Attachment 2 b

PERSONAL ASSESMENT

1. Name and surname.

Krzysztof Marcin Michalski

2. Diplomas and scientific degrees.

1999 – Master of Science, the thesis ”Palaeomagnetism of fractures fills in Devonian limestones from the Holy Cross Mountains”, Department of Geology University of Warsaw in cooperation with Institute of Geophysics PAS; supervisors: Prof. dr hab. Michał Szulczewski (UW), Prof. dr hab. Marek Lewandowski (IGF PAS).

2008 – Ph.D. in Earth Sciences in the field of Geophysics, the thesis “Geotectonics and palaeogeography of the Southern Spitsbergen based on palaeomagnetic investigations of Cambrian, Devonian and Carboniferous rocks from Hornsund”, Institute of Geophysics PAS; supervisor: Prof. dr hab. Marek Lewandowski (IGF PAS).

3. The employment in scientific institutions.

(June 1999 – October 2000) – geophysicist, XXII Expedition of Institute of Geophysics PAS to Polish Polar Station in Hornsund, Spitsbergen.

(September 2001 – February 2008) – assistant, Institute of Geophysics PAS, Department of Magnetism, Palaeomagnetic Research Group.

(March 2008 – February 2017) – assistant professor, Institute of Geophysics PAS, Department of Magnetism, Palaeomagnetic Research Group.

(March 2017 - now) – geophysicist, Institute of Geophysics PAS, Department of Magnetism, Palaeomagnetic Research Group.

4. Scientific achievement according to Dz. U. 2016 poz. 882/Dz. U. 2016 poz. 1311.

a) Title of the scientific achievement.

Identification of tectonic rotations within metamorphic basement of Central Western Spitsbergen based on palaeomagnetic, structural, petrographic and isotopic investigations

b) List of scientific publications setting the basis for habilitation procedure.

[1] **Michalski K.,** Nejbert K., Domańska-Siuda J. & Manby G. 2014. New palaeomagnetic data from metamorphosed carbonates of Western Spitsbergen, Oscar II Land. *Polish Polar Research* **35**: 553–592, doi: 10.2478/popore-2014-0031.

[2] **Michalski K.,** Manby G., Nejbert K., Domańska-Siuda J. & Burzyński M. 2017. Using palaeomagnetic and isotopic data to investigate late to post-Caledonian tectonothermal processes within the Western Terrane of Svalbard. *Journal of the Geological Society* **174**: 572-590, doi: /10.1144/jgs2016-037.

[3] Burzyński M., **Michalski K.**, Nejbert K., Domańska-Siuda J. & Manby, G. 2017. High-resolution mineralogical and rock magnetic study of ferromagnetic phases in metabasites from Oscar II Land, Western Spitsbergen—towards reliable model linking mineralogical and palaeomagnetic data. *Geophysical Journal International* **210**: 390–405, doi: 10.1093/gji/ggx157.

[4] Burzyński M., **Michalski K.**, Manby G. & Nejbert K. 2018. Mineralogical, rock-magnetic and palaeomagnetic properties of metadolerites from Central Western Svalbard. *Minerals* **279**, 8 (7), 28 pages, doi:10.3390/min8070279.

Michalski K. 2018. Palaeomagnetic record of the Kongsfjorden islands (western Spitsbergen) – toward better understanding of late- to post-Caledonian tectonic rotations. *Polish Polar Research* **39 (1)**: 51-75, doi: 10.24425/118738.

c) Description of the scientific goals of the above papers, the results presented and discussions of the application.

Introduction

The palaeomagnetic method has proven to be significantly important in the study of orogenic belts and their metamorphic complexes (e.g. Piper 2009, Appel *et al.* 2012). Palaeomagnetic investigations can provide answers to many questions relating to the evolution of such complexes that cannot be provided by structural analytical methods. Important thermal events which effect the rock complexes simultaneously influence its palaeomagnetic record. From a comparison of the obtained VGPs (Virtual Geomagnetic Poles[1]) with the reference APWP (Apparent Polar Wander Path) those thermal overprints can be dated. Any inconsistency of the VGP with the reference APWP can be explained by palaeogeographic separation, regional tectonic rotations or small-scale tectonic geometry modifications. Such palaeomagnetic experiments require a multidisciplinary approach with a detailed structural, petrographic and mineralogical recognition of palaeomagnetically investigated material. **The main aim of the multidisciplinary analyses presented in this dissertation was to develop a comprehensive model for tectonic evolution of Central Western Svalbard (Fig. 1). This dissertation is based on five publications (Michalski *et al.* 2014, 2017, Burzyński *et al.* 2017, 2018, Michalski 2018).**

According to Harland & Wright (1979) Caledonian basement of Svalbard can be divided into smaller crustal units – terranes which before Late Devonian time were distributed along the Eastern and Northern Greenland margins. This model was questioned by Michalski *et al.* (2012) who, on the basis of their palaeomagnetic results from Hornsund and isotopic data from the Billefjorden Fault Zone, suggested a Late Silurian time for the amalgamation of the terranes. **The Palaeomagnetic samples presented in the study were taken from the Oscar II Land area of the Western Caledonian Svalbard Terrane (WCST) and the Kongsfjorden area of the Central Caledonian Svalbard Terrane (CCTS) *sensu* Harland and Wright, 1979)**, assigned to North Greenland – Pearya Province (NGPP) and Eastern North Greenland Province (ENGP) respectively (Harland 1997). More recently, other authors have redefined the division of Caledonian Terranes proposed by Harland & Wright (1979) suggesting, in addition, that they would be better described as the Southwestern (SWBP), Northwestern (NWBP) and the Northeastern (NEBP) basement provinces (Gee 1986, Gee &

[1] List of acronyms used in dissertation is presented in the final section of the document

Page 1994). These latter divisions have been adopted by a number of authors including (Gee & Tebenkov 2004, Kośmińska *et al.* 2014, Mazur *et al.* 2009, Majka *et al.* 2015) and they appear in the Geoscience Atlas of Svalbard (Dallmann *et al.* 2015). Accordingly, the Oscar II Land area constitutes a part of the SWBP while the Kongsfjorden area is assigned to NWBP provinces (Dallmann *et al.* 2015).

