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**Petrography, bulk-rock geochemistry, detrital zircon U–Pb geochronology and
Hf isotope analysis for constraining provenance: An example from Middle
Triassic deposits (Bravaisberget Formation), Sørkappøya, Svalbard**

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The Bravaisberget Formation is an important succession to better understand time and facies equivalent offshore deposits of the Barents Shelf. However, few of its provenance studies were primarily based on a single-grain method. This study therefore presents new results about these Middle Triassic sandstones based on multi-method approach provenance interpretations. Bulk-rock approaches (petrography and geochemistry) and single-grain methods (detrital zircon ages and Hf isotope analysis) were combined in order to characterise potential upland sources for sediments. The analysed sandstones are quartz arenites, sublitharenites, subfeldsarenites to sublithwackes, attesting to a generally high mineralogical maturity. Trace and rare earth elements link the deposits to source rocks of a felsic composition, related to the late-melt fractionating crust. The zircon age pattern is well known from other deposits of the Arctic region and links the sandstones to a protosource of Laurentian and/or Baltican affinity. The multi-method related input data in our study highlights the importance of sedimentary reworking from older quartz-rich units. Due to the high degree of sedimentary reworking required, the information the zircon age pattern holds has no bearing on the source to sink system in the Middle Triassic in southern Spitsbergen. The Eu and Gd systematics coupled with the Hf isotope data reflect subtle changes in provenance evolution. We assume that the Somovbreen and Karentoppen members of the Bravaisberget Formation shared the same source located in NE Greenland that was a molasse basin filled with a detrital material of eroded low-grade Proterozoic successions of the Caledonides. The Karentoppen Member was additionally supplied by a sedimentary unit coming from the eroded part of an Archaean/Palaeoproterozoic basement. This study has shown that the provenance of compositionally mature sandstones is difficult to disentangle even despite the multi-method approach applied, and that in such cases any interpretations are best grounded by field constraints.

Keywords: provenance, multi-method approach, U–Pb geochronology, Middle Triassic, NW Barents Shelf

Electronic supplement 1A: Logs, Sassendalen Group

Electronic supplement 1B: List of studied samples

Electronic supplement 2: Petrographic data

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Introduction

The Mesozoic successions exposed at the Svalbard Archipelago comprise potential source and reservoir rocks equivalent to the subsurface facies in the Barents Sea. These strata have been the focus of numerous studies because they offer a unique opportunity to understand the reservoir and source-rock properties in the subsurface facies that can be tracked in the offshore of the Barents Shelf (e.g., Faleide et al., 1984; Mørk, 1999, 2013; Mørk et al., 1999; Mørk & Worsley, 2006; Krajewski et al., 2007; Riis et al., 2008; Worsley, 2008; Glørstad-Clarck et al., 2010; Anell et al., 2013; Klausen & Mørk, 2014; Krajewski &

Weitschat, 2015). Provenance studies of the Triassic successions have been conducted both on Svalbard (Mørk, 1999, 2013; Bue & Andresen, 2014) and across the shelf as a whole (Omma, 2009; Soloviev et al., 2015; Fleming et al., 2016; Klausen et al., 2017; Flowerdew et al., 2019; Khudoley et al., 2019; Line et al., 2020). These studies have identified several source areas that delivered sediments to the Barents Shelf during the Triassic. The Lower and Middle Triassic sandstones of Spitsbergen are interpreted to have had a westerly source from Greenland (Mørk et al., 1982; Mørk, 1999; Bue & Andresen, 2014), whereas the Upper Triassic sediments in the eastern and southern parts of the Barents Sea have probably been delivered from the Urals, along the Timan–Pechora depression (Mørk, 1999; Fleming et al., 2016), and from the Baltic Shield (Glørstad-Clarck et al., 2010; Fleming et al., 2016; Flowerdew et al., 2019).

The Mid-Triassic Bravaisberget Formation, the focus of this study, was mapped and sampled from Sørkappøya, a small island adjacent to southernmost Spitsbergen (Figs. 1 & 2). The formation contains sandy deposits previously studied by detailed petrography coupled with geochemical data (Mørk, 1999) or a detrital single-zircon U–Pb dating method to trace sediment source terranes (Bue & Andresen, 2014). Because the studied unit seems to be sourced from the west rather than from the east (Mørk, 1999; Bue & Andresen, 2014), the southernmost Spitsbergen region is relevant for Arctic paleogeography reconstruction and for reservoir-quality sand distribution on the southwest Barents Shelf. It has been claimed that reservoir intervals comprising sediments sourced from a compositionally mature sedimentary precursor have overall better reservoir quality than reservoir intervals composed of clastic material sourced from an immature sedimentary precursor (Ryseth, 2014). The maturity and immaturity of the precursor sedimentary rock provide a specific imprint on the composition of a daughter sediment. Our study has shown that this imprint can be tracked and easily extracted from the daughter sediment using petrographic and whole-rock geochemical studies.

This study integrates different methods commonly used individually in provenance analysis studies in order to unravel sedimentary records from the stratigraphic units. Some provenance studies have advocated the advantage of an integrated approach over using just the single-grain method (Humphreys et al., 1991; von Eynatten & Gaupp, 1999; Morton et al., 2005; von Eynatten & Dunkl, 2012; Morton et al., 2012; Nie et al., 2012; Jian et al., 2013; Garzanti, 2016). The multi-method approach can help to constrain limitations solely associated with a single-grain method, for instance, the conventional U–Pb zircon age data (Chew et al., 2020). As Garzanti (2016) noted, the average content of zircon in sediments is 2 grains out of 10,000. This means there is still much to learn from the remaining 99.98% of the sample. Moreover, factors such as fertility bias, recycling, pre- and post-depositional modifications from sediment transport, and climate imprint, among others, may complicate interpretation of the conventional detrital zircon U–Pb provenance ages (e.g., Nie et al., 2012; Sláma & Košler, 2012; Flowerdew et al., 2019). That is why this study emphasises the importance of evaluating imprints in sediments using bulk-rock methods (petrography and geochemistry).

