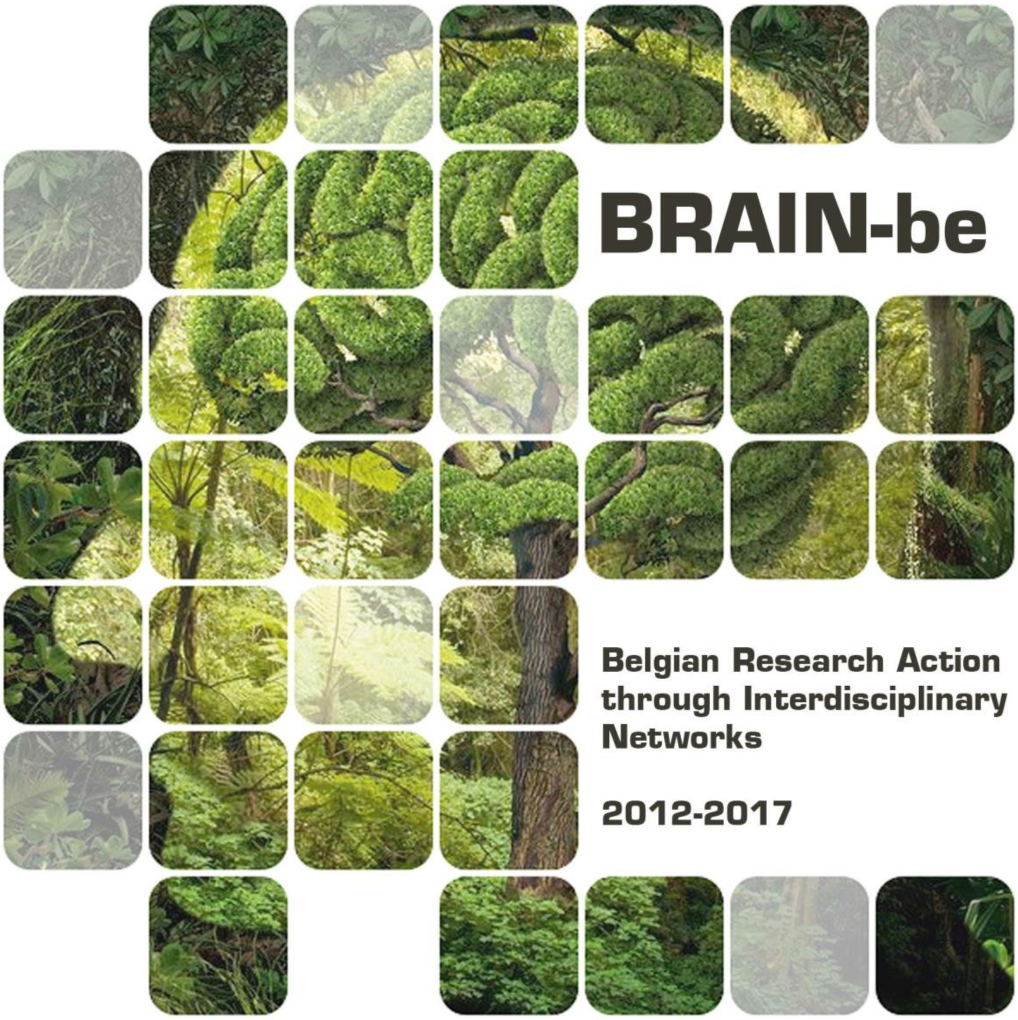

DIABASE

Discovering the Antarctic Basement by using moraines in blue ice fields

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DIABASE

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FINAL REPORT

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ABSTRACT

Context

The vast majority of the Antarctic continent remains concealed beneath a substantial ice layer, obscuring approximately 98% of its underlying lithologies. Only a small number of exposed outcrops offer limited and fragmented insights into the geological history of Antarctica, despite being subject to extensive study. Yet, comprehending this history holds immense significance for addressing crucial inquiries within contemporary geoscience. It allows us to explore fundamental issues like the formation mechanisms of continental crust, the corresponding depletion of the mantle, and their evolution during the early stages of Earth. Additionally, it sheds light on the localized geological processes that played a role in constructing the Antarctic continent.

