlying sedimentary rocks of the Billefjorden Group (?) and Hultberget Formation. An origin as a rollover anticline is incompatible with the inferred geometry of the

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Overgangshytta fault at depth, as this fault may have formed along (a) preexisting steep–subvertical inherited Neoproterozoic fault(s) and is unlikely to be listric. This is supported by satellite images showing numerous steep WNW–ESE-trending fault-related escarpments in exposed Paleoproterozoic to earliest Neoproterozoic basement rocks southeast (Mittag–Lefflerbreen; Figure 3~~Figure 3Figure 3~~a–c) and east of Odellfjellet (Sederholmfjellet; Figure 3~~Figure 3Figure 3~~d), which most likely continue below the studied outcrops of Carboniferous sedimentary rocks, and by field mapping of abundant steep WNW–ESE-striking faults in northern Ny-Friesland (Witt-Nilsson et al., 1998). Conversely, a formation as a potential growth anticline is compatible with the inferred steep geometry of the Overgangshytta fault at depth. The Overgangshytta fault may have propagated upwards from an existing, steep, inherited, Neoproterozoic, basement-seated fault during post-Caledonian Mississippian to earliest Pennsylvanian extension. Such mechanism was recently proposed to explain the geometry of the N–S-striking Løvehovden fault in Billefjorden (Maher and Braathen, 2011). Another possibility is that the Overgangshytta anticline formed as a fault-bend anticline (Rotevatn and Jackson, 2014, their fig. 4b) during downward linkage of the Overgangshytta fault with a preexisting basement-seated WNW–ESE-striking fault during (Late/latest?) Mississippian–Pennsylvanian extension.

Alternatively, the observed anticline (Figure 6~~Figure 6Figure 6~~) formed much later, during Cenozoic contraction–dextral transpression associated with the formation of the West Spitsbergen fold-and-thrust belt (Harland, 1969; Lowell, 1972; Bergh et al., 1997; Leever et al., 2011), thus potentially reflecting top-SSW thrusting. The Overgangshytta fault actually strikes subparallel to most NW–SE-striking Cenozoic thrust faults mapped onshore western Spitsbergen (Braathen and Bergh, 1995; Bergh et al., 1997, 2000) and in nearshore fjords in central Spitsbergen (Bergh et al., 1997; Blinova et al., 2012, 2013). Considering its obliquity with the main N–S- to NNW–SSE-trending axis of the West Spitsbergen fold-and-thrust belt, the Overgangshytta fault might have reactivated as a minor oblique thrust fault, potentially accommodating a few meters to several tens of meters of reverse displacement during a stage of dextral transpression. This is consistent with minor (centimeter- to decimeter-scale) reverse offsets in ~~small~~meter-scale duplexes localized within bedding-parallel dé~~e~~collement levels in shale-dominated beds of the Billefjorden Group in Odellfjellet (Figure 8~~Figure 8~~d–e), which might represent minor inversion of Carboniferous normal faults during Cenozoic transpression~~ (Figure 8d–e)~~. Moreover, analog field studies along fault segments of the San Andreas fault in Indio Hills (Koehl et al., 2017, unpublished) and Mecca Hills

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in California (Bergh et al., 2014, submitted) show that minor thrust faults developed oblique to major strike-slip faults during dextral transpression, and the relative orientation of these oblique thrusts compared to the San Andreas fault matches that of the Overgangshytta fault compared to the BFZ in Svalbard (Figure 1~~Figure 1Figure 1~~ and Figure 4~~Figure 4Figure 4~~).

Despite having potentially reactivated as a minor oblique thrust during Cenozoic dextral transpression, the Overgangshytta fault did not propagate into adjacent cliff-outcrops made of Pennsylvanian deposits (Figure 10~~Figure 10Figure 10~~e, and supplements). We argue that this may be ascribed to the observed steep and inferred subvertical geometries of the Overgangshytta fault at surface and at depth respectively, which were most likely not suitable to accommodate significant reverse displacement (as observed for small-scale duplexes; Figure 8~~Figure 8Figure 8~~d–e). As a result, the fault was only mildly reactivated with little or no upwards propagation, and adjacent sedimentary rocks of the Hultberget Formation and Billefjorden Group were gently folded (Figure 6~~Figure 6Figure 6~~). Alternatively or in addition, low-angle bedding-parallel d~~é~~écollements in shaly beds of the Billefjorden Group might have inhibited Cenozoic deformation, partly decoupling deformation between basement and post-Mississippian sedimentary rocks, thus explaining the lack of inversion structures in the studied outcrops~~,~~. This ~~and~~ resulted~~ing~~ in mild inversion of the Overgangshytta fault (Figure 10~~Figure 10Figure 10~~a) and duplex-like geometries and minor reverse faulting in Mississippian shales (Figure 8~~Figure 8Figure 8~~d–e). Noteworthy, the Overgangshytta anticline might as well be the result of combined Carboniferous normal fault-related folding and Cenozoic inversion.

5.2. Mississippian extension

Mississippian growth strata along basin-oblique faults

Evidence in favor of Mississippian syn-sedimentary extensional brittle faulting include (i) fault slickenside lineations yielding dominant normal dip-slip and subsidiary normal oblique-slip sense of shear (Figure 4~~Figure 4Figure 4~~ and Figure 10~~Figure 10Figure 10~~d), and (ii) ~~thickened~~ sedimentary beds thickened by several tens of centimeters interpreted as fault-growth strata in the hanging wall of NNE-dipping brittle faults cross-cutting coal-bearing sedimentary rocks of the Billefjorden Group (Figure 8~~Figure 8Figure 8~~b and c). Although it was not possible to measure the strike of the faults showing Mississippian growth strata in the hanging wall, they obviously trend sub-parallel to the NNE-dipping Overgangshytta fault (Figure 4~~Figure 4Figure 4~~, and Figure

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8~~Figure 8Figure 8~~b–c). Importantly, in Figure 8~~Figure 8Figure 8~~c, the interpreted syn-tectonic unit in the hanging wall of the NNE-dipping fault displays a proximal sandy wedge and an onlapping (divergent onlap), distal, prograding to sheet-like sand body. On the one hand, based on the thickening of the wedge towards the fault and on intra-bedding surfaces (dotted yellow lines in Figure 8~~Figure 8Figure 8~~c), the proximal sand-rich wedge is believed to reflect a period of normal faulting with rapid accommodation creation (Osmundsen et al., 2014, their fig. 12a). Mississippian normal faulting in Austfjorden is also supported by dominant WNW–ESE- to NW–SE-trending paleo-current data from the Sporehøgda Member in Lemstrømfjellet (Figure 1~~Figure 1Figure 1~~), on the eastern shore of Austfjorden (Gjelberg, 1981; his fig. 4.5), suggesting that sedimentary strata of the Sporehøgda Member, both in Odellfjellet and Lemstrømfjellet, might have deposited along active WNW–ESE-striking faults.

On the other hand, the geometry of the distal prograding to sheet-like sand body in *Figure 8~~Figure 8Figure 8~~*c suggests a period of slow accommodation creation (Osmundsen et al., 2014, their fig. 12c and d), potentially reflecting upward propagation of the fault as a blind fault, as shown in Gawthorpe et al. (1997, their fig. 3a) and as inferred for the Løvehovden fault farther south, in Billefjorden (Maher and Braathen, 2011), and, thus, indicating decreasing fault activity along WNW–ESE-striking faults during the deposition (of the upper part?) of the Sporehøgda Member (Mumien Formation, Billefjorden Group) in Odellfjellet. Unlike the Overgangshytta fault, minor WNW–ESE-striking faults displaying growth strata in cross-section do not extend upwards into red beds of the Hultberget Formation (Figure 8~~Figure 8Figure 8~~b–c). This suggests that extensional faulting along WNW–ESE-striking faults ceased prior to the late Serpukhovian (latest Mississippian), which is consistent with the tectono-sedimentary interpretation of intra-growth-strata packages along these faults that indicate decreasing extension (Figure 8~~Figure 8Figure 8~~c). However, this does not necessarily imply that regional extension ended in the Mississippian.~~,~~ The rheological contrast between interbedded meter-thick shaly beds and sandstone units of the Billefjorden Group may have been high enough to at least partly decouple extensional deformation between basement rocks and post-Mississippian sedimentary units. Evidence for such decoupling in Odellfjellet are found as~~and~~ shallow -dipping, bedding- parallel, duplex-shaped déecollements in (coaly) shale-dominated beds. ~~of the Billefjorden Group in Odellfjellet may have partly decoupled extensional deformation,~~ We believe that the (at least) several tens of meter-thick sedimentary rocks of the Billefjorden Group were thick enough to decouple extension and

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potentially preventing further (Pennsylvanian) movements along margin-oblique WNW–ESE-striking faults (Figure 8Figure 8Figure 8c–e). Such decoupling effects of interbedded shaly beds and sandstone units on (normal) faults is well-known from previous studies (e.g., Wilkins and Gross, 2002).

Nevertheless, the minimum (Late/latest?) Mississippian age of WNW–ESE-striking faults in Odellfjellet is consistent with Mississippian (Visean) ^{40}Ar–^{39}Ar ages obtained on dolerite dykes intruded during extension/transtension and sealing segments of the Trollfjorden–Komagelva Fault Zone in northern Norway (Roberts et al., 1991; Lippard and Prestvik, 1997). It is also consistent with Late Devonian–Mississippian K–Ar ages obtained for fault gouge in northern Norway (Davids et al., 2013; Torgersen et al., 2014; Koehl et al., 2018b) and northeast Greenland (Rotevatn et al., 2018). This also possibly suggests that the Overgangshytta fault initially died out within Mississippian strata of the Billefjorden Group and, later on, propagated into overlying sedimentary deposits of the Hultberget Formation, potentially during a mild episode of inversion of the fault during Cenozoic contraction–transpression. As proposed for the Overgangshytta fault, it is probable that most WNW–ESE-striking normal faults described in the present study formed along reactivated basement-seated Neoproterozoic fabrics (Figure 3Figure 3Figure 3).

By contrast, although showing meter-scale normal offsets and slickenside lineations indicating normal sense of shear (Figure 4Figure 4Figure 4 and Figure 9Figure 9Figure 9), N–S- and NE–SW-striking faults observed in Mississippian–lowermost Pennsylvanian strata of the Billefjorden Group and Hultberget Formation along the riverbed in Odellfjellet (Figure 8Figure 8Figure 8a and Figure 9Figure 9Figure 9b–d) did not display evidence of growth strata. Hence, the timing of formation of these faults remains uncertain. Nevertheless, knowing that the study area (Odellfjellet; Figure 1Figure 1Figure 1 and Figure 4Figure 4Figure 4) and, conceivably, most areas in central Spitsbergen were subjected to tectonic extension in the (Late/latest?) Mississippian (Figure 8Figure 8Figure 8b–c and Figure 10Figure 10Figure 10d), we propose that N–S- and NE–SW-striking faults (at least some of them) formed and acted simultaneously with WNW–ESE-striking faults during Mississippian extension, the only difference being that faults of the former two trends (N–S- and NE–SW-) experienced further normal movement, possibly during (Early–Middle?) Pennsylvanian extension (Braathen et al., 2011), thus cross-cutting rocks of the Hultberget Formation (Figure 8Figure 8Figure 8a and Figure 9Figure 9Figure 9b–d).

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Tilting of Mississippian strata of the Billefjorden Group

In the north, sedimentary strata of the Billefjorden Group appear tilted and dip gently (10–30°) to the southwest, forming an angular unconformity with overlying flat-lying red-beds of the Hultberget Formation (Figure 7~~Figure 7Figure 7~~a). In the south, grey sandstones and coal-bearing sedimentary rocks of the Billefjorden Group are interbedded with and gradually replaced by conformably overlying clastic redbeds of the Hultberget Formation (Figure 6~~Figure 6Figure 6~~ and Figure 7~~Figure 7Figure 7~~c). We argue that the observed angular unconformity in the north represents the distal portion of an uplifted, partly exposed rotated fault-block, and that conformably overlying beds of the Billefjorden Group and Hultberget Formation farther south correspond to proximal, hanging wall, syn-tectonic sedimentary strata deposited in a constantly or repeatedly flooded portion of an active fault-block (Figure 11~~Figure 11Figure 11~~). Consequently, the southwestward tilting of Mississippian sedimentary strata may reflect (Late/latest?) Mississippian extensional faulting along one or several~~(a)~~ NNE- to NE-dipping brittle fault~~(s)~~, possibly the Overgangshytta fault and/or ~~(a)~~ one or more similarly trending and dipping fault~~(s)~~, e.g., Figure 8~~Figure 8Figure 8~~b and c, thus supporting that extension initiated prior to the deposition of red-colored sedimentary strata of the Hultberget Formation. This interpretation is supported by similar observations in western Spitsbergen, where Mississippian coal-bearing sedimentary strata were proposed to have deposited in the hanging wall of an active SSW-dipping normal fault located in Kongsfjorden, forming a WNW–ESE-trending Mississippian basin, the Brøggerhalvøya trough (Bergh et al., 2000). The absence of Mississippian sedimentary strata northeast of Brøggerhalvøya was ascribed to uplift and erosion of the footwall of the fault in Kongsfjorden, and the fining upwards pattern recorded in the strata suggested to represent a break in normal faulting activity near the end of the Mississippian (Fairchild, 1982).