The chemical record of clastic sediments has been widely used for provenance interpretation, e.g., trace elements and their ratios are good indicators of source rocks since felsic and mafic sources can show differences in composition (McLennan et al., 1983; Taylor & McLennan, 1985; Bhatia & Crook, 1986; McLennan et al., 1990; Condie, 1993; Cullers, 1995, 2000, 2002; Akarish & El-Gohary, 2008). Rare earth elements (REE) are also considered to preserve the source-rock composition. Mafic rocks have a less fractionated chondrite-normalised REE pattern, with low $(La/Yb)_N$ ratios and little or no Eu anomalies. In contrast, the felsic rocks generally show a fractionated chondrite-normalised REE pattern, with higher $(La/Yb)_N$ ratios and prominent Eu anomalies (Taylor & McLennan, 1985; Cullers, 1995, 2002). The Eu systematics has been a useful tool for discrimination between the Archaean and Post-Archaean composition of a continental crust, as well as the $(Gd/Yb)_N$ ratio (Taylor & McLennan, 1985; McLennan et al., 1990; McLennan et al., 1993). Additionally,

the Lu–Hf isotope system in a detrital zircon study is a useful tool for analysing the crustal and mantle evolution, with high values of $^{176}\text{Hf}/^{177}\text{Hf}$ indicating a mantle (juvenile) origin for the magma, and low values implying a reworking of the older crustal material (Belusova et al., 2010); thus, the Lu–Hf system is very useful for constraining provenance interpretations inferred from the U–Pb zircon geochronology (e.g., Andersen et al., 2011; Slama et al., 2011; Kristoffersen et al., 2014).

This study thus: 1) presents petrographic characteristics of the Bravaisberget Formation sandstones in detail that have only been studied so far for a few samples north of the study area (Mørk, 1999), 2) for the first time, explores the bulk-rock geochemical signature of the Bravaisberget Formation, 3) adds new zircon U–Pb ages to the existing geochronological database for the Lower Mesozoic of the NW Barents shelf, and 4) for the first time, extends utility of the zircon U–Pb dating, coupled with the Lu–Hf isotopic analysis for the Mesozoic strata of the Barents Shelf. The multi-method approach was applied in order to accomplish the purpose of this study, which has been to constrain provenance of the studied sandstones. Findings from this study are important for understanding that little provenance significance can be drawn from the zircon data if they come from quartz-rich mature sandstones, and when the recycling imprints on sediment composition, the whole-rock studies are crucial in the provenance analysis.

Geological setting

In general, the Triassic succession of Svalbard (Fig. 1A, B) comprises marine facies of the Sassendalen Group and paralic to deltaic facies of the Kapp Toscana Group (Mørk et al., 1999). Two of the youngest units of the Sassendalen Group, the Botneheia and Bravaisberget formations, both enriched in marine organic carbon, are important petroleum source rocks in the Barents Sea (Mørk & Bjørøy, 1984; Karcz, 2010, 2014; Krajewski, 2013). Sandstone bodies within these formations and thick sandstone units of the overlying Kapp

Toscana Group are considered to have good reservoir potential (Worsley & Mørk, 1978; Krajewski et al., 2007; Mørk, 2013).

The Bravaisberget Formation is restricted to west Spitsbergen and has been subdivided into four members: the Passhatten, Somovbreen, Karentoppen and Van Keulenfjorden (Mørk et al., 1982; Mørk et al., 1999) (Fig. 1B). The shale-dominated Passhatten Member comprises an organic-rich succession, which is related to deposition in a shallow-shelf environment (Karcz, 2010; Krajewski & Weitschat, 2015). The overlying sandy and silty deposits of the Somovbreen Member are described as a marine succession encompassing and covering wedges of deltaic sediments (Mørk et al., 1999; Krajewski & Weitschat, 2015). The latter deltaic to marine sandstones are of the Karentoppen Member and limited to the southwestern part of the Sørkapp Land (Mørk et al., 1999). The Van Keulenfjorden Member is made up of siliceous and dolomitic sandstones, shales and spiculitic deposits of prodelta and delta-top environments (Mørk et al., 1999; Krajewski et al., 2007; Krajewski & Weitschat, 2015).

Sandy facies within the Somovbreen Member were deposited in a shallow-marine environment through reworking of the Karentoppen Member deltaic sediments, which were delivered from a local source area as has been indicated by field data (Krajewski & Weitschat, 2015). The source area was located west and southwest of the present coast of Spitsbergen, probably in the land area of northern Greenland (Faleide et al., 1993; Mørk, 1999; Mørk et al., 1999; Riis et al., 2008; Worsley, 2008; Krajewski & Weitschat, 2015).

Derivation of the clastic material from the local source area in the west took place in the Early and Middle Triassic and was restricted only to the western part of Spitsbergen (Bue & Andresen, 2014). It has also been confirmed by a facies analysis of the Karentoppen Member that the deltaic sandstone bodies, observed along the western coast of the Sørkapp Land, disappear north-eastward over a distance of a few kilometres (Krajewski & Weitschat, 2015). In contrast to the Bravaisberget Formation, the sediments of the Botneheia Formation

were partly supplied from distal deltaic systems located in the southeastern part of the Barents Shelf (Glørstad-Clarck et al., 2010). On the contrary, the Upper Triassic deposits accumulated by a supply of a great amount of sediment delivered into the Barents Shelf by large prograding delta systems sourced from rivers draining the Uralides to the southeast (Mørk, 1999; Worsley, 2008; Glørstad-Clark et al., 2010; Bue & Andresen, 2014; Klausen et al., 2015). In the Late Triassic, the easterly derived material reached the present-day western Spitsbergen (Riis et al., 2008; Bue & Andresen, 2014).

Samples and methods

The studied samples were gathered during expeditions by the Polish Academy of Sciences in 2001 and 2014. Sampling covered three sections on Sørkappøya where the Bravaisberget Formation crops out: Trondsenneset, Sørkapplaguna and Sørkapp, with locations shown in Fig. 2. In total, 32 samples were analysed for petrographic data, and 37 for bulk-rock geochemistry. Two samples were used for single-grain zircon U–Pb and Lu–Hf isotopic analyses. Sample locations and logs of the studied sections are shown in Electronic supplement 1A. In addition, Electronic supplement 1B shows a list of samples coupled with analyses that have been conducted on each single sample.

Petrographic investigations of siliciclastic rocks of the Bravaisberget Formation were performed on standard uncovered polished thin-sections using a NIKON Eclipse E600POL polarising microscope. The thin-sections were blue-stained for porosity identification. A framework composition, matrix and cements were quantified by the point-counting method, and 300 points per each thin-section of sandy samples were counted. Furthermore, the size of the framework components was examined. All the studied deposits were classified based on Picard (1971), while the sorting of the framework components was determined using comparison charts (Longiaru, 1987). Sandstones were classified using combined ternary petrographic classification schemes (McBride, 1963; Dott Jr, 1964; Folk et al., 1970;

Pettijohn et al., 1972; Williams et al., 1982). The quantitative petrographic data and the description of most important textural features are listed in Electronic supplement 2A, B.

A bulk-rock geochemical analysis was conducted on 37 samples. The oxides of major elements, trace and rare earth elements were determined by inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Bureau Veritas Minerals Laboratories Ltd. in Vancouver, Canada. The results of these analyses are provided in Electronic supplement 2C–F.