Objective

During this project, we collected samples from circular moraines previously encountered in the Nansen Blue Ice Field. These blue ice fields exhibit a unique ice movement pattern, including a vertical component caused by obstacles impeding the gravity-driven flow. Consequently, the blue ice fields of Antarctica have yielded more than 40,000 meteorites to date, all concentrated through this specific movement. During past Belgian-Japanese expeditions, closed moraine fields that likely sample the underlying rock formations were unexpectedly observed within the Nansen Blue Ice. Although the transported blocks and boulders, which make up the majority of these moraines, are no longer in their original positions, they represent the only retrievable basement samples from this particular section of the Antarctic continent known as the Sør Rondane area. Among these moraine samples, various types of sedimentary, metamorphic, felsic and basaltic igneous rocks have been observed thus far. The DIABASE project conducted a preliminary petrological examination of these moraine samples and further dated the zircons found within these lithologies using detailed and extensive U-Pb dating techniques employing LA-ICP-MS at the University of Manchester in the United Kingdom. This approach of sampling moraines provides valuable insights into the concealed deep basement of the Sør Rondane area in East Antarctica.

Conclusions

By dating the zircons recovered in the moraines in the Nansen Ice Field, we suggest that on the contrary of the common knowledge of rock transportation by ice flow from south to north in Antarctica, it is also possible that the observed moraines in the Nansen Ice Field do sample outcrops located on the south and drawn back to the north by complex ice flow when encountering an obstacle such as a mountain chain. Only three inherited zircons witness ancient Archean geological events. We demonstrate that the approach of moraine sampling is easy and efficient to perform, but also that understanding the ice flow is a preliminary requirement, that might be complicated to unravel. Following the observations of the DIABASE project, our colleagues in glaciology have decided to tackle the issue of the ice flow at the regional scale around the Nansen Ice Field to explain the concentration in meteorites, but this is beyond the scope of this report as their investigations are ongoing.

Keywords

Antarctica, basement, moraines, zircons

1. INTRODUCTION

The Archean continental crust, comprising a mere 7 to 10% of the currently exposed crust (Artemieva, 2006), poses a challenge for uniformitarian interpretation due to its complex geological features (Bédard, 2013; Gerya, 2014). Consequently, it offers an ambiguous record of the geological processes that prevailed during the early stages of Earth. Understanding these processes, particularly the mechanisms of continental lithosphere formation and differentiation, and their implications for our planet's habitability, remain active topics of debate (Gerya, 2014) and represent crucial questions awaiting resolution in modern geoscience. Notably, the most perplexing aspect pertains to the initiation of mobile-lid plate tectonics, as we currently recognize it, on Earth. Estimates of its commencement range from the Hadean period, approximately 4.0 billion years ago (Harrison et al., 2008), to the late Proterozoic, about 0.6 billion years ago (Stern, 2008), introducing considerable variation in scientific assessments.

The challenges posed by these issues are particularly pronounced in Antarctica due to the fact that approximately 98% of the continent's basement is buried beneath an average ice layer that is 1.6 kilometres thick (Godard and Palmeri, 2013), rendering the majority of outcrops inaccessible. Through indirect geophysical measurements, sedimentary basins (Drewry, 1976) and various crustal-scale suture zones (Drewry, 1976) have been identified, likely resulting from multiple orogenic events (e.g., Boger, 2011; Godard and Palmeri, 2013). Among these events is the Panafrican orogeny, which played a significant role in the formation of the Gondwana supercontinent. This orogeny reached its peak metamorphism approximately 600 million years ago when the proto-East and proto-West portions of Gondwana collided, leaving behind a suture zone in the Sør Rondane Mountains of Dronning Maud Land (e.g., Jacobs et al., 2003; Shiraishi et al., 2008).

The Sør Rondane Mountains, home to the Princess Elisabeth Station (PES), predominantly consist of Proterozoic outcrops (Shiraishi et al., 1991; Shiraishi et al., 2008). These outcrops have undergone metamorphism characterized by low-pressure/high-temperature conditions, which are commonly associated with continental collisions (e.g., Hiroi et al., 1991). Within this region, during the Mesoproterozoic period (around 1000 million years ago), protoliths displaying geochemical characteristics of island arcs were emplaced. These protoliths underwent metamorphism up to amphibolite facies in the southwestern terrane and up to granulite facies in the northeastern part, as a result of the Panafrican orogeny (Shiraishi et al., 2008). Furthermore, through zircon dating, four additional magmatic events have been identified. These events involved the intrusion of granite and syenite plutons, as well as the eruption of mafic dykes, occurring between 650 and 500 million years ago (Elburg et al., 2016).

