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U-Pb baddeleyite age for the Ottfjället Dyke Swarm, central Scandinavian Caledonides: new constraints on Ediacaran opening of the Iapetus Ocean and glaciations on Baltica

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ABSTRACT
The Ottfjället Dyke Swarm (ODS) is a prominent component of the Ediacaran mafic magmatism associated with opening of the Iapetus ocean, and hosted in the Särv Nappe, Middle Allochthon of the Scandinavian Caledonides. A U-Pb baddeleyite age of 596.3 ± 1.5 Ma for a thick, well preserved, plagioclase-phyric dolerite dyke in Härjedalen, Sweden, dates emplacement of the swarm. The age represents a robust, inheritance-free reference age for variably deformed and metamorphosed tholeiitic dykes in sandstone-dominated sequences of the lower part of the Middle Allochthon, representing the proximal, rifted Baltoscandian margin preceding the opening of Iapetus. The new age is within the narrow time span between 610 and 595 Ma defined by the most reliable age estimates for mafic dykes in structurally higher nappes (upper part of Middle Allochthon), representing the distal margin during the opening of Iapetus. The Ottfjället Dyke Swarm cuts the Tossåsfjället Group succession, which includes sabkha-related carbonate platform and diamictite couples, one of several correlated Neoproterozoic glaciogenic successions in Scandinavia. The intrusion age of ca. 596 Ma therefore sets a minimum age for the glaciogenic successions. It implies that Neoproterozoic glaciations in Scandinavia predate the ca. 580 Ma Gaskiers glaciation event and are probably part of the ca. 635 Ma Marinoan "Snowball-Earth"-type glaciation.

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Baddeleyite; U-Pb dating; Ottfjället Dyke Swarm; large igneous province; Lillfjället formation; marinoan glaciation; Scandinavia

Introduction and geological setting

The continent Baltica, a precursor to the present Fennoscandian cratonic shield, was formed by the break-up of the supercontinent Rodinia in Neoproterozoic time (e.g., Dalziel 1997; Torsvik et al. 1996). An aborted break-up may have occurred at about 850 Ma in the mid-Tonian period, whereas the final break-up took place in mid-Ediacaran time (Paulsson & Andréasson 2002). The break-up and initial opening of the Iapetus Ocean, separating Baltica from Laurentia to the west/northwest and Amazonia to the south/southwest (Li et al. 2008, 2013), is reflected by a series of dolerite dyke swarms along the Baltoscandian margin (Gee 1975; Solyom et al. 1979; Claesson & Roddick 1983; Andréasson 1987, 1994; Svenningsen 1994a, 2001; Andréasson et al. 1998; Baird et al. 2014; Abdelmalak et al. 2015; Kirsch & Svenningsen 2016; Gee et al. 2017; Jakob et al. 2017; Kjøll et al. 2019; Tegner et al. 2019) and the Laurentian margin (Kamo et al. 1989, 1995; Ernst & Buchan 2001, 2004; Cawood et al. 2001; Puffer 2002; Tegner et al. 2019).

Late Neoproterozoic dolerite dykes can be traced from the autochthonous Baltica basement in the Egersund area in southwestern Norway (Bingen et al. 1998) through a number of Caledonian nappe complexes to northern Finnmark, referred to as the Middle and Upper Allochthons of the Scandinavian Caledonides (Paulsson & Andréasson 2002), altogether 1800 km along the Baltica margin, i.e., along the present Scandies, the Caledonian mountain chain, and ca. 1000 km across the sedimentary basin of the Baltica platform. The map in Figure 1 displays the inferred pre-Caledonian sedimentary sub-basins of the Baltoscandian margin including the various Iapetus-related dolerite dyke swarms.

Those dyke swarms were collectively named the "Baltoscandian Dyke Swarm" by Andréasson (1987), the "Baltoscandian Dyke Swarms" by Andréasson (1994), the "Baltoscandian margin dyke swarm" by Svenningsen (1996) and the "Scandinavian Dyke Complex" by Tegner et al. (2019). We apply here, for simplicity and in accordance with the principle of priority in geologic naming, and for the association to the Neoproterozoic Baltoscandian margin of Baltica, the original name *Baltoscandian Dyke Swarm* (BDS) (Andréasson 1987). The BDS are inferred to reflect an Ediacaran large igneous province (LIP) along the late Neoproterozoic-early Cambrian Baltoscandian margin (Andréasson et al. 2005; Ernst & Bell 2010; Abdelmalak et al. 2015; Gee et al. 2017; Tegner et al. 2019), named the *Baltoscandian Large Igneous Province*, BLIP (Kumpulainen et al. 2016), in harmony with the name Baltoscandian Dyke Swarm. The BDS of the Caledonian nappes have intruded a series of Neoproterozoic basins that developed during the Cryogenian and early Ediacaran periods along the