Furthermore, in the Barents Sea, a major Late Mississippian (Serpukhovian) unconformity was described onshore Bjørnøya (Worsley et al., 2001) and on the Finnmark Platform (Bugge et al., 1995; Koehl et al., 2018a). This unconformity was correlated to a major eustatic sea-level fall at ca. 330 Ma (Saunders and Ramsbottom, 1986; Haq and Schutter, 2008). This short-lived eustatic sea-level fall was followed by eustatic sea-level rise at ca. 325 Ma (late Serpukhovian; Saunders and Ramsbottom, 1986; Haq and Schutter, 2008) coinciding with the deposition of the Hultberget Formation (Cutbill and Challinor, 1965). In Odellfjellet, the local absence of the Late Mississippian unconformity indicates that parts of central Spitsbergen remained flooded through the

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Serpukhovian, and these flooded areas appear to be located in the hanging wall of NNE-dipping faults (e.g., the Overgangshytta fault) that accommodated normal displacement in the (Late/latest?) Mississippian (Figure 11Figure 11Figure 11). Thus, it is possible that areas where beds of the Hultberget Formation conformably overlie Mississippian strata of the Billefjorden Group, like in Billefjorden (central Spitsbergen; Cutbill et al., 1976) and Ditlovtoppen (eastern Spitsbergen; Scheibner et al., 2015), represent proximal portions of hanging walls (i.e., located near the fault) that were down-faulted during active normal faulting in the (Late/latest?) Mississippian.

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Alternatively, tilting of Mississippian strata in Odellfjellet might originate from west-directed Late Devonian–Mississippian (Ellesmerian) thrusting and/or ENE–WSW-oriented Cenozoic transpression. However, Late Devonian–Mississippian transpression does not reconcile the interbedded character of the Hultberget Formation and Billefjorden Group, which conformably overlie one another in the south (Figure 6Figure 6Figure 6, and Figure 7Figure 7Figure 7b–c), and Cenozoic transpression would have resulted in the folding of the unconformity between the Billefjorden Group and Hultberget Formation in the north. Another explanation might be along-strike variation in displacement magnitude along the BFZ during the deposition of sedimentary strata of the Billefjorden Group, resulting in so-called "transverse folds" (Schlische, 1995). However, on the Finnmark Platform in the SW Barents Sea, Mississippian strata appear tilted along brittle normal faults and are partially eroded in distal portions of hanging walls (e.g., Koehl et al., 2018a, their fig. 6a). Thus, we favor an interpretation related to down-NNE normal faulting for the observed southwestwards tilting of Mississippian sedimentary strata in Odellfjelllet (Figure 11Figure 11Figure 11).

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Switch from widespread to localized extension

Our observations in Odellfjellet show that basin-oblique, WNW–ESE- to NW–SE-striking normal faults were active in (until?) the (Late/latest?) Mississippian (Figure 8Figure 8Figure 8b–c). Similarly, in Birger Johnsonfjellet (central Spitsbergen), N–S-striking faults showing growth strata with syn-depositional tilting die out upwards within Mississippian deposits of the Billefjorden Group (McCann and Dallmann, 1996), thus suggesting that at least some N–S-striking faults were active during Mississippian extension. Thus, we propose that central Spitsbergen was subjected to widespread Mississippian extension distributed along numerous faults of varied trends, including margin-oblique WNW–ESE- to NW–SE- (Figure 8Figure 8Figure 8b–c and

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Figure 10~~Figure 10Figure 10~~a) and margin-parallel N–S-striking faults (McCann and Dallmann, 1996), and, conceivably, NE–SW-striking faults, thus possibly representing the rift “initiation” phase as detailed in Gawthorpe and Leeder (2000).

Margin-oblique faults systematically die out upwards within Mississippian (to lowermost Pennsylvanian) strata in Odellfjellet (Figure 8~~Figure 8Figure 8~~b–c), Billefjorden (e.g., Ebbabreen and Kampesteindalen faults; McCann and Dallmann, 1996; Braathen et al., 2011; Smyrak-Sikora pers. comm., 2016) and Bjørnøya (e.g., Russleva fault; Braathen et al., 1999; Koehl, in prep.). In addition, inherited margin-oblique faults in northern Norway were dated to have been last active in the Mississippian (e.g., Trollfjorden–Komagelva Fault Zone; Lippard and Prestvik, 1997). By contrast, only a few margin-parallel (N–S-striking) faults die out within Mississippian sedimentary deposits in central Spitsbergen (McCann and Dallmann, 1996), while most of these (e.g., BFZ; Harland et al., 1974; Braathen et al., 2011) and NE–SW-striking faults (Figure 8~~Figure 8Figure 8~~a and Figure 9~~Figure 9Figure 9~~b–d) cut through Pennsylvanian sedimentary rocks, suggesting that they remained active through the Early–Middle Pennsylvanian. We therefore propose that central Spitsbergen was subjected to an episode of continuous (Late/latest?) Mississippian–Middle Pennsylvanian extension during which normal displacement progressively localized along fewer fault trends (N–S and NE–SW; “interaction and linkage” phase of Gawthorpe and Leeder, 2000) , possibly using shallow -dipping, bedding -parallel dé~~e~~collements in (coaly) shale-dominated beds of the Billefjorden Group (Figure 8~~Figure 8Figure 8~~d–e) to decouple margin-oblique WNW–ESE-striking faults. Eventually, extension localized along a few major faults, such as the BFZ (“through-going fault” phase of Gawthorpe and Leeder, 2000), before ultimately ceasing in the Middle–Late Pennsylvanian.

This is similar to what was observed in the southwesternmost Nordkapp basin and on the Finnmark Platform in the SW Barents Sea (Koehl et al., 2018a), where thickened Mississippian sedimentary deposits and adjacent and/or underlying basement rocks are cross-cut and offset by numerous normal faults showing mostly minor offsets (< 1 km), whereas thickened wedges of syn-tectonic Pennsylvanian deposits are observed exclusively in the hanging wall of a few major normal faults displaying hundred meter- to kilometer-scale offsets (e.g., the Langfjorden–Vargsundet fault; Koehl et al., 2018a). Similarly, a switch from widespread extension with multiple active faults accommodating small amounts of normal displacement (with slow slip rates) during a phase of rift “initiation”, to extension localized along a few major fault surfaces (with high slip rates) during

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“interaction and linkage” to “through-going fault” phases was also suggested for Jurassic rifting in the North Sea, where the high-slip rate Gullfaks–Visund F~~f~~ault (Cowie et al., 2005) may represent a younger offshore analog to the BFZ.

Furthermore, in the NW Barents Sea, a recent seismic study shows thick packages of high-amplitude, south- to southwest-dipping reflections within the Capria Ridge, on the northern flank of the Sørkapp depression (Anell et al., 2016, their figure 3a). These are similar to thick seismic packages in the SW Barents Sea (Koehl et al., 2018a) and North Sea (Phillips et al., 2016; Fazlikhani et al., 2017) potentially representing inverted Caledonian shear zones. In the NW Barents Sea, these thick packages of high-amplitude reflections are disrupted by (sub-) parallel (i.e., E–W- to NW–SE-striking), margin-oblique, high-angle brittle normal faults, displaying thick wedges of potential Devonian (?) to Mississippian sedimentary rocks in the hanging wall. These E–W- to NW–SE- striking normal faults mostly die out near the base of a thin overlying layer of (uppermost?) Pennsylvanian sedimentary deposits showing relatively constant thickness (Anell et al., 2016). Hence, extensive normal faulting and thickened sedimentary wedges (growth strata?) along deep, margin-oblique, E–W- to NW–SE-striking faults in the NW Barents Sea, suggest extensive (collapse-related?) extension in Devonian (?) – Mississippian times and decreasing extension in the Pennsylvanian, which is consistent with field observations in Odellfjellet (Figure 8~~Figure 8Figure 8~~b–c). Decreasing extension in the Pennsylvanian is also supported by field observations in central Spitsbergen, suggesting that transgression–regression cycles in Pennsylvanian–Cisuralian deposits were mostly controlled by eustatic sea-level changes and only moderately by active faulting along margin-parallel faults like the BFZ (Samuelsberg and Pickard, 1999).

A WNW–ESE to NW–SE direction was proposed for late Paleozoic extension along the Lofoten–Vesterålen and SW Barents Sea margins in northern Norway (Bergh et al., 2007; Hansen et al., 2012; Indrevær et al., 2013). We therefore believe that Spitsbergen was subjected to a similarly oriented stress field rather than the ENE–WSW extension direction proposed by McCann and Dallmann (1996). We argue that WNW–ESE- to NW–SE-directed late Paleozoic extension in central Spitsbergen may explain the observed upwards dying-out geometry of unsuitably oriented, inherited, basin-oblique, WNW–ESE- to NW–SE-striking faults, while N–S- and NE–SW-striking faults accommodated further (Early–Middle) Pennsylvanian extensional faulting.

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A major difference between margin-oblique faults in Odellfjellet (central Spitsbergen) with their counter parts in northern Norway is that the latter accommodated dominantly lateral post-Caledonian (transfer) movement, e.g., the Trollfjorden–Komagelva Fault Zone (Koehl, 2018; Koehl et al., submitted), whereas the former accommodated dominantly normal dip-slip to oblique-slip motions (Figure 4~~Figure 4Figure 4~~, Figure 8~~Figure 8Figure 8~~b–c, and Figure 10~~Figure 10Figure 10~~d). A tentative explanation might be that inherited, Neoproterozoic, WNW–ESE- to NW–SE-striking brittle faults in central Spitsbergen reactivated as transverse faults (Ogata et al., 2014) in or near the crest of transverse folds reflecting differential displacement along the BFZ (Schlische, 1995), or as accommodation cross faults (Sengör, 1987), as proposed for the WNW–ESE-striking segment of the Troms–Finnmark Fault Complex in the SW Barents Sea (Koehl et al., 2018a). Such interpretations imply that large-scale normal displacement along margin-parallel faults in central Spitsbergen (e.g., the BFZ) initiated in the Mississippian.

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6. Conclusions

1) Extensional growth strata in the hanging wall of margin-oblique NNE-dipping normal faults~~,~~ and the change from unconformable to interbedded contact between tilted Mississippian coal-bearing sedimentary rocks of the Billefjorden Group and flat-lying to tilted uppermost Mississippian–lowermost Pennsylvanian redbeds of the Hultberget Formation towards major margin-oblique faults (e.g., the Overgangshytta fault) suggest that the former represent early syn-rift deposits that were deposited during (Late/latest?) Mississippian extension.
2) WNW–ESE- to NW–SE-striking faults systematically die out upwards within sedimentary strata of the Billefjorden Group and, occasionally, of the Hultberget Formation.~~, thus~~ This suggests~~ing~~ a switch from widespread extension in the Mississippian, involving faults of as many as three trends (WNW–ESE, N–S, and possibly NE–SW) during the rift “initiation” phase, to more localized extension in (Early–Middle?) Pennsylvanian times when normal displacement progressively localized along fewer fault trends (N–S and NE–SW) during the “interaction and linkage” phase, and, eventually, along a few major basin-parallel faults(e.g., Billefjorden Fault Zone) during the “through-going fault” phase, before extension ceased in the Middle–Late Pennsylvanian.
3) In the Carboniferous, central Spitsbergen was probably subjected to WNW–ESE- to NW–SE-directed extension, thus potentially explaining why unsuitably oriented margin-oblique WNW–

ESE-striking faults die out within Mississippian–lowermost Pennsylvanian strata of the Billefjorden Group and Hultberget Formation, while N–S- and NE–SW-striking faults experienced further normal faulting in the Pennsylvanian.

