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Interactive comment on "Early Cenozoic Eurekan strain partitioning and decoupling in central Spitsbergen, Svalbard" *by* Jean-Baptiste P. Koehl

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Dear Dr. Phillips, thank you very much for your input on the manuscript, it is highly appreciated. Here is my reply to your comments. I hope the changes implemented improve the shortcomings of the manuscript highlighted by your comments and suggestions. Please do not hesitate to contact me shall this not be the case for some comments.

1. Comments from Dr. Phillips Comment 1: 1. The introduction is relatively narrow and the overall aims of the study are unclear. At present the introduction outlines that the study aims to achieve, but does not place these into the wider context. It should be made clearer at this point what are the rationale and key scientific questions to be

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Discussion paper

addressed in this study and how does this compare/contrast with previous studies in the area. Comment 2: In addition, it would be good to consider the wider implications of the study, separated from their local context, e.g. examining how deformation may be partitioned across coal-bearing intervals in rift systems generally as opposed to just in this locality. Comment 3: A further interesting aspect that could be expanded upon is the integration of seismic and field observations and the difference in scale between the two. A scale is required on Figure 3b. Comment 4: 2. The stratigraphy and nomenclature used throughout can be difficult to follow and to relate to the figures. A combination of formation names, groups and ages is used throughout the manuscript. I would recommend establishing these early in the manuscript by establishing a stratigraphic framework and including a stratigraphic column for the area as a figure. Comment 5: In addition, it would be worth increasing the annotation on the figures to enable greater cross-referencing between figures and text. This is especially important with regards to the ages of the different intervals on the seismic section and satellite images, and also to identify features when multiple sub-figures are called out simultaneously in the text. Comment 6: 3. Figures – there are currently only 5 figures in the manuscript which are heavily used and referred to in the text. It would be worth including more information on these figures with increased annotation or including new figures, such as the aforementioned stratigraphic column. Comment 7: In particular, it would be worth including some close-ups of the map based figures to show stratigraphic relationships (e.g. L203, 854). Comment 8: Additional figures such as 5e should be expanded and further explained on the figure itself. Comment 9: 4. The broader implications of the study should be explored in more detail. At present the Discussion focusses on a range of different theories regarding details of the evolution of Spitsbergen. Comparisons and the implications for similar rift systems should be drawn to emphasise the broader implications of this study – e.g. how does this compare to other rift systems where deformation is partitioned. Comment 10: 5. At present, the key points of the paper can be lost in the discussion section discussing the various models and competing ideas for the evolution of various aspects of Spitsbergen geology. This would be

made clearer by incorporating more figures related to these models and establishing the stratigraphic framework early in the paper with the aid of a stratigraphic column. Comment 11: However, the discussion still accounts for a large proportion of the overall paper and could be shortened to focus on the key aspects of the paper as outlined in the title and introduction of the paper and backed up by the data shown. Comment 12: The early points of the conclusions (1-4) are succinct and very interesting, however the latter points are less clear from the figures and do not contribute as much to the overall story. Comment 13: Technical comments Line 82 – When did the orogeny stop? Comment 14: Line 153 – Where is the Billefjorden Fault Zone located? And how does it relate to the Balliobreen Fault and the Odefjellet fault? This is not clear on Figure 1, where the fjord is labelled, but not the fault zone. Comment 15: Also, the text refers to Carboniferous deposits, but the figure to Pennsylvanian. A stratigraphic column would help greatly associated with this figure. Comment 16: L194 – Can you show some indication of the orientation on Figure 1a. It appears to be reflected in the orientation of the fjord and some landscape lineations but this is not clear from the text or figure. Comment 17: L203 – Unconformable relationship is not clear from the figure. Close up of the area would be beneficial. Is the Billefjorden fault zone present on the map? Comment 18: L211 – What is the purpose of the microscopic analyses, is this to confirm structural measurements? Comment 19: Figure 2 – Label the location of the mine entrance, along with other key features referred to in the text (e.g. the different groups and formations) Comment 20: L242 – change to 1-2 m. Comment 21: L244 – potentially change to > 3m. Comment 22: Figure 4 – Basement horizon not always interpreted on the subfigures Comment 23: Figure 4g – Label the well name on the section. Comment 24: Duplex interpretation is clear, but wedge-shaped geometries difficult to identify. Comment 25: Figure 4b,e – Z-shaped geometries not immediately clear on the figure. Label on the figure? Comment 26: L400 – difficult to tell what is being referred to. Comment 27: L557 – Very long sentence that is difficult to follow. Breakup to make clearer. Comment 28: L583 – Is this an example of where there is no decoupling interval present? If so this should be stated. Comment 29: L601 – State

explicitly how this model relates to your observations, is it in agreement? Comment 30: Figure 5 – More labelling is required on the figure, e.g. the collapsing orogen and exhuming core complexes are not present/clear on 5a. Comment 31: L813 – Exposure of the basement is also not shown on the figure?

