Detrital zircon (U-Th)/He ages from Paleozoic strata of the Severnaya Zemlya Archipelago: deciphering multiple episodes of Paleozoic tectonic evolution within the Russian High Arctic

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Abstract

Combined (U-Th)/He and U-Pb detrital zircon geochronological data are reported from Ordovician to Devonian strata of the Severnaya Zemlya archipelago to address the paleogeography of the Kara Terrane in the Russian High Arctic. (U-Th)/He ages from all six samples analyzed were not reset after sediment deposition, indicating that detrital zircons carry information on the exhumation history in the source region of the clastic material. In Ordovician-Silurian strata, (U-Th)/He ages range from 583.8 ± 46.7 to 429.0 ± 34.3 Ma. These ages nicely coincide with significant regional exhumation during the Caledonian and Timanian orogenies. In addition, combined U-Pb and (U-Th)/He dating show that within the source region, zircons that were crystalized during the Timanian Orogeny (U -Pb ages 680-560 Ma) were likely exhumed during younger Caledonian events ((U-Th)/He ages of 455-495 Ma), suggesting potential overlap of these orogens within the source region. In Devonian strata, detrital zircon (U-Th)/He ages range from 517.2 ± 41.38 to 332.9 ± 26.6 Ma, with a peak age of ca. 375 Ma. This 375 Ma event may be correlated with either the Ellesmerian Orogeny or the terminal Solundian/Svalbardian stages of the Caledonian Orogeny.

Introduction

The present day geological structure of the Arctic consists of a collage of terranes of various ages that are either adjacent, or attached, to three large Precambrian cratons: Laurentia, Baltica and Siberia (Fig. 1a). The marginal terranes and cratons are separated by two large, late Mesozoic and Cenozoic oceanic basins, the Amerasian Basin and the Eurasian Basin respectively (Fig. 1a). A number of different Paleozoic and Mesozoic paleogeographic models of the Arctic have been recently published (e.g. Anfinson et al., 2012; Beranek et al., 2013; Bromley and Miller, 2014; Colpron and Nelson, 2011; Ershova et al., 2015b,c, 2016b; Gasser and Andersen, 2011; Hadlari et al., 2014; Lawver et al., 2002; Miller et al., 2010, 2011, Pease and Scott, 2009). Paleogeographic reconstructions of the present day Arctic are complicated by uncertainties in identifying and correlating key tectonic events associated with Early to Middle Paleozoic orogenies. Poorly resolved evolution of the Amerasian Basin further complicates the reconstruction of pre–Cenozoic tectonics and paleogeography. The affinity of the so-called Kara Terrane, comprising the Severnaya Zemlya archipelago and northern Taimyr in the Russian High Arctic (Fig. 1), is a critical piece of the Early-Middle Paleozoic Arctic jigsaw puzzle.

This paper is dedicated to reconstructing the Arctic's Middle Paleozoic based on (U–Th)/He thermochronologic ages and combined U/Pb and (U-Th)/He of detrital zircons collected from Ordovician–Devonian strata in the Severnaya Zemlya archipelago (Fig. 1). (U–Th)/He low temperature thermochronology records the time at which the mineral passes through its closure temperature from 60° to 300^{o} C, depending on the system (Farley, 2002; Reiners et al., 2004). The (U-Th)/He system in zircon closes at temperatures of approximately 170–190°C, which typically occur at 6-7 km depth beneath the surface in continental crust with a typical geothermal gradient of 30°C/km (Reiners 2005; Wolfe and Stockli 2010). Combined U/Pb and (U-Th)/He dating on the same zircon crystal provides both high- and low-temperature ages of detrital grains, corresponding to crystallization (or subsequent high-grade metamorphism) and cooling/exhumational events respectively. Thus the combination of both crystallization and cooling ages can provide more informed and robust provenance interpretations than is possible by just using a single radioisotopic system (Reiners et al., 2004). The (U–Th)/He thermochronologic data, supplemented with new and existing detrital zircon U-Pb ages, offer a new and updated perspective on the Early-Middle Paleozoic exhumation history and subsequent Paleozoic tectonic evolution of the Russian High Arctic, therefore improving our understanding of the paleogeography and tectonics of Kara terrane and neighboring regions.

Early-Middle Paleozoic tectonic events reported from the Arctic

The paleo-positions of terranes now exposed in the High Arctic are poorly known for the time prior to the opening of the Amerasian and Eurasian oceanic basins (Fig. 1a). Uncertainty largely stems from determination of the age and distribution of Paleozoic orogenic events, evidence of which is now scattered across the Arctic realm. The Early-Middle Paleozoic Caledonian Orogen was formed by prolonged Ordovician-late Silurian closure of the Iapetus Ocean, generated by numerous episodes of arc-arc, continent-arc and finally by continent-continent collision between Laurentia and Baltica (e.g. Gee et al., 2013; McKerrow et al., 2000**;** Roberts, 2003). Presently, fragments of the former Caledonian Orogen have been rifted apart by the opening of the younger oceanic basins, and can be traced from the eastern seaboard of North America to Greenland, Scotland and western Scandinavia. However, its continuation further to the east and north from Scandinavia is debatable due to burial of Early-Middle Paleozoic rocks beneath thick younger sedimentary successions of the Barents Sea basin. Due to this uncertainty, numerous models exist postulating the possible continuation of the Caledonian suture and deformation front offshore within the Barents Sea and beyond (Fig. 1a).

Based on geophysical data, Breivik et al. (2005) proposed two major thrust/suture zones in the western portion of the Barents Sea. The first zone is interpreted as a relic of westward dipping Caledonian continental collision or major thrusting. The basement/Moho trend of the first zone projects onto the Billefjorden Fault Zone on Spitsbergen and is a proposed Caledonian suture that divides Svalbard into two tectonic domains. The second zone extends south from Spitsbergen and has a SW-NE orientation (Breivik et al., 2005). Based on the proposed Laurentian affinity of northeastern Svalbard, both Gee et al. (2006) and Barrère et al. (2011) placed the suture between Svalbard and Franz Josef Land, however Barrère et al. (2011) positioned the suture closer to Svalbard than Gee at al. (2006, 2008). Gravity field data from the Barents Sea was used by Henriksen et al. (2011) to identify two distinct regions, a gravity-high to the west and a gravity-low to the east. From this data, Henriksen et al. (2011) suggested that the main part of the Barents Shelf was deformed as part of the Caledonides, placing the Caledonian suture close to the Novaya Zemlya archipelago. Recent Ar-Ar dating of muscovite from metasedimentary bedrock dredged from the Lomonosov Ridge (Knudesen et al., 2017; Marcussen et al., 2015), indicates that this block was also involved in the Caledonian deformation leading Marcussen et al. (2015) to propose a possible continuation of the suture through the Lomonosov Ridge.

Estimates of the Caledonian deformation front location within the Barents Shelf are also intensely debated (Fig. 1a). Gee et al. (2006) propose that it extends to the east of Svalbard, since eastern Svalbard was intensely deformed during the Caledonian Orogeny. Using Ar-Ar and K-Ar data from a single well penetrating the basement of Franz Joseph Land, that indicate that the basement rocks were also affected by Caledonian deformation, Gee et al. (2006) postulated that the deformation front was located to the east of Franz Joseph Land.

Breivik et al. (2005) imply that almost the entire basement of the Barents Shelf was involved in the Caledonian deformation, whilst Barrère et al. (2009, 2011) and Gernigon and Brönner (2012) suggest that the Caledonian deformation front ends just to the southeast of Svalbard (Fig. 1a). In addition, evidence of Caledonian deformation has been identified in many other remote Arctic locations including Pearya, the Chukchi Borderland, De Long Islands and eastern Greenland (Fig. 1) (Bromley and Miller, 2014; Gasser et al., 2014; Gee et al., 2006, 2008; Prokopiev et al., 2015; Roberts, 2003; Trettin, 1987, and references therein).