4) The presence of abundant WNW–ESE-striking fault-related lineaments in Proterozoic basement rocks east and southeast of Odellfjellet indicates that the formation of Mississippian basin-oblique WNW–ESE-striking normal faults (e.g., Overgangshytta fault) in the Billefjorden Trough may have been controlled by preexisting Neoproterozoic (Timanian?) basement-seated faults., which
5) Basement-seated Neoproterozoic brittle faults possibly reactivated as transverse faults or accommodation cross faults in the crest of transverse folds that reflect differential displacement along the Billefjorden Fault Zone, hence suggesting that normal displacement along major margin-parallel faults (like the Billefjorden Fault Zone) initiated in the Mississippian.
6) The juxtaposition of rocks of the Billefjorden Group in the hanging wall of the Overgangshytta fault, where they form a major anticline, with redbeds of the Hultberget Formation in the footwall of the fault possibly indicates that the fault was mildly reactivated as an oblique thrust during Cenozoic transpression–contraction. Alternatively or complementary, kinematic indicators with normal sense of shear along the fault suggest that the anticline might have initiated as a growth anticline due to upwards propagation of a preexisting basement-seated fault during (Late/latest?) Mississippian to Early–Middle Pennsylvanian extension.
7) Bedding-parallel déecollements in gently dipping Mississippian (coaly) shale-dominated beds of the Billefjorden Group potentially decoupled unsuitably oriented margin-oblique WNW–ESE-striking faults, preventing further (Pennsylvanian) normal movements along these, and, eventually, partially reactivated as duplex-shaped déecollements during Cenozoic transpression, largely inhibiting or preventing Cenozoic inversion of steep Mississippian normal faults.

Author contribution

JBPK acquired field measurements, wrote most of the text and drafted all the figures. JMMB contributed with broadening the scope of the discussion and parts of the outcrop description, leading to the addition of multiple paragraphs to the manuscript. Contributions are as follows: JBPK (80%) and JMMB (20%).

Competing interests

The authors declare that they have no conflicts of interest.

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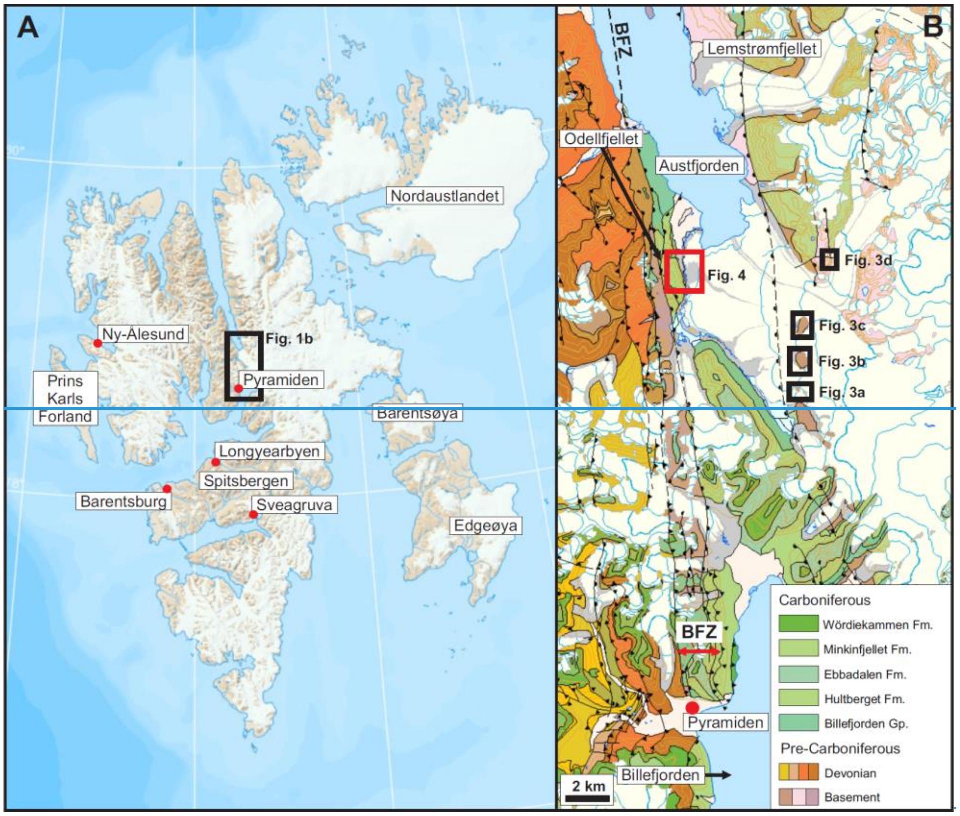
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Ny-Ålesund
Fig. 1b
Pyramiden
Prins Karls Forland
Barentsøya
Longyearbyen
Spitsbergen
Barentsburg
Sveagruva
Edgeøya
B
BFZ
Lemstrømfjellet
Odellfjellet
Austfjorden
Fig. 4
Fig. 3d
Fig. 3c
Fig. 3b
Fig. 3a
Carboniferous
Wördiekammen Fm.
Minkinfjellet Fm.
Ebbadalen Fm.
Hultberget Fm.
Billefjorden Gp.
Pre-Carboniferous
Devonian
Basement
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Pyramiden
Billefjorden
2 km

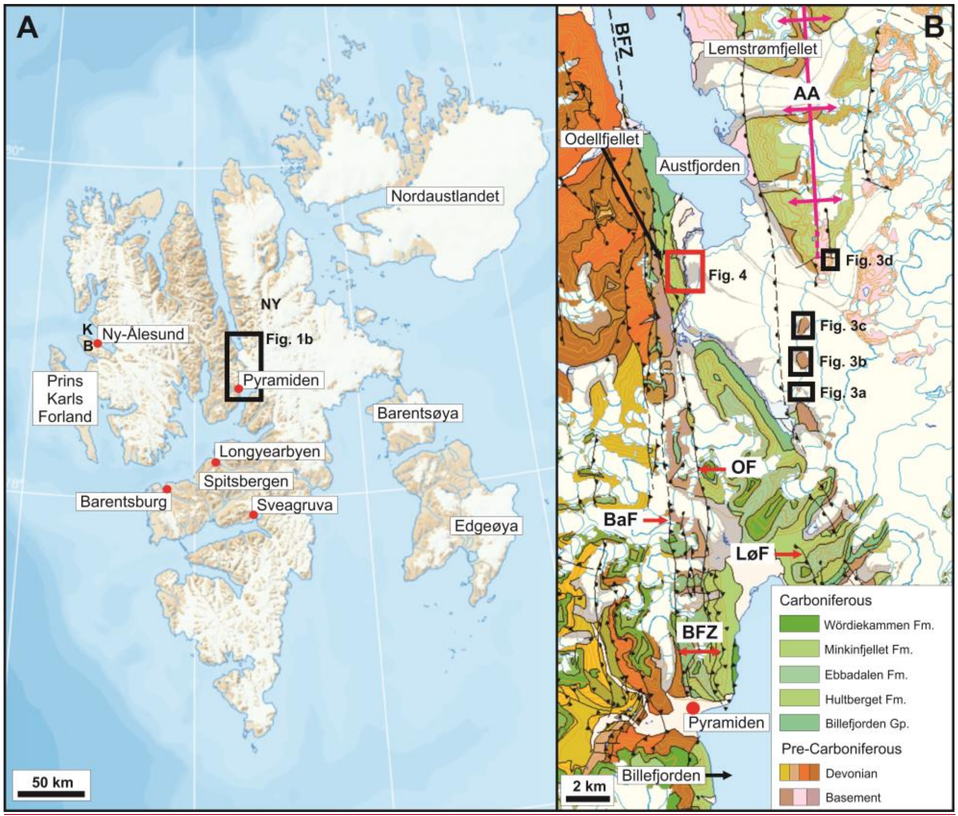

Figure 1: (a) Topography map of Spitsbergen, Svalbard. Modified from toposvalbard.npolar.no. Abbreviations are as follows: B: Brøggerhalvøya; K: Kongsfjorden; NY: Ny-Friesland; (b) Geological map of the Billefjorden–Austfjorden area, which location is shown in (a). The location of studied outcrops is shown by a red frame. The red double arrow shows the width of the Billefjorden Fault Zone (BFZ) at Pyramiden, in Billefjorden. This fault is composed of two main segments, the Balliolbreen Fault (BaF) and the Odellfjellet Fault (OF). The Atomfjella Antiform (AA) is shown in pink. Areas shaded in white represent glaciers. The map is from svalbardkartet.npolar.no. Abbreviations are as follows: AA: Atomfjella Antiform; BaF: Balliolbreen Fault; LøF: Løvehovden Fault; OF: Odellfjellet Fault.

