Reply to Hamed Fazlikhani

Dear Dr. Fazlikhani,

thank you very much for your input on the manuscript, it is highly appreciated. Here is our reply 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. Comments from Dr. Fazlikhani

Comment 1: This an interesting manuscript proposing an alternative model for the accretion of western Barents Sea and Svalbard. As a non-specialist in Timanian orogeny nor in Svalbard/Artic geology, I found it very challenging in comparing existing models, but well worth being published in Solid Earth. Hence, my comments are mainly regarding the methods used and presented observations/interpretations. This study is based on the geophysical methods, that are the interpretation of seismic reflection profiles, total gravity and magnetic field anomalies.

Comment 2: The study area records a very complex geology with several deformation phases (four compressional and two extensional) took place that are overprinting each other as it is stated by the authors.

Comment 3: In addition, the study area is located in the offshore with only three wells presented. Therefore, this study greatly relies on the geophysical methods. In such a case and in order to increase the accuracy of the presented interpretation I would start by carefully characterizing (as much as available data and previous studies allows) geophysical signature (here magnetic, gravity and seismic reflection) of the known Timanian structures onshore/close to the shore.

Comment 4: In this setting, Trollfjorden-Komagelva Fault Zone (TKFZ) as a well-known Timanian structure onshore northern Norway could be the best candidate as the geophysical onshore-offshore data in northern Norway are fairly accessible. It would be very interesting and helpful if authors quantify geophysical character of the TKFZ, its spatial relationship to the overprinting Caledonian and younger events and describe how this structure extends to the offshore then use that as an analogue for the study area.

Comment 5: In potential filed data one would try to used different filtering techniques and attributes in order to separate deeper (presumably older) structures form the shallower (younger) structures and then study spatial development of the interested structures. Without an attempt to separate relative depth of causative bodies observed in potential filed data it is very hard to identify structures related to different tectonic events. I am not sure if we can simply interpret all E-W striking anomalies observed on total magnetic field and gravity data as Timanian and all N-S to NNE-SSW as Caledonian.

Comment 6: I do agree and acknowledge that the main trends can be identified in gravity and magnetic data, but author should also consider and discuss alternative interpretations for observed trends, especially considering spatial geometry of structures over several hundreds of kilometers. In the next step, observations from the potential field data can be compared with the seismic reflection data.

Comment 7: As it is mentioned by the authors, e.g. Barrère et al. 2009, Gernigon et al. 2014 & 2018, and the ATLAS, Geological History of the Barents Sea (Geological survey of Norway, 2009, not cited by the authors) have done such a methodology in different parts of the Barents Sea concluding that post-Timanian events (mainly Caledonian) overprinting the Timanian structures and continuation of Timanian structures is only identified in northern Norway (TKFZ).

Comment 8: I understand that above mentioned studies might have not been aiming for mapping the westward extension of the Timanian structures, but I think it would be of interest if authors consider discussing similarities and differences between potential filed data interpretation in this study and previous ones.

Comment 9: Another major Timanian structure identified in Novaya Zemlya Island is the Baidaratsky Fault Zone (BaFZ, shown in Figs. 1 and 5). BaFZ is mapped onshore Novaya Zemlya as awide (ca. 30 km) fault zone (e.g. Lopatin et al., 2001; Korago et al., 2004). Korago 2004 in their Fig. 8 show a NW continuation of BaFZ (dashed line) and state that "presumably" BaFZ continues NW into the eastern Barents Sea. While Lopatin et al. 2001 also did not studied western offshore Novaya Zemlya and only show the location of BaFZ onshore. Therefore, based on Lopatin et al., 2001 and Korago et al., 2004 it is really difficult to conclude any NW extension of BaFZ into the eastern Barents Sea.

Comment 10: I understand that accessing geophysical data in eastern Barents Sea is challenging, however, some across border studies (e.g. ATLAS, Geological History of the Barents Sea, 2009, Geological Survey of Norway) are available and could be used in gravity and magnetic analysis and interpretations.

Comment 11: Looking at filtered magnetic and gravity and presented derivatives presented in their Chapter 2 (IMAGING DEEP STRUCTURES BENEATH THE SURFACE) I can recognize E-W to ENE-WSW oriented structures onshore and offshore south of Novaya Zemlya Island extending SE into the Russian main land (Pechora Basin?).

Comment 12: Farther west from Novaya Zemlya and into the central Barents Sea main structures are N-S striking. Based on above, I have difficulties tracing BaFZ all the way into the western Barents Sea and link it to the E-W structures south of Olga Basin shown in Fig.1b. I do agree that in the western Barents Sea there are structures orienting E-W and ENE-WSW, but also there are N-S and NE-SW structures. It would be very helpful if authors could explain such a complexity in the western Barents Sea and westward extension of BaFZ specially across the areas with very strong N-S orienting magnetic and gravity signature.