Contrastingly, relying on limited outcrops, researchers have identified eight complexes of Archaean and Early Proterozoic ages (approximately 2900 to 1700 million years ago) across the entirety of the Antarctic continent, including its central region (Boger, 2011). Nonetheless, a significant portion of the land situated to the south and east of the Sør Rondane Mountains remains unexplored in terms of its geological characteristics (Boger, 2011). This uncharted area holds the potential for housing older crust dating back to the Archaean and Paleoproterozoic eras.

2. STATE OF THE ART AND OBJECTIVES

In the absence of visible and well-preserved outcrops, an effective approach to investigate the geology of the Antarctic continent is through the examination of zircons found in igneous, metamorphic, and detrital rocks. During fieldwork, a wide range of lithologies present in the moraines has been extensively sampled (Figure 1) and later analysed in the laboratory. This investigation involves the extraction of zircons, accompanied by detailed petrography and geochemical studies. Zircons are exceptionally valuable for studying the mechanisms involved in the formation and evolution of the lithosphere throughout Earth's history (Roberts and Spencer, 2014). These minerals serve as excellent U-Pb geochronometers due to their resistance to metamorphism and the precise Concordia dating method facilitated by their high U and low Pb content (Lee et al., 1997). Additionally, zircons exhibit durability and resistance to alteration, making them well-preserved in igneous rocks and detrital sediments. In certain cases, they represent the sole accessible archive of eroded or completely recycled crust. One notable example is the Eoarchean to Hadean zircons discovered in the Jack Hills meta-conglomerate of Australia, with one specimen dating back to 4404 ± 8 million years ago (Wilde et al., 2001).

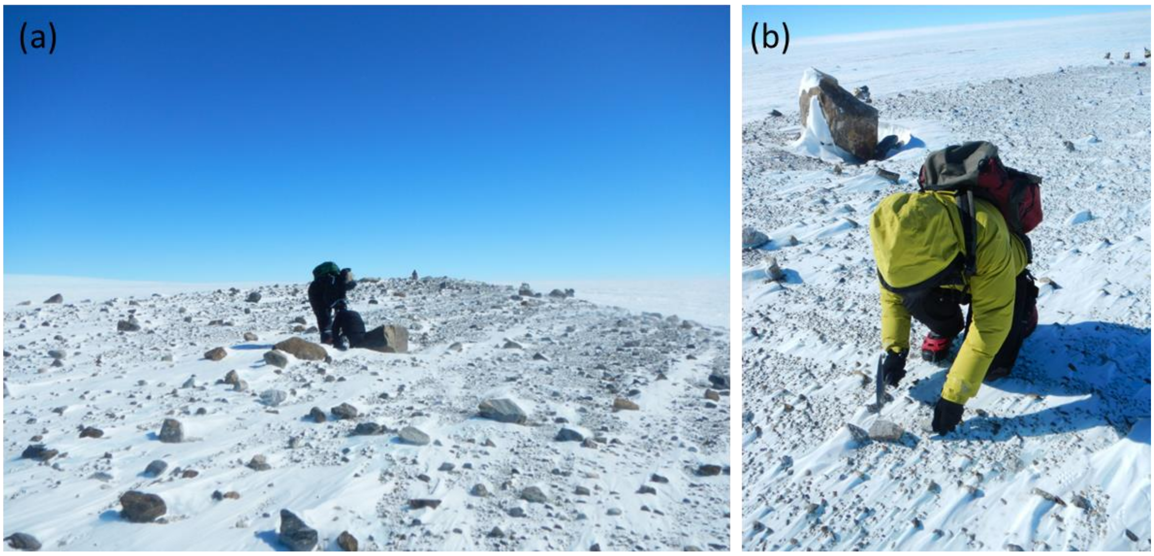

***Figure 1**: Sampling of the moraines encountered on the Nansen Ice Field during the 2012-2013 field campaign. They sharp delimitation can be observed.*

During the 2012-2013 Antarctic field mission, while recovering meteorites on the plateau, samples of felsic and basaltic igneous rocks, as well as sedimentary conglomerates, were collected from the Nansen Blue Ice field located in the southern region of the Sør Rondane Mountains (Figure 1). This specific blue ice field experiences vertical ice movements due to blockages caused by the mountains, leading to a unique transportation mechanism that explains the remarkable concentration of meteorites in the area, gathered by the ice flow over a vast expanse. During this campaign, several circular moraines were also observed, indicating the presence of rocks originating from the Antarctic basement. Although these samples are no longer in their original position, they represent the only direct sampling of the deep basement that is typically concealed beneath several kilometres of ice. Furthermore, these sedimentary and igneous rocks contain abundant detrital and igneous zircons respectively. The crystallization process and ages of these zircons provide insights into the geological, magmatic, and tectonic history that has influenced the basement underlying the Dronning Maud Land region over time. It is reasonable to deduce that these zircons can yield direct or indirect information about past volcanic and magmatic events that contributed to the formation and differentiation of the Antarctic lithosphere, particularly during the Archean and Paleoproterozoic eras. It is believed that the eastern part of Antarctica comprises such ancient lithologies (Boger, 2011).