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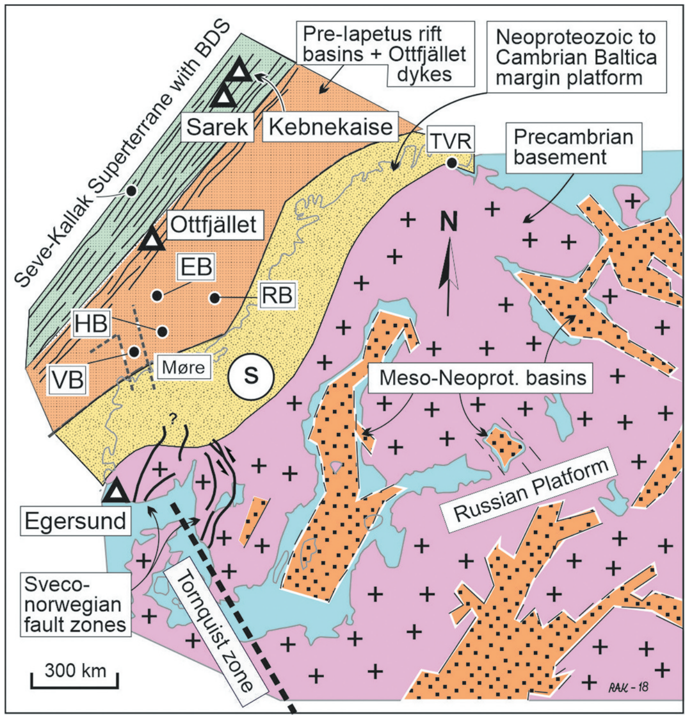

Figure 1. Sketch map showing positions of dyke swarms of the Baltoscandian Dyke Swarm (BDS) in a palaeogeographic setting of the Neoproterozoic Baltoscandian marginal zone, modified from Pease et al. (2008), with data on the BDS components from Andréasson et al. (2005) and Jakob et al. (2017). Egersund, Ottfjället, Sarek and Kebnekaise indicate inferred original position of dyke swarms. The map area of Figure 2 in relation to the present-day geography is indicated approximately by a broken circle. VB, Valdres Basin; HB, Hedmark Basin; EB, Engerdalen Basin; Ottfjället gives the approximate position of the Tossåsfjället Basin; RB, Risbäck Basin; TVR, Varangerfjorden-Tanafjorden Region.

western margin (present day coordinates) of Baltica (e.g., Kumpulainen & Nystuen 1985; Gayer & Greiling 1989; Vidal & Moczydłowska 1995; Siedlecka et al. 2004; Pease et al. 2008; Nystuen et al. 2008).

The *Egersund Dyke Swarm* in the autochthonous Baltica basement (Fig. 1) has yielded an age of 616 ± 3 Ma (U-Pb, baddeleyite; Bingen et al. 1998, 2005). The dykes run ESE-WNW, a direction parallel to the Tornquist fault zone along the southwestern Baltoscandian margin, where the Baltica, Laurentia and Amazonia plates are presumed to have formed a triple junction (Bingen et al. 1998; Fig. 11 in Tegner et al. 2019).

The *Ottfjället Dyke Swarm* (ODS) in the Särv Nappe of the Middle Allochthon in Jämtland, west-central Sweden (Fig. 2), is the "classical" Neoproterozoic dyke swarm in the Scandinavian Caledonides. It penetrates a sedimentary succession with well established lithostratigraphy (Kumpulainen 2011 and references therein). This, in addition to previous studies, establishes the ODS as the reference dyke swarm for the Baltoscandian Dyke Swarm as a whole.

The Ottfjället Dyke Swarm was recognised by Törnebohm (1873) and described petrographically also by Törnebohm (1877). Its general distribution was outlined initially in a 1:1 000 000 map by Högbom (1885), and was described in additional detail from the Ottfjället Mountain region by Holmquist (1894). Further mapping by Strömberg (1955), Strömberg (1961, 1969) showed that this dyke swarm was limited to a particular tectonic unit, the Särv Nappe, located tectonostratigraphically below the Seve Nappe Complex. He inferred an Ordovician age for these dykes, reinterpreting an earlier supposition by Törnebohm (1896, p. 110) that they were post-Silurian in age. Later work has shown that the ODS belongs to the pre-Caledonian development of the Baltoscandian margin (e.g., Gee 1975; Kumpulainen & Nystuen 1985).