Comment 13: I would assume that westward extension of identified thrust zones into the onshore Svalbard is based on the gravity and magnetic data.

Comment 14: Looking at Fig.5, onshore Svalbard is at the edge of the dataset and it is not really possible to see any trends, while filtered magnetic and gravity maps shown in the ATLAS, Geological History of the Barents Sea, 2009 covers the entire Svalbard and its western offshore, showing N-S trends being very pronounced. I would suggest authors compare their observations with above mentioned reference and discuss potential differences and similarities observed.

Comment 15: Also, as Fig. 1b shows there are seismic profiles available on the western offshore Svalbard, do those seismic profiles have also been studied? Do they show extension of identified thrust zones across Svalbard? Sine authors argue that Timanian structures onshore Svalbard are unnoticed because of the remoteness of the area and the strongly eroded character of the area, showing the extension of Timanian structures west of Svalbard could provide an additional proof for the presence of Timanian structures across the Svalbard.

Comment 16: I assume that the shown seismic reflection profiles are the best examples from many other studied and interpreted profiles. However, the quality of presented profiles really does not allow readers to attempt interpreting profiles, even higher quality version of seismic profiles made available by authors did not help.

Comment 17: I would suggest authors to use higher quality and less noisy profiles (if available), in the shown profiles I can see some intra-basement trends, but I also can add in much more patterns. As an example, along the profile shown in Fig.3b lost of patterns are not interpreted in the center of the profile, what would those reflections represent?

Comment 18: In addition, confirming thrust zones dip direction (since dip directions mentioned in the text are apparent dip) it would be much more convincing if author show at least one profile parallel to 3a and 3c farther east as fig.1b shows that are more profiles available east of 3a and 3c.

Comment 19: As profile 3b is semi-perpendicular to main Caledonian N-S trend, it would be very interesting if authors consider interpreting Caledonian structures along profile 3b and show/discuss the spatial relationship between Timanian and Caledonian structures.

Comment 20: Authors claim that that thicker Precambrian basement rocks shows higher Bouguer anomaly values (lines 532-535) and take this as an evidence for the thrusting causing thickening of basement rock into the footwall of thrust faults. Looking at profile 3a, the southern parts of the profile shows thickest Devonian-Permian sedimentary rocks and thinner Precambrian basement rocks. Such a configuration should be reflected as low Bouguer anomaly (thick sedimentary rocks) while shown gravity anomaly profile in the lower panel show high gravity values. On the opposite end of the same profile (Fig. 3a) where the Precambrian units are thicker gravity anomaly profile shows very low values. Same inconsistency also appears along profiles 3b (in the center) and 3c (to the north). This is confusing, please consider clarifying.

Comment 21: Closest well utilized for well-seismic tie in the study is the well Hopen-2 which is located 40-45 km north of profile shown in Fig. 3b. According to Harald and Kelly 1997 and Anell et al. 2014 well Hopen-2 is drilled into Late Carboniferous sedimentary rocks and the top basement is not reached.

Comment 22: Please consider briefly explaining how boundaries between Precambrian, Cambrian-Silurian, Devonian-Mississippian and Devonian-Permian are identified and interpreted.

Comment 23: In the proposed model shown in Fig. 7, I am wondering when a several km thick shear/thrust zone inherited form the Timanian event exist (Fig. 7a) why such a structure is not simply reactivated as strike-slip fault/shear zone and instead it is folded and cross-cut by Caledonian structures? Could authors back up this model with natural cases or modeling studies? A discussion elaborating this would be of interest.

Comment 24: In general, this is a well-written article presenting geophysical evidence for and further highlighting existing models proposing westward extension of Timanian structures across the Barents Sea. The study also discusses pre-Caledonian plate tectonics implications of such a configuration that it might be of great interest for Solid Earth readers. I believe the paper is very interesting and can be published after addressing my comments. I would be happy to further discuss my comments and look forward to seeing this manuscript being published.

2. Author's reply

Comment 1: agreed.

Comment 2: agreed, though it is now becoming clear that one of the contractional events, the Ellesmerian Orogeny, never occurred in Svalbard and the Barents Sea (e.g., Koehl, 2021).