The Caledonian basement of Western Spitsbergen has been subjected to several late to post-Caledonian tectonic and tectono-thermal events. Caledonian greenschist facies metamorphism was followed by Late Devonian – Early Carboniferous Svalbardian (Ellesmerian ?) deformation events (*e.g.* Manby & Lyberis 1992, Bergh *et al.* 2011, Majka *et al.* 2017), Late Paleozoic - Mesozoic extensional tectonism including Cretaceous injection of dolerites (*e.g.* Nejbert *et al.* 2011, Clark *et al.* 2014, Polteau *et al.* 2016), Late Cretaceous - Paleogene Eurekan (*sensu lato*) intracontinental folding and thrusting (*e.g.* Lyberis & Manby 1993, Maher *et al.* 1995, Bergh *et al.* 1997, Braathen *et al.* 1999, Leever *et al.* 2011, Piepjohn *et al.* 2016) as well as extension related to the opening of the North Atlantic system (*e.g.* Eiken 1994, Brevik 2003). The lithological responses of the metamorphic complex rocks to the subsequent brittle events noted above and the lack of any extensive Late Paleozoic/Mesozoic cover across large areas of Western Spitsbergen render it difficult to assess how far the younger processes have modified the geometry of the metamorphic basement. The lack of any significant post-Caledonian thermal events in the region often make it difficult to distinguish some of the Caledonian effects from those formed during the Eurekan deformation event.

Here, an attempt is made to define precisely the parameters and the origin of the components of the Natural Remanent Magnetization (NRM) in the metamorphic basement of Central Western Spitsbergen. Potentially, pre-Caledonian (primary ?) components could quantify the spatial palaeogeographic relations between the two investigated terranes/provinces and the adjacent Laurentia, Baltica continents before the final Caledonian amalgamation. In turn, using late to post-Caledonian secondary NRM components, tectonic rotations within the basement can be traced. To this end 16 palaeomagnetic sites of metabasites from Oscar II Land as well as 21 palaeomagnetic sites of metacarbonates from Oscar II Land and Kongsfjorden areas were sampled. An additional 4 sites representing the unmetamorphosed sandstones infilling fractures within the metamorphic basement of the Kongsfjorden area were collected. A t**otal of 279 independently oriented**

palaeomagnetic samples from 41 sites were subjected to palaeomagnetic and rock-magnetic procedures.