Radiometric dating of the ODS began in the 1970s, using the ^{87}Rb-^{86}Sr whole-rock and ^{40}K-^{40}Ar methods. A relatively imprecise Rb-Sr age of 735 ± 260 Ma was obtained, while ^{40}K-^{40}Ar dates ranged from 650 to 2600 Ma, indicating the likely effects of excess argon (Claesson 1976, 1977; Claesson & Roddick 1983). The study by Claesson & Roddick (1983), focused on ^{40}Ar/^{39}Ar analyses of plagioclase from the dolerites, implied that intrusion and alteration of the dykes took place in the age range 600–700 Ma. A revised assessment of the ^{40}K-^{40}Ar and ^{40}Ar-^{39}Ar systematics within the dykes led these authors to suggest an emplacement age of 665 ± 10 Ma (Claesson & Roddick 1983).

Dolerite dyke swarms in sandstones occur in several nappes correlated with the Särv Nappe in the northern Hedmark-Trøndelag-northern Møre area (Fig. 1) in Central Norway (Gee 1977, 1980; Beckholmen & Roberts 1999; Hollocher et al. 2007). Dolerite dykes in the Hummelfjellet Nappe in northern Hedmark (Törnebohm 1896; Nilsen & Wolff 1989), correlated with the Särv Nappe (Gee et al. 1985), have intruded a sandstone succession; the Hummelfjellet Dyke Swarm thus represents, so far, the southernmost expression of the Ottfjället dolerite dykes. Dolerite dykes, commonly transformed into amphibolites in the Sætra Nappe of the Oppdal area have in less strained lenses given a ^{87}Rb-^{86}Sr whole-rock igneous age of 745 ± 37 Ma (Krill 1980).

The Ottfjället dolerite dykes and their equivalents define one magmatic region with dykes having transitional MORB-like

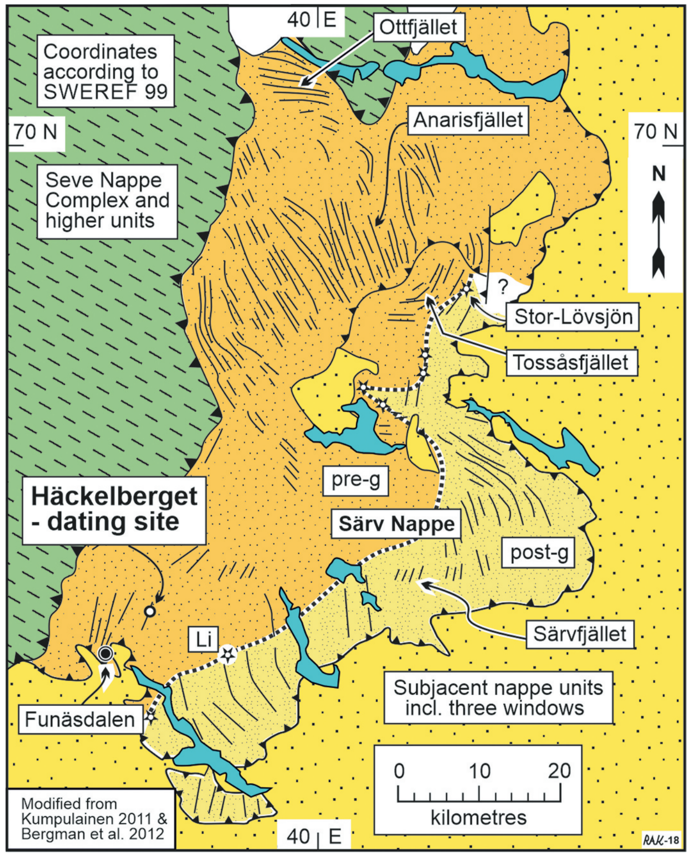

Figure 2. Simplified map of the main outcrop area of the Särv Nappe in the southwestern Swedish Caledonides, showing location of sampling site. Surface trends of the Ottfjället dolerites are shown on the map with black curves. The dotted line within the Särv Nappe divides the Tossåsfjället Group succession into pre-glacial (pre-g) and post-glacial (post-g) parts, respectively. The dotted line itself corresponds to the carbonate-diamictite couplet, passing from the southwest via Lillfjället (Li), the type locality of the Lillfjället Formation, to the Lake Stor-Lövsjön area, where the upper diamictite member of the formation may be studied. The stars along the dotted curve mark the exposures of the carbonate-diamictite units. Modified from Kumpulainen (2011) and Bergman et al. (2012)

