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Review of doctoral dissertation by mgr inz. Grzegorz Ziemniak entitled:

Provenance reconstruction within Caledonian basement provinces of Svalbard using detrital zircon geochronology

Summary of the thesis

The reviewed dissertation consists of eight chapters. Chapter 1 gives a short introduction to the topic, contains acknowledgments and a presentation of the publication stage of various parts of the dissertation. Chapter 2 presents the geological background for the study, mainly focusing on the introduction of Proterozoic sedimentary successions of the North Atlantic region as well as an introduction of the pre-Devonian geology of Svalbard. Chapter 3 introduces the analytical methods applied in this study. Chapters 4 to 6 present the results of detrital zircon analyses from various units of the southwestern basement province (SBP) of Svalbard. A total of 16 new detrital zircon samples are presented in these chapters. A summary of the 16 new samples is given in Table 1 below.

The detrital zircon samples are assigned to six different groups with specific depositional ages and provenance, from the oldest to the youngest: (1) One sample from the Gullichsen Formation of the Eimfjellet complex, representing a >1.2 Ga deposit, (2) Six Samples from U35, the Isbjørnhamna Group and the Müllersnesset Fm representing distal LTG2 rocks, deposited post ca. 1000 Ma but pre ca. 950 Ma, (3) Two samples of the St. Jonsfjorden Group, possibly part of a proximal LTG2 with a local source, (4) Two samples previously assigned to the Eimfjellet complex, but now interpreted as an upper part of the Isbjørnhamna Group, representing proximal LTG2 rocks, (5) Four samples of the Deilegga and Nordbukta Group representing LTG3, deposited after ca. 950 Ma but prior to the Torrelian unconformity and Marinoan (ca. 640-635 Ma) glaciogenic deposits, and (6) One sample from the Sofiebogen Group, deposited after the Torrelian unconformity, representing LGT4 (Tab. 1). These results are discussed and compared with other Proterozoic successions of Svalbard, the Arctic and the North Atlantic region.

Chapter 7 contains structural field observations from three areas on Oscar II Land referred to as Western and Eastern Svartfjellstranda and the Chaotic Zone. Within the Müllernesset Formation of the Western Svartfjellstranda, three deformation phases were separated (D1, Dm2, Dm3), with D2m representing a sinistral phase of shearing. At Eastern Svartfjellstranda, the Müllernesset Formation is juxtaposed with Carboniferous rocks, and the structures are less consistent, but D2m and D3m are recognizable. For the chaotic zone east of the SEDL, a scheme of D1 to D3 is presented, which is different from the scheme for the other two areas. Petrological observations were conducted on two garnetiferous samples from Western Svartfjellstranda. Relicts of a M1 metamorphic event are observed, overprinted M2 corresponding to D2m sinistral shearing. Monazites associated with the S2m foliation were dated to 410±8 Ma in one sample, and monazites of potentially different generations give a less-well defined average age of 428±25 Ma in the second sample. The results are discussed within the framework of sinistral-transpressive early Devonian shearing affecting the SBP of Svalbard.

Chapter 8 contains concluding remarks and paleogeographic models for (1) the deposition of the LTG1-3 and (2) the Silurian-Devonian tectonic assembly of the different Svalbard provinces.

Table 1: Summary of all presented detrital zircon samples from the SBP of Svalbard. The colours correspond to groups of samples which are interpreted to have a similar depositional age and provenance.