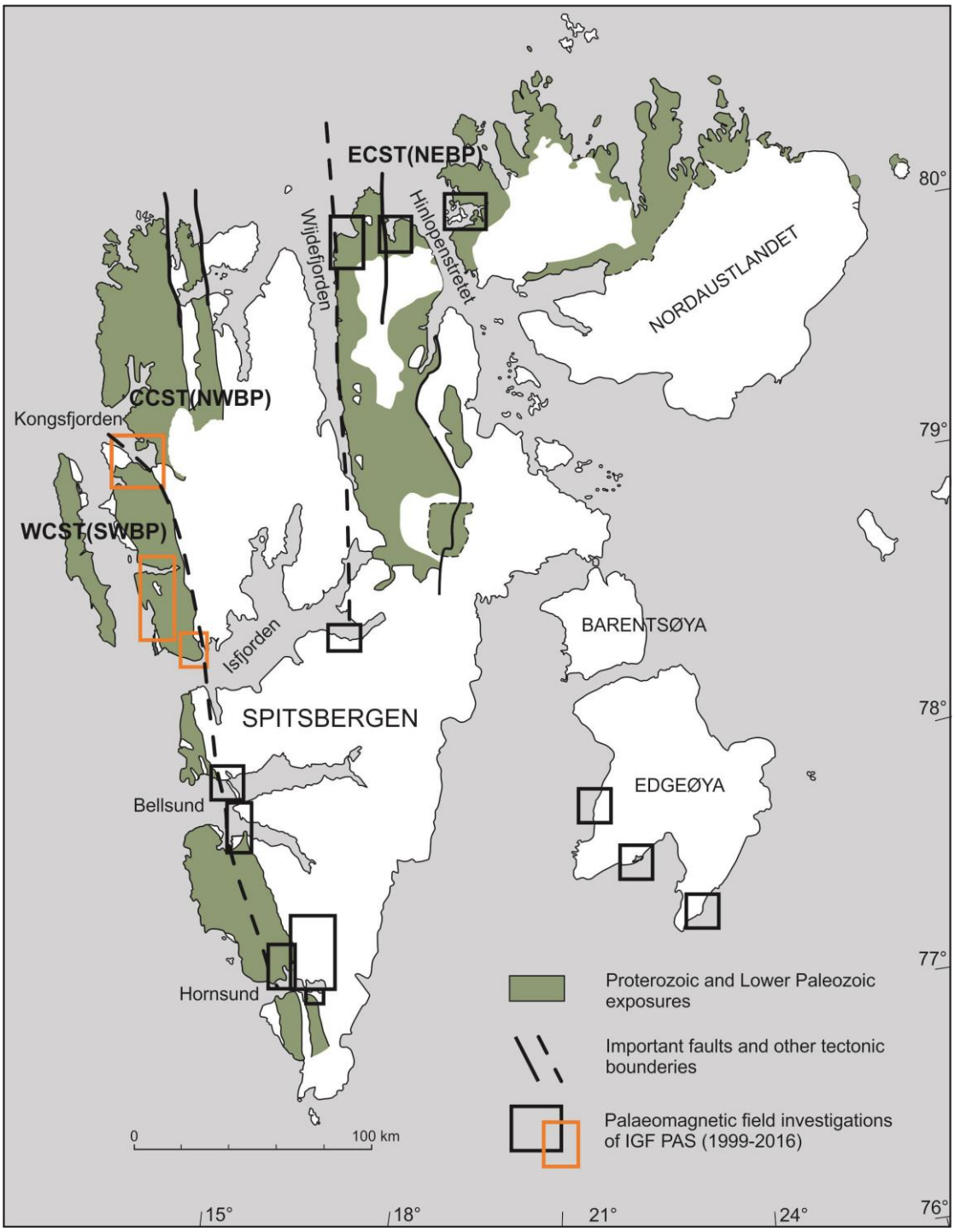

Fig. 1. Geological sketch of Svalbard Archipelago. Orange rectangles indicate areas of investigations related to habilitation dissertation (Oscar II Land and Kongsfjorden). Black rectangles represent other areas of palaeomagnetic field investigations of IGF PAS, 1999 - 2016 (I led most of them except palaeomagnetic investigations of Bellsund in 2016). Palaeomagnetic samples collected in Hornsund (1999-2004) were partly included into my Ph. D. dissertation. Palaeomagnetic field investigations of Edgeøya (2016) were organized in

the course of Norwegian „Trias North" project coordinated by University of Oslo. Symbols of Caledonian terranes / provinces are explained in the text.

In this work the VGPs calculated from the identified NRM components were compared to APWP of Baltica, Laurentia and Laurussia (Torsvik *et al.* 2012). The majority of published palaeomagnetic data demonstrate that Svalbard was a part of Baltica at least from Devonian (e.g. Jeleńska & Lewandowski 1986, Michalski & Lewandowski 2004, Nawrocki 1999, Lewandowski *et al.* 2005) or even from Late Silurian time (Michalski *et al.* 2012). **Considering previously published palaeomagnetic data from Svalbard including those of Michalski et al. (2012), any significant inconsistency of the secondary late to post – Caledonian Svalbard palaeopoles with the Baltica/Laurussia reference path can be explained by tectonic rotations rather than a palaeogeographic separation. In the experiments presented, the "independent estimation of the age" of the identified secondary NRM components was crucial. The integrated petrographic, mineralogical and structural observations supported by the separation of ferromagnetic minerals allowed, in many cases, the observed ferromagnetic carriers to be assigned to particular stages of rock evolution and narrow the time window of magnetization. The possible survival of any pre-Caledonian (primary) palaeomagnetic carriers was of particular interest.** Alongside the palaeomagnetic procedures, *in situ* $^{40}Ar/^{39}Ar$ data obtained from the adjacent host rocks, allowed us to identify the ages of the most important thermal events that may have generated secondary magnetic overprints in the investigated area. The Low field Anisotropy of Magnetic Susceptibility (AMS) ellipsoids were monitored in each of the investigated palaeomagnetic sites to exclude from further analyses those directions that could be tectonically disturbed.

The investigations were conducted via multidisciplinary international cooperation. Palaeomagnetic and rock-magnetic experiments conducted in the Laboratory of Palaeomagnetism Institute of Geophysics Polish Academy of Sciences (IGF PAS) were supplemented by detailed structural recognition of sampled sites by Dr Geoffrey Manby from Natural History Museum of London, Great Britain. Precise *in situ* $^{40}Ar/^{39}Ar$ age determinations of adjacent host-rocks were performed by Dr Sarah Sherlock at the Geochronology Centre for Earth, Planetary, Space and Astronomical Research (CEPSAR), Faculty of Science, The Open University, Great Britain. Petrographic and mineralogical experiments were conducted by Dr Krzysztof Nejbert and Justyna Domańska – Siuda at the University of Warsaw Inter-Institute Analytical Complex, in the Faculty of Geology. The

separation of ferromagnetic carriers from the Oscar II Land metabasites and rock-magnetic experiments on ferromagnetic separates proved an important part of the investigations. Selected part of those experiments formed the core of Mariusz Burzyński's (M.Sc.) Ph. D. dissertation entitled "Palaeomagnetic, rock–magnetic and petrographic investigations of meta-magmatic rocks of the Western Spitsbergen" (main supervisor: Prof. dr hab. Marek Lewandowski IGF PAS; co-supervisor: Dr Krzysztof Michalski IGF PAS; Burzyński 2018).

This study is the part of the PALMAG project (2012-2016) entitled "Integration of palaeomagnetic, isotopic and structural data to understand Svalbard Caledonian Terranes assemblage" funded by Polish National Science Centre (NSC) – grant number 2011/03/D/ST10/05193 (led by Dr Krzysztof Michalski, IGF PAS).

My participation in presented study

I have been involved in palaeomagnetic and geological studies of Svalbard since 1999. My previous Arctic scientific experience allowed me to properly define the priority of the scientific goals related to the Caledonian basement of Svalbard and successfully apply for funding of a carefully constructed plan of multidisciplinary investigations. I was responsible for conceptualization of the "PALMAG" project (2012 – 2016) which constitutes the basis of the "scientific achievement" presented. I gathered together leading experts in structural geology, isotopic investigations and the identification of ferromagnetic minerals. I successfully managed the scientific team and the funding of the "PALMAG" project which resulted in the timely production of important scientific data that has been published in peer-reviewed scientific journals recorded in the in JCR database.

A. I was responsible for the concept of the fieldwork and coordinated four scientific expeditions to Oscar II Land, Forlandsundet and Kongsfjorden (2006, 2012, 2013, 2015), during which the material for analysis presented here was collected.
B. As the leader of the PALMAG project I was responsible for the general concept and coordination of all laboratory experiments (detailed structural, mineralogical, petrographical and isotopic investigations were co-coordinated and conducted by particular scientists involved in the PALMAG project: Dr G. Manby, Dr K. Nejbert, Dr J. Domańska-Siuda, Dr S. Sherlock respectively).

C. I am the only author of the detailed concept of majority of presented palaeomagnetic and rock-magnetic experiments. I coordinated laboratory investigations. I directly conducted selected experiments. The only exception is the part of the laboratory work related to Mariusz Burzyński's (M.Sc.) Ph.D. dissertation (Burzyński 2018).