Tectonic events across the Caledonides group into four major compressive/transpressive stages (Corfu et al., 2014; Roberts, 2003 and references therein). The oldest phase, Trondheim (Early Ordovician), involved collision between Baltica, or an adjacent microcontinent, and Iapetus island arcs. The second phase, the Taconian (Middle - Late Ordovician), was associated with accretion of an island arc to the Laurentian margin. The third phase, the Scandian (Middle Silurian - Early Devonian), involved rapid subduction of the Baltican margin beneath Laurentia and culminated in continental collision between Baltica and Laurentia (Roberts, 2003). The final phase, the Solundian or Svalbardian phase (Late Devonian-Early Carboniferous), is primarily described from the onshore Scandinavian Caledonides and Svalbard, but its interpretation and relationship to other events of the

Caledonian Orogeny are controversial (Bergh et al., 2011; Eide et al., 2002; Fossen, 2010; Roberts, 2003; Sturt and Braathen, 2001; Torsvik et al., 1986). Some researchers (e.g. Eide et al., 2002; Fossen, 2010; Roberts, 2003) interpret the Solundian phase as an orogenic collapse with widespread extension/transpression. However, Torsvik et al. (1986) and Sturt & Braathen (2001) document compressional deformation and low-grade metamorphism of the same age. In addition, Bergh et al. (2011) describe Late Devonian folding, oblique thrusting and basement uplift in Svalbard, relating these events to the final compressional activity associated with the Caledonian Orogeny.

Roughly coeval to the Solundian/Svalbardian phase is the enigmatic tectonic event commonly referred to as the Ellesmerian Orogeny in many other regions of the Arctic (e.g. Anfinson et al., 2013; Embry, 1988, 1993; Higgins et al., 2000; Lawver et al., 2011). There is evidence of Late Devonian to Early Carboniferous deformation and magmatism reported from the Canadian Arctic Islands, north slope of Alaska, north Yukon, north Greenland, Svalbard, the New Siberian Islands, Wrangel Island and Chukotka (Anfinson et al., 2013; Ershova et al., 2016a; Harrison et al., 1995; Harrison and Brent 2005; Gilotti et al., 2004, 2014; Lane, 2007; O’Brien et al., 2016; Piepjohn, 2000; Piepjohn et al., 2008, 2015; Prokopiev et al., 2015; Rippington et al., 2010; Soper & Higgins, 1990, and references therein) (Fig. 1a). However, there are many uncertainties about tectonic causes, distribution, and consequences of the Ellesmerian Orogeny in the Arctic realm. It has been interpreted to be the result of collision between the Pearya Terrane and Svalbard with the Franklinian Basin of Laurentia (Piepjohn et al., 2015), or between Laurentia and an enigmatic continental block that comprised the Pearya Terrane, Chukotka, Chukchi Borderland, Svalbard, and other Arctic terranes that is commonly referred to as Crockerland (Anfinson et al., 2012; Anfinson et al., 2013; Embry, 1993), and more recently described as being part of the proposed Arctida landmass (Anfinson et al., 2016). Moreover, due to the opening of younger oceanic basins, uncertainty exists regarding whether the Ellesmerian Orogeny and the latest stages of the Caledonian Orogeny represent the same tectonic episode, or whether they were truly separated in time and space. Thus the Late Devonian tectonic episode and metamorphism in Svalbard is correlated to either the terminal stage of the Caledonian Orogeny (Bergh et al., 2011), or the Ellesmerian Orogeny (Kosminska et al., 2016; Piepjohn, 2000). More precise temporal correlation is clearly needed between Late Devonian-Early Carboniferous magmatic and tectonic events of the entire Arctic region and those of the Russian Arctic.

Geological Background of the Severnaya Zemlya archipelago (Kara terrane)

The Severnaya Zemlya archipelago comprises four main islands called Pioneer, October Revolution, Komsomolets and Bol'shevik, along with numerous other small islands and island groups such as the Sedov Islands.

Together with the northern part of the Taimyr Peninsula and intervening shelf, it makes up the core of the Kara Terrane, also named Kara Block, Kara Plate or North Kara Terrane (KT on Fig. 1a) (Drachev et al., 2010; Lorenz et al., 2008a). The northeastern boundary of the Kara Terrane corresponds to the margin of the continental shelf of the Cenozoic Eurasia Basin. Towards the south, the Kara Terrane abuts central Taimyr and Siberia along the Main Taimyr Thrust and Diabazoviy Fault respectively (Vernikovsky, 1996). To the southwest, it is likely separated from the South Kara Basin and West Siberia by the linear North Siberian Arch (Drachev et al., 2010). The continuation of the Kara Terrane northwest of the North Siberian Arch is debated.

Paleomagnetic data seem to suggest that the Kara Terrane was an isolated crustal block throughout the Paleozoic (Metelkin et al., 2000). The NW–SE orientation of the structural high separating the eastern Barents Sea and the northern Kara Sea (Kara Terrane), is imaged by geophysical data and illustrated by the 3D model of Klitzke et al. (2015), and is likely to correlate with the Timanide suture. This high is therefore assumed to mark the collision between the Kara Terrane and Baltica during the Timanian Orogeny in the latest Neoproterozoic (Klitzke et al., 2015; Lorenz et al., 2008a). Based on seismic data, Paleozoic strata of the northeastern part of the Barents Sea can be traced into the North Kara Basin (Daragan-Suschova et al., 2013), supporting ideas that the Kara Terrane was attached to Baltica during most of the Paleozoic. Furthermore, based on the continuity of magnetic anomaly data patterns, Gee et al. (2006) suggest that the Kara Terrane can be extended into northern Novaya Zemlya and represents an integral part of Baltica (Lorenz et al., 2008a,b). However, defining the eastern boundary of the Kara Terrane is severely hampered by Meso-Cenozoic rifting of the Laptev Shelf prior to opening of the Eurasia Basin.

Several different tectonic models consider the tectonic affinity of the Kara Terrane. According to Zonenshain et al. (1990), during the Paleozoic this terrane was part of a larger continental block called Arctida. Lorenz et al. (2008b) suggest that the Kara Terrane was a marginal part of Baltica, whilst other researchers (Bogdanov et al., 1998; Gramberg and Ushakov, 2000; Metelkin et al., 2000) suggest the Kara Terrane was an independent terrane or microcontinent during the Paleozoic. A number of previous detrital zircon studies suggested that the terrane was a marginal part of Baltica during the Early-Middle Paleozoic (Ershova et al., 2015; Lorenz et al., 2008b; Pease and Scott, 2010).

Stratigraphy of Severnaya Zemlya archipelago

The Paleozoic stratigraphy of the Severnaya Zemlya archipelago comprises Cambrian to Permian sedimentary deposits (Ershova et al., 2015d, 2016a; Gramberg and Ushakov, 2000; Makariev, 2012; Matukhin & Menner, 1999 and references therein). The Pioneer, October Revolution and Komsomolets islands are mainly comprised of Cambrian to Upper Devonian deposits with locally distributed Carboniferous and Permian strata. Predominantly Cambrian-Ordovician deposits are exposed on Bol'shevik Island, with a few outcrops of

Upper Carboniferous–Permian and Mesozoic deposits (Makariev, 2012) (Fig. 2). The lateral continuity and facies of the sedimentary succession are quite variable across the archipelago (for a more detailed description of the stratigraphy see Ershova et al., 2016a.