The objective of this project was twofold. Firstly, it aimed to examine the geological history, specifically the igneous events, recorded in zircons found in moraine samples recovered from the Nansen Blue Ice Field. Secondly, through this analysis, a comprehensive understanding of the basement nature has been obtained, shedding light on geological events that may predate the Proterozoic era, as previously observed in the Sør Rondane Mountains (Shiraishi et al., 1988; Shiraishi et al., 2008). By comparing the findings with existing literature on exposed outcrops, the potential of these moraines to provide insights into the concealed Antarctic basement can be explored.

After characterizing the nature and chemical composition of their host rocks, thereby unravelling the nature of the basement as sampled in moraines, the targeted zircons were measured for their U-Pb ages. This provided new constraints on the ages of igneous episodes that affected the Antarctic continent in the past, as well as their role in the formation and differentiation of the continental lithosphere (Hawkesworth and Kemp, 2006; Belousova et al., 2009; Harrison et al., 2008; Belousova et al., 2010; Hawkesworth et al., 2010; Roberts and Spencer, 2014). It should be emphasized that this work was exploratory and opened new doors for further investigations of the Antarctic basement.

3. METHODOLOGY

The moraine samples were collected during the 2012-2013, 2019-2020 and 2022-2023 Antarctic field expeditions. They were randomly sampled along the way on the Nansen Blue Ice field, located south of the Sør Rondane Mountains. The sample locations and sample names can be divided into: Nansen B East and Conglomerate Moraine BC1 (S72.860682˚, E24.309263˚), Nansen B West (S72.84865˚, E24.25427˚), and Field collect area B (S72.87206° E24.34120°). During the 2022-2023 field expeditions, terrestrial rocks were collected in the Nils Larsen area, in the Maquetknausane moraine (S72. 34036˚, E22.85633˚) but have not been analysed yet in the present report and will not be mentioned in the following. They will be aimed for a follow-up study likely in the frame of a master thesis.

A range of optical different rock types and conglomerates were picked to create a statistically robust representation of the population. The samples consist of larger conglomerates (rock fragments glued together by a sandy matrix) and pebbles and cobbles derived from metamorphic and igneous rocks. From the collected samples, a total of 4.8 kg was chosen for analyses in this study.

The conglomerate samples (app. 2.5 kg in total) were crushed at the ULB, using an Enerpac hydraulic jaw crusher and sieved with a 1 mm sieve. The cobbles and pebbles on the other hand, were cut into two parts, roughly dividing each rock into 1/3 and 2/3 (Figure 2). One third of each rock fragment was kept and stored in a separate bag for future analyses (e.g. preparation of thin sections) and the other part of each rock fragment (2/3 of the rock) was sent to SELFRAG AG, Switzerland, where the samples were crushed using the SELFRAG Microprocess Vessel. All material was sieved at 1 mm and send back to the ULB for further analyses. The crushed sampled were then further sieved at the ULB, using a 0.5 mm sieve. Afterwards, this fraction was further sorted, using heavy liquid mineral separation (methylene iodine with ρ= 3.3) to receive a concentration of the denser minerals, including zircon with a density of 4.65 (Figure 3.a).

Figure 2: *Diversity of the pebbles collected in the moraines of the Nansen Ice field, cut in 1/3-2/3. (a) biotite-bearing gneiss (NBE); (b) gneiss (NBW); (c) bimodal felsic and mafic metamorphic lithology (NBE); (d) granite (NBE); (e) garnet-bearing metagranite (NBE); (f) biotite-bearing gneiss (NBW).*