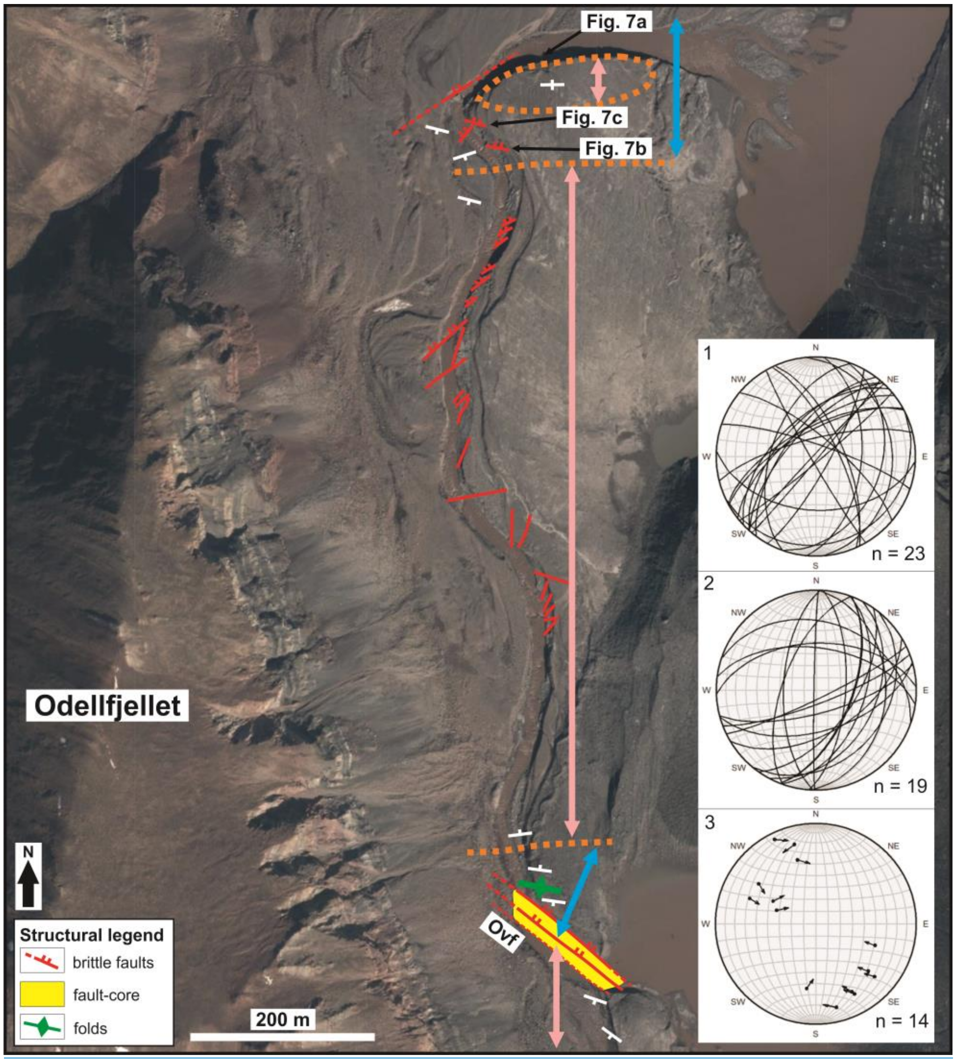

Fig. 7a
Fig. 7c
Fig. 7b
Odellfjellet
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Structural legend
brittle faults
fault-core
folds
200 m
Ovf
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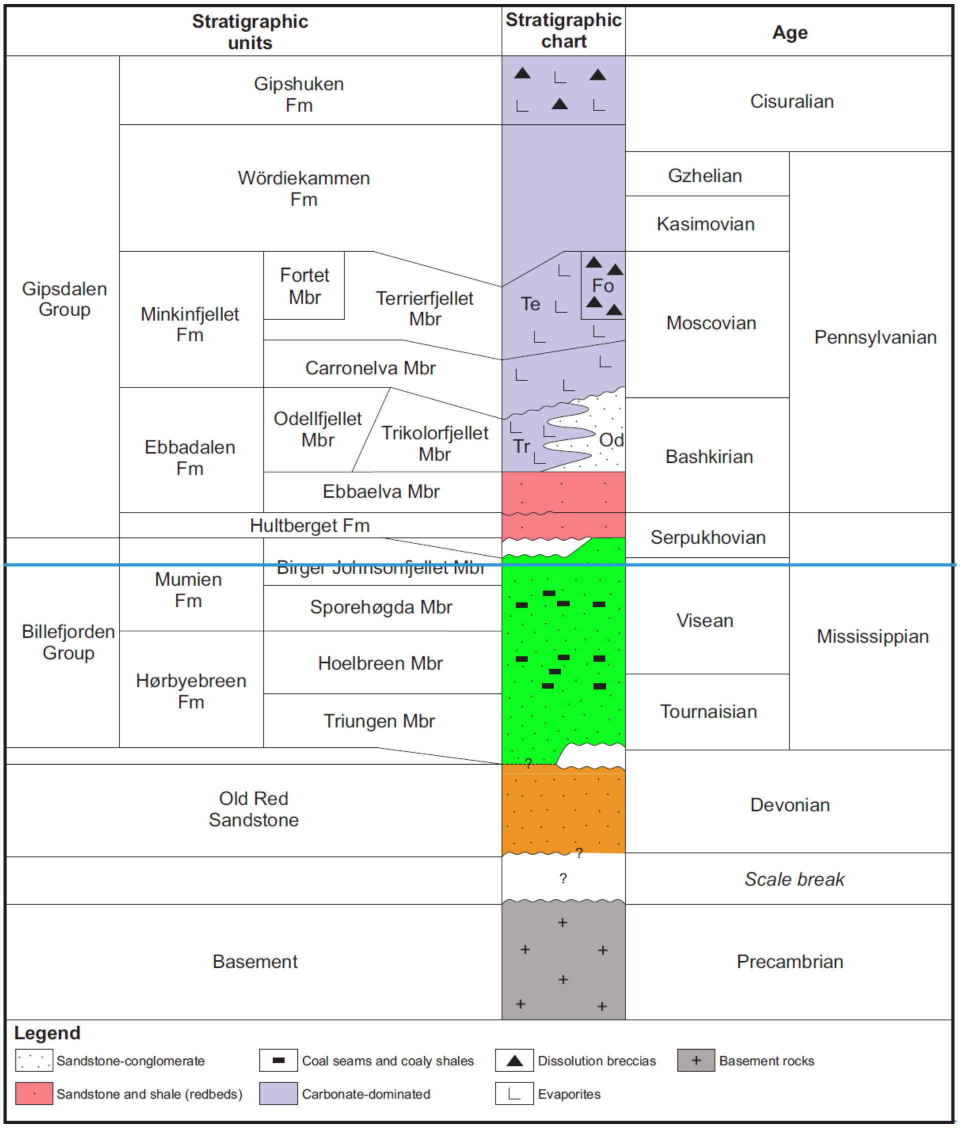
n = 23
2
n = 19
3
n = 14


Stratigraphic units
Stratigraphic chart
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Cisuralian
Wördiekammen Fm
Gzhelian
Kasimovian
Gipsdalen Group
Minkinfjellet Fm
Fortet Mbr
Terrierfjellet Mbr
Te
Fo
Moscovian
Pennsylvanian
Carronelva Mbr
Ebbadalen Fm
Odellfjellet Mbr
Trikolorfjellet Mbr
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Od
Bashkirian
Ebbaelva Mbr
Hultberget Fm
Serpukhovian
Birger Johnsonfjellet Mbr
Mumien Fm
Sporehøgda Mbr
Visean
Billefjorden Group
Mississippian
Hørbyebreen Fm
Hoelbreen Mbr
Tournaisian
Triungen Mbr
Old Red Sandstone
Devonian
Scale break
Basement
Precambrian
Legend
Sandstone-conglomerate
Coal seams and coaly shales
Dissolution breccias
Basement rocks
Sandstone and shale (redbeds)
Carbonate-dominated
Evaporites

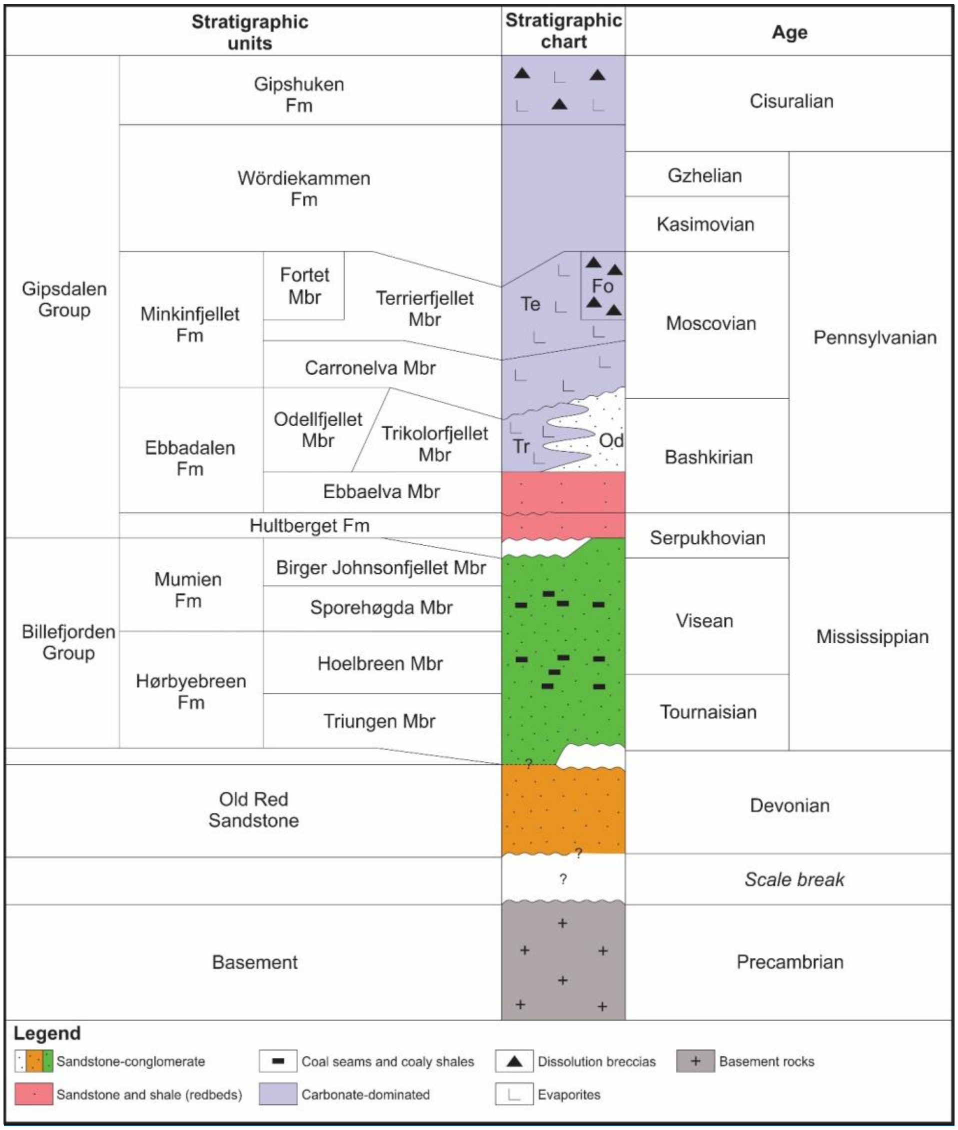
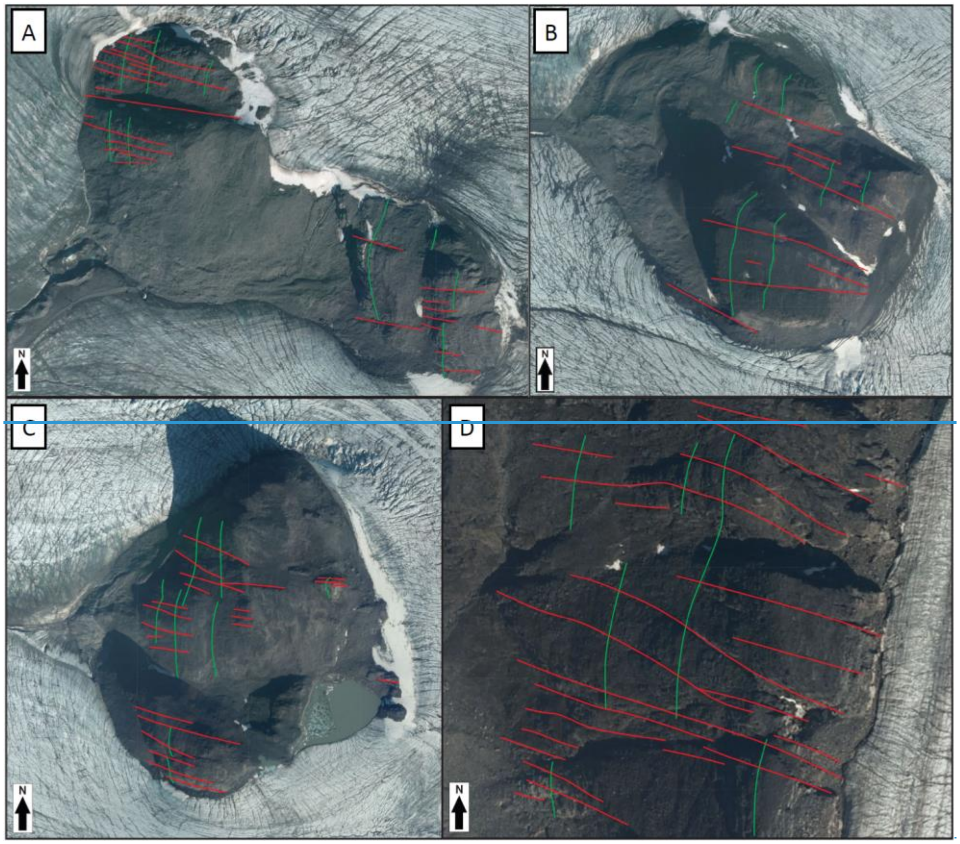


Figure 2: Lithostratigraphic chart of late Paleozoic sedimentary rocks in central Spitsbergen. The chart is based on descriptions by Gee et al. (1952), McWhae (1953), Playford (1962), Cutbill and Challionor (1965), Holliday and Cutbill (1972), Cutbill et al. (1976), Johannessen (1980), Gjelberg (1981, 1984), Gjelberg and Steel (1981), Johannessen and Steel (1992), Lønøy (1995), Dallmann (1999), Braathen et al. (2011), and Scheibner et al. (2015).

1170 

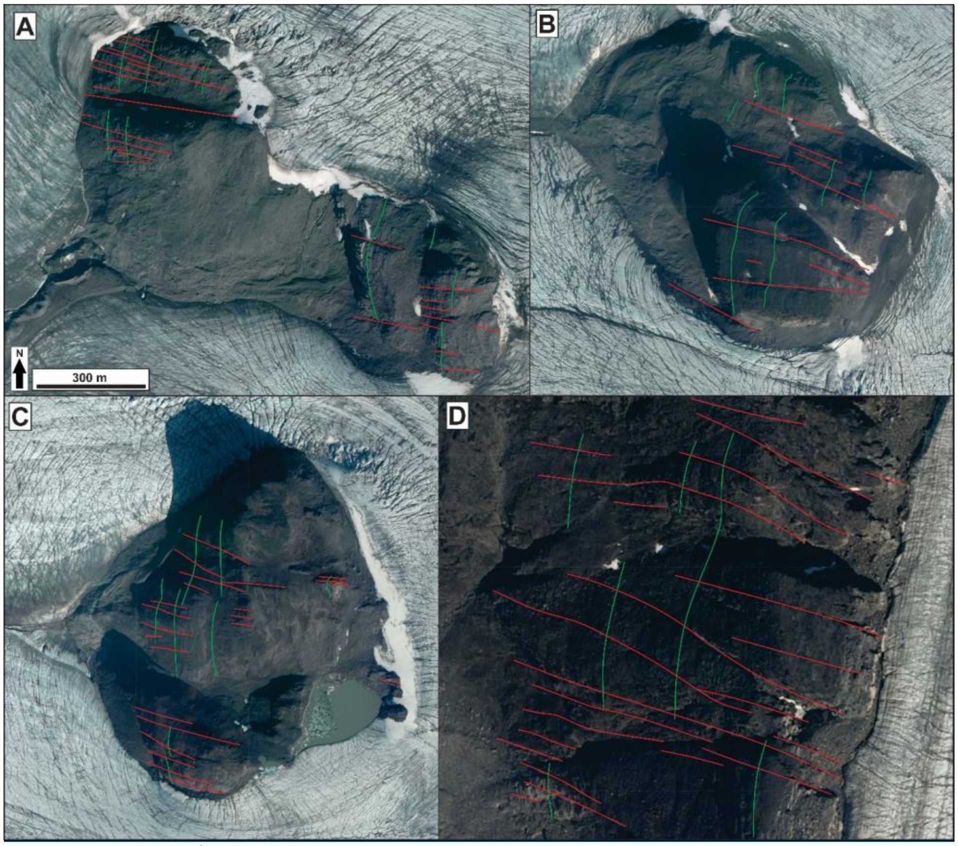


Figure 3: Satellite images from toposvalbard.npolar.no showing arcuate to rectilinear lineaments representing the prominent N–S-trending gneissic foliation of the Atomfjella Antiform and WNW–ESE-trending lineaments interpreted as steep Neoproterozoic brittle faults in basement exposures east and southeast of Odellfjellet, in (a) Framstakken, (b) Heclastakken, (c) Furystakken, and (d) southernmost Sederholmfjellet. Locations are displayed as black frames in Figure 1Figure 1Figure 1b. The photographs are approximately one kilometer wide North and scale are common to all four satellite images and are displayed in (a).