The Cambrian strata are represented by alternating varicolored sandstones, siltstones, and marls with subordinate beds of limestone, which have thickness ranging from 1000 to 2000 m. According to Lorenz et al. (2007), an angular unconformity separates overlying Ordovician strata from Cambrian deposits. However, according to others (Makariev , 2012; Markovsky et al., 1988), this boundary is a disconformity. Ordovician deposits comprise two distinct successions, the Lower to lowest Middle Ordovician succession is mainly represented by alternating sandstones, clays, and siltstones with subordinate beds of carbonate and a few volcanic tuffs at the base (Lorenz et al., 2007; Makariev, 2012). The Middle–Upper Ordovician succession is comprised primarily of limestone with subordinate beds of clastic beds and evaporites. The approximate thickness of the Ordovician strata ranges from 650 to 1400 m. Silurian deposits lie conformably on the Ordovician, comprising 700-1100 m of Llandoverian-Ludlovian carbonates and marls, overlain by up to 700 m of Pridolian interbedded shales, rare sandstones and carbonates (Matukhin and Menner, 1999).

The Lower Devonian deposits are disconformably overlain by different levels of Silurian deposits and comprise up to 600 m of carbonates and evaporites, with beds of shales and sandstones in the lower part of succession (Makariev, 2012; Matukhin and Menner, 1999). The Middle to Upper Devonian succession is typically 1000 to 1500 m thick and is comprised of continental red-colored sandstones and siltstones with subordinate beds of gravelly- to pebbly-conglomerates (Makariev, 2012). Carboniferous-Permian deposits are sparsely distributed across the archipelago and consist of continental clastics up to a few hundred meters in thickness (Ershova et al., 2015d; Makariev, 2012).

Overview of previous provenance studies from the Paleozoic rocks of the Severnaya Zemlya archipelago

Previous provenance studies have revealed that Cambrian strata within the archipelago have two main detrital zircon age groups. The younger age group consists of 500-600 Ma zircons and is likely derived from the Timanian Orogen (Lorenz et al., 2008b; Ershova et al., 2015a). The older age groups, ranging from ca. 0.9-1.2 Ga and 1.4-1.8 Ga, are attributed to the Sveconorwegian-Grenvillian Orogen and the basement of Baltica respectively. Ordovician deposits contain many of the same detrital zircon ages as the Cambrian strata, but also contain a primary age group of 450-500 Ma (Lorenz et al. 2008a). Lorenz et al. (2008a) suggested that the Ordovician grains are sourced from local magmatic units exposed in the Severnaya Zemlya archipelago. However, the significant thickness of Ordovician strata (up to 2000 m) and its broad distribution across almost the entire archipelago suggest that an alternative source of clastic sediment is also viable.

Lorenz et al. (2008a) document the prominent shift in detrital zircon age spectra between pre-Devonian and Devonian strata. Within the Devonian deposits, Precambrian detrital zircons are dominated by Sveconorwegian-Grenvillian (0.9-1.2 Ga) and Baltica basement (1.4-1.8 Ga) age groups. Upper Carboniferous to Lower Permian sandstones however contain a primary age group ranging from 450 to 570 Ma, with a predominance of Early-Middle Ordovician zircons (Ershova et al., 2015d). The detrital zircon age distributions suggest that the Upper Carboniferous to Lower Permian sandstones were derived locally from the erosion of Lower Ordovician deposits (Ershova et al., 2015d). The temporal variability in geochronologic ages within the archipelago suggests a complex tectonic history in the provenance area and warrant analysis of the exhumation history by thermochronologic techniques, which are lacking for the region to date. The recent U-Pb detrital zircon studies of the Lower-Middle Paleozoic rocks across the Russian High Artic revealed many similarities between the provenance areas of clastics in Novaya Zemlya, Severnaya Zemlya, and the New Siberian Islands (Ershova et al., 2015a, b,c, 2016a,b; Lorenz et al., 2008a,b, 2013). The principal conclusion from these studies was that these now geographically separated regions belonged to the marginal part of Baltica during the Early-Middle Paleozoic.

Methods

Detrital zircon (U-Th)/He analyses were performed on six samples within the Severnaya Zemlya archipelago. Additional detrital zircon double dating (U-Pb and (U-Th)/He) ages were performed on three of the samples to provide additional geochronologic constraints. Samples were crushed and the heavy minerals were concentrated using standard techniques at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences. (U–Th)/He and U-Pb dating of detrital zircons was carried out at the UTChron geochronology facility in the Department of Geosciences at the University of Texas, Austin. All U-Pb LA-ICPMS detrital zircon analyses were performed on whole grain mounts (instead of polished mounts) to preserve the grains for (U-Th)/He analyses. LA-ICPMS instrument parameters and expanded data reduction methods can be found in the Supplementary File 1. For grains older than 1.0 Ga, the 207Pb/206Pb age is reported, while for grains younger than 1.0 Ga, the 206Pb/238U age is selected. Following U-Pb analyses, selected grains were chosen for additional (U-Th)/He analyses. Specific grains that were at least 70 μm in diameter were chosen, and they appeared to have few, if any, visible inclusions, and were Ordovician or older in age. Due to the detrital nature of the samples and potential dispersion in (U-Th)/He cooling ages, up to 13 single grains/per sample were analyzed for some samples, leading to a total of 41 analyses. Analyses were conducted following analytical procedures described in Wolfe and Stockli (2010) and a brief description of these methods can be found in Supplemental File 1. All ages were corrected for the effects of α-ejection

(Farley et al., 1996) and are reported with a ~8% (2σ) analytical uncertainty. Detailed analytical methodology, detrital zircon U-Pb analytical results, and (U-Th)/He analytical results are provided in Supplemental Files 1, 2 and 3, respectively.

Results of Detrital Zircon (U-Th)/He Dating

Six samples with depositional ages ranging from Ordovician to Devonian were analyzed for detrital zircon (U-Th)/He geochronology. All obtained ages are older than the depositional ages of the host strata, indicating that the samples were not buried deeply enough (>7 km) to reset the isotopic system. Therefore, the ages can be reliably interpreted to indicate the exhumation history within the source region of the clastic material (Figs. 3a,b).

Sample 13AP15 is an Upper Ordovician fine- to medium-grained sandstone collected from the Matusevich River of October Revolution Island (Figs. 1, 2), whilst sample 13AP03 is a Lower Silurian fine- to medium-grained sandstone from Figurnyi Island (Figs. 1, 2). Eleven detrital zircon grains from the two samples yield (U-Th)/He ages ranging from 583.8 297 ± 46.7 to 429.0 ± 34.3 Ma (Fig. 3a), with a peak age at ca. 465 Ma (Fig. 3c).

Combined (U-Th)/He and U-Pb dating of zircons from Upper Ordovician strata (13AP15) indicate that some of the Latest Neoproterozoic (U-Pb age) zircons were partially reset during the Caledonian Orogeny, whilst some of them retained their initial uplift/cooling ages (Fig. 3b).

Four Devonian samples were selected for detrital zircon (U-Th)/He dating. Sample 13AP05 was collected from Frasnian medium-grained sandstones on Figurnyi Island (Figs. 1, 2), whilst sample 13AP09 was collected from Upper Devonian (Frasnian-Famennian) medium-grained sandstones on Pioneer Island. Sample 13AP13 was collected from medium- to coarse-grained Frasnian sandstones on October Revolution Island (Matusevich River), whilst sample 13AP14 was collected from late Early Devonian fine- to medium-grained sandstones from the same locality (Figs. 1, 2).

In the Devonian strata, thirty detrital zircon grains from four samples yielded (U-Th)/He ages ranging from 517.2 ± 41.38 to 332.9 ± 26.6 Ma (Fig. 3a). In contrast to the older (Ordovician-Silurian) clastic rocks, (U-Th)/He ages from the Devonian deposits have a main age peak at ca. 375 Ma (Fig. 3c) A subordinate zircon population shows a peak age of ca. 465 Ma (Fig. 3b), equivalent to the age peak in older Ordovician-Silurian clastic rocks.

The combined U-Pb and (U-Th)/He dating of Devonian sandstones depicted in Fig. 3b suggest that detrital zircons that crystallized in the Cambrian and Precambrian (U-Pb ages) were subsequently exhumed in the Middle Ordovician and Late-Devonian ((U-Th)/He ages).