Comment 3: agreed. However, the present manuscript is the first account of the seismic character of Timanian faults next to the shore of Svalbard. Timanian magnetic and gravimetric anomalies in the northern Norwegian Barents Sea were first described in Klitzke et al. (2019). In northern Norway/northwestern Russia, the Trollfjorden–Komagelva Fault Zone/Central Timan Fault (i.e., the Timanian front thrust) and related anticlines on the Varanger Peninsula (e.g., dome-shaped Ragnarok Anticline; Siedlecka and Siedlecki, 1971) and in Russia (e.g., WNW–ESE-trending Mikulkin Antiform on the Kanin Peninsula; Lorenz et al., 2004; see also their figures 5 and 6) are, as shown in figure 5 in the present manuscript, characterized by positive WNW–ESE-trending magnetic and gravimetric anomalies that can be traced from Varanger Peninsula in northeasternmost Norway to the Kanin Peninsula in northwestern Russia. The magnetic anomaly related to the Trollfjorden–Komagelva Fault Zone in northeastern Norway is also shown in Nasuti et al. (2015) and Koehl et al. (2019). In addition, ongoing work suggest that the Sørøya–Ingøya shear zone, a presumed Caledonian thrust first described in Koehl et al. (2018), actually represents the folded continuation of the Trollfjorden–Komagelva Fault Zone, which was folded and partly reactivated as a thrust during the Caledonian Orogeny (Koehl, in prep.). Thus, one may view the geometry of the Sørøya–Ingøya shear zone on seismic data in Koehl et al. (2018) as an analog to Timanian thrust systems in the northern Barents Sea. In northwestern Russia, the seismic character of major Timanian thrusts is shown in various studies, including notably Kostyuchenko et al. (2006, their figure 17 notably). However, studies onshore northwestern Russia and northeasternmost Norway are still far away from the northern Norwegian Barents Sea. Thus, the authors of the present manuscript feel that it is more appropriate to describe the structures they identified first, and to compare them with known examples of Timanian faults in adjacent areas in the discussion. Noteworthy, the correlation of Kostyuchenko et al. (2006) of magnetic data and Timanian structures is unambiguous: “The drillholes into the basement beneath the Pechora Basin […] demonstrated that the very strong magnetic anomalies of the Pechora Zone outlined by the 'Pre-Pechora' Faults (shown in Figs 11 and 18) coincided with a belt of volcanic and volcano-sedimentary rocks with major gabbro-diorite intrusions and granites”, i.e., that WNW–ESE-trending magnetic anomalies in northwestern Russia can be directly correlated to volcanic belts bounded by Timanian faults (see also their figures 2, 3 and 18). Their correlation of Timanian structures with gravimetric anomalies is also unambiguous: “The grade of metamorphism correlates well with the gravity data. Thus, strong positive gravity anomalies occur over the Kanin Peninsula [where the Mikulkin Antiform of Lorenz et al. (2004) occurs], whereas much less positive anomalies cover the general area of the Timan Range”, and they easily correlated thickened dense basement with high metamorphic grade to positive gravimetric anomalies. The authors of the present manuscript concede that these correlation onshore northwestern Russia could be further specified in the manuscript.

<u>Comment 4:</u> see response to comment 3. The western continuation of the Trollfjorden-Komagelva Fault Zone has been extensively debated in the past few years. Initially the fault was thought to proceed in a rectilinear fashion offshore (Gabrielsen and Færseth, 1989; Gabrielsen et al., 1990; Roberts et al., 2011). However, recent studies of this fault complex on 2D and 3D seismic data (Koehl et al., 2018), magnetic data and fieldwork (Koehl et al., 2019) suggest that it is not the case. Notably, there is no fault on 3D seismic data in the footwall of the Måsøy Fault Complex where the Trollfjorden–Komagelva Fault Zone is believe to proceed offshore (Koehl et al., 2018 their figure 8). This fault is now believe to be folded and to continue as a NE–SW-trending thrust system (Koehl, in pre.; see Sørøya–Ingøya shear zone in Koehl et al., 2018). The magnetic signature of the fault is described in Nasuti et al. (2015) and Koehl et al. (2019) and correlates with positive magnetic anomalies related to Mississippian dolerite dykes intruded along WNN–ESE-striking segments of the fault complex (Roberts et al., 1991; Lippard and Prestvik, 1997). The gravimetric character of the fault is still unclear (essentially not discussed in existing literature), but based on the new correlation of the Trollfjorden–Komagelva Fault Zone with its folded continuation offshore to the west (Sørøya–Ingøya shear zone of Koehl et al., 2018), the fault correlated with a

positive gravimetric anomaly that bends in the same way as the fault in the west offshore (Skilbrei et al., 2000). However, since this work is still being written into a manuscript, it does not sound natural to include it in the present manuscript. The spatial interaction of the Trollfjorden–Komagelva Fault Zone with Caledonian structures is illustrated by the dome-shaped geometry of the Ragnarokk Anticline of Siedlecka and Siedlecki (1971) on the Varanger Peninsula (refolding of a Timanian, thrust-related anticline during the Caledonian Orogeny; see present manuscript lines 807–810 and 843–847).