The detrital zircon U–Pb and Lu–Hf analyses were performed by LA-ICP-MS using a Nu Plasma HR mass spectrometer and a Cetac LSX-213 G2+ laser microprobe equipped with a HelEx cell at the Department of Geosciences, University of Oslo. The analytical protocols of Rosa et al. (2009) and Andersen et al. (2009) were used for the U–Pb geochronology. In total, 119 and 88 zircon grains from two samples were analysed. Combined histograms and probability density plots were created for a statistical presentation of the results. $^{207}\text{Pb}/^{206}\text{Pb}$ ages were plotted for zircons >600 Ma and $^{206}\text{Pb}/^{238}\text{U}$ ages for younger zircons. The histograms and probability density plots include only zircon ages that are less than 10% discordant. Datasets of the U–Pb zircon analyses are listed in Electronic supplement 2G.

For the Lu–Hf analysis, the analytical protocols of Elburg et al. (2013) were applied. A decay constant value for ^{176}Lu of 1.867×10^{-11} (Söderlund et al., 2004), and the present-day chondritic $^{176}\text{Hf}/^{177}\text{Hf} = 0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0336$ (Bouvier et al., 2008) have been used in all ϵHf calculations. The depleted mantle (DM) parameters of Griffin et al. (2000) were adopted; this model, modified to the decay constant and the chondritic uniform reservoir (CHUR) parameters, gives present-day $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ (+ 16.4 ϵHf , similar to average mid-ocean ridge basalt) from a chondritic $^{176}\text{Hf}/^{177}\text{Hf}$ at 4.56 Ga and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0388$. High values of $^{176}\text{Hf}/^{177}\text{Hf}$ (positive ϵHf) indicate mantle-related magmas, and low

values of $^{176}\text{Hf}/^{177}\text{Hf}$ (negative ϵHf) point to a crustal influence (Belusova et al., 2010).

Datasets of the Lu–Hf analyses are presented in Electronic supplement 2H.

Results

Petrography

Samples of the Karentoppen Member (KM) are fine to medium grained, well to very poorly sorted sandstones. Among the framework components, quartz predominates (Fig. 3A–G). The quartz is mostly monocrystalline. Polycrystalline quartz is also present but in small quantities. Lithic grains were observed (Fig. 3A, D–G) and the lithoclasts of crystalline rocks (mainly metamorphic, represented by schist) are the most common. The lithoclasts of sedimentary rocks, such as siltstones, fine-grained sandstones, or cherts, have a subordinate presence. K-feldspar and plagioclase were rarely observed. The other framework elements, such as micas, glauconite, bioclasts, organic matter and heavy minerals were noted only in trace amounts. An average framework composition of the KM sandstones is $\text{Q}_{93}\text{F}_1\text{L}_6$. The deposits have very little matrix, which consists of very fine-grained detrital grains. According to a petrographic classification, the analysed sandstones are predominantly quartz arenites (Fig. 3A–C) and sublithic arenites (Fig. 3A, D–G). There are different types of cement in the KM samples. Quartz cement, which is developed mostly as overgrowths around the quartz grains, has been noted in many samples (Fig. 3B–D). Calcite (Fig. 3D–G) and dolomitic (Fig. 3C) cements have also been observed in several samples. The total volume of cement varies in a range of c. 8–43%. Overall, the studied deposits have very low visible porosity (up to 1%).

Samples of the Somovbreen Member (SM) are represented by a wide group of very fine-grained rocks, as silty sandstones (Fig. 4A–D), sandy siltstones, siltstones (Fig. 4E), and mudstones (Fig. 4F). For further investigations, only the sandstones and silty sandstones were considered. A mean grain size (M_z) of the sandstones falls in a very fine sand fraction.

Sorting is varied; from well to very poorly sorted. Among the framework components, quartz is the most common (Figs. 3A & 4A, B), with monocrystalline quartz dominating. Polycrystalline quartz grains are present in small quantities. Lithic grains of crystalline and sedimentary rocks were also counted (Figs. 3A & 4B–D). K-feldspars and plagioclases are more abundant than in the KM deposits. As with the KM, micas, bioclasts, glauconite, organic matter and heavy minerals were noted in trace amounts. An average framework composition of the SM sandstones is $Q_{92}F_3L_5$. Matrix content varies from 2% to 15%. The studied sandstones are quartz arenites (Figs. 3A & 4A), sublithwackes (Figs. 3A & 4B), sublitanes (Figs. 3A & 4C, D) and subfeldsarenites (Fig. 3A). A high diversity of cements was observed. Carbonate cements predominate (Fig. 4C–D), with an important addition of dolomite-ankerite phases (Fig. 4B–D). Iron oxides and/or hydroxides were also noted (Fig. 4A), as well as clay minerals. Visible porosity values are very low (up to 1%).

Bulk-rock geochemistry

Oxides of major elements and geochemical classification

The distribution of the oxides of major elements differs in the KM and SM samples. The most abundant element of the KM sandstones is SiO_2 . The silica source is mostly quartz and, subordinately, also crystalline lithic grains, mainly metamorphic, as well as quartzose cement. Na_2O and K_2O contents are very low, with the Na_2O related to plagioclases and the K_2O to K-feldspars. This is consistent with the petrography, where both the plagioclases and the K-feldspars are present in small quantities among the framework components. Some of the studied samples of the KM are highly enriched in CaO, associated with the presence of the carbonate cement in all the studied KM deposits, as confirmed by the petrographic results and a low correlation between the CaO and Al_2O_3 . Other oxides such as Fe_2O_3 , MgO, TiO_2 , P_2O_5 and MnO occur as only trace amounts in the KM samples.

The distribution of major elements in the SM deposits is slightly more diversified than in the KM. As in the latter, the SiO_2 is the most abundant component, but generally has a slightly lower content. The Na_2O and K_2O contents are very low, but slightly higher than in the KM, consistent with a slightly greater number of plagioclase and K-feldspar grains as observed in the petrographic work. Moreover, as in the KM, the number of K-feldspars is higher than the number of plagioclase grains. In contrast to the KM deposits, the Al_2O_3 content in the SM samples is visibly higher. The CaO value confirms a significant content of the carbonate cement in these deposits, and the MgO values marking the presence of the dolomitic cement, consistent with the petrographic analysis. Distributions of the Fe_2O_3 , TiO_2 and MnO show higher contents than in the KM deposits. The distribution of the P_2O_5 is overall similar to that in the KM deposits, excluding a few samples where the enrichment is related to horizons with phosphoritic nodules.

In a geochemical classification of sedimentary rocks in Fig. 5, the KM sandstones are classified as quartz arenites, whereas most of the SM samples plot as sublitharenites. Generally, the distribution of the oxides of the major elements reflects the mineralogical composition of the studied samples and supports the results of the petrographic analysis (Figs. 3A & 5).