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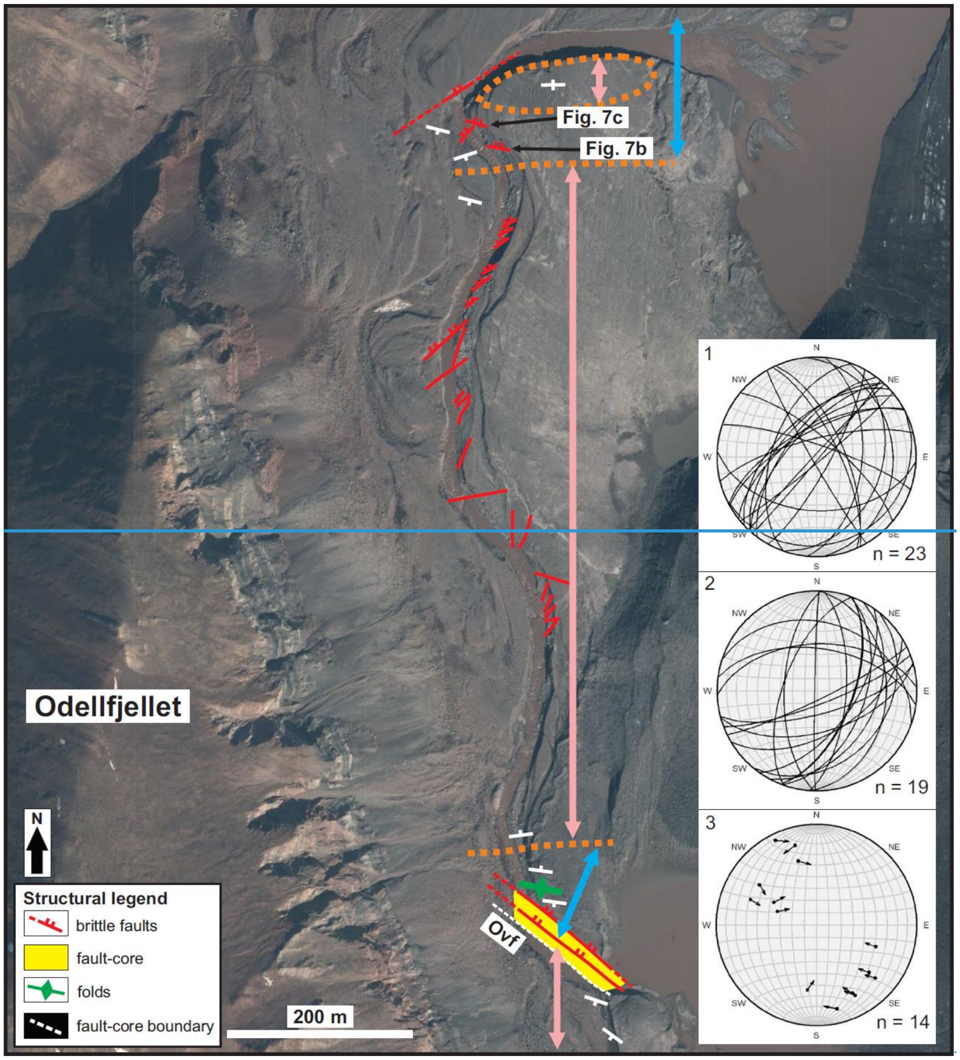
Fig. 7c
Fig. 7b
Odellfjellet
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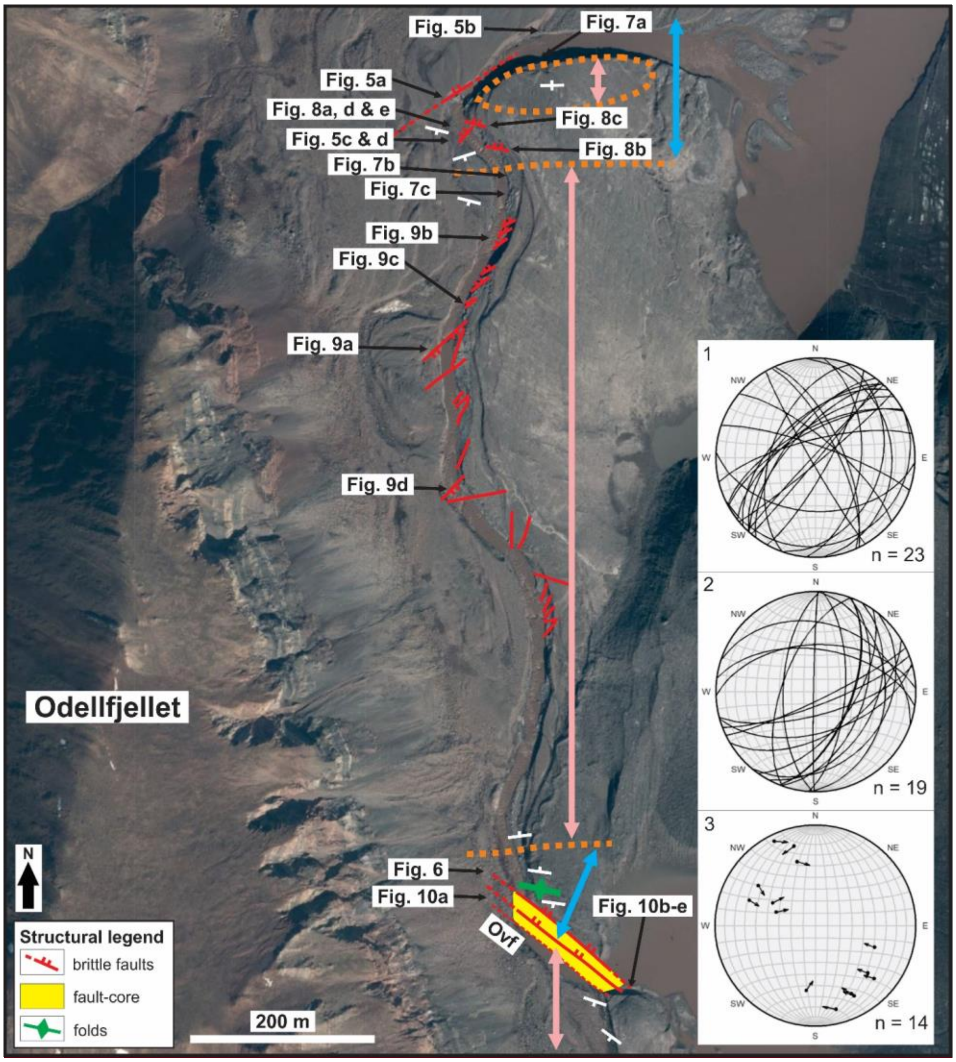

Figure 4: Satellite image from toposvalbard.npolar.no showing the study area in Odellfjellet. The studied outcrops are located along a riverbed and consist of sedimentary rocks of the Billefjorden Group (blue double arrows) and Hultberget Formation (pink double arrows) cross-cut by brittle faults (e.g., the Overgangshytta fault – Ovf). The riverbed runs sub-parallel to mountain cliff-outcrops made of sedimentary strata of the Hultberget, Ebbadalen and Minkinfjellet formations (Odellfjellet). Dotted orange lines represent stratigraphic boundaries between the Billefjorden Group and Hultberget Formation. Bedding surface measurements as white lines. Stereoplots show (1) great circle fracture surfaces within rocks of the Billefjorden Group and (2) Hultberget Formation, and (3) poles and vectors of slickenside lineations along brittle faults cross-cut rocks of the Billefjorden Group and Hultberget Formation. Location is shown by a red frame in Figure 1Figure 1Figure 1b.

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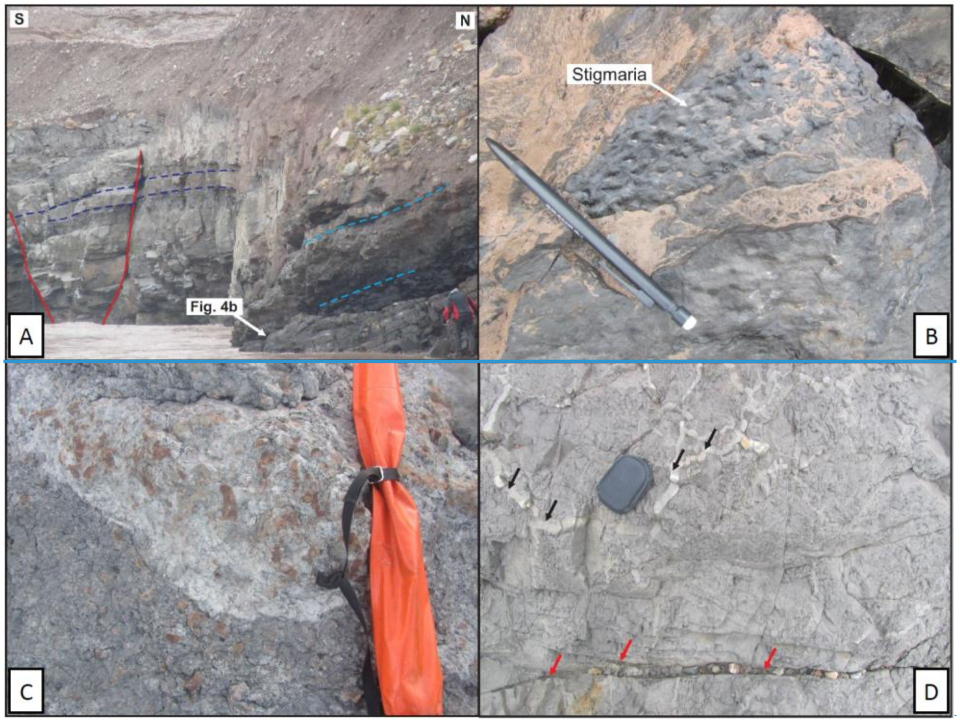
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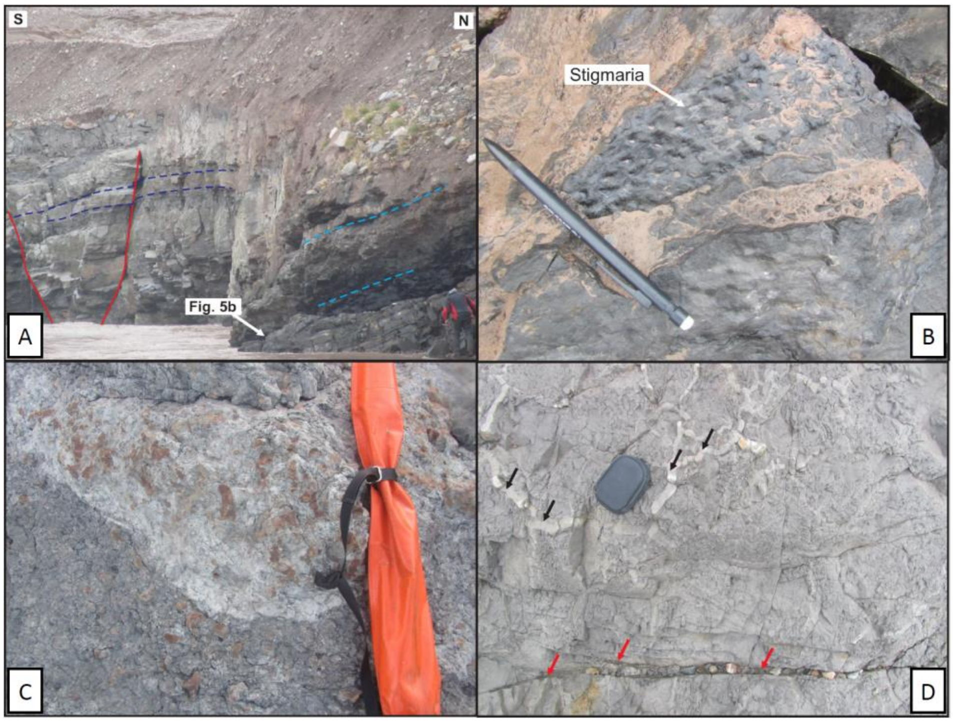