D. I processed the palaeomagnetic data obtained using available palaeomagnetic software (except 6 sites of metadolerites from SW Oscar II Land, Burzyński *et al.* 2018). I performed the statistical selection, identified the NRM components, calculated the VGPs and compared them with the available reference data for Baltica, Laurentia and Laurussia (Torsvik *et al*. 2012).

E. From the palaeomagnetic results obtained I prepared the final palaeogeographic and tectonic simulations. I modeled rotations around Euler poles for different positions and those related to contractional and extensional tectonic regimes. It should be pointed out that those final tectonic models also employ data obtained by other members of the PALMAG team (structural data provided the basis of the tectonic corrections, petrographic and mineralogical experiments led to the age estimation of the carriers of particular NRM components). It is evident, therefore, that all members of the PALMAG team contributed toward the final interpretations.

F. As the corresponding author I fully coordinated and largely wrote three of five presented publications (Michalski *et al.* 2014, 2017, Michalski 2018). I actively took a part in preparation of two other manuscripts (Burzyński *et al.* 2017, 2018). coordinated by my Ph.D. student Mariusz Burzyński (M.Sc.) In the latter two papers I was co-author of the final tectonic and paleogeographic interpretation of the achieved results. I was also responsible for the final corrections and improvements of entire manuscripts.

Overview of publication number 1

The first manuscript published in *Polish Polar Research* presents the results of the multidisciplinary palaeomagnetic, structural and petrographic investigations of the Proterozoic – Lower Paleozoic metacarbonates from St. Jonsfjorden, Western Oscar II Land. The investigated area belongs to WCST (*sensu* Harland & Wright 1979) and to SWBP (sensu Dallmann *et al.* 2015) basement structural units. The structural observations confirmed the polyphase evolution of the investigated rocks. Two ductile D1 & D2 tectonic events related to the Caledonian metamorphism were followed by late to post-Caledonian (Eurekan?) brittle deformation events.

It is pointed out in the manuscript that D1 and D2 events were accompanied by extensive carbonate and quartz veining which reflects dewatering and fluid migration. Dehydration and complex Caledonian deformations destroyed the primary structure of the metacarbonates and rendered them less susceptible to deformation. As the consequence, it is suggested here that the post-metamorphic deformation of the metacarbonates was restricted mainly to rigid blocks displacements.

Petrographic analyses revealed that the metacarbonates, in the course of greenschist facies metamorphism, were subjected to extensive thermally induced recrystallization and its primary (pre-metamorphic) fabric was spatially reorganized. Combined petrographic, mineralogical and rock-magnetic experiments proved that in the course of metamorphism the primary (detrital/diagenetic) ferromagnetic (*sensu lato*) assemblage was completely replaced by secondary ferromagnetic (*sensu lato*) carriers. Monoclinic secondary pyrrhotite appeared to be dominant ferromagnetic carrier.

Of the twelve investigated palaeomagnetic sites statistically significant results were obtained only from the SW overturned limb of the Holmesletfjellet Syncline. The scattering of the directions in the other eleven sites is partly explained in the manuscript by the low signal of the NRM (<0.2 mA/m) and as the consequence incomplete thermal cleaning of particular NRM components. A scattering of directions in particular sites can be partly induced by D3 brittle deformation.

The most stable middle-temperature NRM component from the SW Holmesletfjellet site does not fit the Baltica reference path. This component is carried by pyrrhotite, which is more probably of metamorphic origin. Its coincidence with Silurian-Devonian sector of the reference path requires 130^0 unfolding of the Holmestelfjellet Syncline. This result suggests synfolding origin of Holmesletfjellet pyrrhotite magnetization. The original, Late Caledonian, upright open fold was apparently rotated during the later progressive, eastward-directed, Eurekan (?) thrust fault motion.

Overview of publication number 2

The article number 2 published in *Journal of the Geological Society of London* comprises results of palaeomagnetic investigations of 10 sites of the Proterozoic-Lower Paleozoic (?) metabasites from Western Oscar II Land (St. Jonsfjorden, Venernbreen moraine, Kinnefjellet, Ommafjellet). The investigated area constitutes the part of WCST (*sensu* Harland & Wright

1979) and the part of SWBP (sensu Dallmann *et al*. 2015). Detailed rock-magnetic and petrographic study suggest intensive remagnetization of the metabasites during greenschiest facies metamorphism. *In situ* $^{40}Ar/^{39}Ar$ age determinations simultaneously conducted in adjacent host rocks revealed three important thermal events in the 426-380 Ma Caledonian (*sensu lato*) and the 377-326 Ma and c. 300 Ma intervals which could have influenced the magnetic record. The latter two can be linked to Devonian-Carboniferous and Carboniferous – Permian rift – conditioned subsidence events recognized in SW Barents Shelf (Clark *et al.* 2014).

The VGPs calculated according to the most stable middle-high temperature NRM components recognized in the metadolerites do not fit any sectors of the reference Baltica – Laurentia - Laurussia APWP but they are clustered east of the reference path. In the manuscript several palaeogeographic and tectonic models were tested to explain observed inconsistency.

A. A Great circle palaeogeographical model (A) reflects a lateral displacement of the Western Svalbard block along a large-scale lineament, such as a strike-slip fault, toward Pearya. This solution, however, does not change significantly the position of calculated VGPs with relation to reference Baltica – Laurentia – Laurussia reference path. It should be emphasized that the presented results do not rule out the role of large-scale strike slip faulting in modification of Svalbard-Greenland-Pearya palaeogeography and tectonism. Such rotations do not explain, however, the obtained palaeomagnetic results.
B. A Small circle palaeogeographical model (B) implies rotation toward Pearya around vertical axis which is situated in vicinity of the Western Spitsbergen. Such model requires however substantial rotation of Western Svalbard with respect to Greeenland and existence of significant east-west extensional regime between Western Svalbard and Pearya which is not supported by the geological evidence.
C. The first of the tectonic model's (C) links rotations of the paleomagnetic directions with thrusting and with transport of the thrusts along the listric surfaces to the East. Such a mechanism, however, increases the distance between calculated site means and the reference path.
D. Finally, the second tectonic model (D) is related to extension and faulting of Western Spitsbergen during opening of North Atlantic system which could have resulted in eastward tilting of the basement blocks along west-dipping listric normal faults. Such correction of 40^0 for listric faulting will move part of observed site means back to the

Carboniferous sector of the reference path. This solution is consistent with results of $^{40}Ar/^{39}Ar$ age determinations which point out to important Carboniferous-Permian thermal overprints within Western Svalbard.