Discussion

The obtained detrital zircon (U-Th)/He ages have not been reset since deposition, constraining the maximum burial of the studied succession to <~7 km. The detrital zircon (U-Th)/He ages indicate two distinct source regions for the Ordovician-Silurian and Devonian clastic sedimentary rocks of Severnaya Zemlya. The (U-Th)/He detrital zircon ages from Ordovician- Silurian strata show a primary age peak at ca. 465 Ma (Fig. 3c) which, within error, can be attributed to the early orogenic episodes reported from the Scandinavian Caledonides (Roberts, 2003). The (U-Th)/He data correlate well with previously published U-Pb ages of detrital zircons from the Ordovician rocks of Severnaya Zemlya (Lorenz et al., 2008b), which contain prevailing Late Cambrian-Ordovician zircons including the main population grouped at ca. 462 Ma (Fig. 3d), along with minor populations at 530 Ma and ca. 600 Ma. Furthermore, the similarity of the U-Pb and (U-Th)/He ages indicate that shortly after crystallization there was likely rapid exhumation of magmatic complexes, typical of an active margin setting (ex. Spikings and Simpson, 2014). However, the 465 Ma ages correspond to arc-continent, and not continent-continent collision, within Caledonian orogen (Roberts, 2003). Moreover, the comparison between data presented here and Ar-Ar cooling ages from different regions affected by Caledonian deformation (fig 4) shows that this 465 Ma event is more clearly seen in Svalbard and Greenland rather than in Scandinavian Caledonides. However, earlier pre-Scandian exhumational phases were likely overprinted by a Scandian event within Caledonian orogen, which corresponds to the main pulse of continent-continent collision. Thus, the (U-Th)/He ages presented here and U-Pb data of detrital zircon from Lorenz et al. (2008) clearly indicate extensive tectono-magmatic activity in the Middle-Late Ordovician within the source region of studied clastic rocks. Thus, our data favor the Peri-Baltica model for the affinity of the Kara Terrane proposed by Lorenz et al. (2008a,b), suggesting that clastics have been sourced from northeastern part of Baltica (modern coordinates). Moreover, double dating of detrital zircon indicate that detrital zircons crystallized during the Timanian Orogeny (U-Pb ages 680-560 Ma) were partially reset during the Caledonian Orogeny ((U-Th)/He ages of 455-495 Ma) in the source area, suggesting that within the source region, the Timanian Orogen was likely overprinted by Caledonian exhumational events. We therefore suggest that the primary source area of these sediments, is an Ordovician continental arc built on Timanian-age crust. The arc was part of the active Margin of the Iapetus Ocean, and its remains are presently located within the modern Arctic Ocean. Although much of the source region for these sediments is now likely submerged as part of the Amerasian and Eurasian basin continental shelves, there are a few on-shore localities that contain evidence of a similar geologic history. For instance, the basement of the Franz Josef Land archipelago (north-eastern Barents sea; Figure 1), contains Ar-Ar cooling ages suggesting Latest Neoproterozoic-Cambrian (?) deposits experienced a Caledonian metamorphic event (Pease et al., 2001). Within the De Long Islands (part of the New Siberian Islands Archipelago in the Russian Eastern Arctic), one can find Timanian-age basement (Ershova et al., 2016) which experienced significant uplift and exhumation in the Early-Middle Palaeozoic (Prokopiev et al., this issue). Thus, there is growing evidence that indicates Timanian age basement within the Arctic realm, that was potentially part of the Early Paleozoic northern margin (modern coordinates) of the Baltica paleocontinent, and experienced younger Caledonian orogenic events.

Furthermore, recent Ar/Ar dating of metamorphic muscovite from the arkosic metasedimentary rock dredged from the Lomonosov Ridge indicates that a metamorphic pulse was associated with an orogenic event around 470 Ma, which could be correlated with the early stages of the Caledonian Orogeny (Marcussen et al., 2015, Knudsen et al., 2017). The age of the metamorphic event on the Lomonosov Ridge is similar, within error, to the 465 Ma exhumation event recorded within the provenance area for the Ordovician-Silurian successions of Severnaya Zemlya presented here. The data presented here is close in the exhumation-age reported from the basement of Franz Joseph land and Lomonosov ridge suggest that the rocks involved in the Caledonian Orogeny and/or deformation front affected most of the Barents Shelf including its northeastern part. It also indicates that the deformation front may have also extended further to the north and affected the Lomonosov Ridge. This part of Caledonian orogen likely represented the main provenance for studied Ordovician-Silurian clastics. These findings are in good agreement with recent models, which suggest, based on geophysical data, that the main suture of the Caledonian Orogen is close to the Franz Josef Land and Novaya Zemlya archipelagoes (Gac et al., 2016; Gee et al., 2006).

The change in provenance from pre-Devonian to Devonian successions is notable in both the detrital zircon (U-Th)/He and U-Pb data (Lorenz et al., 2008b). Lorenz et al. (2008b) note that in the Devonian deposits the detrital zircon populations are dominated by Mesoproterozoic ages, with typical age peaks around 1600 Ma, 1450 Ma, 1250 Ma and 1050 Ma, and Neoproterozoic ages grouped at ca. 570, 600 and 980 Ma (Fig. 3d), whilst

Caledonian zircons as well as younger zircons that are close to the age of sedimentation are rare. Thus, based on U-Pb ages of detrital zircons, Lorenz et al. (2008b) assumed that the source region of Devonian clastics was uplifted pre-Caledonian basement of the Grenvillian-Sveconorwegian Orogeny, suggesting its continuation further to the north (Lorenz et al., 2008b, 2012). Detrital zircon (U-Th)/He ages suggest that multiple episodes of tectonic uplift occurred in the clastic source area for Devonian sandstones of Severnaya Zemlya. The minor, ca. 465 detrital zircon (U-Th)/He age peaks, may be correlated to episodes of arc-continent collision within Caledonides (Corfu et al., 2014; Gee et al., 2008; Roberts, 2003,) (Fig. 3c). The dominance of Late Devonian (~375 Ma) (U-Th)/He ages correlate well with the timing of the Ellesmerian Orogeny or the Solundian/Svalbardian phase of Caledonian deformation (Anfinson et al., 2013; Eide et al., 2002; Lane, 2007; O’brien et al., 2016; Rippington et al., 2010; Roberts, 2003; Piepjohn, 2000, 2008). The combined U-Pb and (U-Th)/He dating approach depicted in Fig. 3b suggests that detrital zircons crystallized in the Cambrian and Precambrian were subsequently exhumed during the terminal Early-Middle Paleozoic orogenic events. Hence, in conjunction with recent evidence from many localities across the Arctic, this data provides further evidence for a major orogenic event of Late Devonian–Early Carboniferous age (Ershova et al., 2017; Harrison, et al., 1995; Harrison and Brent 2005; Lane, 2007; Piepjohn et al., 2015; Prokopiev et al., 2015; Rippington et al., 2010; Kosmi´nska et al., 2016, and references therein). In addition, recent U-Th-Pb monazite dating of metapelites obtained by Kosmi’nska et al. (2016) show evidence for Ellesmerian age metamorphism within the crystalline basement of Svalbard, with an early prograde stage at ca. 370 Ma. Thus, Svalbard was assembled as a whole and positioned north of the main Laurentia–Baltica collision zone by Silurian-early Devonian (Gasser, 2014). Our data from the Devonian deposits of Severnaya Zemlya corresponds well with the recent findings in Svalbard, suggesting the exhumation of older rocks in the Late Devonian in the provenance area. Therefore, this is an additional line of evidence for considering the Kara Terrane as a marginal part of the Baltica continent during the Early-Middle Paleozoic.