Sample Nr	Unit	Locality	Main peak	Youngest grain	Correlation/comment
HL12-019	Sofiebogen	SWJL	1300-1700	1037	LTG4? Post-Torrelian unconformity, NE-block of SWJL, Comfortlessbreen?
SP4208	Deilegga	SWJL	1000-1500 1700	974	LTG3, pre-Torrelian unconformity, Daudmannsodden? Richarddalen? Pearya?Seve, Särv, Sørøy? 710, 670 magmatism/metamorphism?
HL12-018	Deilegga	SWJL	1400-1600	710(?) 992	LTG3, pre-Torrelian unconformity, Daudmannsodden? Richarddalen? Pearya? Seve, Särv, Sørøy? 710, 670 Ma, magmatism/metamorphism?
UB1703	Nordbukta	CWJL	1000-1700	946	LTG3, pre-Torrelian unconformity, Daudmannsodden? Richarddalen? Pearya?Seve, Särv, Sørøy? 710, 670 magmatism/metamorphism?
UB1706	Nordbukta	CWJL	1000-1500 1700	935	LTG3, pre-Torrelian unconformity, Daudmannsodden? Richarddalen? Pearya?Seve, Särv, Sørøy? 710, 670 magmatism/metamorphism?
HL12-014	Eimfjellbreane	SWJL	1700 1500	1144	Upper Isbjørnhamna ->new unit LTG2 proximal deposits on top of IBH? Laksefjord nappe/Timanian basin?
HL12-012	Skjerstranda	SWJL	1800 1500	1124	Upper Isbjørnhamna ->new unit LTG2 proximal deposits on top of IB? Laksefjord nappe/Timanian basin?
PSG02	St. Jonsfjorden	OscarII		1439	Only four grains!
PSK01	St. Jonsfjorden	OscarII	2600-3000	1008	Proximal, 560 metagabbros, unique unit?
PSB06	Müllernesset	OscarII	1700 1400 1100	991	Distal LTG2, pre-950, Krossfjorden, Biscayarfonna, Krummedal, Morar, Torridon, Sleat, Westing, Heggmo, Sværholt
PSB04	Müllernesset	OscarII	1700	1014	Distal LTG2, pre-950, Krossfjorden, Biscayarfonna, Krummedal, Morar, Torridon, Sleat, Westing, Heggmo, Sværholt
SP1631	Martinfjella (Deilegga?)	NWJL	1700	1011	Distal LTG2, pre-950, Krossfjorden, Biscayarfonna, Krummedal, Morar, Torridon, Sleat, Westing, Heggmo, Sværholt
SP21/08	Isbjørnhamna	SWJL	1600 1000-1900	1000	Distal LTG2, pre-950, Krossfjorden, Biscayarfonna, Krummedal, Morar, Torridon, Sleat, Westing, Heggmo, Sværholt
HL12-008	Unit 35	Sørkapp	Broad	1040	Distal LTG2, pre-950, Krossfjorden, Biscayarfonna, Krummedal, Morar, Torridon, Sleat, Westing, Heggmo, Sværholt
HL12-010	Unit 35	Sørkapp	1700 1000-2800	1070	Distal LTG2, pre-950, Krossfjorden, Biscayarfonna, Krummedal, Morar, Torridon, Sleat, Westing, Heggmo, Sværholt
HL12-017	Gullichsen Fm/Eimfjellet	SWJL	2700 1700-1900	1719	LTG1, Oldest unit, >1200 Ma; Stoer, Gardar, Peary Land, Tanahorn etc

Overall assessment of the scientific quality of the presented dissertation

The reviewed dissertation covers a wide topic dealing with at least 800 million years of geological evolution of the southwestern basement province of Svalbard, from the deposition of the Gullichsenfjellet Formation at ca. 1200 Ma to the strike-slip assemblage of the basement province at ca. 400 Ma. In addition, the thesis covers a large geographic area, analysing and digesting geological information from the Laurentian margin of the British Isles and Greenland Caledonides via the Scandinavian Caledonides along the Baltican margin to various terranes spread across the Arctic. This width in both geological time and geographic extension is reflected in an extensive literature list, documenting that the candidate was able to introduce himself to a large amount of scientific literature. The candidate also applied highly different methods, spanning from U-Pb detrital zircon analysis through structural field work, petrological thin section observations and U-Th total Pb dating of monazites in situ, resulting in a candidate which is able to perform variable analyses needed for a holistic approach for reconstructing the evolution of crystalline bedrock.

The scientific results presented in the dissertation contribute to a better understanding of the geological evolution of the SBP of Svalbard in various ways, with the main findings in my opinion summarized as follows:

(1) The Eimfjellet complex as previously defined is not a coherent unit, but consists of at least two widely different successions, with the structurally lower part representing a younger depositional unit,

(2) Distal LTG2 units might occur all along the province, from Sørkapp Land in the South to Oscar II Land in the north (unit 35, Isbjørnhamna, Martinfjella, Müllernesset),

(3) The LTG3 units Deilegga and Nordbukta are correlatives, and have a different provenance pattern from the LTG2 units,

(4) Sinistral shearing affected the western part of central Oscar II Land at ca. 410 Ma, extending the occurrence of sinistral late Silurian to early Devonian shearing northwards from the previously documented occurrences on Wedel Jarlsberg Land.