Trace elements

A variable depletion in the transition trace elements (TTE), such as Sc, V, Cr, Co, Ni and Cu, relative to the upper continental crust (UCC), is observed in the KM sandstones. The Zn content in these deposits is highly variable: depleted to enriched compared to UCC. The Large Ion Lithophile Elements (LILE: Rb, Ba, Cs, Sr) show a depletion, with exception of Ba which is enriched in several samples compared with the UCC. Concentrations of the High Field Strength Elements (HFSE: Y, Zr, Nb, Hf, Ta, Th, U) are depleted relative to the UCC, excluding Y and U, which are slightly enriched in several samples.

The TTE values in the SM deposits are higher than in the KM and slightly depleted compared to the UCC. The LILE are depleted but less than the KM samples. The Cs content is visibly higher than in the KM, but depleted relative to the UCC. Concentrations of the HFSE are usually much higher than in the KM. Zr and Nb are depleted relative to the UCC. Y and U contents are usually higher than in the KM samples, and their values are enriched compared to the UCC. Ta, Th, Hf show a variable low depletion; however, several samples are enriched in Hf relative to the UCC.

Rare earth elements

The average content of total rare earth elements (REE) in the KM deposits is 55.07 ppm and depleted relative to the UCC (148.14 ppm; Rudnick & Gao, 2003). In the SM samples, the average of the total REE is 291.17 ppm, pointing to an enrichment in comparison to the UCC. The light rare earth elements (LREE; avg. 47.70) and the heavy rare earth elements (HREE; avg. 7.37) in the KM are depleted relative to the UCC (133.80 and 14.34, respectively; Rudnick & Gao, 2003). In the SM, the average of the LREE and HREE values is enriched relative to the UCC (252.24 and 38.93, respectively). The average of the LREE/HREE ratio is nearly similar in both the studied members (avg. 7.05 for the KM and 6.38 for the SM), and the values are lower than in the UCC (9.33; Rudnick & Gao, 2003). In Fig. 6, the mean chondrite-normalised REE patterns for both members are variably enriched in the LREE, and the enrichment is significantly higher for the SM deposits. The HREE patterns are flat, with a higher enrichment in the SM deposits. The Eu negative anomaly (Eu/Eu^*) is variable, and for the KM and SM samples the values are 0.46–0.83 (avg. 0.66) and 0.54–0.75 (avg. 0.68), respectively.

U–Pb geochronology and Hf isotope of detrital zircon

The U–Pb analysis of a detrital zircon was undertaken on the sample SO-13.1 from the SM and the sample SO-23 from the KM. In total, 210 zircon grains were studied for the U–Pb geochronology, the results of which are presented as combined histograms and probability density plots, and kernel density estimation plots (Fig. 7).

343

344 Sample SO-13.1, SM, Sørkapp section. In total, 88 zircons were analysed, of which 26
345 grains were more than 10% discordant, and these were excluded from the analysis. The
346 youngest dated grain is Devonian in age (385 Ma) and the oldest is Archaean (2815 Ma)
347 (Fig. 7A). The Archaean ages are minor (3.2%) and focused in the range 2700–2850 Ma.
348 The age spectra are dominated by the Palaeoproterozoic ages (51.5%) which fall in a range
349 of 1608–1940 Ma. There is also one grain of c. 2064 Ma. The Mesoproterozoic ages are also
350 very common (35.5%) and fall in the range 1039–1546 Ma. Neoproterozoic ages make up
351 3.2% of all the analysed zircons in this sample, yielding ages of c. 580 and 955 Ma. Zircon
352 grains with Palaeozoic ages comprise 6.5% of the population and fall in the range c. 385–
353 505 Ma. There are two gaps, at c. 600–950 Ma and 2100–2700 Ma, and one smaller one at
354 c. 1950–2050 Ma.

355

356 Sample SO-23, KM, Sørkapplaguna section. Of the 122 zircon grains analysed in this
357 sample, 77 have less than 10% of discordance. The distribution of the zircon age population
358 is quite similar to the other sample, with the youngest age of 397 Ma, and the oldest age of
359 3188 Ma (Fig. 7B). The Archaean ages represent 8% of all grains and fall mostly in a range
360 of c. 2500–2800 Ma, and one grain of c. 3200 Ma is present. The Palaeoproterozoic ages
361 are the most common (62.3%) and fall in the ranges 1615–2025 Ma and 2420–2474 Ma. The
362 Mesoproterozoic ages are mostly focused in the range 1002–1474 Ma comprising 26% of all
363 the zircon age spectra, whereas the Neoproterozoic ages represent only 1.3% of the whole
364 age population, represented by just one grain of c. 948 Ma. Palaeozoic ages comprise 2.6%
365 of the zircon age spectra and are represented by grains of c. 397 Ma and 447 Ma. A lack of
366 ages in the range c. 450–945 Ma was noted. Other gaps span the age intervals of c. 1500–
367 1600 Ma, 2050–2400 Ma and 2800–3100 Ma.

368

369 The Lu–Hf isotopic analysis was carried out on the same zircon samples as were used for
370 the U–Pb dating and a total number of 115 analyses were performed. The Hf isotope data

are presented in ϵHf vs. time diagrams (Fig. 7A, B). In general, the SM and KM samples show a similar pattern and only one difference is noted. The rare Caledonian grains show the low ϵHf values, from c. - 3 to - 25. The Neo- and Mesoproterozoic ages yield similar patterns with, in general, positive values, ranging from c. - 2 to + 8 for the SM and c. - 13 to + 8 for the KM. The pattern for the Paleoproterozoic zircons in part looks the same for both samples, and mainly positive ϵHf values are noted in a range from ca. - 5 to + 7. Additionally, in the KM sample there is also a frequent group of zircon ages of c. 1600–1900 Ma, with very low ϵHf values ranging from c. - 5 to - 27. The very few Archaean grains are present in both samples, and the general trend is that they show slightly negative values, despite of that they plot in a broad range varying from ca. 0 to - 19.

Discussion and interpretation

The bulk-rock geochemical data obtained in this study allow us to constrain the composition of the potential uplands sourcing the sediments of the studied area in the Middle Triassic. The trace element data show that the geochemical signature of all the studied Bravaisberget Formation samples is compatible with a felsic source-rock composition (Fig. 8A–E; Tab. 1), i.e., similar to the late-melt fractionating crust (Hiscot, 1984; Bhatia & Crook, 1986; Condie & Woronkiewicz, 1990; Condie, 1993; Cullers, 2002; Cullers & Podkovyrov, 2002; Rudnick & Gao, 2003; Armstrong-Altrin et al., 2004; Bracciali et al., 2007). In general, the chondrite-normalised mean REE patterns of the studied samples are variably enriched in the LREE, and the HREE patterns are flattened (Fig. 6). This is expressed by the $(\text{La}/\text{Sm})_{\text{N}}$ ratio with average values of 3.14 and 3.98 for the SM and KM sandstones, and the $(\text{Gd}/\text{Yb})_{\text{N}}$ ratio with average values of 1.99 and 2.13, respectively. Moreover, the $(\text{La}/\text{Yb})_{\text{N}}$ ratio shows fractionation of the total REE with averages of 8.00 and 10.39 for the SM and KT samples. These results, together with the Eu anomalies with averages of 0.64 and 0.66, respectively, fit with the general characteristics of felsic source rocks.