Comment 5: disagreed. Timanian faults formed in the latest Neoproterozoic and are several kilometers (to several tens of kilometers thick; see seismic sections in figure 3). Later on, these faults controlled the formation of new faults and folds during the entire Phanerozoic. The same (Timanian and Caledonian) trends are therefore to be found at depths shallower than Top-basement (post-orogenic and future rift basins controlled by existing basement grains). Separating all depths in the magnetic and gravimetric datasets would imply assuming that each tectonic event affected only one layer of the crust and none of the underlying nor overlying layers. It is by disentangling the whole dataset (all levels of the crust influenced by Timanian structures) that one may resolve the issues approached by the present manuscript. It is not the aim of the authors of the present manuscript to interpret all (overall) WNW–ESE-trending magnetic and gravimetric anomalies as Timanian and all N–S- to NE–SW-trending anomalies as Caledonian, but as anomalies composed of Timanian structures and all younger superimposed structures that localized along these existing Timanian structures (Caledonian reactivation, late Paleozoic extensional basins, possibly Mesozoic basins, early Cenozoic basins and inversion, and possibly in the west late Cenozoic rift basins) and that, therefore, formed with the same trend. The sum of all these superimposed structures developed along the dominant two structural trends (Timanian and Caledonian) is believed to have further anchored the two structural trends in the crust, which therefore shows very nicely on potential field data at present.

Comment 6: the only structures with WNW–ESE strikes in northeasternmost Norway and northwestern Russia are all related to the Timanian Orogeny and to reactivation/overprinting of Timanian structures.

Comment 7: agreed. It is appropriate to add the Geological Atlas of the Barents Sea to the present manuscript's reference list. Importantly, the NE–SW-trending seismic profile in the Russian Barents Sea (profile C–D, pp. 53 in Smelror et al., 2009; location of the profile shown pp. 43) clearly shows the Baidaratsky Fault Zone in the central part with a similar configuration as in figure 3d in the present manuscript, i.e., a major, low-angle basement-seated fault inverted as a listric normal fault that localized the deposition of a Paleozoic basin. However, it is incorrect that the Timanian trend was identified exclusively in northern Norway. Recent work off the coasts of Finnmark now clearly show that Timanian grain is present in the crust of the southeastern Norwegian Barents Sea too and had a tremendous impact on subsequent tectonic events by controlling the formation of subsequent fault and basins (Hassaan et al., 2020a, 2020b, 2021; Hassaan, 2021).

Comment 8: agreed. This is done lines 766–768, 817–821, and 1072–1078 for the Marello et al (2010) and Barrère et al. (2011) studies, and lines 606–610, 720–730, and 784–790 for the Gernigon and Brönner (2012) and Gernigon et al. (2014) studies. Notably, lines 817–821: "Furthermore, Barrère et al. (2011) suggested that basins and faults in the southern Norwegian Barents Sea are controlled by the interaction of Caledonian and Timanian structural grain, and Marello et al. (2010) argued that elbow-shaped magnetic anomalies reflect the interaction of Caledonian and Timanian structural grains in the Barents Sea, potentially as far west as the Loppa High and the Bjørnøya Basin", the authors of the present manuscript discuss the geometry of magnetic and gravimetric anomalies in the perspective of the reworking of Timanian grain during the Caledonian Orogeny, which was also previously inferred by previous studies in the southern and central Norwegian Barents Sea, i.e., similar findings. The main difference with previous studies is that the present study goes further because the present manuscript includes interpreted seismic sections in the northern Barents Sea and onshore–nearshore Svalbard with well tie showing clear thrust fault geometries (Figure 3).

Comment 9: disagreed. Lopatin et al. (2001) present their interpretation of a nearby offshore seismic profile in their figure 1 (figure caption: "Geological section after offshore seismic profiling"). They also mention in their abstract that their data include "seismic profiling". Thus, they did investigate the western continuation of the Baidaratsky fault zone west of Novaya Zemlya with data available to them. The Lopatin et al. (2001) is then cited by Korago et al. (2004) to be the study that has produced the work on seismic data to map the Baidaratsky Fault Zone in the Russian Barents Sea, although the short Lopatin et al. (2001) article only shows the extent of the fault onshore and nearshore: "The Baidaratsky fault zone is expressed by a series of strike-slip faults, which can be seen on the seismic records in the Barents Sea (Lopatin *et al.* 2001)" (second paragraph after the abstract in Korago et al., 2004).

Comment 10: agreed. It is not possible to access data covering Russian territory outside Russia. We also agree that the Smelror et al. (2009; Geological Atlas of the Barents Sea) should be cited in the present manuscript in referred to in the text when discussing our interpretation. See also response to comment 7.

Comment 11: agreed.

Comment 12: agreed. The "complexity" mentioned by Dr. Fazlikhani is part of the issue raised and discussed by the present manuscript. The magnetic signature of the Baidaratsky Fault Zone locally disappears in the central Russian Barents Sea because this portion of the Barents Sea was mildly deformed into large synclines during Caledonian contraction because located away from the collision front, i.e., magnetic signal of Timanian faults pushed down and more difficult to trace at the location of major Caledonian synclines (this will be added to the discussion). In the west, i.e., closer to the Caledonian collision front, Timanian faults were extensively reworked, but not to the point of not being able to identify them as seen on seismic data (Figure 3 in the present manuscript). The present manuscript further highlights that Timanian faults are being reactivated/overprinted gradually less and less in the plate interior as shown by the ongoing reactivation of Timanian grain in the Fram Strait and Storfjorden (offset of seafloor in present manuscript Figure 3, and Koehl et al., 2021), whereas Timanian faults below the Olga Basin and in the central Barents Sea were last active in the late Paleozoic (Figure 3d and Smelror et al., 2009 their profile C–D pp. 53).