These main findings are discussed within the framework of the geological evolution of various units within the North Atlantic region, reaching the following tectonic conclusions:

(1) The distal LTG2 units of the SBP have provenance patterns similar to a wide range of units both in the northwestern basement province of Svalbard (Krossfjorden and Biscayarfonna), Greenland, Scotland, Shetland and Norway, belonging to wide successor basins within Rodinia. However, two more proximal LTG2 samples (upper Isbjørnhamna Group) show similarities with the samples from the Baltican Laskefjord Nappe, possibly tying the SBP to northern Baltica at the time of deposition.

(2) The LTG3 units have provenance patterns similar to other units on Svalbard (Daudmannsodden, Richarddalen complex) and on Pearya, as well as units within the middle allochthon of the Scandinavian Caledonides, showing less similarities with similarly-aged Laurentian-margin successions.

(3) The main units of the SBP might originate from the Baltican side of the Iapetus suture, were transferred by sinistral movements to the northern margin of Laurentia by ca. 425 Ma escaping the main Scandian collision, and where then juxtaposed by sinistral movements with the eastern province of Svalbard at ca. 410 Ma.

These findings and the subsequent conclusions represent a step forward in the understanding of the complex tectonic evolution of the SBP of Svalbard and help to systematize the origin and evolution of various rock units appearing in this province. The results also raise several new questions, and the author of the dissertation points out several new research topics throughout the thesis, showing that he is thinking ahead and critically assesses his own data and the limitations arising from it.

The preparation, structure and language of the dissertation is of moderate quality. The detrital zircon data (chapters 4-6) could have been presented more logically, particularly chapter 4 does not fit in the row, since it presents samples from various lithotectonic units, whereas chapter 5 and 6 are organized according to their lithotectonic origin. This makes it difficult for the reader to see the big picture, and a summary and compilation of all obtained samples is missing (i.e. a table similar to table 1 in this review would have been very useful, which the reviewer had to produce herself to get an overview). Several of the figures are of bad quality, and both figures and text contain numerous typing, formatting and language errors, so a proper proof-reading would have been necessary. The thesis only contains an abstract/summary in Polish (if page 5 represents a summary?), and an English version would have been beneficial to be able to assess whether the candidate managed to extract the main points of the dissertation in a coherent manner.

Specific comments and questions by chapter are summarized in the next section.

Specific comments and questions

Chapter 1. Introduction

p.6: here, you define three hypotheses, but those are quite general and you never come back to them specifically, so those are not very well integrated in the thesis and it is a bit unclear what was the starting point and the research questions initiating this thesis.

p. 7: here you mention one published and several submitted or in prep manuscripts, but it is unclear to me whether some of the chapters directly correspond to the manuscripts, and if yes, which chapter corresponds to which manuscript? If the chapters correspond to manuscripts with several co-authors, this should be clearly stated at the start of each chapter.

Chapter 2. Geological background

p. 18, 2.1.4.2: here and at several other places you name geological features without showing them on a map (e.g. Biscayerhalvøya, Krossfjorden terrane, Hannabreen Fault)

Fig. 1 and Fig. 4 are of bad quality/resolution in the printed version and it is difficult to read any details