2. Author's reply Comment 1: agreed. Comment 2: agreed. Comment 3: agreed. Comment 4: agreed. Comment 5: agreed. Comment 6: agreed. Comment 7: these field relationships are described in other studies and would require the addition of specific field photographs that do not add to the manuscript's discussion. Comment 8: partly agreed. The location of the schematics in figure 5e is shown in figure 5d. These schematics are to be directly compared with onshore field studies by other workers at these localities (e.g., Harland et al., 1974; Lamar et al., 1986; Lamar and Douglass, 1995). Comment 9: agreed. Comment 10: agreed. Comment 11: partly agreed. However, the present manuscript describes new structures along a major fault with long-lived tectonic history. Interpretation of these structures, inferring potential formation mechanism(s) and discussing their impact on the tectonic history of Spitsbergen (e.g., non-occurrence of the Ellesmerian Orogeny in central Spitsbergen) may have important implications for future studies and need to be discussed appropriately. In addition, major issues such as the along-strike variations in the geometry and kinematics of well-studied faults like the Billefjorden Fault Zone require extensive review and mention of previous works and uncertainties in order to reconcile all previous observations into a unified model. Comment 12: partly agreed. Point 5 of the discussion suggests that Ellesmerian tectonism is not necessary to explain differential deformation between folded Devonian strata of the Andrée Land Group and Mimerdalen Subgroup and poorly deformed Pennsylvanian–Permian strata of the Gipsdalen Group in central Spitsbergen. This is a crucial importance for future studies that will hopefully reexamine evidence of Ellesmerian tectonism throughout the Arctic and consider these with care. Point 6 is also quite important in that it highlights the large uncertainties surrounding the geometry of the most-studied fault zone in Svalbard, the Billefjorden Fault Zone. Points 5 and 6 of the conclusion therefore contribute to important ongoing

debates about key tectonic features of the archipelago. Comment 13: agreed. Comment 14: the Billefjorden Fault Zone consists of the Balliolbreen and Odellfjellet fault segments, both of which are labelled in figure 1b. Comment 15: agreed. Comment 16: these structures are located in western Spitsbergen, i.e., away from the study area. These are not the main targets of the manuscript and are therefore not necessary to add to figure 1. See include literature for structural maps of western Spitsbergen. Comment 17: agreed. To show such relationship, one would need to add a field photograph, which can be found in the study referred in the sentence (Harland et al., 1974). Reference to the figure is to show the location of Sentinelfjellet. Comment 18: microscopic analyses were used to confirm the absence of Proterozoic basement and the presence of Devonian quartzitic sandstone on both sides of the N–S-striking fault encountered in the field. The implications of these field relationships are further discussed in section 5.3. Comment 19: agreed. Comment 20: disagreed. Solid Earth standards require spelling of number from one to ten. Comment 21: see reply to comment 20. Comment 22: agreed. This is due to the high amounts of uncertainty as to what lies below sedimentary strata of the Billefjorden Group in places (especially in Sassenfjorden; figure 4a and d). Comment 23: the well name is included in the figure caption. Comment 24: agreed. Comment 25: agreed. Comment 26: agreed. Comment 27: agreed. Comment 28: no, it is not. At the Robertsonbreen locality, coals and coaly shales of the Billefjorden Group may also host a décollement as shown by bedding-parallel thrusts between the Billefjorden Group and Wordiekammen Formation (Dissmann and Grewing, 1997 their figure 6). Comment 29: agreed. Comment 30: the collapsing orogen and metamorphic core complexes were not located in Billefjorden but farther west and east from the area shown in figure 5a. This is not clearly stated in the manuscript. Comment 31: agreed. Exhumation did not necessarily occurred during Carboniferous normal faulting. It may also have occurred during Devonian normal faulting, and due to early Cenozoic thrusting and erosion.