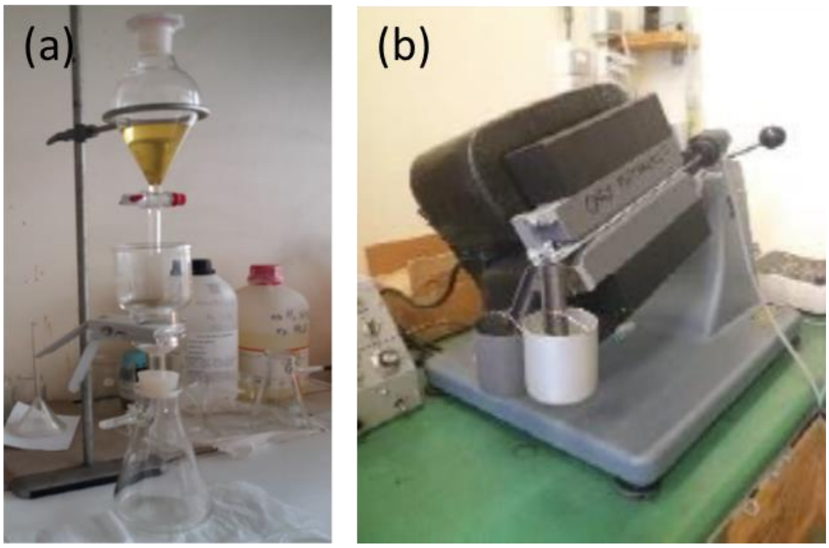

Figure 3: *(a) heavy liquid separation using methylene iodine; (b) Frantz magnetic separator.*

Following the heavy mineral separation, magnetic separators were used to extract the non-magnetic fraction. The magnetic separation was performed using a hand magnet followed by separation with a Frantz magnetic separator at the ULB (Figure 3.b). From the remaining mineral fraction, the zircon crystals were handpicked under a ZEISS Axioscope 5 microscope at the AMGC, VUB. Some pebbles did not contain any zircon grains, or the grains were too small (<10 um) for U-Pb analyses and were therefore discarded. All selected grains were mounted into epoxy resin disks at the Vrije Universiteit Brussels and polished with silicon carbide grinding paper to remove the surface layer of epoxy and cut the grains back to almost half their depth to reveal their internal structures (e.g. rims, cores). This process was followed by polishing with 3 µm and 1 µm diamond paper to remove scratches from the surface. Some of the smaller grains were lost during this process.

The mounts were covered in a thin carbon coat prior to obtaining high resolution element maps and backscatter electron (BSE) images of each zircon grain using the JEOL JSM IT-300 Scanning Electron Microscope (SEM) coupled to an Oxford energy dispersive spectrometer, located at the VUB. BSE images were also acquired using the Quanta 20 ESEM (FEI), with energy-dispersive spectroscopy at the RBINS. Afterwards, cathodoluminescence (CL) images were taken to reveal the internal structure of each zircon grain (i.e. zoning) (Figure 4). CL images were obtained using a cold-cathode (optical) CL system at the University of Mons and in collaboration with Jean-Marc Baele.

The mounts were then shipped to the University of Manchester for U-Th-Pb analyses using a Teledyne Photon Machines Analyte Excite+ 193 nm ArF Excimer laser ablation system coupled to an Agilent 8900 triple quadrupole ICP-MS. Due to the worldwide Covid situation, it should be noted that first, our international partner (NIPR, Japan) could not deliver any measurements and we had to find a back-up solution thanks to our colleague Prof Romain Tartèse at University of Manchester. Second, even travelling to the United Kingdom was impossible and spots for U-Pb analyses were placed remotely. The analytical spots were carefully chosen, using the BSE and CL images as guidance to avoid cracks, inclusions, or different CL zones. The data was then filtered, excluding all data points which were >10% discordant or reversely concordant, respectively.

In the following, the $^{207}Pb/^{206}Pb$ age is used for zircon older than ~1.2 Ga, whereas the $^{206}Pb/^{238}U$ age used for all ages younger than ~1.2 Ga (e.g., Gehrels et al. 2008). Zircon with Th/U values <0.1 were in general interpreted as metamorphic, and zircon with Th/U >0.1 as igneous (e.g., Rubatto and Gebauer 2000), but CL features (i.e. internal zoning) were also taken into account.