Figure 5: Outcrop photographs showing (a) southwestwardly tilted sedimentary rocks of the Billefjorden Group consisting of interbedded coal-bearing shales and grey sandstone in the lower part (light blue), and interbedded coaly shales, grey sandstone, and grey claystone with iron nodules in the upper part (dark blue). Person as scale in the lower right corner; (b) Stigmaria ficoide in the lower part of the Billefjorden Group succession. Location shown in (a); (c) grey claystone with abundant iron nodules in the upper part of the Billefjorden Group succession. Rifle orange cover as scale (approximately 1.20 m-long); (d) soil features in grey claystone cross-cut by fractures (red arrows) and polygonal fractures (black arrows) in the upper part of the Billefjorden Group succession. Camera cover (15x10 cm) as scale. Outcrop locations shown in Figure 4~~Figure 4~~.

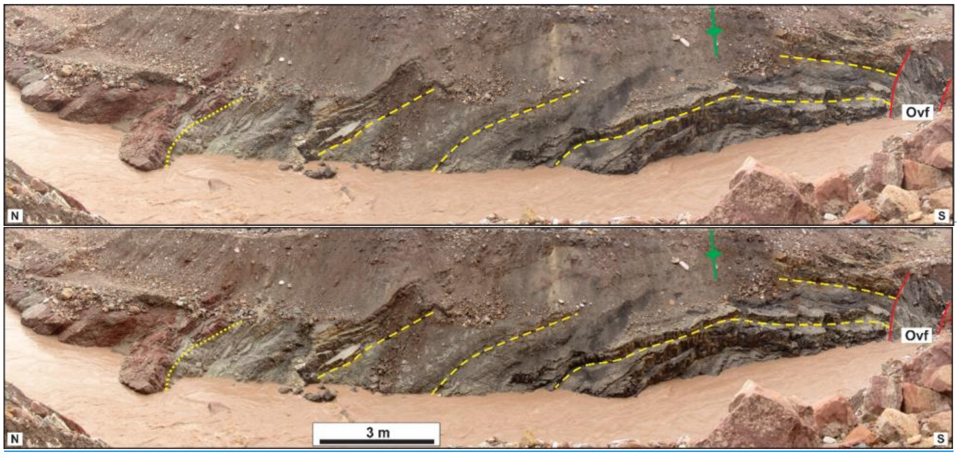
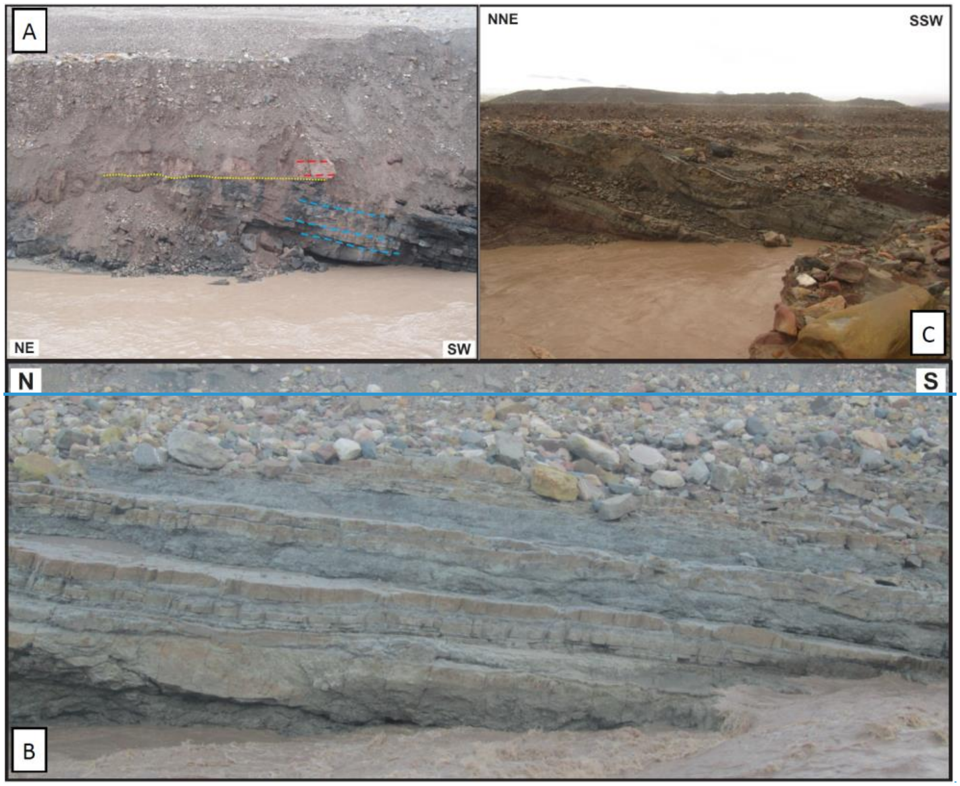


Figure 6: Eastward view of folded sedimentary strata (bedding in dashed yellow) forming an E–W- to WNW–ESE-trending, open, upright anticline (green) in the hanging wall of the Overgangshytta fault (red; Ovf), along the southern portion of the riverbed (Figure 4Figure 4Figure 4). Note the boundary (conformity?) between grey sandstones and coaly shales of the Billefjorden Group and red sandstones and shales of the Hultberget Formation in dotted yellow. The outcrop is approximately 10–15 m wide and 2–2.5 m high. See green line in Figure 4Figure 4Figure 4 for location of the anticline.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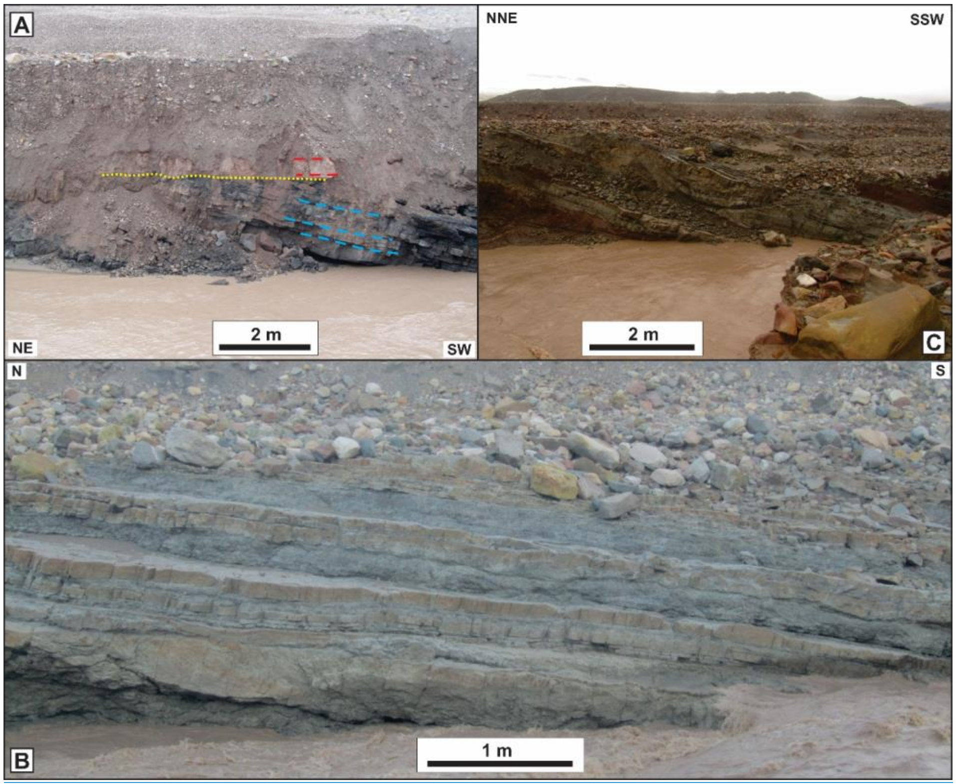
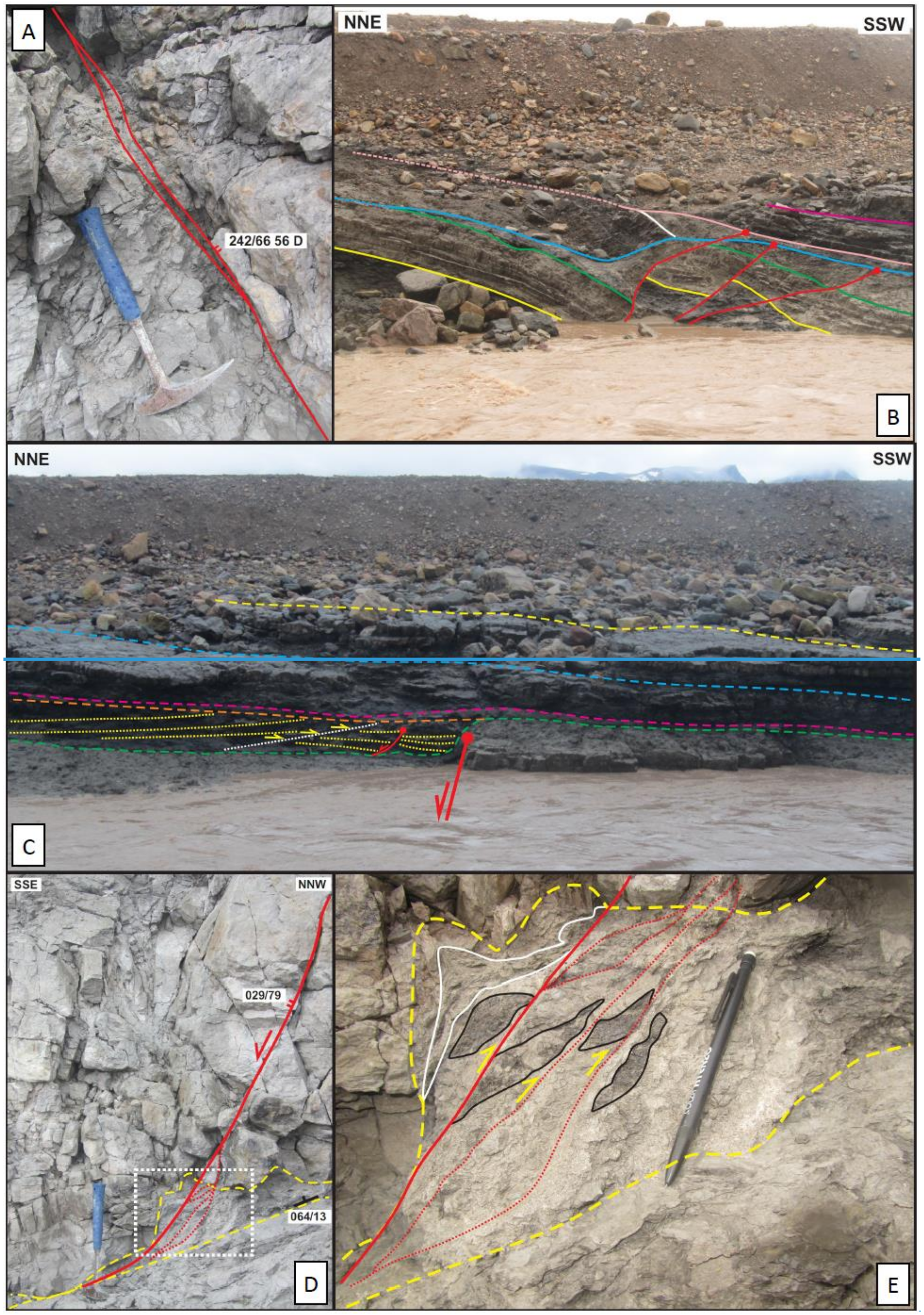