In the article, for the first-time, an important role of listric faulting modifying the geometry of Western Spitsbergen Caledonian basement proved likely. Simultaneously, again for the first time, important Late Palaeozoic thermal events (377-326 Ma and c. 300 Ma) within Caledonian basement were notified.

Overview of publication number 3

The manuscript number 3 published in *Geophysical Journal International* constitutes continuation and simultaneously complementary part of the experiments presented in *Journal of Geological Society*. Rock-magnetic investigations which were conducted on the Western Oscar II Land metabasites were supplemented by the separation of the ferromagnetic phases. In the manuscript a comparison of the "whole-rock" rock magnetic experiments and those conducted directly on "ferromagnetic separates" is presented.

The main question here was "are there any relicts of pre-Caledonian (primary) ferromagnetic (*sensu lato*) carriers in the investigated metabasites that survived the greenschist facies metamorphism". Several mineralogical (optical, SEM - Scanning Electron Microscopy, BSE – Backscatter Electron Imaging) as well as rock-magnetic procedures (determination of the coercivity spectra and parameters of hysteresis loops, SIRM - Saturation Isothermal Remanent Magnetization, three component IRM - Isothermal Remanent Magnetization experiments) were applied to identify ferromagnetic (*sensu lato*) phases and describe their relations to rock-forming minerals.

In the metadolerites experiments, the abundance of ferromagnetic (*sensu lato*) minerals related to Caledonian metamorphism – pyrrhotite and magnetite were confirmed. Two groups of grains were selected as potential source of pre-metamorphic palaeomagnetic signal. Those were grains of ilmenite containing visible voids after dissolution of magmatic hematite as well as titanite pseudomorphs after primary/magmatic magnetite. The rock-magnetic experiments conducted on ferromagnetic separates suggests, that also in those two kinds of grains the process of metamorphic recrystallization and dissolution were completed. Grains of ilmenite did not reveal ferromagnetic signal. The weak ferromagnetic signal in titanite grains is probably related to metamorphic magnetite or maghemite.

Detailed rock-magnetic investigations of metavolcanics allowed for precise location of ferromagnetic signal carriers but did not exclude existence of pre-Caledonian record. Considering, however, the high inclination of the dominant NRM component (s) it should be concluded that the palaeomagnetic record in metavolcanics is dominated by Late Mesozoic – Cenozoic remagnetization.

Overview of publication number 4

In the article number 4 published in *Minerals* the palaeomagnetic results from 6 additional metabasite sites from SW Oscar II Land (Daudmanndalen, Daudmannsøyra, Protectorbreen) are presented. Combined petrological, mineralogical and rock-magnetic studies supported by experiments on magnetic separates suggest a lack of any relicts of pre-Caledonian (primary) ferromagnetic (*sensu lato*) minerals. Magmatic Fe, Fe-Ti oxides were replaced by metamorphic titanite and anatase. Dominating carriers of palaeomagnetic signal are metamorphic pyrrhotite and Fe – oxides.

In five of the six sites precisely defined low-temperature site means (demagnetized below 250^0C) revealed high inclinations (~70-80^0) which points to a Mesozoic-Cenozoic remagnetization event. In contrast, statistically significant middle-high temperature components (demagnetized above 250^0C), potentially of metamorphic origin, were obtained only from two sites. The VGPs calculated according to those two-site means that qualified for further tectonic interpretation are significantly shifted from the combined APWP of Baltica - Laurentia - Laurussia. The observed shift of the VGPs from the Caledonian (*sensu lato*) sector of the reference path can be the combined effect of Late Mesozoic – Cenozoic listric faulting of the Caledonian basement identified in the Western Oscar II Land and additional rotations generated by localized shearing and west-dipping families of small scale faults observed in investigated area.

Overview of publication number 5

Article number 5 published in *Polish Polar Research* comprises the paleomagnetic results from metamorphic basement of Kongsfjorden (Blomstrandhalvøya and Lovénøyane islands). In contrast to the previous four presented papers, this manuscript comprises the data from Central Caledonian Svalbard Terrane (CCST) *sensu* Harland & Wright (1979) or the Northwestern Basement Province (NWBP) *sensu* Dallmann *et al*. (2015). Metacarbonates from 9 sites and undeformed red sandstones from 4 sites infilling the irregular fractures within

metamorphic basement of Kongsfjorden were subjected to palaeomagnetic and rock-magnetic procedures supplemented by AMS experiments.

No relicts of pre-Caledonian palaeomagnetic record were identified. The VGPs from the metacarbonates fit the Caledonian (*sensu lato*) - Svalbardian? and Late Mesozoic/Cenozoic sectors of the Baltica-Laurussia APWP, suggesting two important pulses of remagnetization.

VGPs calculated from the red sediments infilling the karstic/tectonic fractures, fit the Caledonian (*sensu lato)*, Carboniferous and Late Mesozoic/Cenozoic sectors of the reference path, pointing to three important stages of magnetization. Palaeomagnetic results from fracture-infillings confirm that fracturing and karstification of Caledonian basement could have taken place as early as the Late Silurian – Early Devonian interval following the collapse and unroofing of the Caledonian Orogen (Braathen *et al*. 2017).