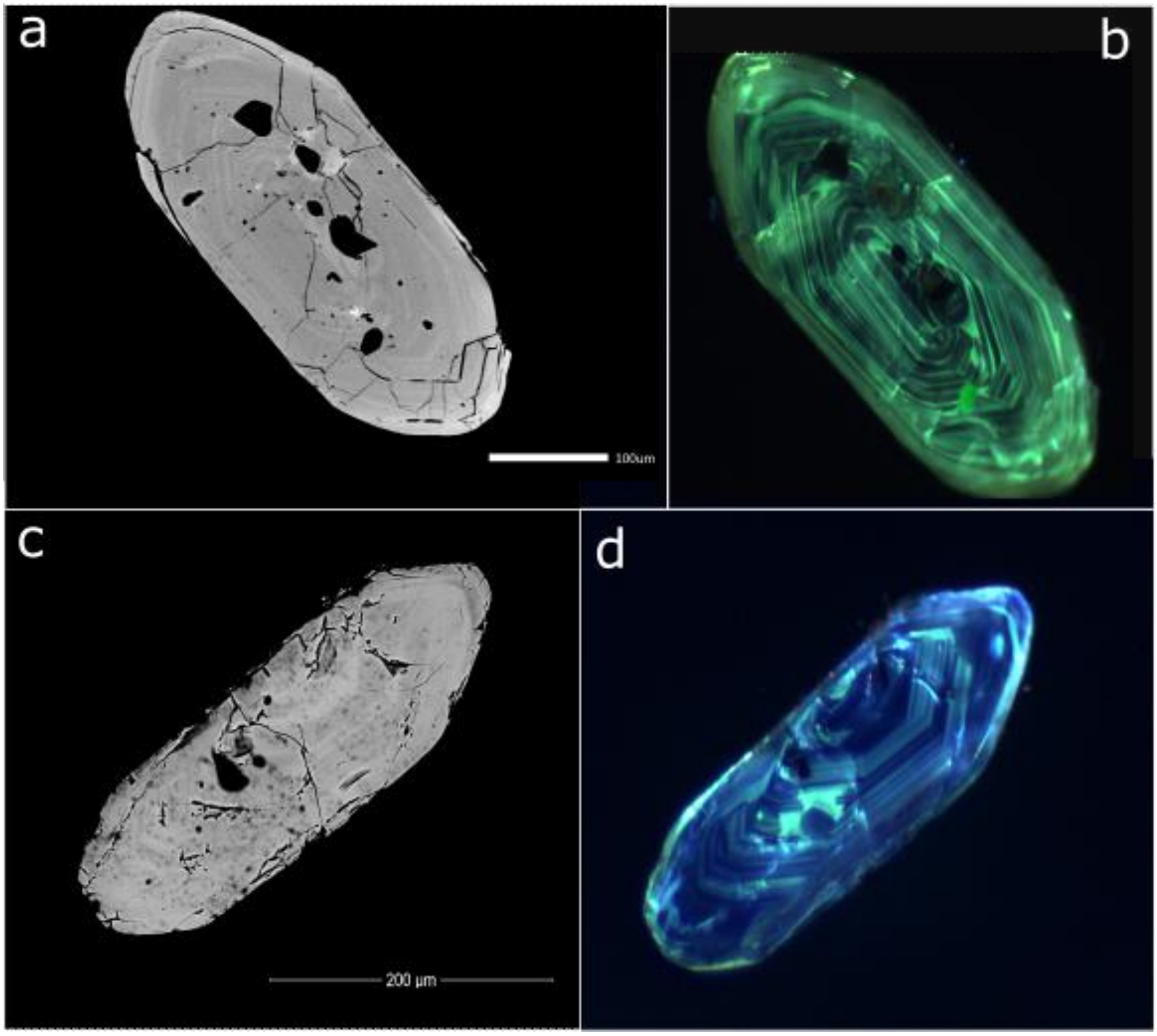

Figure 4: *Cathodoluminescence images of selected zircons documented and measured in the study.*

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

Approximately 2000 grains were hand-picked and mounted, but during the polishing process several grains were lost and from the remaining grains, app. 1000 grains were considered for further analyses. From the conglomerate samples, all zircon grains (ca. 450 grains) were considered for analyses since these samples contain zircon from unknown and random host rocks, enhancing the possibility that these may have originated from Archean bedrock. From the zircon grains extracted from the igneous and metamorphic pebbles and cobbles (Nansen B West and East), U-Pb data from Nansen B West (NBW) zircon were yielded at first. Zircon mounts with larger grains were chosen for analyses to allow placing several spots in one grain (for instance, in different CL zones). After the U-Pb ages for NBW were obtained, only a few mounts from Nansen B East (NBE) were chosen for additional U-Pb dating. These mounts were selected based on the lithology from which the zircon grains were extracted (e.g., similar lithology to the oldest ages yielded from NBW).

