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PhD (Doctoral) Dissertation Assessment
(Recenzja pracy doktorskiej)

Author: **Dhanushka Devendra**
Title: ***Late-glacial and Holocene Paleoceanographic Changes in the European Arctic Based on a Multiproxy Approach***

Supervisor: Prof. dr hab. Marek Zajączkowski, co-supervisor: dr. Magdalena Łącka-Wojciechowska

1. Introduction

In the modern period of rapid climate change, paleoceanographic studies are crucial for understanding past climate dynamics and predicting future changes. The globally fastest warming North Atlantic is critical in that context as it plays a pivotal role in global ocean circulation, mainly through the formation of North Atlantic Deep Water, a vital driver of the thermohaline circulation, as well as for the planet's albedo and energy balance, through sea-ice extent changes. The existing temperature, salinity, and sea-ice cover reconstructions are obtained from sediment cores and various proxies, including ice-rafted debris, marine microfossils, etc. These insights help clarify the mechanisms behind rapid climate shifts and their potential impacts on modern-day climate systems.

However, despite decades of research on Nordic Seas paleoceanography, numerous questions remain unanswered. The number of studied cores is relatively limited; consequently, the spatial resolution of reconstructions is also restricted. The next issue is related to limitations in temporal coverage and resolution. The applied methods focused in the past mainly on identifying the main dominating water masses through planktic and benthic foraminifera and the interpretation of icebergs and sea ice using ice-rafted debris indicators. The recent decades resulted in advances mainly due to

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new methods (e.g., geochemical and biogeochemical), significantly increased resolution, and a better understanding of land – ice – atmosphere – ocean linkages.

The PhD dissertation by Dhanushka Devendra, submitted for evaluation, aligns with these recent research trends in paleoceanography and presents detailed documentation of three sediment cores collected from various parts of the North Atlantic (NE Greenland margin and western Barents Sea and Spitsbergen margin). The presented results have partly been published in good scientific journal (*Global and Planetary Change*) and thus have already been evaluated by international experts. The new data include basic sedimentological data, results on foraminifera species composition, as well as their isotopic composition, biomarkers, sediment geochemistry, and radiocarbon dating, which provided dataset used for discussion on the changes of Atlantic Water influence, meltwater pulses and general paleoenvironmental variability.

2. General description of the thesis

The thesis is mainly written in English and consists of a short preface, acknowledgments, table of contents, abstracts (in English and Polish), c. 15-pages summary of the thesis with a brief description of the background, goals, methods, and the main achievements (in English and Polish), the three multi-author manuscripts and declaration of co-authorship. The main text of the thesis is 121 pages long.

The thesis's main goal is to "reconstruct the impact of water mass changes on the paleoenvironment in the European Arctic during the late-glacial and Holocene", so it is very general. As the leading research questions, the author identified partly overlapping problems related to "paleoenvironmental dynamics," "meltwater pulses," "abrupt climate shifts," "Holocene variability," and "recent millennia changes." Several more specific questions follow them.

The key part of the thesis consists of three papers. Two are already published, while the third is in review. Six to nine coauthors author the papers; however, the PhD candidate is the first and corresponding author in each case. Each manuscript is based on a single core study from different parts of the North Atlantic region. The papers are as follow:

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1) Dhanushka Devendra, Magdalena Łącka, Maciej M. Telesiński, Tine L. Rasmussen, Kamila Sztybor, Marek Zajączkowski, Paleoceanography of the Northwestern Greenland Sea and Return Atlantic Current evolution, 35–4 kyr BP, *Global and Planetary Change*, Volume 217, 2022, 103947.

2) Dhanushka Devendra, Magdalena Łącka, Natalia Szymańska, Małgorzata Szymczak-Żyła, Magdalena Krajewska, Agnes K.M. Weiner, Stijn De Schepper, Margit Hildegard Simon, Marek Zajączkowski, The development of ocean currents and the response of the cryosphere on the Southwest Svalbard shelf over the Holocene, *Global and Planetary Change*, Volume 228, 2023, 104213.

3) Dhanushka Devendra, Natalia Szymańska, Magdalena Łącka, Małgorzata Szymczak-Żyła, Magdalena Krajewska, Maciej M. Telesiński, Marek Zajączkowski, Postglacial environmental changes in the northwestern Barents Sea caused by meltwater outbursts, *Climate of the Past*, in review.