Figure 7: (a) Outcrop photographs showing southwestwardly tilted sandstone- and coaly shale-rich beds of the Billefjorden Group (dashed blue) unconformably (unconformity in dotted yellow) overlain by flat-lying (dashed red) redbeds of the Hultberget Formation. Outcrop located at the northern end of the riverbed in (see Figure 4Figure 4Figure 4); (b) Grey sandstone and shales interbedded with thin beds of yellow sandstones (transitional between Billefjorden Group and Hultberget Formation?). Outcrop location in Figure 4Figure 4; (c) Red shale interbedded with grey and yellow sandstone characteristic of the Hultberget Formation in Odellfjellet, Austfjorden. See Figure 4Figure 4 for outcrop location.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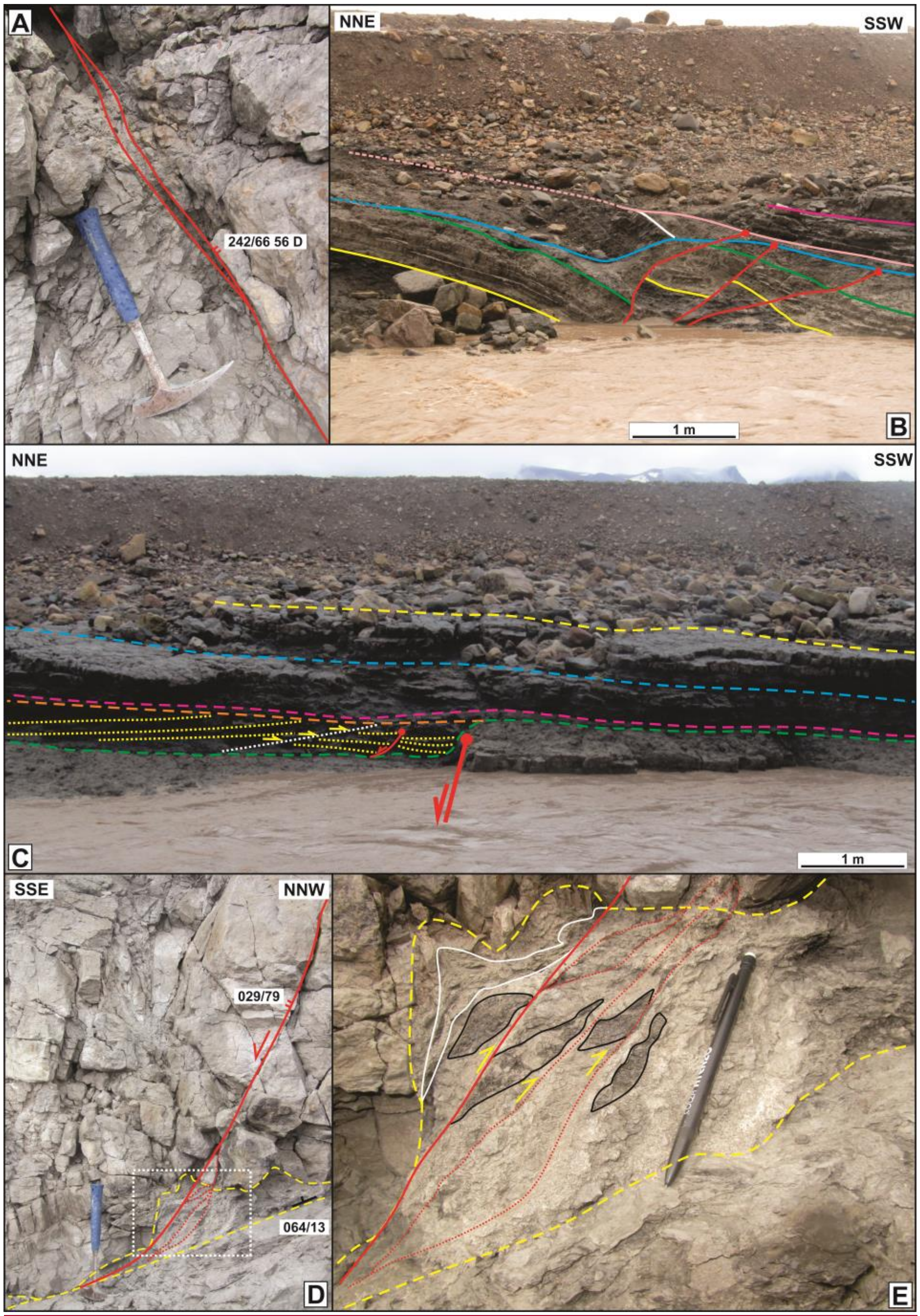
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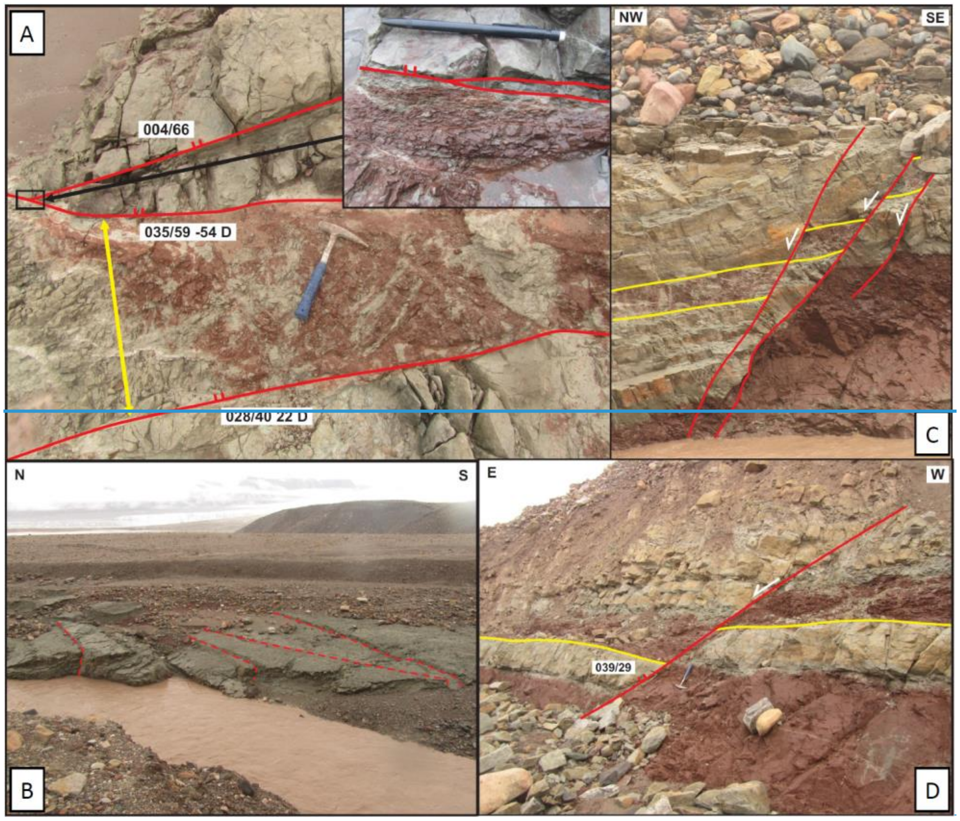
Figure 8: Outcrop photographs showing (a) centimeter–decimeter thick lenses of light-colored non-cohesive fault-rock gouge along a brittle fault truncating grey sandstones of the Billefjorden Group. Figure location in Figure 4Figure 4.; (b) NNE-dipping normal faults showing meter-scale down-NNE movement and potential growth strata (between the green and blue markers). The faults cross-cut sandstones and shales of the Billefjorden Group in which they die out upwards. See Figure 4Figure 4 for location. The outcrop width is approximately 5–6 m wide; (c) potential fault-growth strata made of dark sandstone (between the green and orange markers) in the hanging wall of a NNE-dipping brittle fault with decimeter–meter-scale normal displacement. The fault dies out upwards within sedimentary strata of the Billefjorden Group. The interpreted syn-tectonic growth strata is composed of two sedimentary packages, including a proximal sandy wedge thickening towards the fault, and a distal prograding to sheet-like sand rich body onlapping (divergent onlap; yellow arrows) the proximal wedge. The two packages are separated by an angular unconformity (dotted white line) and are both eroded upwards (orange dashed line). Yellow dotted lines represent intra-bed surfaces. Outcrop location in Figure 4Figure 4. The outcrop width is approximately 7–8 m wide; (d) Outcrop photograph showing a high-angle brittle normal fault (red line) in grey sandstone of the Billefjorden Group flattening and soling into a gently south-dipping shale-dominated bed (dashed yellow lines) displaying significant thickness variations. The dotted white frame shows the location of (e), and white boxes structural measurements (fault surface in red, and bedding surface in black). See Figure 4Figure 4 for outcrop location; (e) Zoomed in photograph showing thickening of the shale-dominated bed (dashed yellow lines) in the footwall of the flattening normal fault (red line), including fine-grained (meso- to ultra-) cataclasite and preserved fragments of coaly shale host-rock (black lines) seemingly offset in a reverse top-northwest fashion by small-scale faults that form a duplex-shaped structure (dashed red lines). In the hanging wall, the shale-dominated bed significantly thins and is preserved as a lens of partly squeezed shale (white line) and cataclasite. Location shown by a dotted white frame in (d).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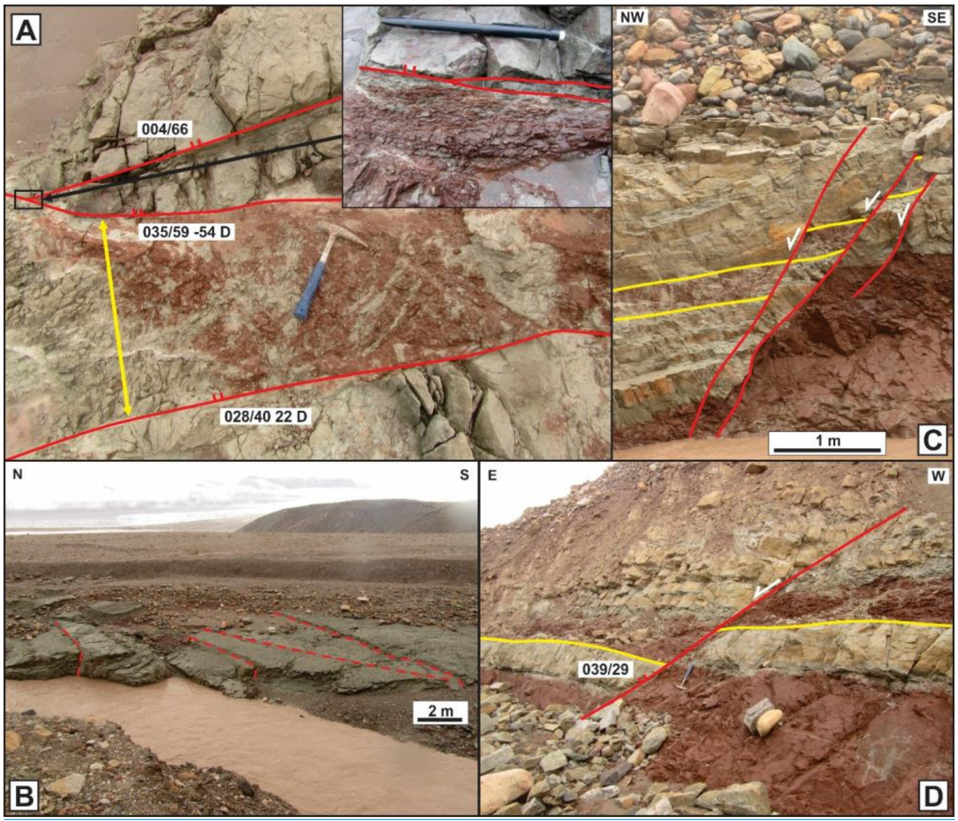
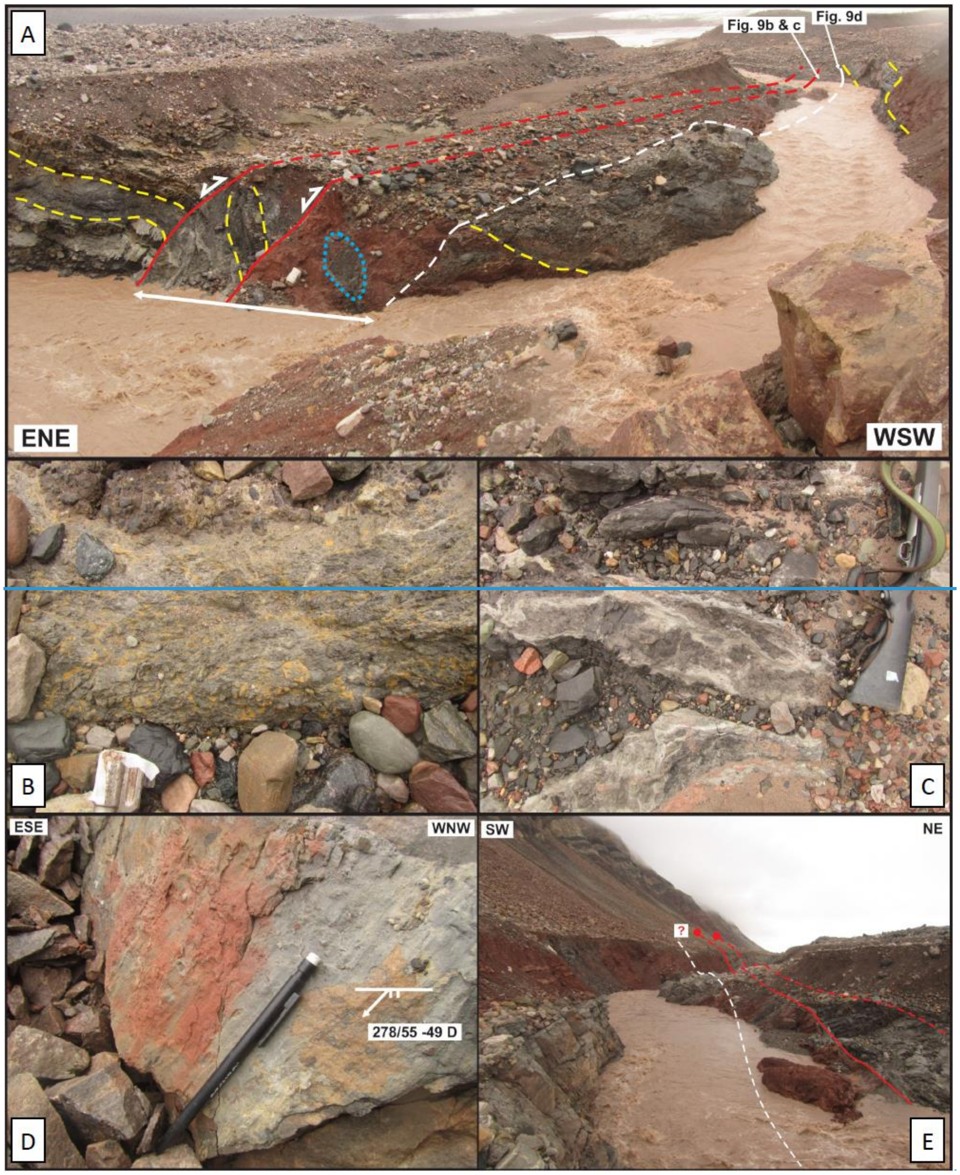