The majority of the VGPs calculated according to *in situ* components identified in Kongsfjorden fit the Caledonian up to Mesozoic-Cenozoic sectors of the Baltica-Laurussia reference path. This observation supports the thesis that the sampled metamorphic basement of Kongsfjorden islands escaped the main Eurekan deformation events (e.g. Thiedig *et al.* 2001), which are evident in the adjacent Brøggerhalvøya Peninsula (e.g. Bergh *et al.* 2000, Saalmann & Thiedig 2001, 2002). Modification of the Blomstrandhalvøya geometry and Lovénøyane islands by listric faults activity related to the opening of the North Atlantic, postulated in the publication number 2 (Michalski *et al.* 2017), in adjacent Forlandsundet/Oscar II Land area, was not confirmed.

Summary:

This dissertation constitutes an original and interdisciplinary approach. The leading palaeomagnetic method was supplemented by precisely designed set of additional experiments which allowed a proper interpretation of the palaeomagnetic data. Multidisciplinary petrographical – mineralogical – rock magnetic analyzes, including experiments performed on magnetic separates, led to the determination of the origin of the ferromagnetic (*sensu lato)* carriers. *In situ* ^{40}Ar/^{39}Ar age determinations of the host rocks estimated the time of important thermal events which could have influenced the palaeomagnetic record. Particular stages of the investigations were proceeded in close cooperation with an experienced structural geologist. The final interpretation employed different palaeogeographic models was based on variable positions of Euler pole. The

applied tectonic models considered rotations related to contractional as well as extensional regimes. Simultaneously, the dissertation represents a pioneering series of investigations. The Caledonian basement of Central Western Spitsbergen has not been, until now, analyzed palaeomagnetically. The multidisciplinary and innovative analyzes presented here have confirmed their effectiveness in recognizing rotations within the Oscar II Land – Kongsfjorden Caledonian basement suggesting that such an approach would be useful in the interpretation of other tectono-metamorphic complexes.

Direct scientific achievements of presented study are as follows:

1. In the investigated metamorphosed rocks from Central Western Spitsbergen (Oscar II Land, Kongsfjorden) which constitute the part of WCST/CCST terranes *sensu* Harland & Wright (1979), alternatively the part of SWBP/NWBP provinces *sensu* Dallmann *et al.* (2015), no relicts of pre-Caledonian palaeomagnetic carriers were identified. The examined metacarbonates were found to have been subjected to extensive recrystallization and spatial reorganization of their primary structures and mineral associations. Both metacarbonates and metadolerites contained common break-down or replacements of the detrital/magmatic ferromagnetic (*sensu lato)* minerals by secondary palaeomagnetic carriers.
2. *In situ* $^{40}Ar/^{39}Ar$ age determinations of the host rocks of WCST/CCST terranes (SWBP/NWBP provinces) revealed three important thermal events which could have influenced the magnetic record of the investigated area. Those are 426 – 380 Ma related to Caledonian *sensu lato* metamorphism and two younger overprints at 377-326 Ma and *c.* 300 Ma, that were recognized for the first time in this study and which can be correlated with rift-conditioned subsidence and extension of the Western Barents Shelf in Devonian-Carboniferous (Svalbardian?) and Carboniferous – Permian times respectively.
3. The presented palaeomagnetic results reveal that the geometry of the Caledonian basement of Central Western Spitsbergen was modified in variable degree.

A. For the first time, important role of listric faulting in modification of Western Oscar II Land onshore area geometry was noted. The presence of listric faults is modelled on offshore seismic profiles that are considered to be related to the opening to the North Atlantic Ocean.

B. Distinct sites within Oscar II Land, such as the Holmesletfjellet Syncline, reveal syn-folding magnetization which overprints the ductile Caledonian schistosity and predates brittle late or post-Caledonian (Eurekan?) significant refolding.
C. The results from Kongsfjorden suggest that this area escaped the main Eurekan deformation. In contrast to the adjacent Oscar II Land area, any modification of Kongsfjorden Caledonian basement by west dipping listric faults could not be confirmed.

5. Other scientific achievements

1b. Age determination of the final amalgamation of Caledonian Terranes of Svalbard based on palaeomagnetic investigations of Southern Spitsbergen and isotopic study of Billefjorden Fault Zone

The Palaeomagnetic and rock-magnetic investigations of Southern Spitsbergen presented in this chapter (1b) were conducted in the course of my Ph.D. research (Michalski 2007). The data derived from additional published (Szlachta *et al.* 2008, Michalski *et al.* 2012) isotopic and Mössbauer spectroscopy analyses obtained after submission of my Ph.D. thesis are included in this dissertation as they have contributed significantly to the final presented interpretation.

The manuscript concerned with the investigation of the Cambrian Slaklidalen Formation from Hornsund (Southern Spitsbergen) and isotopic analysis of BFZ were published in the *Geological Magazine* (Michalski *et al.* 2012). The secondary palaeomagnetic overprints identified in the Slaklidalen Fm suggests that the Hornsund area (Central Caledonian Svalbard Terrane (CCST) *sensu* Harland & Wright 1979; South Western Basement Province (SWBP) *sensu* Dallmann *et al.* 2015) and Baltica were amalgamated in Silurian time. Furthermore, the 450 Ma $^{40}Ar/^{39}Ar$ isotopic age obtained from the mylonites along the BFZ, which separates the CCST and ECST terranes (provinces NWBP and NEBP), also suggests that motion along the BFZ had effectively ceased by that time. These findings do not support, therefore, the large-scale Late Devonian lateral displacement of Svalbard's Caledonian terranes as proposed by Harland & Wright (1979). The assembled data rather suggests that the amalgamation of the Caledonian terranes was largely accomplished in Silurian time.

The extended abstract from the Polish Mössbauer Community Meeting published in Acta Physica Polonica A (Szlachta *et al*. 2008) presents an interesting comparison of two systems

for the identification of ferromagnetic minerals (*sensu lato*). The results of classic rock-magnetic experiments and those obtained from Mössbauer spectroscopy analysis are confronted. The latter method revealed the occurrence of maghemite in the samples of Cambrian Slaklidalen Formation which was not identified by the rock-magnetic studies.