The first paper assesses the Atlantic Water flow in the Northwestern Greenland Sea. The paper aims to "investigate variations in the properties and flow of the Atlantic Water, especially from the Return Atlantic Current and associated changes over the NE Greenland margin during the last ~35 kyr BP". To achieve this goal, the authors applied a multi-proxy study of benthic and planktic foraminiferal fauna assemblages, stable isotopes of oxygen and carbon in foraminifera tests, ice-rafted debris (IRD), and other geochemical and sedimentological proxies to a 135 cm long sediment core GR02-GC, collected from 1170 m water depth. The authors presented a detailed reconstruction of the evolution of the RAC for a period of ~35 to 4 kyr BP. The results suggested that Atlantic Water was almost always present in the NW Greenland Sea during the studied period. The authors interpreted excursions in the $\delta^{18}O$ values at ~34.5 and 33 kyr BP as meltwater signals associated with the adjacent NE GIS melting. They interpreted increased iceberg calving and melting between 29 and 23.5 kyr BP. During the Last Glacial Maximum, the extensive sea ice cover was associated with subsurface AW at the study site. They recorded fluctuations of the Atlantic Water properties concerning major climate oscillations, such as Younger Dryas. The Holocene Thermal Maximum was interpreted as the period with the most substantial inflow of the Atlantic Water masses. To some

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extent, this paper overlaps and reuses data with the paper by Telesiński et al. (2022 in Holocene). The PhD candidate is not a coauthor of the second paper, and it should be clearly explained which data were provided for the newer paper.

The second paper is based on a core from the already well-studied west Spitsbergen margin. It focuses on core OCE2019-HR7-GC retrieved from the southwestern Svalbard inner shelf, influenced by different ocean currents and local water masses. The primary goals of the paper were twofold. First, to reveal the impact of the interplay between warm Atlantic, Arctic, and cold local water on the dynamics of sea-ice coverage and second, to analyze how these changes affected the local and regional climate during the Holocene. In this work, for the first time in this region, sea ice reconstruction was constructed using the biomarker IP25 in combination with the phytoplankton biomarkers. Moreover, the work contributed new surface and bottom water temperature estimates using alkenones and Mg/Ca, while water masses were identified using foraminifera assemblages. The results revealed extensive sea ice cover between 11 and 10.2 kyr BP, and confirmed that the warmest Holocene conditions on the SW Svalbard shelf characterized the period between 10 and 7 kyr BP. This interval is also interpreted to be characterized by high surface water productivity and an enhanced AW influx, causing sediment redeposition. After 6.5 kyr BP, the SW Svalbard shelf was characterized according to the reconstruction by a dynamic environment with cold and unstable conditions, which, after 3.5 kyr BP, were characterized by an increase in sea ice cover and iceberg rafting until 2.2 kyr BP, followed by brief warm period between 2.2 and 1.8 kyr BP and a colder state with the presence of sea ice until 1.5 kyr BP.

The third paper is based on a single core from the Barents Sea's western (or even south-western) margin. However, in the title and throughout the text, it is stated that it is about the northwestern Barents Sea, which is incorrect. The paper aims to reconstruct paleoceanography for the last 14.7 ka, focusing on reconstructing potential meltwater pulses. The multiproxy reconstruction was based on foraminifera, biomarkers, stable isotopes and sediment properties. The primary outcome of the paper is the suggestion of a potential record of four periods/events with significant meltwater release. The finding is interesting, although its interpretation needs to be specified in the future. The last one is interpreted as evidence of the 8.2 ka Storegga tsunami.

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3. Assessment and comments

My general opinion about the presented doctoral dissertation is positive. The author presented a work based on high-quality analyses of rich and unique research material. Many of the applied methods are time-consuming and require specialized skills. The author showed a very good knowledge of the current literature related to paleoceanography and the studied areas. He proved he could identify the problem, formulate research objectives, apply appropriate methodology, and critically discuss the results. Last but not least, he proved to be able to publish the results he obtained in leading geoscientific journals.

Nevertheless, paying attention to some shortcomings and emerging questions is also necessary. First, I will underline some deficiencies related to the structure and overall assessment of the thesis. Then, I will give examples of discussion questions emerging from the data-rich documentation. The reviewer hopes that at least some of these comments will be addressed by PhD candidate during the PhD examination.

The PhD thesis lacks a single specific common problem and aim. The presented one is very general. The three papers are poorly linked. There is a similar set of methods. However, I miss the compilation of the presented data in the three independent papers. Some of the postulated events and changes could happen in all the studied regions (e.g. Younger Dryas, Storegga). Why are some of them recorded while others are not? It could be done in the summary of the works.

Second, although the declaration of the contribution by the individual authors is attached to the thesis, they are very general. I miss clear, straightforward information about the work that the PhD candidate actually did; again, it should be stated in the summary of the thesis.

Although, I appreciate the extensive knowledge of the existing literature on the topics studied by the author, I am slightly disappointed with how it is used for the data interpretation. The papers would benefit significantly if a more detailed comparison of the obtained data were made with existing offshore and onshore records. In some cases, the previously studied cores were relatively close to the new ones and presented contradictory interpretations to the ones offered by the PhD candidate. Unfortunately, the critical discussion is often missing. For instance, in one of the discussed papers by Sternal et al. 2014 (the data from which are used in one of the figures), it is concluded that the East Spitsbergen Current was initiated between 10.3 and 9.2 ka BP, while here it is considered

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that its impact was already significant between 11 and 10.2 kyr BP – at that time most of the northwestern Barents Sea could be still ice-covered. Hence, the formation of the current is unlikely. There is also the contradictory interpretation of the timing of maximum Atlantic Water flux, etc., and both cores were collected nearby and analyzed with various sets of methods in very high resolution. There is also no broader discussion about the latest Holocene record, many lake records and ice-core records are covering the same time period of Neoglacial and Little Ice Age. I would also like to see a more extensive presentation of state-of-the-art knowledge and identification of existing gaps in the understanding; again, it could be presented in part as a "summary."