Comment 13: the prolongation of the WNW–ESE-striking thrust systems into eastern and central Spitsbergen is also based on seismic interpretation (see Koehl, 2021 and supplements S2c and S2d of the present manuscript).

Comment 14: the authors of the present manuscript have already interpreted magnetic and gravimetric data over the whole Svalbard Archipelago (see EGU Keynote by Koehl, 2020), which show clear evidences of continuation of Timanian grain across Svalbard (see for example slide 129 in Koehl, 2020). However, as mentioned in the present study and in our response to various comments, the structural setting along the western Barents Sea and western Spitsbergen margin is slightly more complicated because they are located adjacent to paleo-plate boundaries during the Caledonian Orogeny and Eurekan tectonic event, both of which reworked Timanian structures more than their counterparts farther east (e.g., from central–eastern Spitsbergen where Timanian faults become relatively easy to trace and correlate). Thus, we consider that it is necessary to discuss the interpretation of magnetic and gravimetric data over Spitsbergen in a separate manuscript. This manuscript will also include bathymetric data around the Svalbard Archipelago and data from previous field campaigns, which do not fit in the present study and therefore warrant a separate manuscript. The following paragraph is a glimpse at the content of the hereby referred manuscript that is currently under writing.

Gravimetric data over Svalbard (see Figure 1 attached below) show a major change in gravimetric signal between northern and southern Svalbard exactly at the location of the mapped continuation of the Kongsfjorden–Cowanodden fault zone (high gravimetric anomalies in the north and low in the south). Notably, the low gravimetric anomaly correlated to the Central Tertiary Basin (Eurekan foreland basin) appears to continue across the Kongsfjorden–Cowanodden fault zone but with a significantly reduced width (dotted white lines). Since there are no Cenozoic sedimentary rocks equivalent to those of the Central Tertiary Basin in northwestern Spitsbergen (north of Kongsfjorden), we conclude that the anomaly is partly reflecting basement grain and that this grain (most likely a major N–S- to NNW–SSE-trending syncline) matches the geometry of the Central Tertiary Basin. The abrupt decrease in width of the major syncline suggests that it is offset in a top-SSW reverse manner and, thus, that the Kongsfjorden–Cowanodden fault zone continues all the way to western Spitsbergen. Moreover, tilt-derivative of magnetic data over Spitsbergen clearly show that N–S-trending anomalies are laterally offset by E–W- to NW–SE-trending lineaments (Koehl, 2020 pp. 129).

Comment 15: authors of the present manuscript have interpreted the whole seismic database around Svalbard and found evidences supporting the continuation of WNW–ESE-striking Timanian thrust across the whole archipelago and even some continental fragments with Timanian shear zones in the Fram Strait (e.g., Koehl, 2020 pp. 162–165). Also see response to comment 14 and Figure 1 attached below. Again, these will be published in a separate manuscript in order to adequately address their implications for the opening of the Fram Strait and ongoing processes such as earthquake cycles and methane seepage.

Comment 16: the authors of the present manuscript have provided high-resolution versions of the figures at DataverseNO: dataverse.no/dataset.xhtml?persistentId=doi:10.18710/CE8RQH). Notably, figure 3a, b and c are several hundreds of megabytes each and one may easily zoom in individual structures.

<u>Comment 17:</u> agreed. The authors of the present manuscript did not interpret every single structure on the seismic sections because there is simply not enough time to interpret them all. The interpreted structures displayed in Figure 3 in the present manuscript took overall three years to interpret. In addition, two years were necessary to interpret the whole dataset prior to making detailed interpretations as those shown in Figure 3 in the present manuscript. It is of course always possible to add to one's interpretation, but the authors of the present manuscript are confident that the presented structures are sufficient to support the argumentation and the conclusions detailed in the present manuscript. A lot of the reflections in the center of profile 3b represent N–S-trending, hundreds of meters wide Caledonian folds. It was however not possible to interpret them all due to time constraints. Interpreting them all would also be irrelevant if their interpretation does not add to the manuscript.

<u>Comment 18:</u> The present manuscript already includes such a N–S-trending seismic profile east of profiles 3a and 3c. The profile is shown in Figure 3d. We also note that all data are from the DISKOS database and are publicly accessible via contacting the Norwegian Petroleum Directorate.

<u>Comment 19:</u> agreed. These structures are described lines 365–382 and 414–442 and discussed lines 783–821, and 825–895 in the present manuscript. Caledonian structures are indeed interpreted in figure 3b and corresponds to the N–S-trending folds in lower Paleozoic basins and underlying basement.