So far, neither published data nor data presented here provide concrete evidence that the Late Devonian event could be considered either as a discrete tectonic event (Ellesmerian Orogeny) or belonging to the terminal stages of the Caledonian Orogeny. However, our data could be used as evidence that the Caledonian Orogeny sensu stricto was overprinted by a Late Devonian Ellesmerian or Solundian/Svalbardian tectonic event (Fig. 4b). Moreover, (U-Th)/He dating of detrital zircon from the Devonian strata of Artic Canada (Anfinson et al., 2013) show similar ages of exhumation (fig.4), providing additional evidence of widespread Late Devonian exhumation in Arctic Realm. Taking into account the broad distribution of Late Devonian–Early Carboniferous deformation, felsic magmatism, and metamorphism across the now disparate Arctic terranes (Fig. 1), we propose that terrane accretion and collisional processes are primarily responsible for tectonic events of this age. However, we speculatively suggest that this juxtaposition of continental scale terranes in Late Devonian likely represented the final northward propagation (in present day coordinates) of collision between Laurentia and a marginal region of Baltica. Recent data on the potential Baltican origin of now separated Arctic terranes from the Russian Arctic–Severnaya Zemlya Archipelago, New Siberian Islands and Chukotka, including Wrangel Island (Lorenz et al., 2008b; Ershova et al., 2015 a,b,c; Ershova et al., 2016a,b; Miller et al., 2010), accompanied by reported evidence of Late Devonian deformation within those regions (Prokopiev et al., 2015; Verzhbitsky et al., 2015), lends additional support to our proposed model.

Further work is needed to address the complex puzzle of Late Devonian-Early Carboniferous tectonics within the Arctic tectonic blocks and to correlate the tectonic and magmatic activities back to a well-defined orogenic event.

Conclusions

The detrital zircon (U-Th)/He ages from Ordovician-Devonian strata of the Severnaya Zemlya archipelago are older than the depositional age of the host sediments and have not been reset since deposition. Consequently, the studied succession has not been buried beneath a thick succession of younger sediments and lacks any indication of rapid exhumation during the Paleozoic.

Dual U-Pb and (U-Th)/He geochronology supports previous U-Pb detrital zircon studies (Lorenz et al., 2008b), indicating two distinct source regions for Ordovician-Silurian and Devonian clastics. The (U-Th)/He detrital zircon ages from Ordovician-Silurian strata suggest the primary source region was located within the Caledonian and Timanian orogens. Furthermore, the combined U-Pb and (U-Th)/He dating on the same zircon crystal demonstrates that within the source region, the Timanian Orogen was likely overprinted by younger Caledonian events. The obtained detrital zircon (U-Th)/He ages suggest that the clastic source area for the Devonian sandstones was affected by multiple stages of uplift. The oldest stage (Ordovician) corresponds to the Caledonian Orogeny, and the youngest (Late Devonian) to the Ellesmerian Orogeny or the terminal Solundian/Svalbardian stages of the Caledonian Orogeny. That supports the tectonic model proposed by Lorenz et al. (2008), suggesting that the Kara Terrane formed a marginal part of Baltica in the Early–Middle Paleozoic and received clastics from its northeastern part (modern coordinates).

The 375 Ma event revealed from the (U-Th)/He data, in conjunction with recent evidence of coeval tectonic deformation, felsic magmatism and metamorphism reported from many localities across the Arctic, lead us to suggest that juxtaposition of continental scale terranes in Late Devonian likely represented the final northward propagation (in present day coordinates) of collision between Laurentia and a marginal region of Baltica.

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Figure captions

Fig.1. (a) Map of the Arctic region depicting the names and locations mentioned in the figures and text. Different scenarios for the continuation of Caledonian suture and deformation front are depicted. The orange color marks regions affected by Caledonian deformations and/or magmatism (Gee et al., 2013; McKerrow et al., 2000**;** Roberts, 2003 and references therein) while purple color regions affected by Ellesmerian/Svalbardian deformations and/or magmatism (Anfinson et al., 2013; Bergh et al., 2011; Ershova et al., 2016a; Harrison, et al., 1995; Harrisonand Brent 2005; Kosminska et al., 2016; Lane, 2007; O’Brien et al., 2016; Piepjohn, 2000; Piepjohn et al., 2008, 2015; Prokopiev et al.,

2015; Rippington et al., 2010; Soper and Higgins, 1990, and references therein)(b) Simplified geological map of Kara Terrane (from Morozov and Petrov, 2004; Makariev, 2012) with location of studied samples. Additionally locations of samples from the Lorenz et al., 2008b discussed in the text are shown.

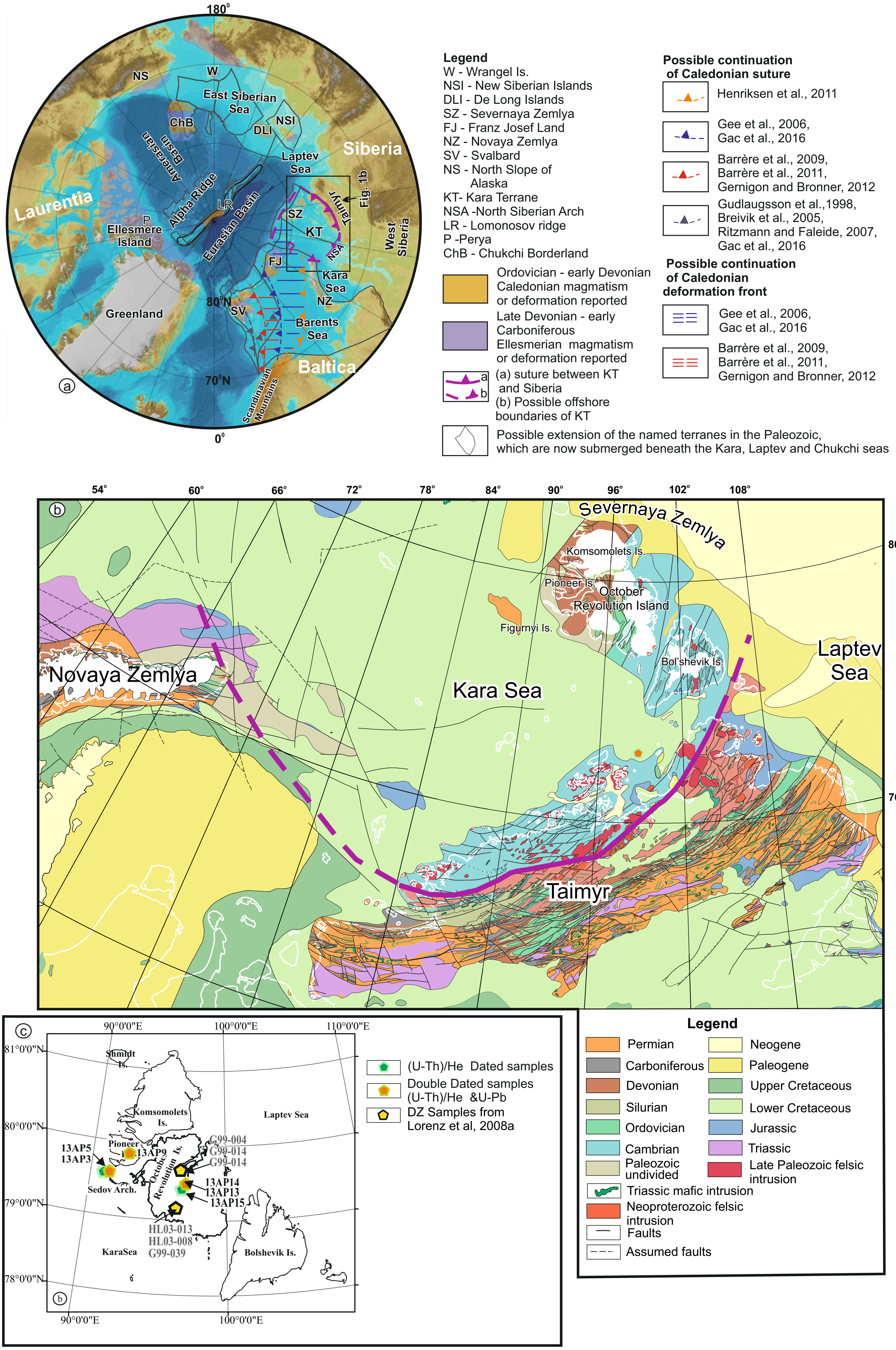
Fig.2. Generalized stratigraphic framework of Paleozoic strata of Severnaya Zemlya Archipelago based on Ershova et al., 2015d, 2016; Gramberg and Ushakov, 2000; Makariev et al., 2012; Markovsky et al., 1988; Matukhin and Menner,1999. Numerical ages from Cohen et al., 2016.