Chapter 3. Methods

A general comment on the methods: ***Detrital zircon analysis*** comprises the main part of the dissertation. I missed a more thorough introduction of the concepts and methods behind detrital zircon analysis, in particular (1) the introduction of maximum depositional age (MDA) techniques and the problems associated with (e.g. Dickinson & Gehrels, 2009; Coutts et al., 2019; Andersen et al., 2019), (2) the problem of number of analysed grains (e.g. Vermeesch, 2004; Andersen, 2005); (3) which diagrams and graphs should be used to present the data (e.g. Vermesch, 2012, Andersen et al., 2018), (4) which statistical methods should be applied to compare the data (e.g. Vermeesch, 2013; Vermeesch et al., 2016, Spencer & Kirkland, 2015; Andersen et al., 2018) and (5) how detrital zircon spectra should be interpreted in terms of provenance and recycling (e.g. Andersen, 2013, 2014; Andersen et al., 2016). It seems to me that the technique of detrital zircon analysis is applied relatively uncritically, without discussing the issues raised in the cited publications above (and many more – there is an extensive literature on general topics related to detrital zircon analysis!). The method section could have profited from a thorough introduction of the DZ method citing the most important literature dealing with methodological issues from this field.

p. 23, 3.2. here you mention 7 samples by SIMS and 7 by LA-ICPMS – I counted a total of 16 samples, not 14? Where were the remaining two samples analysed, and by which technique? Why did you apply different techniques at all? And why do the SIMS samples have way less analysed grains than the LA-ICP-MS samples? Maybe the choice of methods was not that thoroughly planned?

p. 23, 3.3. Why was 1200 Ma chosen as cut-off between 207/206 and 206/238 ages? As far as I know, 1000Ma or 900 Ma is more common? This paragraph also contains some repetition/inconsistency – was 5% reverse discordance or 10% reverse discordance used as cut-off value?

Chapter 4. Defining tectonic boundaries using…

Does this chapter correspond 1:1 to the published GSA Special Paper contribution? If yes, this should be stated clearly, also adding the co-authors.

p. 26, Fig. 5: the sample numbers in the Eimfjellbreane and Skjerstranda Fm are confused in the figure – according to the text HL12-012 is from the Skjerstranda, and HL12-014 is from the Eimfjellbreane?

p. 28-30: the description of the results of the detrital zircon analyses is very little systematized, and the information is given differently for each sample. It helps the reader if the information is summarized the same way for each sample, using the same wording as much as possible. In particular, the information on the youngest grains (or the MDA based on various methods) is not given systematically. All these samples also have very low numbers of analysed grains – what is the reason for that? Did the samples not contain enough grains? Or were the SIMS analyses to expensive/time-consuming? The numbers are so low that minor important populations could have been missed, and a statement of caution should have been introduced somewhere.

p. 31: you quickly conclude with group A-C belonging to LTG1-LTG3/4, but this is too quickly for the reader, you should first introduce your arguments and comparisons.

p. 31: the ***K-S tests*** are shown differently – in some cases the tables are nearly symmetric (as in Fig. 10, except for the comparison of HL12-010 with SP21/08), in others the lower part shows something else (what does the maximum vertical distance between the samples mean?) -> the theory behind K-S tests and the meaning and interpretation of the values in the tables should have been introduced in the methods section.

p. 31, Fig. 10: why did you not include HL12-014 in this figure and the table?

p. 32, 4.3.2.: the Gullichsenfjellet formation is above the 1.2. Bratteggdalen Fm, but is interpreted to be older ->so do you interpret the succession to be inverted?

p. 34 and many other places: you separate between ***proximal*** and ***distal*** units – how do you define this and what observations is this based on? From the sample descriptions, most samples are quartzites, which are coarse-grained quartz-rich mature, well-sorted sandstones – how can you assign them to either a distal or proximal origin, and distal and proximal to what? The nearest landmass? A certain continent? Since these two terms are quite central for your tectonic correlations in the end, they should have been introduced much better, and the field/stratigraphic evidence for it should have been presented.

p. 34: the Eimfjellbreane and Skjerstranda formations are separated from the Isbjørnhamna unit by a thrust – and now you also postulate a shear zone between the Eimfjellbreane and Skålfjellet formations – so why do you assign the Eimfjellbreane and Skjerstranda to the Isbjørnhamna unit at all? The two samples have a different provenance pattern as well, so it would have been much clearer to assign them to an own unit, and not call them Upper Isbjørnhamna unit which is confusing, since it does not relate to the Isbjørnhamna unit and previous authors have postulated a thrust separating them.

p. 35: you in some places use “successor basin” for the LTG2 units, in some places “foreland basins” – the two basin concepts are quite different, the first being subsequent to an orogeny, whereas the other is a consequence of ongoing orogeny – which one do you think is the case?