The grains range in size from 20 µm to 1 mm allowing to place several spots into some of the grains. In total, U-Pb data was obtained from 590 grains and app. 1750 analytical spots were placed. The obtained U-Pb dates range from 143 Ma – 1995 Ma, but the main age peak observed in all samples is at 550-650 Ma (Figure 5). Another smaller age cluster in some of the samples (NBW, NBE and Conglomerate Moraine BC1) is seen at 800-1000 Ma, but this peak is missing in zircon grains from the Field collect conglomerate, which yielded U-Pb dates ranging from 400-700 Ma. In the overall age distribution, all samples lack Archean (>2,5 Ga) or Hadean (>4 Ga) ages, but three grains (from NBW) yielded Paleoproterozoic ages (1.6 Ga, 1.85 Ga and 2 Ga). The youngest ages (157 Ma and 224 Ma, two grains) were derived from zircon in NBE samples, but these Jurassic and Triassic ages were not observed in any of the other samples.

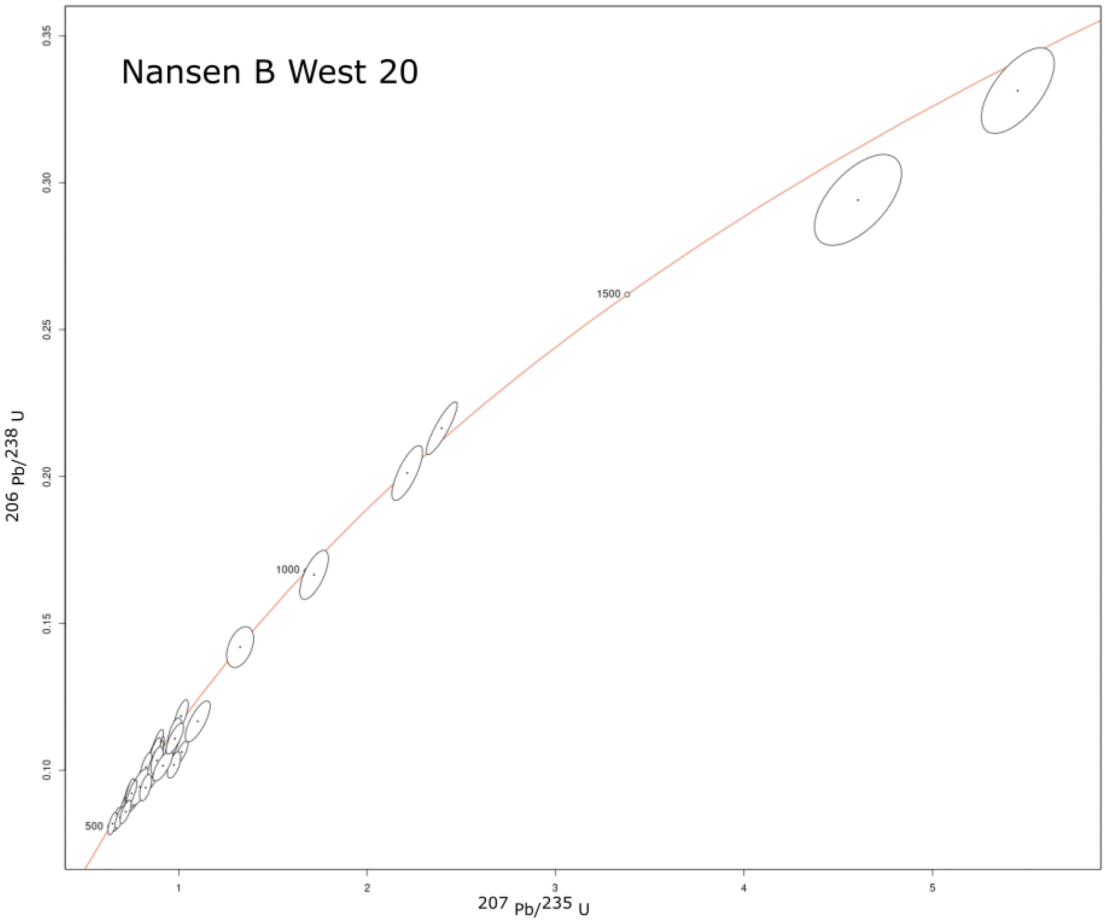

Figure 5: *$^{207}Pb/^{235}U$ vs $^{206}Pb/^{238}U$ concordia diagram of all zircons collected in the Nansen B west field.*

The late Neoproterozoic age cluster (ca. 500-650 Ma) found in all samples is interpreted to be linked to the Panafrican orogeny, which represents the collision of West and East Gondwana along the East African-Antarctic Orogen (e.g., Ruppel et al. 2015). This process left a shear zone, dividing the Sør Rondane Mountains into two different terranes; the Northeastern and the Southwestern terrane. This age cluster is also observed in other published zircon U-Pb data from the Sør Rondane Mountains (e.g., Elburg et al. 2016, Jacobs et al. 2017) and these ages can be further differentiated into four thermal pules at 650-600 Ma, 580-550 Ma, ca. 530 Ma, and between 510-500 Ma (Elburg et al. 2016).