On the diagram of Fig. 8F, all samples of the SM are related to post-Archaeon sources. Accordingly, the KM may be linked to both post-Archaeon and Archaeon felsic sources (Fig. 8F). Hence, the KM samples may reflect: (1) exhumation of the Archaeon crystalline rocks in a source area, in addition to a post-Archaeon source, (2) recycling of the sedimentary units enriched in the Archaeon component. Along a similar line, the SM deposits probably do not have a connection with an Archaeon protolith and accordingly contain only the post-Archaeon signature. Based on the results we may assume that some tectonic movements took place in the source area which resulted in deposition of the KM. These inferred movements would have led to an exhumation of the Archaeon crystalline basement block or sedimentary sequences containing a redeposited Archaeon component. Because there is no appreciable Archaeon zircon population in the KM sample (Fig. 7B), we may assume that the latter alternative is more probable. This inferred tectonic activity was probably of a short-lived event type because the same Archaeon signature is not present anymore in the SM samples (Fig. 8F), which have been interpreted as a product of redeposition of the KM (Krajewski & Weitschat, 2015). On the other hand, if the SM is the product of the KM reworking, in the SM samples there should be at least a minimal fingerprint linked to the Archaeon signature. The lack of such a fingerprint argues against the idea of recycling. We therefore assume that the SM and KM shared predominantly the same source, but that the KM was additionally supplied from another source that shows the Archaeon affinity.

The petrographic studies show that the Bravaisberget Formation sandstones have a high mineralogical maturity. That is reflected in the petrofacies, among which the quartz arenite, sublitharenite and subfeldsarenite are the most common (Fig. 3A). The analysed sandstones are similar in their composition to other petrographically studied, westerly sourced, Triassic deposits from West Spitsbergen and Arctic Canada (Fig. 3A; Mørk, 1999; Omma, 2009). The mineralogical maturity is a pattern expected from recycling of older sedimentary rocks. The monocrystalline non-undulatory quartz grains are the most common in all the studied samples and this also favours recycling, as the monocrystalline quartz can be an effect of a

disintegration of grains, which primarily were polycrystalline; and the probability that the disintegration would have increased with the length of transport from a source to a sink, the number of sedimentary cycles involved, and is dependent on the energy of the sedimentary environment (Zaid, 2012). On the other hand, the mineralogical maturity of daughter sediments may also be related to an intensive weathering of the crystalline source rocks under humid climatic conditions. The highly positive correlation of the TiO_2 with the Al_2O_3 in the studied samples indicates that chemical weathering in the source area was the main process controlling the mineralogy (Jorge et al., 2013), and such chemical weathering is an indicator of climatic conditions. A humid climate in a source area tends to produce the quartz arenitic composition of sandstones by a chemical destruction of unstable grains (Suttner & Dutta, 1986; Dutta & Wheat, 1993). The very low content of feldspars, limited number of lithoclasts, and domination of quartz in the framework composition of the Bravaisberget Formation sandstones suggest that the source rocks could have been in an area with a humid climate. Furthermore, the positive correlation of the Na_2O and K_2O with the Al_2O_3 has been stated in the studied samples, suggesting an accumulation of these elements, being an effect of feldspar weathering, with clay minerals among the finest fraction. The Al_2O_3 content is very low, suggesting a very low presence of the feldspar alteration products even among the finest clayey particles; thus, it is unlikely that the studied deposits were sourced directly from crystalline felsic rocks, such as granites or gneisses. These datasets provide evidence that the composition of the Bravaisberget Formation sandstones was controlled primarily by the mature character of the source rocks that had likely experienced the humid climate. The climatic interpretation in our study is consistent with the paleoclimatic literature data, which point to hot and humid conditions in Mesozoic time in Svalbard and adjacent areas (Preto et al., 2010).

The bulk-rock trace element geochemistry is also strongly supportive of high degrees of sedimentary reworking. In the Th/Sc vs. Zr/Sc ratio diagram (McLennan et al., 1993) of Fig. 9A, there are two trends. The first trend shows a compositional variation that correlates with a direct influx from primary sources. The second trend, expressed by a rise of the Zr/Sc ratio,

is related to sedimentary processes affecting the composition of the deposits. The Zr content reflects the abundance of heavy minerals, particularly zircon, and therefore is used as an indicator of sediment recycling (McLennan et al., 1993). The Bravaisberget Formation sandstones do not vary much according to their source composition, but the data are scattered parallel to the line of the second trend, pointing to the heavy mineral accumulation by sediment recycling (Fig. 9A). This is also confirmed in the diagram of Fig. 9B, where the SM and KT samples plot parallel to the zircon addition arrow.

Based on the paleogeographic reconstructions of the Triassic period (Doré, 1991; Smelror et al., 2009), the present Barents Sea was flanked by the following main geological provinces that could supply the basin with sediments:

- 1) Greenland and Arctic Canada (Fig. 10A) containing zircon signatures related to the Archaean and Proterozoic igneous and metamorphic rocks of northern Laurentia (Henriksen et al., 2009), as well as to their sedimentary cover (e.g., Higgins, 1988; Kalsbeek et al., 1993, 2000; Strachan et al., 1995; Watt et al., 2000; Leslie & Nutman, 2003; Dhuime et al., 2007; Røhr et al., 2008, 2010; Henriksen et al., 2009; Kirkland et al., 2009; Slama et al., 2011; Anfinson et al., 2012a, 2012b, 2016; Malone et al., 2014) (e.g., Fig. 7C.3, C.7);
- 2) The Caledonian nappes and intrusions (Early Palaeozoic ages) of eastern Greenland (e.g., Tucker et al., 1993; Strachan et al., 1995; Watt et al., 2000; Kalsbeek et al., 2001, 2008; Collinson et al., 2008; Henriksen et al., 2009; Fossen, 2010; Slama et al., 2011) (Figs. 7C.8 & 10A), Svalbard (Witt-Nilsson et al., 1998; Johansson et al., 2001, 2004; Pettersson et al., 2010; Braathen et al., 2018; Beranek et al., 2020) (Figs. 7C.6 & 10A) and Fennoscandia (e.g., Kirkland et al., 2005, 2007, 2008; Zhang et al., 2015) (Figs. 7C.4 & 10A), as well as the Ellesmerian Fold Belt (the Middle/Late Palaeozoic) of northern Greenland and Arctic Canada (Embry, 1988, 1991; Anfinson et al., 2012b; Fig. 10A) with the zircon signatures that point to the recycled basement of Laurentian and/or Baltican affinity, and/or an influx of juvenile magmatic components related to the tectonic activity during these events;