p. 36: I don’t really like that the Deilegga and Sofiebogen units are treated together, since they are separated by a major unconformity and of different depositional age, therewith representing different time slices, so I would prefer treating the Sofiebogen sample as a clearly younger unit of LTG4 (see my table 1)

p. 36: Here you correlate the Deilegga and Sofiebogen Groups with the Daudmannsodden and Comfortlessbreen Groups, but note that Gasser&Andresen 2013 placed the Daudmannsodden and Comfortlessbreen Groups above the Torrelian unconformity, whereas the Deilegga/Nordbukta are placed below the unconformity (see Fig. 4 in Gasser and Andresen, 2013) – what is your evidence that the Daudmannsodden unit should be placed below the unconformity as well?

p. 37-38: several of the reasonings here appear somewhat unmatured, and I prefer the more thorough discussion presented in chapter 5 about the LTG2, so I wonder whether this discussion in chapter 4 really is the published version in GSA Special Paper?

Chapter 5. LTG2

p. 40 5.2.1: this is a locality description, not a sample description as indicated with heading 5.2.

p. 40: I find the "Deilegga Group (?)" name confusing – you could have stated in the introduction that this unit has earlier been correlated with the Deilegga Group, but that it is lithologically and provenance-wise different, and therefore a new name is introduced (Martinfjella unit or something like that). That would have made it easier for the reader to NOT connect it to the Deilegga Group.

Fig. 12: it is strange that the figure is placed on two pages – A-C should be on the same page. Fig. 12C has a possible mistake on the northern shore of St. Jonsfjorden, where the polygon with sample PSG01 is assigned to the Daudmannsodden Group, but according to the map in Gasser&Andresen is assigned to the St. Jonsfjorden Group – what is correct?

Fig. 12: Sample PSG01 is shown but never explained. It could also have been useful to show the locations of samples 1, 2, and 3 from Gasser&Andresen on this map.

Fig. 13: the figure caption contains several confusions between east and west? The Sofiebogen Group is shown in the east and the Deilegga in the west? Is the sample location visible on the photograph?

p. 43 and following: wrong figure references to Fig. 14 (should be 15).

p. 46: the lack of Archean grains in sample 1 compared to PSB04 and PSB06 could be the result of much higher number of analyses in the latter two samples.

Fig. 16: the K-S results are presented inconsistently, sometimes as own table, sometimes included in a figure with CPP – could be homogenized.

p. 48: you suddenly mention the Lovliebreen Formation, but this has not been introduced previously, do you mean your sample PSK01 is from the Lovliebreen Formation? Or do you refer to literature results here? Unclear to me

p. 49: If the Isbjørnhamna and Müllernesset units are correlatives, would you expect a record of Torrellian metamorphism also in the Müllernesset units and it is just not detected yet? Or do they share a common history during deposition, but a separate tectonic/metamorphic evolution after that due to their different positions relative to the VKZ shear zone?

p. 49, table 2 caption: I guess you refer to inter-sample correlations, not intra-sample correlations?

p. 50: here, you refer again to proximal vs. distal, which I think is not documented good enough.

p. 50: "the differences in the detrital zircon spectra for the upper Isbjørnhamna and St. Jonsfjorden groups highlight the VKZ as a major tectonic boundary separating two domains of LTG2 metasediments with various source areas". I do not understand this sentence – the Isbjørnhamna sensu stricto and the Müllernesset samples are similar, even though they are separated by the VKZ. The UISB and the St. Jonsfjorden samples are from each side of the VKZ, and are different, but since the Isbjørnhamna and Müllernesset are similar, the difference between UIB and St. Jonsfjorden cannot be explained by the VKZ?

p. 54: there should be a new paragraph starting at the third line, beginning with "The detrital zircon age spectra and the geological record of the more proximal…." Since the following information is different from the previous, and deals with the particular position of the UISB.

p. 54: you state that the UISB overlies the Isbjørnhamna, but I thought this was previously mapped as a thrust? Should be elaborated on more in the text.