Among the great methodological problems of paleoceanography are spatial and temporal resolution, the problem of quantitative interpretation, as well as the problem of representativeness. In all three papers, the studies are based on a single core. While it is clear that the study of a single core is already very time-consuming, to answer questions related to spatial changes in the past, the single core seems to be not enough. The spatial changes of Atlantic Water flow and their impacts are among the study goals. There is also always the question of how representative a single core is. Some of the dated material was excluded from the age models in all the cores, suggesting local sediment reworking, mixing, etc., there is also evidence of erosion and redeposition. One may consider if it would be better to focus on a single region and solve the problem more complexly instead of analyzing single cores from the various areas and often providing speculative interpretations, at least in the context of spatial variations.

In my opinion, the missed opportunity is the lack of the youngest part of the record, which could be calibrated or at least compared with recent in situ monitoring data on water masses, sea-ice etc. I am aware that it is a common problem in paleoceanography. However, the author mentioned several times in the thesis that the conditions were warmer or cooler than at present, while the present is not actually represented in the record.

The presented interpretations are, in my opinion, sometimes simplified, exaggerated and speculative. For instance, I find the statement that “inflow of Atlantic Water via Return Atlantic Current significantly influenced … the stability of the NE Greenland Ice Sheet” to be very speculative. The presence of Atlantic Water Masses on the continental slope (not on the shelf, which is also particularly wide in this part of Greenland) does not even mean that they were in contact with the ice masses, not to mention causing the ice sheet instability (what are the proofs for the

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instability?). The authors also seem to neglect the atmospheric and insolation forcings in the interpretation.

Another example of poorly documented and highly exaggerated interpretation is related to the Storegga tsunami. The author stated for instance " One of the key highlights … is the evidence of the Storegga tsunami's impact around 8.2 kyr BP…, which is likely reached and redistributed sediments in the northwestern Barents Sea. Our research provides new insights into the expansion of tsunami currents over the Barents Sea, an area with limited previous knowledge on this topic". While the Storegga tsunami very likely passed over the Barents Sea (as suggested by numerical models) the way it is argued is not correct in my opinion. First, the event is evidenced by the isotopic signature considered to be indicatory of meltwater pulse (why the exact mechanism can not be responsible or at least discussed as the cause of associated sedimentary changes?). Then the author claims that tsunami would bring the abundance of terrestrial material from Norwegian Sea with the backwash from land located hundreds km away. It reveals a lack of understanding of the scale of the process. The Storegga tsunami was discussed and documented already in the study area (e.g., in several cores collected next to the studied one - Rüther et al., 2012; Sternal et al., 2014), mainly as erosional contact, so actually redeposition on a local scale would be possible, and would explain the documented changes in grain size, magnetic susceptibility and age reversals, but it requires a detail careful analysis. There is extensive literature on tsunami deposits onshore and offshore and possible diagnostic features. Moreover, even if the interpretation is correct, a single core site from the western margin of the Barents Sea does not allow to state about the redistribution of sediments by the tsunami in the northwestern Barents Sea region.

4. Conclusion

This thesis represents a great deal of work. The results are well presented, and their interpretation is generally correct and satisfactory, which is documented by publishing them in a good scientific journal. The above comments and discussions intend to encourage the PhD Candidate to be more specific in the interpretation, which should be more process-based, and to ignite the debate during the public PhD defense. However, they do not neglect the value of the thesis. In my opinion, the dissertation by Mr. Dhanushka Devendra documents the general and practical knowledge of the

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candidate in the field of Earth Sciences, his ability to conduct and present independent scientific research, and the thesis presents original solutions to scientific problems of at least regional importance. Consequently, the thesis complies with both Polish and international standards for PhD dissertations in the field of geosciences.

Wniosek końcowy

Stwierdzam więc, że przedstawiona do recenzji praca spełnia wszystkie wymagania stawiane rozprawom doktorskim. Stanowi ona istotny, nowy wkład do dotychczasowej wiedzy i dowodzi, że Pan Dhanushka Devendra w pełni opanował umiejętność prowadzenia badań naukowych. Recenzowana praca spełnia zatem wymagania określone w "Ustawie o stopniach naukowych i tytule naukowym oraz o stopniach i tytule w zakresie sztuki" z dnia 14 marca 2003 r. (Dz. U. z 2017r. poz. 1789 i ze zm.). Tym samym wnioskuję o dopuszczenie Pana Dhanuski Devendry do dalszych etapów przewodu doktorskiego.

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