compositions with relatively low LREE enrichment, in contrast to dykes with more LREE-enriched alkaline compositions in an adjacent region; the alkaline rocks are inferred to have been influenced by a source of hotspot-related, enriched mantle during Late Neoproterozoic rifting of Baltica from Rodinia (Hollocher et al. 2007). Other geochemical studies of Baltoscandian dolerites (Tegner et al. 2019 and references therein) confirm a mantle plume origin of the BDS, discussed further below.

Mafic dyke swarms are present in a series of nappe complexes referred to as the Middle and Upper Allochthons in the northern part of the Swedish Caledonides. They include the Sarek Dyke Swarm and the Kebne Dyke Complex (also named the Kebnekaise Intrusive Complex) (Svenningsen 1987, 1994a, 1996; Andréasson et al. 1992; Paulsson & Andréasson 2002; Baird et al. 2014; Kirsch & Svenningsen 2016) and amphibolite dykes in the Pältsa area (Stølen 1996). The Sarek Dyke Swarm in the Seve Nappe Complex has given precise ages of 608 ± 1 Ma (ID-TIMS U-Pb single and multigrain zircon fractions) in its northern part (Svenningsen 2001) and 607 ± 2 Ma (ID-TIMS U-Pb single fraction titanite) in its southern part (Root & Corfu 2012). The Kebne Dyke Complex in the Seve Nappe Complex has yielded varying intrusive ages, including 605 ± 42 Ma (single SIMS U-Pb spot analysis of a zircon rim; Paulsson & Andréasson 2002), 608–596 Ma (ID-TIMS U-Pb single zircon crystal; Baird et al. 2014) and 578 ± 9 Ma (SIMS U-Pb zircon rims; Kirsch & Svenningsen 2016). The Sarek and Kebne dyke swarms intruded a sedimentary succession of assumed late Neoproterozoic age, including a carbonate formation with magnesite beds and overlying diamictites of inferred glaciogenic origin (Svenningsen 1994b), recently documented in the Sarek area as carbonate platform facies and glacial deposits, respectively (Kjøll 2020).

The northernmost dyke swarm province of supposed Ediacaran age is represented by amphibolites cutting Neoproterozoic sandstones, today in the Kalak Nappe Complex in northernmost Troms and western Finnmark (Stølen 1989, 1994a, 1994b, 1996), northern Finnmark (Nasuti et al. 2015), and also within the Finnish Caledonides (Lehtovaara 1989). The age of the Corrovare Dyke Swarm (Zwaan & Van Roermund 1990) in the Corrovare Nappe in northeastern Troms in northern Norway has been inferred to be ca. 580 Ma by Andréasson et al. (1998). Collectively, the range of all published U-Pb age determinations of dolerite dykes of the BDS spans 616–578 Ma (Table 1).

In west-central Sweden, the ODS intrudes the sedimentary Tossåsfjället Group of Neoproterozoic age (Figs. 3 and 4). The lower and the upper parts of the group are dominated by fluvial to shallow-marine clastic deposits. In its central part there is a carbonate-diamictite-shale-sandstone succession. The glaciogenic Lillfjället Formation (Kumpulainen 1980, 1981, 2011) is deposited on top of a carbonate unit known as the Storån Formation. The Lillfjället Formation contains two glaciogenic diamictite units, separated by a more than 600 m thick un-

Table 1. Radiometric age determinations of the Neoproterozoic dolerite dykes in the Scandinavian dyke swarms. The Egersund dykes are located in the autochthonous basement in SW Norway and the others within Caledonian nappe complexes.