Chapter 6. LTG3

Sample HL12-018 from chapter 4 should have been included here for comparison (f. eks in Fig. 23).

p. 59: 6.4.1. should be LTG3, not LTG2

p. 60: again, the correlation of the Deilegga with the Daudmannsodden Group depends on how the Torrelian unconformity continues northwards, this should be stated somewhere

p. 61, last paragraph: here, proximal is used again, but in which sense?

p. 62: Fig. x – missing figure reference

Fig. 25: here, a K-S test is missing, and it is not clear from the text into how many different distinct provenance signatures you want to separate these samples. You want to group the Deilegga and Nordbukta with the Baltica-related samples, but this is not easily visible from Fig. 25.

Chapter 7. sinistral transpression

Müllernesset is written differently (Müllerneset) – what is correct?

Fig. 26: contains references to Fig. xA and xB

Fig. 27: what are the red dots on the map? From this figure, it is not obvious which regions you refer to in the subsequent subchapters "western Svartfjellstranda" and "eastern Svartfjellstranda" – you could have indicated this on the map.

Shear sense indicators on Fig. 29C and 30E/F: I see how you argue for sinistral shear sense, by interpreting the layering in the quartzite as an S1 foliation being sheared into parallelism by S2. However, I think the same structures could also have formed by asymmetric folding of S2-parallel layering, therewith representing dextral shearing for 29C and sinistral for 30F…Quartzite layers in phyllites have a different competence than the phyllites and would be prone to folding. So only based on these pictures presented in the study I am not 100% convinced about the kinematics of shearing in these rocks.

Fig. 31D: impossible to see the boudinaged dolomites if you don't know where they are – consider drawing your structural interpretation onto the picture

p. 76: how many samples did you scan for monazites?

p. 88: what do you mean with autochthonous basement? I guess nothing in western Svalbard is autochthonous?

p.88 7.4.2.2. I find this section hard to follow – you say that the deformation events can be correlated, but at the same time, D2 east of SEDL is something quite different from D2 at Svartfjellstranda, so this would need a table showing how you correlate the different events across the SEDL.

Fig. 37B: the sketch to the right shows top ENE-thrusting, but the figure caption says top-W thrusting – what is correct?

p. 90: regarding the PKF, Ellesmerian deformation is not mentioned

Chapter 8. Concluding remarks

Concluding remarks is maybe an understatement – you present here your two most complete tectonic models, so this is not just small concluding remarks!

Fig. 38: I am confused about the difference between B/D and D/E – you state that B/D is the scenario with the Valhalla orogeny, whereas D/E is with a Sveconorwegian/Grenvillian propagation to the north – but actually C/E and D show the Valhalla orogeny, but not B! So I think something must have gone wrong with C (should not contain the blue polygon?) and possibly E (should not contain it either?)

p. 95: I am maybe least convinced about your conclusion that LTG3 shows a decreasing contribution from Laurentian sources, I think this is not convincingly documented (partly due to the poor structure and missing K-S test in Fig. 25 mentioned above).

Fig. 39: interesting model – which process do you think could have caused the detachment and out-of-sequence strike-slip emplacement of Barentsia at ca. 410 Ma?

Appendix

The analyses for each detrital zircon are not sorted according to age or discordance, so it is difficult to quickly find the youngest grains, filter out the analyses with high discordance, etc. Particularly in cases where the reader is not able to play around with the table themselves (when the data is provided in pdf or print format), it is important that (1) the discordant analyses are shown separately, and (2) the remaining analyses are sorted according to age (and clearly indicated where the 207/206 vs. 206/238 age is used by for example putting the used ages in bold).

Conclusions

The reviewed doctoral dissertation of mgr Grzegorz Ziemniak represents a valuable scientific contribution, showing that the candidate has achieved a high level of scientific knowledge about the geological evolution of the area and is able to apply various analytical methods. However, the dissertation could have profited from a somewhat more thorough and careful approach to the main method (detrital zircon geochronology) as well as more careful proof-reading. Nevertheless, the manuscript meets the requirements for a doctoral dissertation, and I herewith confirm with pleasure that mgr. Grzegorz Ziemniak can be admitted to the further stages of the process.

Leikanger, Norway, 22.12. 2020

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Deta Gasser

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