3) Eastern and southeastern source areas relate to the Baltican zircon signature (Archaean–Proterozoic ages) (e.g., Kirkland et al., 2007, 2008; Figs. 7C.4 & 10A) that also includes the Timanian source (the Late Neoproterozoic–Early Palaeozoic ages) (e.g., Gee & Pease, 2004; Kirkland et al., 2008; Andresen et al., 2014; Zhang et al., 2015; Figs. 7C.5 & 10A), and to the Uralides (Late Palaeozoic–Early Mesozoic) (e.g., Bue & Andresen, 2014; Soloviev et al., 2015; Fleming et al., 2016; Klausen et al., 2017; Line et al., 2020; Fig. 10A). The Timanian ages are rather exotic to northeastern Laurentia (Fig. 10A); however, they have been recorded also from North Greenland (Rosa et al., 2016) and Arctic Canada (Anfinson et al., 2016).

The sandstones of the SM and KM have significant similarities in their zircon U–Pb dating patterns, even though there are some differences (Fig. 7A, B), with the most common zircon ages focused in the range c. 900–2100 Ma (Fig. 7C.1). Our study shows that the zircon patterns recorded in the samples from the Bravaisberget Formation are non-unique. A pattern similar to this is seen in Proterozoic successions from Svalbard (Pettersson et al., 2009; Beranek et al., 2020; Fig. 7C.2), East Greenland (Strachan et al., 1995; Watt et al., 2000; Leslie & Nutman, 2003; Fig. 7C.3) and northern Norway (Kirkland et al., 2007; 2008; Fig. 7C.4, C.5), and indicates a Late Palaeoproterozoic–Late Mesoproterozoic derivation from the same source terranes (Malone et al., 2014) with affinities to both Laurentia and Baltica. This similarity, noted over wide regions, became grounds for indicating that zircon patterns fail to separate Baltican and Laurentian units (Slagstad & Kirkland, 2017). To further complicate this fact, the pattern is recycled through the younger geological periods. It can be seen, among others, in the Silurian and Devonian sediments on Svalbard (Pettersson et al., 2010; Beranek et al., 2020; Fig. 7C.6), the Silurian and Devonian strata of the Franklinian Basin of Arctic Canada (Anfinson et al., 2012a, 2012b; Fig. 7C.7) and the Devonian and Carboniferous deposits of East Greenland (Slama et al., 2011; Fig. 7C.8). Furthermore, the same or very similar zircon pattern is recorded from the Mesozoic successions throughout the Arctic region: both from those interpreted as having been supplied by the western (i.e.,

Laurentia; Fig. 7C.9) and the southern (i.e., Baltica; Fig. 7C.10) source areas. The westerly-derived zircon age pattern has been reported from the Lower Triassic sediments of East Greenland (Slama et al., 2011), the Triassic–Cretaceous strata of the Sverdrup Basin (Røhr et al., 2010; Omma et al., 2011; Anfinson et al., 2016; Midwinter et al., 2016) and the Lower Cretaceous units of the Wandel Sea Basin of North Greenland (Røhr et al., 2008). The Neoarchaeon and Proterozoic age range linked to the southern source area is widely recorded from the Triassic and Jurassic sediments of the Barents Sea (Fleming et al., 2016; Klausen et al., 2017, 2018; Flowerdew et al., 2019; Line et al., 2020). Deposits of the Triassic Kobbe Formation of the southwestern Barents Shelf are interpreted as time and facies equivalents of the Bravaisberget Formation of this study (Fig. 1B). Zircon age ranges recorded from these two samples are presented on Fig. 7C.1, C.10. Excluding the Timanian zircon ages, which are commonly noted in the Kobbe Formation sample, the zircon patterns of the Kobbe and Bravaisberget formations are similar. In consideration of the paleogeography of the Arctic region during the Triassic period, there was a vast ocean between Baltica and Laurentia, and the Bravaisberget and Kobbe formations were deposited on the opposite sides of this ocean. As has been claimed (Mørk, 1999; Bue & Andresen, 2014), the sediment supply from the southeastern source had not reached the present western Svalbard by the Middle Triassic. Paleocurrent observations of the successions in Sørkapp Land suggest that the sediment transport was from the SW and W. Hence, Baltica as a source for the zircon grains from the Bravaisberget Formation seems unlikely. Both the compared samples, however, have a common Laurentian–Baltican protosource, and the zircon pattern is non-indicative of the direct source for these deposits. Thus, our study shows that the repeated sedimentary reworking has revealed that the information the zircon signature holds is no longer directly relevant to the source to sink system in the Middle Triassic of Svalbard.

Lu–Hf isotope analysis was applied to extend the utility of the U–Pb zircon geochronology. The ϵ_{Hf} for the SM sample displays mostly positive values and they are linked to the

dominant zircon age range, i.e., Meso- and Palaeoproterozoic (Fig. 7A). Contrary to this, the KM sample contains also a group of Palaeoproterozoic zircons (c. 1700–1900 Ma) displaying prominently low ϵ_{Hf} values (Fig. 7B), i.e., it has a non-mantle-like zircon Hf signature, pointing to reworking of the older crustal material during the protosource formation. The age of the extraction of the zircons from their parent mantle-magmas is linked to Archaean (mostly the Neo- and Mesoarchaeal) time (Fig. 7B). Signs of any Archaean affinity are not present among the Palaeoproterozoic zircons of the SM (Fig. 7A). This is consistent with the trend from the Eu/Eu* and Gd/Yb systematics (Fig. 8F), and indicates that the KM deposits are composed of the Archaean component that was affected by Palaeoproterozoic orogenesis. The Lu–Hf data, together with the trace element geochemical data, may reflect subtle provenance differences between the KM and SM deposits. In comparison with other known Hf isotope data from the Arctic region, the Hf isotope pattern recorded in the KM is quite similar to the pattern from the Lower Triassic sandstones of East Greenland (Slama et al., 2011). The Hf isotope signature of the SM is similar to the Neoproterozoic Eleonore Bay Supergroup of the East Greenland Caledonides (Slama et al. 2011). However, the differences are not very distinctive, and both the studied Hf isotope patterns can be linked to the basement rocks of the Canadian–Greenland Shield and East Greenland Caledonides (Røhr et al., 2008, 2010; Slama et al., 2011). The similar Hf pattern can be tracked throughout the Neoproterozoic to Cretaceous successions from East Greenland (Slama et al., 2011), the Cretaceous deposits of the Wandel Sea Basin of northern Greenland (Røhr et al., 2008), the Cretaceous sediments of the Sverdrup Basin of Arctic Canada (Røhr et al., 2010), and the Silurian and Devonian strata of NW Svalbard (Beranek et al., 2020). Moreover, this Laurentian-related Hf isotope pattern mimics the Hf pattern recorded from Fennoscandian granitoids (Andersen, 2013). Hence, the Hf isotope pattern follows the trend of the U–Pb zircon pattern, i.e., it is non-unique. Even though the U–Pb and Lu–Hf isotopes of zircon fail to indicate the direct potential source areas, the Hf pattern together with the Eu/Eu* vs. Gd/Yb systematics may be used for tracking the subtle changes in provenance evolution. Whilst the Eu/Eu* vs. Gd/Yb systematics show the primary age signature, the Hf

isotope analysis indicates whether the primary crustal signature was overprinted by subsequent tectonothermal events.