Fig. 3. Detrital zircon (U-Th)/He and U-Pb age data. (a) (U-Th)/He ages of zircons (ZHe) plotted against effective uranium concertation (e(U), depicting that there is no significant influence of e(U) on the (U-Th)/He ages, (b) - Double-dated (U/Pb and (U–Th)/He) zircons, (c) Relative probability plots of (U-Th)/He ages from Ordovician-Silurian and Devonian samples; *n* is the number of (U-Th)/He ages, (d) - U–Pb age populations from the Ordovician and Devonian strata after Lorenz et al., 2008b. ZHe data from Devonian sandstones are all represented by markers filled with dark brown, whereas the older samples are represented by markers filled with dark and light green. The shaded bars indicate the main orogenic events that affected the provenance area of the studied clastics. The ZHe ages for Ordovician-Silurian rocks suggest Caledonian and Timanian sources for clastics, furthermore combined U/Pb and (U-Th)/He dating show that within the source region, the Timanian Orogen was likely overprinted by younger Caledonian events. Devonian samples revealed that the source region was affected the Ellesmerian Orogeny or the terminal Solundian/Svalbardian stages of the Caledonian Orogeny.

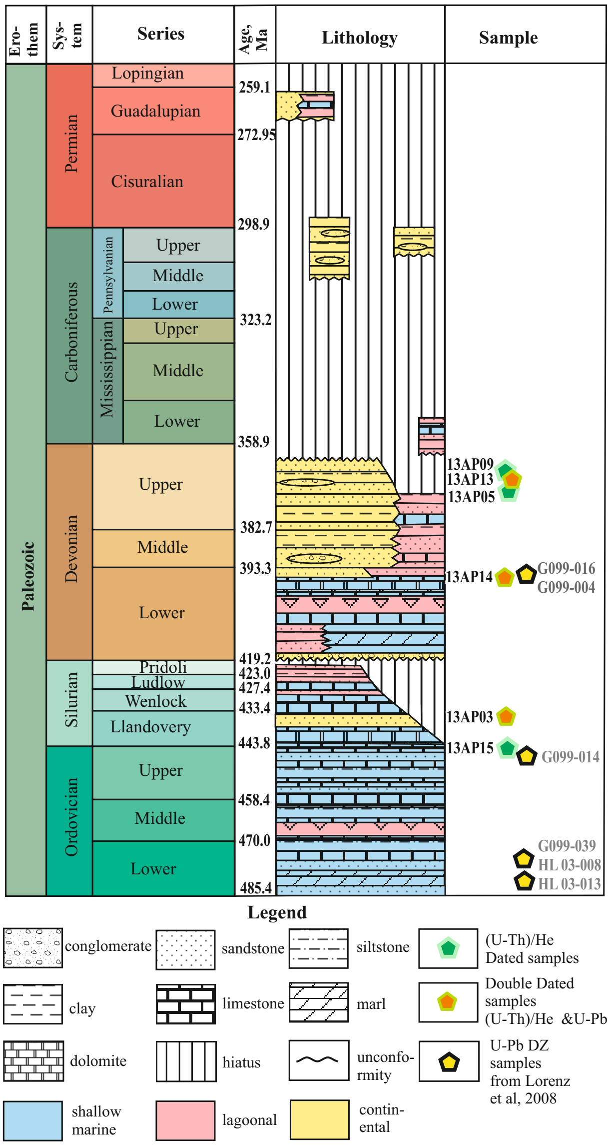
Fig.4. Summary chart comparing existing Ar-Ar cooling ages, showing the exhumation history of regions affected by Caledonian orogeny (Greenland, Svalbard and Scandinavian Caledonides) data from the database available on http://geo.ngu.no), and (U-Th)/He data from Arctic Canada (Anfinson et al., 2013) and Severnaya Zemlya Archipelago (this study).

Fig.5. The proposed Artic model for Late Silurian (a) and Late Devonian (b), (modified after Anfinson et al., (2012, 2013); Beranek et al., (2013); Ershova et al., (2015, a,b, 2016); Lawver et al., (2002); Lorenz et al., (2008); Miller et al.,(2010, 2011) and references therein); constructed with GPlates open-source software (www.gplates.org). Grey lines illustrate the possible extent of the named terranes in the Paleozoic, terranes which are now submerged beneath the Kara, Laptev and Chukchi seas. Late Mesozoic-Cenozoic extension further complicates the interpretation of Paleozoic terranes boundaries across these shelves. The red dashed line highlights terranes with a Baltica affinity (based on Ershova et al., 2015 a,b, 2016 a,b; Lorenz et al., 2008 a,b; Miller et al., 2010). The outlines are based on present day configuration (therefore no stretching or other deformations have been taken into account). The blue, dashed line highlights the area likely affected by significant extension (up to hyperextension) in Late Mesozoic (ex. Drachev, 2016). A more details reconstruction of this region cannot be done due to limited seismic and lack of well data.

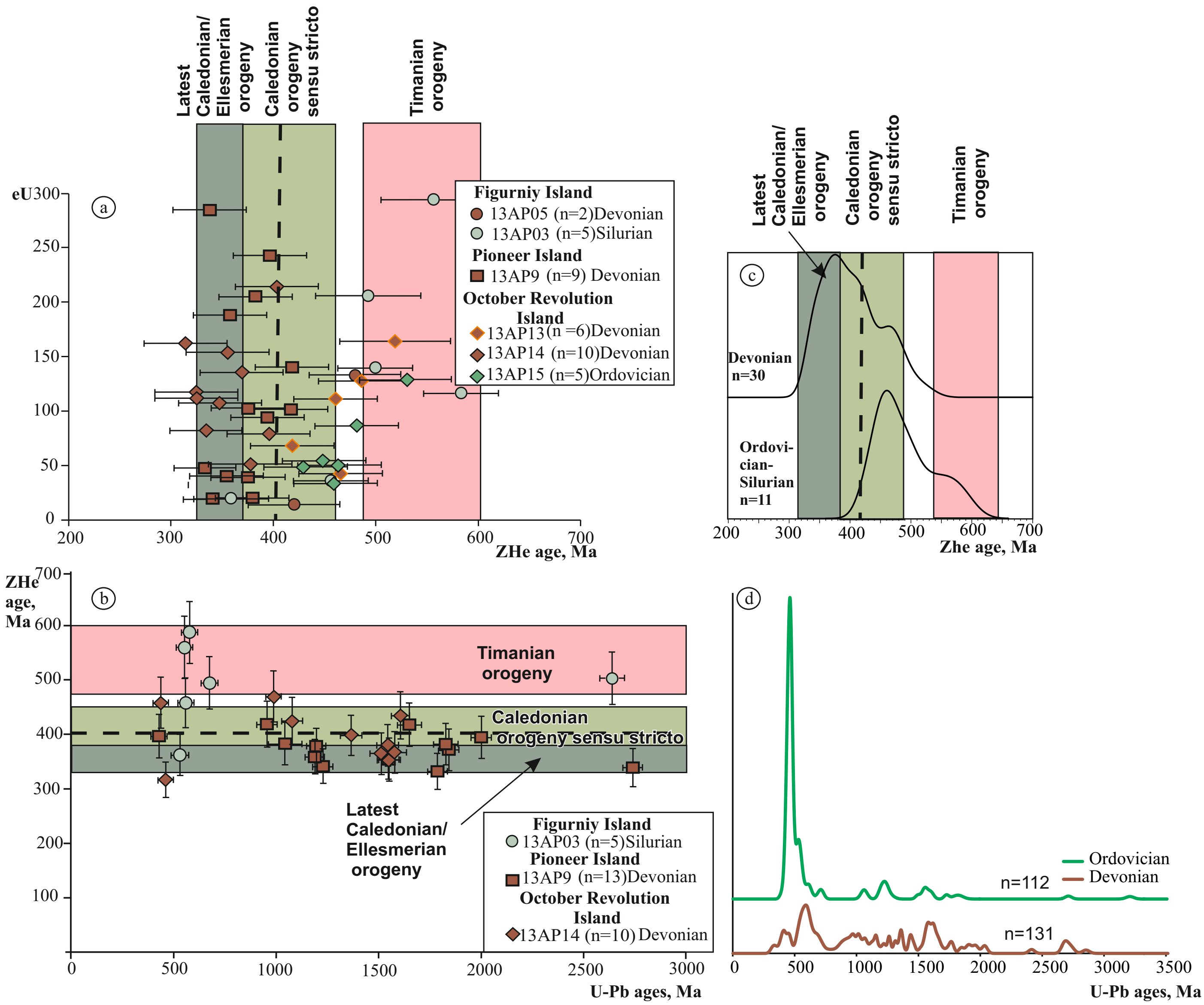
Supplemental file 1. Analytical approach
Supplemental file 2. Results of U-Th-He dating
Supplemental file 3. Results of U-Pb dating