<u>Comment 20:</u> agreed. It is the thickening of the denser portion of basement rocks (i.e., those with higher metamorphic grade, e.g., mylonites) that is thought to be responsible for the high gravimetric anomalies (see also clear correlation of high-grade Timanian metamorphic rocks with WNW–ESE-trending Bouguer anomalies in Kostyuchenko et al., 2006). This was clarified in the present manuscript following the response to comment 3. It is true that, in that specific instance (southernmost portion of profile 3a), the gravimetric anomaly further increases south of the thrust. The authors of the present manuscript do not argue that Timanian faults are the only features that may contribute to positive gravimetric anomalies in the Barents Sea. However, one may observe that the general correlation established between high-grade metamorphic rocks within Timanian thrust and positive gravimetric anomalies by the present manuscript is generally respected throughout the Barents Sea (Figure 3 in the present manuscript, Lorenz et al., 2004 and Kostyuchenko et al., 2006). Notably, the Kinnhøgda–Daudbjørnpynten fault zone correlates with a positive gravimetric anomaly (Figure 3a) even though another positive anomaly is found south

of the fault. Timanian faults are therefore major contributors to elevated Bouguer anomalies in the Barents Sea, but other features may, in places, also influence gravimetric anomalies (e.g., Caledonian folds and thrusts; Figure 5a).

Comment 21: agreed.

Comment 22: agreed. The boundaries between Devonian–Permian and Mesozoic sedimentary successions were tied to the three exploration wells mentioned in the present study for offshore parts of the study area. The boundary between Devonian–Mississippian and Pennsylvanian–Permian units onshore Svalbard are interpreted as a major unconformity truncating Devonian–Mississippian dykes (see Figure 3e). The boundary between Precambrian, lower Paleozoic and upper Paleozoic offshore are major unconformities that truncate underlying reflections and fold structures (e.g., Figure 3a, b and c).

Comment 23: agreed. The Timanian thrusts presented were oriented sub-orthogonal (c. 70 degrees) to the E–W principal stress during the Caledonian Orogeny in Svalbard. Thus one would expect that they were reactivated as strike-slip faults, which they partly did in repeated occasions, such as during the Caledonian Orogeny (e.g., Majka et al., 2008; Mazur et al., 2009; Faehnrich et al., 2020) and post-Caledonian Devonian collapse (e.g., Ziemniak et al., 2020). However, a reactivation simply and solely as strike-slip faults is not likely as the Timanian thrusts are low-angle faults and are therefore more prone to accommodating vertical movements. Hence, Caledonian E–W contraction produced more easily N–S-trending folds (vertical uplift and folding of rocks not hampered by any rocks upwards), which extended almost all the way to Novaya Zemlya (Figure 5), whereas partial strike-slip reactivation was restricted to areas proximal to the Caledonian collision front (e.g., western Spitsbergen; Majka et al., 2008; Mazur et al., 2009; Faehnrich et al., 2020; Ziemniak et al., 2020) because lateral transport of rocks from the Caledonian collision front towards the inner portions of the Barents Sea in the east was hampered by rock units constituting the crust of the Barents Sea, northern Norway, northwestern Russia and other adjacent areas. Therefore, despite a partial reactivation as strike-slip faults, these faults were also folded and locally overprinted by N–S-striking thrusts (e.g., in Nordmannsfonna; Figure 3e–f). This is what is illustrated in Figure 7 and it should be better explained in the discussion chapter in the present manuscript.

Comment 24: agreed.

3. Changes implemented

Comment 1: none recommended by the referee's comment.

Comment 2: none recommended by the referee's comment.

Comment 3: specified in the "Methods and datasets" section "bounding magmatic complexes and/or intruded by magmatic bodies" lines 243–244, and added reference to the work by Kostyuchenko et al. (2006) line 245. Added to the Introduction chapter reference to the Mikulkin Antiform on the Kanin Peninsula of Lorenz et al. (2004) lines 90–91 ("– and related Mikulkin Antiform"), line 125 ("(and associated thrust anticline, the Mikulkin Antiform)"), lines 241–242 ("(e.g., Mikulkin Antiform; Lorenz et al., 2004)"), lines 548–549 ("and associated Mikulkin Antiform"), and reference to Lorenz et al. (2004) lines 91, 126, 242, 560, 567, 727, 732, 735, 738–739, 748–749. Added "and its eastwards continuation, the Central Timan Fault (Lorenz et al., 2004; Kostyuchenko et al., 2006)" lines 734–735. Rewrote the sentence lines 736–740 into "In addition, the size of Timanian thrust systems and related thrust anticlines in the Timan Range and Kanin Peninsula (e.g., Central Timan Fault and Mikulkin Antiform) are comparable (≥ 3–4 seconds TWT thick thrusts and 5–15 kilometers wide thrust-related major anticlines; Lorenz et al., 2004 their figures 3 and 5; Kostyuchenko et al., 2006 their figure 17) to that of thrust and fold systems in the northern Norwegian Barents Sea and Svalbard (**Error! Reference source not found.**a and c–d).". Added "and associated major anticlines" line 745, ", 5–15 kilometers wide anticlines" lines 746–747, and "and fold system" line 751. Added "with high metamorphic grade" line 241 and reference to Kostyuchenko et al. (2006) line 242. Added ", possibly with higher metamorphic grade" lines 536–537 and "(i.e., higher metamorphic grade)" line 595. Also added Lorenz et al. (2004) to the reference list.