The bulk-rock techniques applied in our study, i.e., the petrography and bulk-rock geochemistry, allow us to state that the potential source rocks were the quartz-rich sedimentary rocks linked to the composition of the felsic protosource. From the zircon age pattern alone we can only infer the protosource rock terranes. Because the pattern is non-unique, i.e., widely encountered in Proterozoic successions through to younger sediments, little provenance significance can be drawn from the zircon data. The petrography and the geochemical data are indicative of a high degree of sedimentary reworking. Due to the degree of sedimentary reworking required, the original source of the zircon mineral has no bearing on the source to sink system in the Middle Triassic of Svalbard. The clastics of the Bravaisberget Formation could have been supplied from a source located somewhere in NE Greenland. This source could be molasse deposits composed of units eroded from the Caledonides. The molasse basin infill did not apparently comprise eroded material from the internal high-grade metamorphic and granite-bearing parts of the orogen, but reworked low-grade Proterozoic successions with a zircon pattern common to that recorded from the studied Middle Triassic rocks. Later sedimentary reworking of such molasse deposits occurred episodically, and is recorded in the Triassic of southern Spitsbergen (this study) and the Cretaceous of the Wandel Basin of NE Greenland (Røhr et al., 2008), among others. Differences between the geochemistry of the Somovbreen and Karentoppen members may reflect a subtle provenance evolution, where the Karentoppen Member is also composed of detrital material derived from the eroded part of an Archaean/Palaeoproterozoic basement. This model is in line with the paleotopography of Greenland and adjacent areas in the Middle Triassic (Fig. 10B) as proposed by Andrews & Decou (2018). Our study has shown that even with a multi-proxy approach, the provenance of compositionally mature sandstones, as those of the Bravaisberget Formation, is inherently

difficult to unravel. In such cases, where possible, any interpretations are best grounded by field constraints on the size of the sedimentary systems and direction of sediment transport.

Conclusions

(1) A combination of the bulk-rock and single-mineral techniques has been utilised for provenance studies of the Bravaisberget Formation (Middle Triassic) from Sørkappøya, Svalbard. This multi-proxy approach adds value to the provenance interpretation in such aspects as the mineralogy of the potential source rocks, the protosource ages, tracking the crustal evolution of the potential source terranes, as well as tracking the recycling and climatic fingerprints.

(2) The analysed sandstones have a quartz-dominated framework composition, and the identified petrofacies, which are quartz arenites, sublitharenites, subfeldsarenites and sublithwackes, point to a high mineralogical maturity. The content and distribution of the major element oxides confirm the results of the petrographic studies.

(3) The bulk-rock trace element analysis, together with the REE and Eu anomalies, indicate that the geochemical signature of the Bravaisberget Formation sandstones is compatible with a felsic composition for the protosource, i.e., similar to the late-melt fractionating crust.

(4) The integrated approach from our study adds the following evidence for multiple recycling of the clastic material of the Bravaisberget Formation sandstones from older sedimentary units: 1) a high mineralogical maturity highlighted by the monocrystalline quartz-dominated framework composition, 2) the mineralogical and bulk-rock geochemical features linking a potential source to quartz-rich strata, 3) a bulk-rock trace element pattern expressed by a rise of the Zr/Sc ratio values in relation to the UCC, and 4) a broad and relatively continuous range of detrital zircon ages.

(5) The zircon age signatures are dominated by Palaeo- and Mesoproterozoic ages, with a significant content of Neoarchaeon ages, and only a minor quantity of Neoproterozoic and Palaeozoic grains. The zircon age pattern is non-unique, i.e., it is widely present in sedimentary rocks across the Arctic region, from the Proterozoic successions through to

younger sediments. Given the degree of sedimentary reworking required, the information the zircons hold is no longer directly relevant to the last episode of erosion, transport and deposition in the Middle Triassic of southern Spitsbergen.

(6) The Hf isotope pattern follows the trend of the U–Pb zircon pattern, i.e., it is non-unique. Even though little provenance significance can be drawn from the Hf isotope pattern, this pattern coupled with the Eu/Eu* vs. Gd/Yb systematics are good indicators of the subtle differences in provenance evolution between the SM and the KM deposits. Both the members were in general supplied from the same post-Archaeon source, but the KM also displays an Archaeon contribution.

(7) The provenance of compositionally mature sandstones of the Bravaisberget Formation in southern Spitsbergen is inherently difficult to unravel and no more constrained than the original field data may have suggested. The deposits could have been supplied from a molasse basin located in NE Greenland, and filled with detrital material eroded from the reworked Proterozoic successions of the Caledonides.

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Table 1. Range of elemental ratios of the Bravaisberget Formation (Somovbreen and Karentoppen members) compared to the ratios in similar fractions sourced from felsic and mafic rocks, and the upper continental crust (Condie & Woronkiewicz, 1990; Cullers, 2002; Armstrong-Altrin et al., 2004; Rudnick & Gao, 2003).

Elemental ratio	Range of sediment from Somovbreen Mb. (n=20)*	Range of sediment from Karentoppen Mb. (n=17)*	Range of sediment from felsic sources**	Range of sediment from mafic sources**	Upper continental crust***
La/Sc	2.81-6.50	7.15-20.20	2.50-16.30	0.43-0.86	2.21
Th/Sc	0.66-1.90	0.80-2.10	0.84-20.50	0.05-0.22	0.75
La/Co	3.72-83.79	4.56-44.50	1.80-13.80	0.14-0.38	1.79
Th/Co	1.00-2.23	0.25-3.00	0.67-19.40	0.04-1.40	0.61
Cr/Th	6.65-10.53	0.00-14.66	4.00-15.00	25.00-500.00	8.76
Th/Cr	0.10-0.15	0.07-0.15	0.13-2.70	0.018-0.046	0.11
Eu/Eu*	0.54-0.75	0.46-0.83	0.40-0.94	0.71-0.95	0.69
(La/Lu)N	6.02-20.96	9.00-18.96	3.00-27.00	1.10-7.00	10.39

*This study; **Condie & Woronkiewicz (1990); Cullers (2002); Armstrong-Altrin et al. (2004); ***Rudnick & Gao (2003).