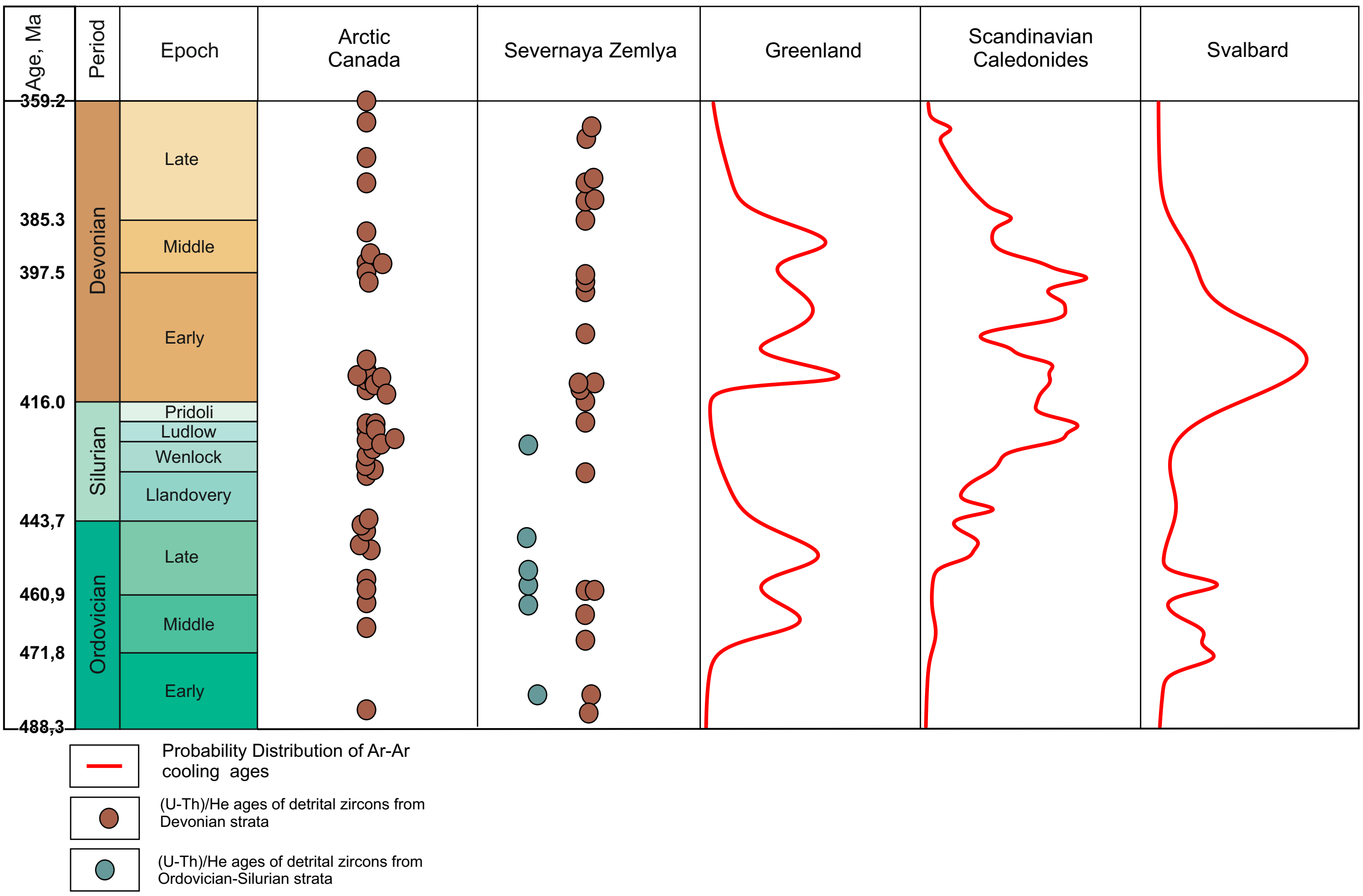
a
180°
0°
80°N
70°N
NS
W
East Siberian Sea
ChB
NSI
DLI
Amerasian Basin
Laptev Sea
Siberia
Alpha Ridge
LR
Eurasian Basin
Laurentia
P
Ellesmere Island
SZ
KT
Taimyr
Fig. 1b
West Siberia
NSA
FJ
Kara Sea
NZ
SV
Barents Sea
Greenland
Baltica
Scandinavian Mountains
Legend
W - Wrangel Is.
NSI - New Siberian Islands
DLI - De Long Islands
SZ - Severnaya Zemlya
FJ - Franz Josef Land
NZ - Novaya Zemlya
SV - Svalbard
NS - North Slope of Alaska
KT- Kara Terrane
NSA -North Siberian Arch
LR - Lomonosov ridge
P -Perya
ChB - Chukchi Borderland
Ordovician - early Devonian Caledonian magmatism or deformation reported
Late Devonian - early Carboniferous Ellesmerian magmatism or deformation reported
(a) suture between KT and Siberia
(b) Possible offshore boundaries of KT
Possible extension of the named terranes in the Paleozoic, which are now submerged beneath the Kara, Laptev and Chukchi seas
Possible continuation of Caledonian suture
Henriksen et al., 2011
Gee et al., 2006, Gac et al., 2016
Barrère et al., 2009, Barrère et al., 2011, Gernigon and Bronner, 2012
Gudlaugsson et al.,1998, Breivik et al., 2005, Ritzmann and Faleide, 2007, Gac et al., 2016
Possible continuation of Caledonian deformation front
Gee et al., 2006, Gac et al., 2016
Barrère et al., 2009, Barrère et al., 2011, Gernigon and Bronner, 2012
b
54° 60° 66° 72° 78° 84° 90° 96° 102° 108°
80°
76°
Severnaya Zemlya
Komsomolets Is.
Pioneer Is.
October Revolution Island
Figurnyi Is.
Bol'shevik Is.
Laptev Sea
Novaya Zemlya
Kara Sea
Taimyr
c
90°0'0"E 100°0'0"E 110°0'0"E
81°0'0"N
80°0'0"N
79°0'0"N
78°0'0"N
Shmidt Is.
Komsomolets Is.
Laptev Sea
Pioneer
13AP5
13AP3
13AP9
Sedov Arch.
October Revolution Is.
G99-004
G99-014
G99-014
13AP14
13AP13
13AP15
HL03-013
HL03-008
G99-039
KaraSea
Bolshevik Is.
(U-Th)/He Dated samples
Double Dated samples (U-Th)/He &U-Pb
DZ Samples from Lorenz et al, 2008a
Legend
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Paleozoic undivided
Triassic mafic intrusion
Neoproterozoic felsic intrusion
Faults
Assumed faults
Neogene
Paleogene
Upper Cretaceous
Lower Cretaceous
Jurassic
Triassic
Late Paleozoic felsic intrusion