The Tonian (1000 – 850 Ma) ages yielded from zircon in this study are interpreted to be igneous crystallization ages, derived from the Tonian Ocenic Arc Super Terrance (TOAST, Jacobs et al. 2017, Elburg et al. 2016), which is a juvenile block with oceanic arc affinity. Tonian ages from the Sør Rondane Mountains are in general well represented in the literature (e.g. Kamei et al. 2013, Jacobs et al. 2017). Cryogenian (850 – 750 Ma) age components are mainly observed in zircon from NBW and Conglomerate Moraine BC1, but absent in moraine samples NBE and Field collect, indicating different drainage areas from which the moraine samples were derived. Similar Cryogenian ages were found in zircon from samples collected in the SW-terrane (e.g. Kamei et al. 2013).

The observed age very similar to the Sør Rondane themselves (e.g., Shiraishi et al., 2008) has important implications for the ice flow south of the Sør Rondane Mountains, which is still not clearly understood. Zekollari et al. (2019) concluded that the ice flow of the Nansen blue ice field originates from the south (upstream) of the ice field. However, the main source region of the moraine samples analysed in this study seems to be the Sør Rondane Mountains (lying to the north of the Nansen ice field), where late Neoproterozoic ages were previously obtained from igneous and metamorphic rocks and which are linked to the Panafrican orogeny (Jacobs et al., 2017). One explanation is that the Sør Rondane Mountains stretch further to the south, hidden beneath the thick ice sheet of East Antarctica. These observations imply that most of the moraine samples were derived from very local source rocks. However, three Paleoproterozoic ages were found from two NBW samples and this may imply hidden Paleoproterozoic crustal rocks south of the Nansen ice field.

So far, this project has led to the identification, characterization and interpretation of past volcanic/magmatic events that affected the Antarctic continental lithosphere and thus, broaden our knowledge of the Antarctic crust hidden underneath the ice in the Sør Rondane Mountains. Even though the extracted zircons mainly evidence the Panafrican orogenesis, it was actually unexpected that the Sør Rondane Mountains are actually sampled by a south-north ice flow instead of a south-north flow. The team of Harry Zekollari in glaciology is now spending more time on understanding the specific nature of the glacier flow surrounding the Nansen Ice Field.

Second, from a methodological point of view, the results of our study provide a direct evaluation of the potential of moraines located in blue ice fields to sample the rock basement in regions covered by ice caps or inlandsis. Our results highlight the fact that the ice flow is more complex than usually thought in meteorite accumulation area. Following the machine-learning approach to identify meteorite accumulation in blue ice area (Tollenaar et al., 2022), we realize that not only physical characteristics of the ice are important (temperature, velocity, etc…), but detailed investigations of the ice flow should be performed to fully understand why and how meteorites accumulate. Nevertheless, sampling moraines is certainly a powerful tool to increase our knowledge of the basement in this area, either for fundamental bedrock geology, or to identify the presence of features of societal interest (such as particular sedimentary rocks to be used to retrieve past climatic evolution, or ore deposits). This particularly underlines the need for multidisciplinary studies, for example by coupling geology and glaciology.

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5. DISSEMINATION AND VALORISATION

So far, the project has produced very interesting results. However, several drawbacks occurred during the main course of the project. Fiona Thiessen, the post-doc hired on the project, started her contract at ULB in Feb. 2020 just before the lockdown. She resumed her activities as soon as possible in June 2020, and was then hired in Aug. 2020 at VUB, until Feb. 2021 when she was hired at the RBINS. However, she left her position in August 2021 to start working at the European Space Agency in the Netherlands. As such, she worked only 18 months on the project, minus all the months lost during lockdown, and also being slowed down when facilities outside Belgium were still closed for a longer period (Japan, and UK as the back-up solution for zircon analyses). Remotely, after she left Belgium, she still managed to have all the zircons measured, but could not present any result in international conferences during the course of her contract. All the results have now been obtained and the team is in close relationship with Fiona to write the paper altogether.

Notably, our observations are now discussed with our colleagues in glaciology in order to help them modelling the ice flow surrounding the Nansen Ice Field in the goal to provide a better understanding of meteorite accumulation.

6. PUBLICATIONS

At the present time, no publication has been submitted and accepted, but this will be done as soon as possible.

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