Szlachta K., **Michalski K.**, Brzózka K., Górka B. and Gałazka – Friedman J. 2008. Comparison of Magnetic and Mössbauer Results Obtained for Palaeozoic Rocks of Hornsund, Southern Spitsbergen, Arctic. Proceedings of the Polish Mössbauer Community Meeting 2008. Acta Physica Polonica A, **Vol. 114, No. 6**, 1675-1682.

Michalski K., Lewandowski M., Manby G.M. 2012. New palaeomagnetic, petrographic and 40Ar/39Ar data to test palaeogeographic reconstructions of Caledonide Svalbard. Cambridge University Press. Geological Magazine **149 (4)**, 696-721.

2b. New palaeomagnetic data from Triassic rocks of Southern Spitsbergen

The presented investigations were concentrated on the southern part of West Spitsbergen Fold and Thrust Belt (WSFTB) - Sørkapp and Torell Land. 13 sites of Lower Triassic Vardebukta Fm were sampled. The samples were subjected to multidisciplinary set of experiments. Palaeomagnetic and rock magnetic procedures were supported by petrographic and mineralogical analyses. Primary Triassic directions were not confirmed in any of investigated sites. Sites localized within Eurekan belt revealed complicated NRM structure which in many cases indisposed identification of NRM components. Better grouping of calculated VGPs from Torell Land in the L. Mesozoic – Cenozoic sector of the Baltica reference path after unfolding of the sampled beds to a horizontal position suggests pre-Eurekan secondary magnetization. This secondary overprint can be related to Cretaceous extension and injection of dolerites (Clark *et al.* 2014, Nejbert *et al.* 2011) or to early stages of WSFTB formation. Low parameters of the vitrinite reflectance (expected T < 200ºC) point to chemical rather than a thermal origin of observed secondary magnetization. This secondary NRM component (s) can be related to common sulphide mineralization recognized in thin sections.

Presented results constitute the main part of Ph. D. thesis of my student M. Sc. Katarzyna Dudzisz, entitled "Palaeomagnetic and rock magnetic investigations of the Triassic rocks from Svalbard Archipelago" (supervisor: dr hab. R. Szaniawski, auxiliary supervisor dr K. Michalski; Dudzisz 2018). The thesis received positive revisions and was publicly defended on 21st September 2018 (the thesis was awarded). The results from Torell Land and N Sørkapp were recently published in Geological Magazine (Dudzisz *et al.* 2018).

Dudzisz K., **Michalski K.**, Szaniawski R., Nejbert K., Manby G. 2018. Palaeomagnetic, rock-magnetic and mineralogical investigations of the Lower Triassic Vardebukta Formation from the southern part of the West Spitsbergen Fold and Thrust Belt. Geological Magazine, First View, DOI: https://doi.org/10.1017/S0016756817001145

3b. Applying the anisotropy of magnetic susceptibility to the study of evolution of the West Spitsbergen Fold and Thrust Belt and its foreland

The AMS experiments were focused on the Lower Triassic Vardebukta Fm. Sampling sites were located in the southern and central sectors of the West Spitsbergen Thrust and Fault Belt – WSFTB (N Sørkapp - S Torell Land, Bellsund) and on its foreland (Sassenfjorden). The main aim of the study was to test the usefulness of the AMS method in defining tectonic mechanisms which led to the formation of particular sectors of WSFTB. Low-field AMS were supported by high-field anisotropy measured on a torque magnetometer. To identify the carriers of observed anisotropy several methods were applied including changes of the bulk susceptibility of the specimen's vs temperature, three-component IRM experiments (Lowrie 1990) and registration of hysteresis parameters. Paramagnetic minerals (potentially phyllosilicates and Fe-rich carbonates) appeared to be the main AMS signal carriers. As the AMS axis can reflect strain directions, the measurements of magnetic anisotropy can supplement structural observations and deliver important arguments to the ongoing discussion regarding the wider palaeogeographic and geotectonic context of the origin of WSFTB (e.g. Lyberis & Manby 1993, Maher *et al.* 1995, Leever *et al.* 2011). The results presented confirm that the sampled sectors of the WSFTB (Hornsund, Bellsund) formed in a compressional regime. Testing of the strain partitioning model requires sampling of other parts of WSFTB. The AMS for the Sassenfjorden, which was not affected by the main Eurekan deformation, is dominated by the Triassic palaeocurrent directions.

Investigation of the Lower Triassic Vardebukta Fm AMS constitutes one of the main topics of Ph.D. thesis of my student M.Sc. Katarzyna Dudzisz (Dudzisz 2018). The AMS results were presented in two manuscripts published in Polar Research (Dudzisz *et al.* 2016) and in Tectonophysics (Dudzisz et al. 2018).

Dudzisz K., Szaniawski R., **Michalski K.**, Manby G. 2016. Applying the anisotropy of magnetic susceptibility technique to the study of the tectonic evolution of the West Spitsbergen fold-and-thrust belt. Polar Research 2016, 35, 31683.

Dudzisz K., Szaniawski R., **Michalski K.**, Chadima M., 2018. Rock magnetism and magnetic fabric of the Triassic rocks from the West Spitsbergen Fold-and-Thrust Belt and its foreland. Tectonophysics 728–729, 104-118.

4b. Tectonics and palaeogeography of North-Eastern Svalbard based on integrated palaeomagnetic structural, petrographical and isotopic investigations of Ny Friesland and Nordaustlandet

This study constitutes another part of PALMAG NSC project (grant number 2011/03/D/ST10/05193) which was described in details in the previous parts of this dissertation. This time the samples were collected from remote areas of the Northern Ny Friesland and Murchisonfjorden in the Western Nordaustlandet. The area of investigations belongs to the Eastern Caledonian Svalbard Terrane (ECST) *sensu* Harland & Wright (1979) and the Northeastern Basement Province (NEBP) *sensu* Dallmann *et al.* (2015). Palaeomagnetic samples were collected from the Proterozoic amphibolites and metacarbonates of Ny Friesland (9 sites) and Neoproterozic unmetamorphosed carbonates and tillites of Murchisonfjorden (6 sites). Palaeomagnetic investigations (conducted in IGF PAS) were supplemented by *in situ* $^{40}Ar/^{39}Ar$ age determinations (conducted in the Open University, UK) of amphibolites of the Western Ny Friesland and mylonites from adjacent Eolusletta Shear Zone. The study was supported by careful petrographical examination of sampled rocks as well as detailed structural observations of the palaeomagnetic sites and their vicinities.