3. Changes implemented Comment 1: replaced “ discusses the presence of “ by “has potential implications for strain partitioning in rift systems and distal parts of fold-and-

thrust belts. Notably, the study describes ” line 54. Added “, which were, thus far, not described” and “discusses “ line 57. Added “Hence, the study contributes to our understanding of deformation partitioning in fold-and-thrust belts consisting of thick sedimentary successions, and for the extent of the Ellesmerian Orogeny in the Arctic, which presumably extends from Arctic Canada and northern Greenland to Spitsbergen.” lines 84–87. Changed “Finally, the study has implication for the segmentation and linkage of rift-bounding fault with long-lived tectonic histories. Thus far, although segmentation of the Billefjorden Fault Zone was described (e.g., Bælum and Braathen, 2012), along-strike geometrical and kinematics variations along the Billefjorden Fault Zone have been poorly addressed and tentatively attributed to the complex tectonic history of this fault. The present study further discusses the significant along-strike variations in geometry and kinematics, the extent, and potential segmentation of the Billefjorden Fault Zone in conjunction with a new trend of NNE-dipping faults striking suborthogonal to the main N–S-trending structural grain in the study area. The role of these suborthogonal faults in Eurekan strain partitioning is briefly discussed.” into “Finally, the study has implication for the segmentation and linkage of rift-bounding fault with long-lived tectonic histories. Thus far, although segmentation of the Billefjorden Fault Zone was described (e.g., Bælum and Braathen, 2012), along-strike geometrical and kinematics variations along the Billefjorden Fault Zone have been poorly addressed and tentatively attributed to the complex tectonic history of this fault. The present study further discusses the significant along-strike variations in geometry and kinematics, the extent, and potential segmentation of the Billefjorden Fault Zone in conjunction with a new trend of NNE-dipping faults striking suborthogonal to the main N–S-trending structural grain in the study area. The role of these suborthogonal faults in Eurekan strain partitioning is briefly discussed.” lines 88–97. Comment 2: changed “discusses the presence of ” into “has potential implications for strain partitioning in rift systems and distal parts of fold-and-thrust belts. Notably, the study describes ” lines 53–54. Comment 3: added “The identification of structures showing comparable geometries and kinematics (e.g., bedding-parallel décollements) within discrete stratigraphic units (e.g.,

coals and coaly shales of the Billefjorden Group) both on nearshore seismic data and onshore during structural fieldwork further validates the use of seismic interpretation in areas where extensive (glacial) erosion resulted in partial destruction and covering of outcrop transects with loose material, and where large portions of the outcrops available for field mapping are hardly accessible for detailed inspection because located on steep slopes and cliffs. The study also illustrates the complementarity between fieldwork, which provide detailed lithological and structural data, and seismic transects providing continuous transects through deformation belts and fault zones." lines 61–69 and added a scale to figure 3b. Also added "See blue hammer (c. 40 cm) on the foreground and person (c. 1.75 m) in the background for scales." lines 1439–1440. Comment 4: a figure with a stratigraphic column was added (new figure 2). Comment 5: see replies to comments 19 and 25. Comment 6: see replies to comments 4 and 5. Comment 7: none. Comment 8: added boxes in figure 5d to show the location of the schematics in figure 5e and "The location of the schematics in (e) is shown as black frames in (d)." to the figure caption. Comment 9: see replies to comments 1–3. Comment 10: see replies to comments 4 and 5. Comment 11: deleted "Based on field data in Pyramiden and seismic data in Sassenfjorden and Reindalspasset, and on previous work (Harland et al., 1974; Lamar et al., 1982, 1986; McCann, 1993; Lamar and Douglass, 1995), " lines 786–788. Comment 12: none. Comment 13: added "late Cambrian–Silurian " lines 101–102. Comment 14: none. Comment 15: see reply to comment 4. Comment 16: none. Comment 17: added "see location in " line 222. Comment 18: none. Comment 19: added labels of Andrée Land, Billefjorden, and Gipsdalen groups and of mine entrance in figure 2. Comment 20: none. Comment 21: none. Comment 22: none. Comment 23: none. Comment 24: replaced "wedge-shaped" by "sigmoid-shaped" lines 437, 438, 441, and 533. Comment 25: added labels "Z-shaped reflections" in figure 4b and e. Comment 26: added " within the Gipshuken Formation" line 427. Comment 27: replaced ", thus explaining " by ". This would explain " line 560, ", " by ". These contractional duplexes " lines 562–563, "decoupling" by "decoupled" line 563, and "shielding" by "shielded" line 565. Comment 28: none. Com-

ment 29: added “All these earlier models and observations are in agreement with the model of strain partitioning and decoupling along bedding-parallel décollements and thrusts proposed by the present study in Pyramiden.” Lines 634–636. Comment 30: added “in the west and east” line 812. Comment 31: added “or kept “ and “relatively close to the surface “ line 844.

Additional revisions by the author of the present manuscript -Added reference to new stratigraphic chart figure lines 124, 128, 178, 182, 195, 199, 252, 266, 273, 349, 357, and 365. -Changed “are” by “were” line 559. -Changed “Koehl et al. submitted” into “Koehl et al., 2020” lines 607, 610, 738, and 929. -Changed “suggest” into “suggests” line 804. -Corrected “province” into “provenance” line 871. -Replaced “-“ by “ “ line 1449.

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