Figure 9: Outcrop photographs along the southern half of the riverbed (Figure 4~~Figure 4Figure 4~~) showing (a) meter-scale fault-core (yellow arrow) along a SW-dipping fault comprising light-colored and reddish~~ non-cohesive~~ fault-~~rock~~ gouge derived respectively from adjacent grey sandstone and red shales of the Hultberget Formation. The upper right inset shows shattered sedimentary rocks truncated by numerous sub-parallel brittle shears along the main fault surface; (b) decimeter-scale fault scarps related to decimeter– ~~to~~ meter-scale down-northwest and down-west normal movements along NE–SW- and N–S-striking brittle faults in the Hultberget Formation; (c) decimeter-scale down-NW normal offset (yellow lines) along a NE–SW-striking brittle fault cross-cutting red shale and grey sandstone of the Hultberget Formation; (d) meter-scale down-SE offset (yellow lines) along a low angle normal fault truncating the Hultberget Formation. Figure locations in Figure 4~~Figure 4~~.


A
Fig. 9b & c
Fig. 9d
ENE
WSW
B
C
ESE
WNW
278/55 -49 D
D
SW
NE
?
E

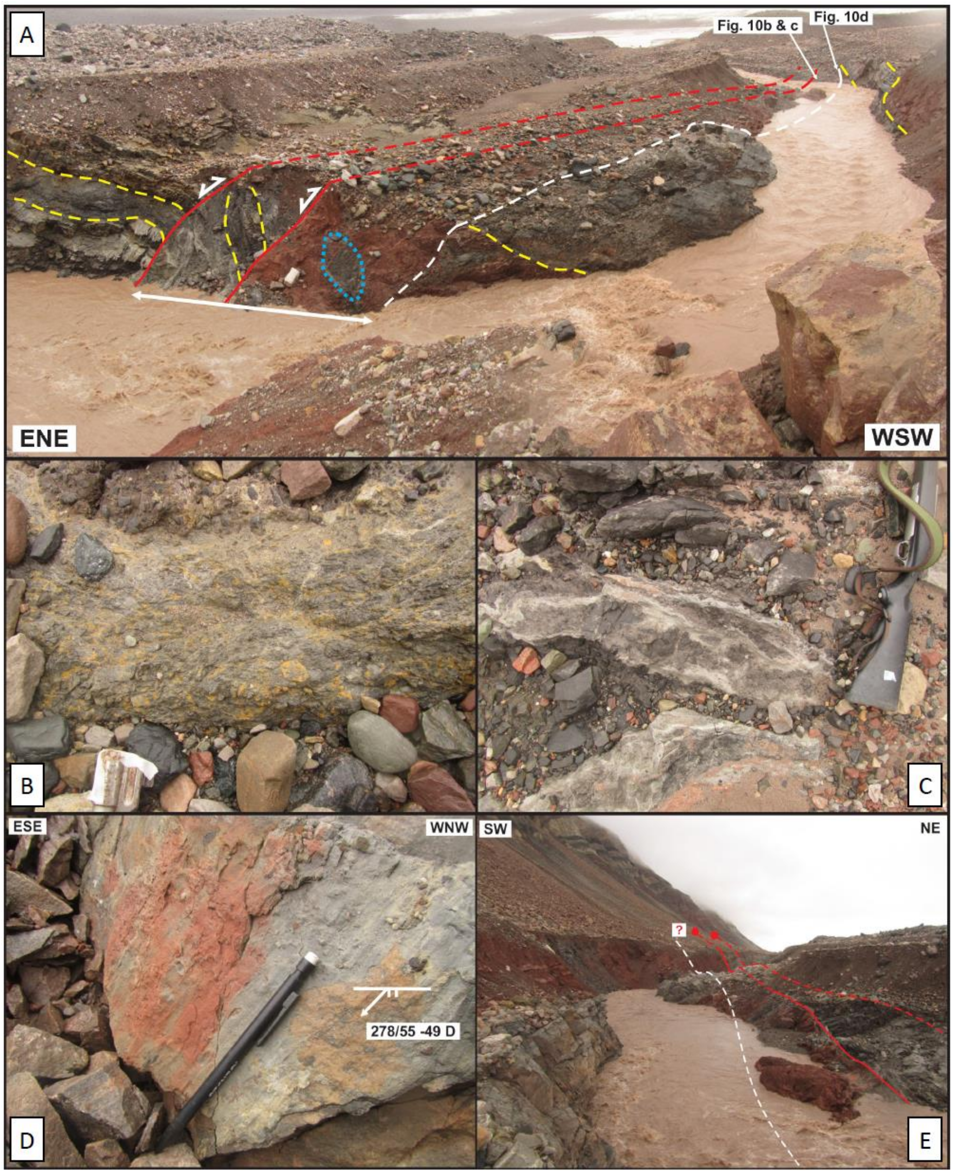
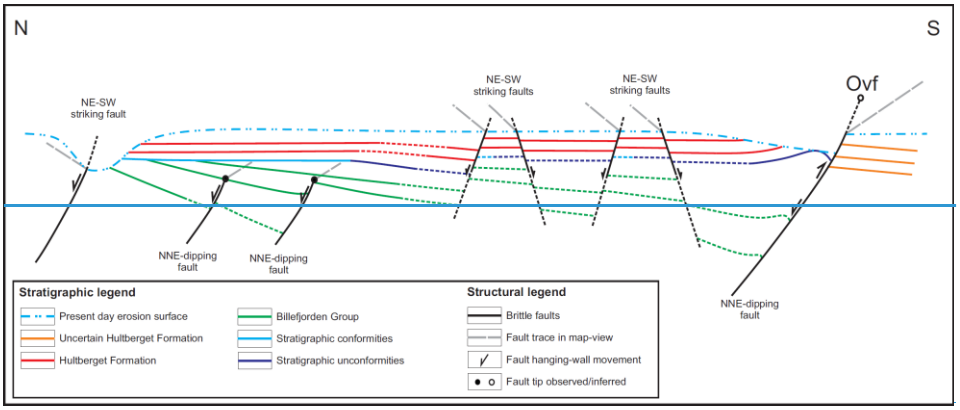


Figure 10: Outcrop photographs showing the geometryEastward view of the Overgangshytta fault in the southern portion of the study area. Figure locations in Figure 4Figure 4. (a) 2–3 meters wide core (sub-horizontal white arrow shows the width of the core, and dashed white lines) of the Overgangshytta fault (red) incorporating meter-size lenses of host-rock (dotted blue). Note the potential meter-scale reverse offset, possibly drag-fold in the hanging wall, and highly tilted (bedding in dashed yellow) character of coaly shales and grey sandstones of the Billefjorden Group across the fault; (b) decimeter-scale light-colored and (c)

approximately ~~ca.~~ 10 cm-wide yellowish lenses of ~~non-cohesive~~ fault-~~rock~~ gouge within the Overgangshytta fault core; (d) slickengrooves and asperities indicating normal dip-slip movement within the Overgangshytta fault core. See Figure 10~~Figure 10Figure 10~~a for location; (e) northwestward view of the Overgangshytta fault and adjacent cliff-outcrops made of sedimentary rocks of the Hultberget, Ebbadalen and Minkinfjellet formations suggesting that the fault dies out vertically and/or laterally. The fault core is limited by the dashed white and dashed red lines and is approximately 3 meters wide.



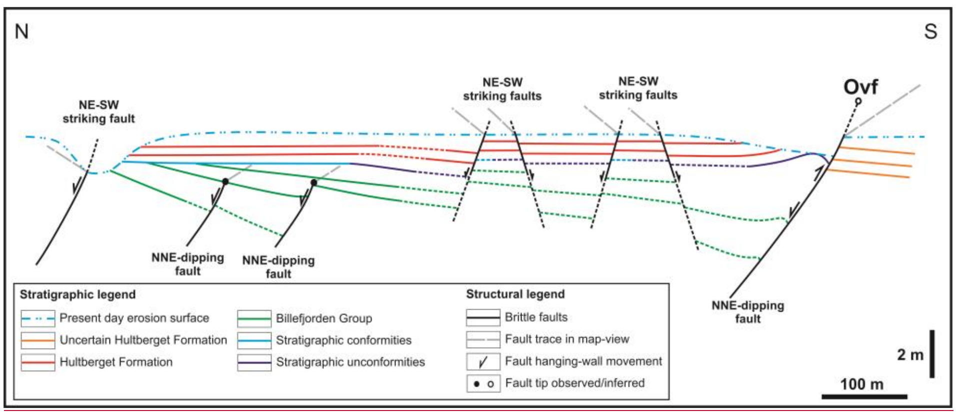


Figure 11: Approximately one km-long ~~S~~schematic N–S-oriented cross-section of the studied outcrops in Odellfjellet. The section summarizes observations made along the riverbed and includes upwards dying-out NNE-dipping normal faults with Mississippian growth strata, abundant N–S- and NE–SW-striking normal faults with decimeter–meter-scale offsets, and the Overgangshytta fault (Ovf), a potential Mississippian NNE-dipping normal fault formed along steep, inherited, basement-seated, Neoproterozoic fabrics. The anticline in the hanging wall of the Overgangshytta fault suggests that the fault was inverted as a thrust during Cenozoic transpression. Note the southward change from unconformity (light blue) to conformity (dark blue) between sedimentary strata of the Billefjorden Group and Hultberget Formation.