The palaeomagnetic results suggest a common Caledonian (*sensu lato)* remagnetization of the Ny Friesland rocks. Simultaneously, the 340–460 Ma interval gained from isotopic studies corresponds broadly to the Caledonian thermal event. The unique palaeomagnetic results from Murchisonfjorden (Nordaustlandet) appear to represent a primary Neoproterozoic record. Analysis of palaeolatitudes from Murchisonfjorden suggests that at least, through part of Neoproterozoic (Cryogenic?) time, Eastern Svalbard appears to have been positioned a minimum of 10º to the North of NW Baltica, on the palaeolatitudes coeval with those expected for NE Laurentia (Greenland/Ellesmere Island). Further comparison of palaeopoles calculated for the Murchisonfjorden sites with the key reference Neoproterozoic palaeopoles for Baltica and Laurentia (after Buchan 2013) suggests that, at least through part of Neoproterozoic (Cryogenic?) time, Eastern Svalbard could have constituted a separate microplate.

The results of multidisciplinary investigations of Ny Friesland – Nordaustlandet area were presented during 33rd Nordic Geological Winter Meeting in Copenhagen, Denmark, in January 2018 (Michalski *et al.* 2018) as well as during 16th Castle Meeting in Chęciny, Poland, in June 2018 (Michalski 2018). The manuscript of publication was sent to *Journal of Geological Society of London* and it is under review (title of the manuscript: "Palaeomagnetic investigations across Hinlopenstretet border zone: from Caledonian metamorphosed rocks of Ny Friesland to foreland facies of Nordaustlandet (NE Svalbard)"; authors: Michalski K., Manby G. Nejbert K., Domańska – Siuda J., Burzyński K.)

Michalski K., Manby G. Nejbert K., Domańska – Siuda J., Burzyński K. 2018. Integration of palaeomagnetic, isotopic and structural data to understand Svalbard Caledonian Terranes assemblage. 33rd Nordic Geological Winter Meeting in Copenhagen, Denmark, 10-12 January 2018, book of abstracts, p. 114-115.

Michalski K. 2018. Palaeomagnetism in the High Arctic. Palaeomagnetic Investigations of Svalbard Archipelago conducted by the Institute of Geophysics Polish Academy of Sciences from 1999 to 2018. 16th Castle Meeting "New Trends on Paleo, Rock and Environmental Magnetism", Chęciny, Poland, 10-16 June 2018 (invited talk), *published in* Publications of the Institute of Geophysics Polish Academy of Sciences 423 (C-112), p. 99-100.

5b. Svalgeobase workshop: Proterozoic and Lower Palaeozoic basement of Svalbard – state of knowledge and new perspectives of investigations

Svalgeobase workshop was organized 1-8 September 2013 and managed by a consortium of three institutions: (1) Norwegian Polar Institute (Tromsø, Norway), coordinator Winfried Dallmann; (2) Laboratory of Palaeomagnetism, Institute of Geophysics, Polish Academy of Sciences, Warsaw (Poland), coordinators: Krzysztof Michalski, Piotr Głowacki; (3) Departament of Mineralogy, Petrography and Geochemistry AGH University of Science and Technology, Kraków (Poland), coordinator: Maciej Manecki. The organizers gathered together world leading scientists involved in the investigation of Svalbard's Caledonian basement as well as tectonics of Svalbard and Greenland. The workshop was organized onboard the scientific vessel "Horyzont II". The aim of the expedition was to visit crucial Proterozoic – Lower Paleozoic exposures along Western and Northern Spitsbergen, as well as those in Western Nordaustlandet. The main goals of the workshop were to review and discuss the state of knowledge regarding Svalbard's basement as well as creating a multidisciplinary platform and developing strategies for future investigation of Svalbard and the adjacent Arctic

regions of Greenland and Ellesmere Island. An important aim of this scientific enterprise was to guide and promote early career scientists. The Svalgeobase project was partly funded by the Svalbard Science Forum. A report of the Svalgeobase project including descriptions of the field excursions, extended abstracts of the presentations and an evaluation and strategy for the future was published as monograph by the Norsk Polar Institute.

Official Svalgeobase website (managed by me): svalgeobase.igf.edu.pl

I was co-initiator and co-coordinator of the workshop. I was responsible both for the financial management of the expedition and I shared responsibility for its scientific plan. It was on my initiative that the route of the workshop was extended to take in the exposures of the basement situated in NW and N Spitsbergen and W Nordaustlandet. I was the co-editor of the final report of the Svalgeobase monograph and co-author of four extended abstracts and description of field excursions. I am also the author of the article about Svalgeobase which appeared in Biuletyn Polarny.

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Acronyms

AMS – Anisotropy of Magnetic Susceptibility

APWP – Apparent Polar Wander Path

BSE – Backscatter Electron Imaging

BFZ - Billefjorden Fault Zone

CCST - Central Caledonian Svalbard Terrane

ECST - Eastern Caledonian Svalbard Terrane

ENGP - Eastern North Greenland Province

IGF PAS – Institute of Geophysics Polish Academy of Sciences

IRM – Isothermal Remament Magnetization

NEBP – Northeastern Basement Province

NGPP - North Greenland – Pearya Province

NRM – Natural Remanent Magnetization

NSC - National Science Center

NWBP – Northwestern Basement Province

SEM - Scanning Electron Microscopy

SIRM – Saturation Isothermal Remanent Magnetization

SWBP – Southwestern Basement Province

T_{ub} – unblocking temperature

WCST - Western Caledonian Svalbard Terrane

WSFTB – West Spitsbergen Fold and Thrust Belt

VGP – Virtual Geomagnetic Pole

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