Figure 1. (A) Simplified geological map of Svalbard showing the distribution of lithostratigraphic groups and simplified structural elements (based on data from the Norwegian Polar Institute; Dallmann, 2015). (B) Lithostratigraphy of the Triassic of Svalbard and the Barents Sea region (modified from Mørk et al., 1999).

Figure 2. Detailed map of Sørkappøya and the most important parts of the studied sections (the red lines) of the Bravaisberget Formation (whole logs are presented in Electronic Supplement 1A). Samples for zircon dating and links to the thin-section images of Figs. 3 & 4 are plotted on the logs.

Figure 3. (A) Petrographic classification of sandstones of the Karentoppen and Somovbreen members in a QFL triangular diagram (the diagram is compiled and modified after: McBride, 1963; Dott Jr, 1964; Folk et al., 1970; Pettijohn et al., 1972; Williams et al., 1982). Q – quartz, F – feldspars, L – lithoclasts. The literature data for the Triassic sandstones of West Spitsbergen (Mørk, 1999) and the Sverdrup Basin (Omma, 2009) are plotted for comparison. (B–G) The petrofacies distinguished in the Karentoppen Member sandstones: (B) Poorly sorted quartzose cemented quartz arenite (Q – quartz grains, q – quartz overgrowths, Lt – lithoclasts); sample 2001-SO-23; (C) Moderately well sorted quartzose cemented quartz arenite (Q – quartz grains, q – quartz overgrowths); dolomitic cement (d, red arrows) has also been noted; sample 2014-SO-7.1; (D) Well sorted quartzose cemented sublitharenite (Lt – lithoclasts); calcite cement (c) has been sparsely noted; sample 2001-SO-14A; (E–G) Poorly sorted carbonate cemented sublitharenite (Q – quartz grains, Lt – lithoclasts, c – calcite cement); sample 2001-SO-8B (E) and 2001-SO-8A (F, G). Cross-polarised light: B–E, G; plane-polarised light: F.

Figure 4. Petrofacies of the Somovbreen Member deposits: (A) Very fine-grained, moderately well sorted, Fe-carbonate cemented quartz arenite (Q – quartz grains, fe – iron oxides and/or hydroxides); sample 2014-SO-13.2; (B) Poorly sorted carbonate cemented sublithic wacke (Q – quartz grains, Lt – lithoclasts, d – dolomitic cement); sample 2001-SO-26; (C, D) Very poorly sorted carbonate cemented sublitharenite (Lt – lithoclast, c – calcitic cement, d – dolomitic cement, om – organic matter); the lithic fragment is a chert; sample 2001-SO-24; (E, F) Very fine grained petrofacies: (E) siltstone; sample 2014-SO-11.2; (F) mudstone; sample 2001-SO-10. Cross-polarised light: A, B, D–F; plane-polarised light: C.

Figure 5. Geochemical classification of the deposits of the Bravaisberget Formation from Sørkappøya (diagram after Herron, 1988).

Figure 6. Patterns of the mean chondrite-normalised rare earth elements of the Bravaisberget Formation from Sørkappøya (the chondrite values are from e, 1985). The UCC and PAAS values are plotted for comparison (UCC values are from Rudnick & Gao, 2003; PAAS values are from Taylor & McLennan, 1985). UCC – upper continental crust, PAAS – post-Archaean Australian shale.

Figure 7. (A, B) Combined probability density plots and histograms of detrital zircon U–Pb ages, and plots of U–Pb ages (time) vs. initial ϵ_{Hf} of the Middle Triassic samples from Sørkappøya: (A) Somovbreen Member; (B) Karentoppen Member. The histograms and probability density plots show only ages that are less than 10% discordant; $n = 61(88)$ presents the number of grains of less than 10% discordance relative to the total number of analysed grains. Shaded areas represent the most important zircon age ranges. CHUR – chondritic uniform reservoir, DM – depleted mantle. The reference line is the ϵ_{Hf} growth curve for rocks with an upper crustal $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.015, anchored at 2.5 Ga. Values below the line indicate the Archaean protolith;

(C) KDE plots (C1-3 & C6-10) and PDP (C4 & 5) for this study and for literature data discussed in the text. PDP of C4 & C5 taken from Fleming et al. (2016).

Figure 8. Selected trace elements and their ratios applied for the characteristic potential source rocks: (A) Th/Co vs. La/Sc diagram (Cullers, 2002) showing a felsic composition of the Bravaisberget Formation source rocks; (B) Cr/V vs. Y/Ni diagram (Hiscott, 1984) showing the samples plotted between the granitic and UCC compositions; (C) La–Th–Sc ternary diagram (Bhatia & Crook, 1986; Cullers, 2002) displaying the felsic composition of potential source rocks. Average compositions of basalt, andesite and granite are plotted for comparison; (D) The potential source rocks composition based on the V–Ni–Th*10 ratio (Bracciali et al., 2007); (E) Th/Sc vs. Eu/Eu* diagram (Cullers & Podkovyrov, 2002) linking potential sources to felsic rocks, mostly ranging between the granodiorite-tonalitic and granitic compositions; (F) Eu/Eu* vs. (Gd/Yb)_N diagram (McLennan et al., 1990) showing the Archaean and post-Archaean rocks as sources for the siliciclastic material of the Bravaisberget Formation deposits. More explanation is given in the text.

Figure 9. (A) Th/Sc vs. Zr/Sc diagram (McLennan et al., 1993) showing datapoints for the studied deposits. All samples are distributed parallel to the same line of the sediment recycling trend; (B) The figure shows the diagram of $15 \cdot \text{Al}_2\text{O}_3\text{--Zr--}300 \cdot \text{TiO}_2$ ratio (Garcia et al., 1994) displaying accumulation of the studied samples along the zircon addition arrow, pointing to sediment recycling.

Figure 10. (A) General geography of the Arctic region with potential source areas and other places discussed or mentioned in the text (modified after Rosa et al., 2016). (B)

Paleogeographic reconstruction of the North Atlantic region in the Middle Triassic (Andrews &

Decou, 2018), with paleotopography of the potential source area for the studied sandstones discussed in the text.

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A

B

Sørkapplåguna

covered

Sørkapp

(m)

under the sea-level

Fig. 4A

Zr

covered by beach deposits

Fig. 4E

Fig. 4F

Fig. 3E

Fig. 3F, 3G

covered by beach deposits

Fig. 3C

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● Karentoppen Mb. ● Somovbreen Mb. ● UCC ● PAAS