Comment 4: see response to comment 3.

Comment 5: none.

Comment 6: none recommended by the referee's comment.

Comment 7: reference to the Geological Atlas of the Barents Sea was added to the reference list. Added " This is supported by a similar configuration of the Baidaratsky Fault Zone and the Kongsfjorden–Cowanodden fault zone, including a basement-seated, low-angle thrust geometry of both faults and inversion as a normal fault and deposition of several seconds (TWT) thick sedimentary strata in the hanging wall of the faults in the late Paleozoic (**Error! Reference source not found.**d and Smelror et al., 2009 their profile C–D pp. 53)." lines 650–654. Also added reference to Hassaan et al. (2021) and Hassaan (2021) lines 53. Added “, and the southeastern Norwegian Barents Sea (Hassaan et al., 2021)” lines 570–571. Added “in the southeastern Norwegian Barents Sea (Hassaan et al., 2020a, 2020b, 2021; Hassaan, 2021),” lines 736–737.

Comment 8: none recommended by the referee’s comment.

Comment 9: none.

Comment 10: see response to comment 7.

Comment 11: none recommended by the referee’s comment.

Comment 12: added “ Caledonian folding of Timanian thrusts also explains the weaker magnetic and gravimetric signal of Timanian faults at the location of major Caledonian synclines where Timanian faults were transported downwards and, therefore, may not show well on potential field data (e.g., major two, NE–SW- to N–S-trending, negative gravimetric anomalies in the Russian Barents Sea just west of Novaya Zemlya; **Error! Reference source not found.**a).” lines 864–868.

Comment 13: none recommended by the referee’s comment.

Comment 14: none. To be addressed in a new manuscript focusing in Svalbard that is the natural progression of this work.

Comment 15: none. See supplementary figures and note the dataset used is publicly available.

Comment 16: none. See supplementary figures and note the dataset used is publicly available.

Comment 17: none. See supplementary figures and note the dataset used is publicly available.

Comment 18: none. See figure 3d.

Comment 19: none recommended by the referee’s comment.

Comment 20: added “Magnetic and gravimetric anomalies not related to Timanian and Caledonian grains will not be discussed in the present study.” lines 247–248.

Comment 21: none recommended by the referee’s comment.

Comment 22: added “The boundary between Precambrian, lower Paleozoic and upper Paleozoic successions offshore are interpreted as major unconformities that truncate underlying reflections and fold structures (e.g., Figure 3a, b and c). The boundaries between Devonian–Permian and Mesozoic successions were tied to the Raddedalen-1, Plurdalen-1, and Hopen-2 exploration wells for offshore parts of the study area. The boundary between Devonian–Mississippian and Pennsylvanian–Permian onshore Svalbard are interpreted as a major unconformity truncating Devonian–Mississippian dykes (see Figure 3e).” lines 235–241.

Comment 23: added “This further explains why Timanian faults were not reactivated exclusively as strike-slip faults despite being oriented sub-orthogonal (c. 70°) to E–W Caledonian contraction. Portions of Timanian faults near the Caledonian collision zone were locally deformed into subvertical geometries suitable to accommodate lateral movement, whereas their counterparts retaining their moderate–low-angle dip away from the paleo-plate boundary were more prone to accommodate vertical movements. Moreover, lateral transport of rocks from the Caledonian collision front towards the inner portions of the Barents Sea in the east was hampered by rock units constituting the crust of the Barents Sea, northern Norway, northwestern Russia and other adjacent areas. Hence, Caledonian E–W contraction produced more easily N–S-trending folds (e.g., Figure 3b and e and Figure 4f), which extended almost all the way to Novaya Zemlya (Figure 5), whereas partial strike-slip reactivation was restricted to areas proximal to the Caledonian collision front (e.g., western Spitsbergen; Majka et al., 2008; Mazur et al., 2009; Faehnrich et al., 2020; Ziemniak et al., 2020).” lines 933–945.

Comment 24: none recommended by the referee’s comment.