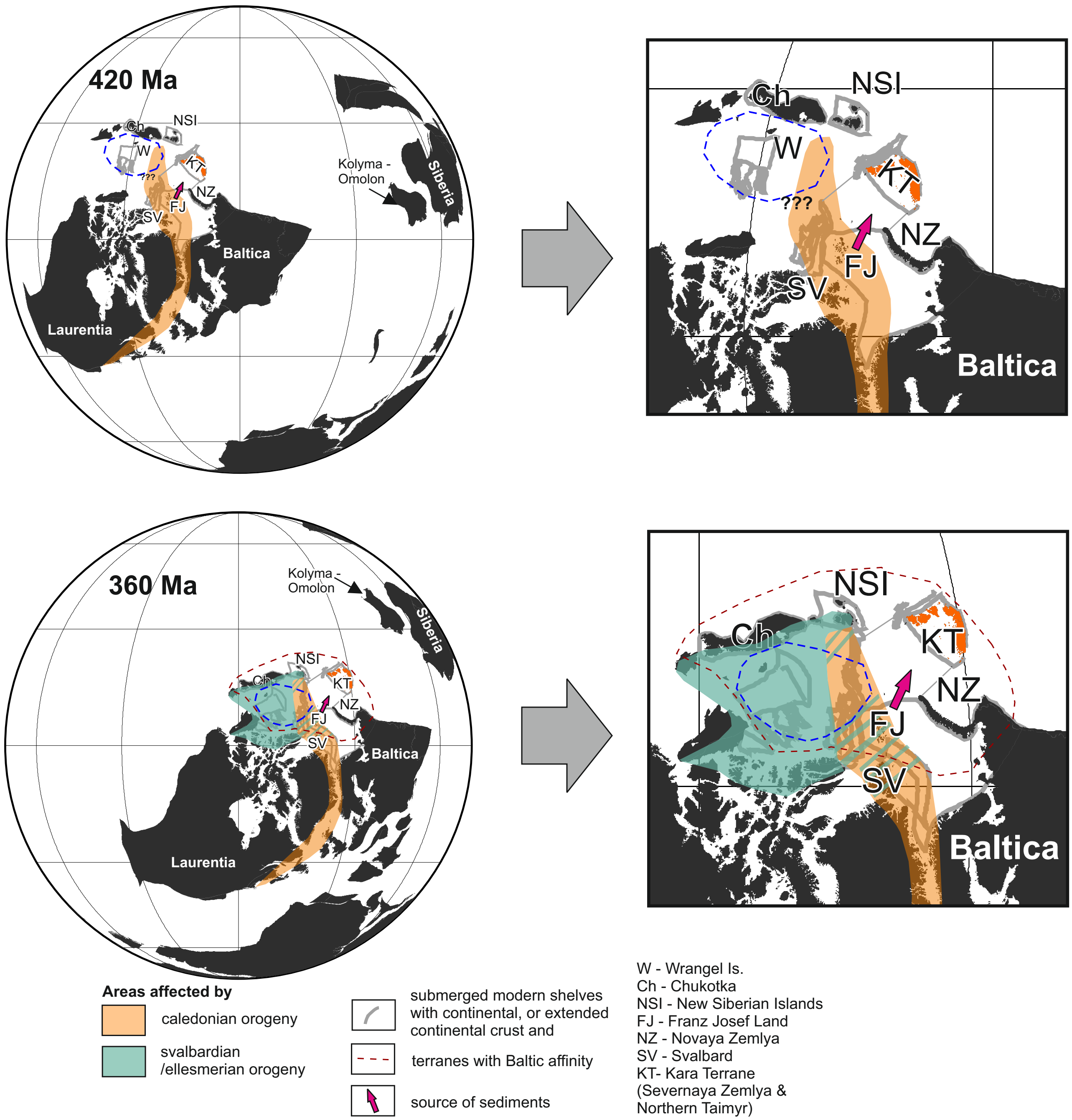
Ero-them
Sys-tem
Series
Age, Ma
Lithology
Sample
Paleozoic
Permian
Lopingian
Guadalupian
Cisuralian
Carboniferous
Pennsylvanian
Upper
Middle
Lower
Mississippian
Upper
Middle
Lower
Devonian
Upper
Middle
Lower
Silurian
Pridoli
Ludlow
Wenlock
Llandovery
Ordovician
Upper
Middle
Lower
259.1
272.95
298.9
323.2
358.9
382.7
393.3
419.2
423.0
427.4
433.4
443.8
458.4
470.0
485.4
13AP09
13AP13
13AP05
13AP14
G099-016
G099-004
13AP03
13AP15
G099-014
G099-039
HL 03-008
HL 03-013
Legend
conglomerate
sandstone
siltstone
(U-Th)/He Dated samples
clay
limestone
marl
Double Dated samples (U-Th)/He &U-Pb
dolomite
hiatus
unconfo-rmity
U-Pb DZ samples from Lorenz et al, 2008
shallow marine
lagoonal
contin-ental



a
b
c
d
Latest Caledonian/ Ellesmerian orogeny
Caledonian orogeny sensu stricto
Timanian orogeny
eU
ZHe age, Ma
Figurniy Island
13AP05 (n=2)Devonian
13AP03 (n=5)Silurian
Pioneer Island
13AP9 (n=9) Devonian
October Revolution Island
13AP13 (n =6)Devonian
13AP14 (n=10)Devonian
13AP15 (n=5)Ordovician
Devonian n=30
Ordovician-Silurian n=11
Zhe age, Ma
ZHe age, Ma
Timanian orogeny
Caledonian orogeny sensu stricto
Latest Caledonian/ Ellesmerian orogeny
Figurniy Island
13AP03 (n=5)Silurian
Pioneer Island
13AP9 (n=13)Devonian
October Revolution Island
13AP14 (n=10) Devonian
U-Pb ages, Ma
Ordovician
Devonian
n=112
n=131
U-Pb ages, Ma



Age, Ma
Period
Epoch
Arctic Canada
Severnaya Zemlya
Greenland
Scandinavian Caledonides
Svalbard
359.2
385.3
397.5
416.0
443,7
460,9
471,8
488,3
Devonian
Silurian
Ordovician
Late
Middle
Early
Pridoli
Ludlow
Wenlock
Llandovery
Late
Middle
Early
Probability Distribution of Ar-Ar cooling ages
(U-Th)/He ages of detrital zircons from Devonian strata
(U-Th)/He ages of detrital zircons from Ordovician-Silurian strata


420 Ma
Ch
NSI
W
???
KT
NZ
FJ
SV
Kolyma - Omolon
Siberia
Baltica
Laurentia
Ch
NSI
W
KT
???
NZ
FJ
SV
Baltica
360 Ma
Kolyma - Omolon
Siberia
NSI
Ch
KT
NZ
FJ
SV
Baltica
Laurentia
NSI
Ch
KT
NZ
FJ
SV
Baltica
Areas affected by
caledonian orogeny
svalbardian /ellesmerian orogeny
submerged modern shelves with continental, or extended continental crust and
terranes with Baltic affinity
source of sediments
W - Wrangel Is.
Ch - Chukotka
NSI - New Siberian Islands
FJ - Franz Josef Land
NZ - Novaya Zemlya
SV - Svalbard
KT- Kara Terrane (Severnaya Zemlya & Northern Taimyr)