Attached figures

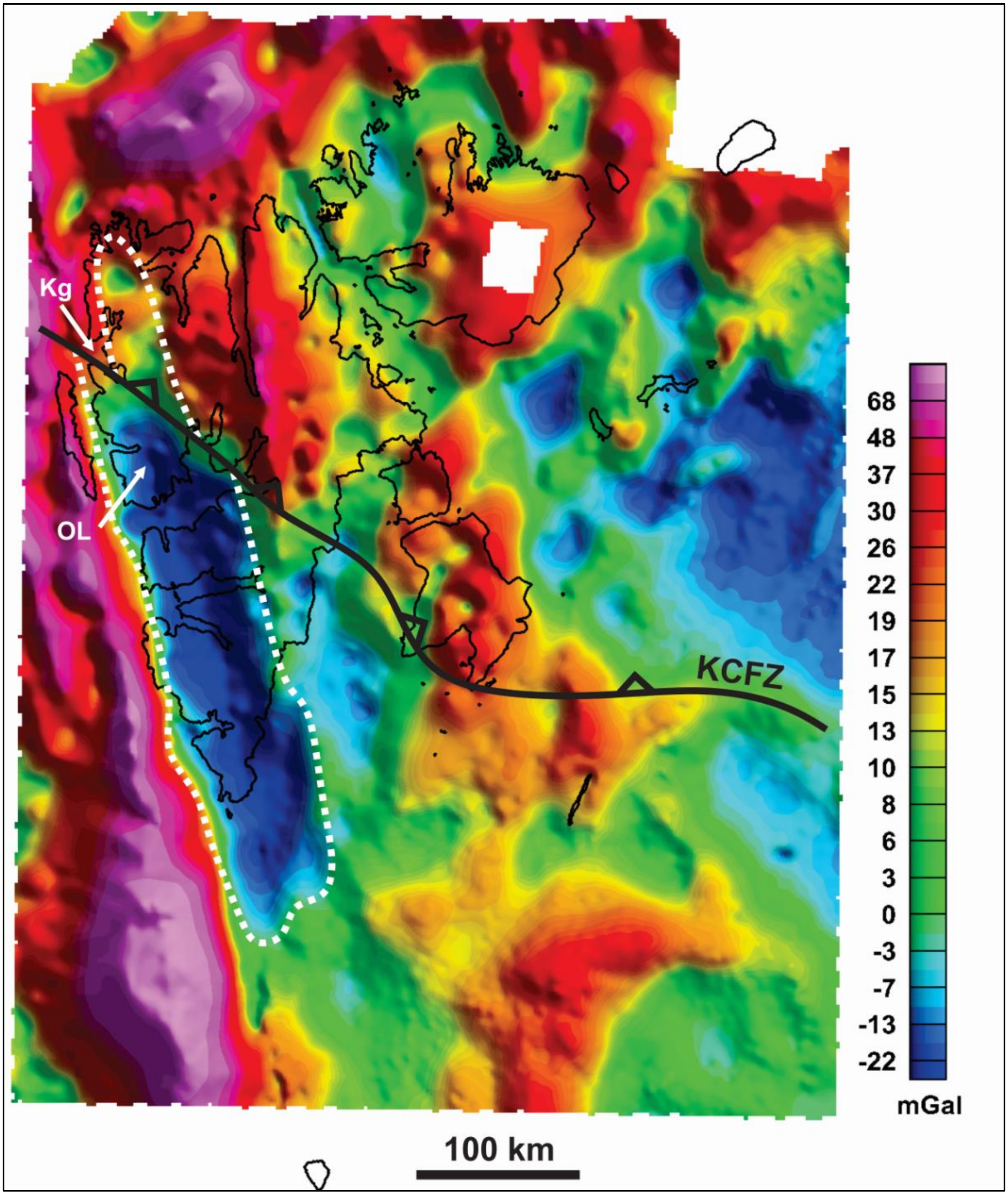

Figure 1: Gravimetric anomaly map over the Svalbard Archipelago from the Geological Survey of Norway (Skilbrei et al., 2000) showing a major negative anomaly in western Spitsbergen. The anomaly correlates with the early Cenozoic Central Tertiary Basin in central and southern Spitsbergen. However, since there are no lower Cenozoic sedimentary deposits north of Kongsfjorden (Kg) in northwestern Spitsbergen, it is very likely that the negative anomaly also

reflects basement attitudes, most likely a N–S- to NNW–SSE-trending synform. This synform is abruptly narrows across Kongsfjorden, thus suggesting fault offset. This offset is interpreted as being accommodated by the continuation of the Kongsfjorden–Cowanodden fault zone (KCFZ) in Kongsfjorden. The fault accommodated dominantly top-SSW reverse movements, which may very well explain the observed offset of the synform across the fjord. The narrowing of the gravimetric anomaly therefore most likely reflects uplift and partial erosion of the N–S-trending synform in northwestern Spitsbergen, which is supported by the absence of lower Cenozoic sedimentary rocks in the north. This interpretation shows that some of the Timanian faults presented in the present manuscript do extend west of Svalbard.