Age	Dyke swarm	Method	Reference
745 ± 37 Ma	Sætra, Oppdal	Rb-Sr whole rock	Krill 1980
735 ± 260 Ma & 625 ± 380 Ma	Ottfjället	Rb-Sr whole rock	Claesson 1976
2640 ± 675 Ma	Ottfjället	K-Ar whole rock	Claesson 1976, Claesson 1977
665 ± 10 Ma	Ottfjället	Ar-Ar plagioclase	Claesson & Roddick 1983
616 ± 3 Ma	Egersund	U-Pb baddeleyite	Bingen et al. 1998, Bingen et al. 2005
608 ± 1 Ma	Sarek north	U-Pb single & multigrain zircon	Svenningsen 2001
608 to 596 Ma	Kebne	U-Pb single zircon	Baird et al. 2014
607 ± 2 Ma	Sarek south	U-Pb single titanite	Root & Corfu 2012
605 ± 42 Ma	Kebne	U-Pb single zircon	Paulsson & Andréasson 2002
605.7 ± 1.8 Ma	Corrovarre	U-Pb single zircon	Kjøll et al. 2019
596.3 ± 1.5 Ma	**Ottfjället**	**U-Pb baddeleyite**	**this paper**
582 ± 30 Ma	Corrovarre	Sm-Nd clinopyroxene and plagioclase grains	Zwaan & Van Roermund 1990
578 ± 64 Ma	Corrovarre	Rb-Sr whole rock	Zwaan & Van Roermund 1990
578 ± 9 Ma	Kebne	U-Pb single zircon	Kirsch & Svenningsen 2016

Figure 3. Photograph of the southern slope of Mt. Anarisfjället within the Särv Nappe displaying the general character of the dolerite–sandstone relationships. Dykes are marked by ridges and sandstones by the depressions. Dykes dip 50–60° to the west and sandstones ca. 40–50° to the east.

named mudstone-sandstone unit (UNU). The lower of the two glaciogenic units is exposed and embedded in a thick dolerite dyke in the northern hillside of Lillfjället, the type locality of the Lillfjället Formation (Fig. 5). The glaciogenic formation is overlain by an approximately 1500–2000 m thick shallow-marine sandstone grading upwards to a gravelly, fluvial formation, possibly glaciofluvial in origin (Kumpulainen 2011). A similar glaciogenic succession is present in the Varangerfjorden-Tanafjorden region in eastern Finnmark, northern Norway (Fig. 6). Here, the glaciogenic Smalfjord and Mortensnes formations, being separated by the ≤350 m thick sandstone-shale dominated Nyborg Formation, have been interpreted on the basis of chemostratigraphy to represent the Marinoan (635 Ma) and the Gaskiers (580 Ma) glaciations, respectively (Halverson et al. 2005; Rice et al. 2011). Neoproterozoic glacial units in Scandinavia, underlain by carbonate platform units and overlain by siliciclastic formations, have been correlated and are interpreted to be closely related in time of formation (Nystuen et al. 2008). Thus, the age of mafic dykes penetrating this Neoproterozoic stratigraphic column is crucial for understanding the timing of Neoproterozoic glaciation in Scandinavia and the relationship to other Neoproterozoic glaciations on Earth.

In the present study, we present the results of ID-TIMS U-Pb analysis of baddeleyite recovered from the thick Ottfjället dyke at Häckelberget (Fig. 7), in the Jämtland region. The purpose is two-fold: (1) to discuss implications of the resulting age with respect to other recent, precise constraints on the timing of break-up of Rodinia along the Baltoscandian margin and the initial opening of the Iapetus Ocean, and (2) to improve the constraints on the timing of the Neoproterozoic glaciation in Scandinavia.

Petrography of the dolerite

The Ottfjället dolerite dykes are generally fine-grained and variably porphyritic in the type area in Jämtland (Törnebohm 1877; Högbom 1885; Holmquist 1894). The common phenocrysts are either plagioclase, augite or olivine. The magmatic mineral assemblage is variably altered (Törnebohm 1877; Strömberg 1961; Claesson & Roddick 1983; Gilotti 1989). In the best-preserved samples, plagioclase is partially transformed to epidote, augite (or clinopyroxene) to fibrous amphibole and olivine to serpentine. In the highly deformed, mylonitized lower part of the Särv Nappe, the original magmatic assemblage is entirely converted to a greenschist facies mineral assemblage composed of biotite + epidote + albite + quartz + sphene ± chlorite ± muscovite (Gilotti 1989; Gilotti & Kumpulainen 1986). Rare coarse-grained dolerite dykes have been observed, from two localities, one at Lillåsvallen, ca. 7.5 km NE of Funäsdalen (Strömberg 1955) and the other on the summit of Häckelberget, ca. 4 km NE of Funäsdalen.

Sample collection and analytical procedures

Samples for U-Pb geochronology were collected from the ca. 20 m-thick, relatively well-preserved, plagioclase-porphyritic dolerite dyke exposed on the eastern flank of Häckelberget

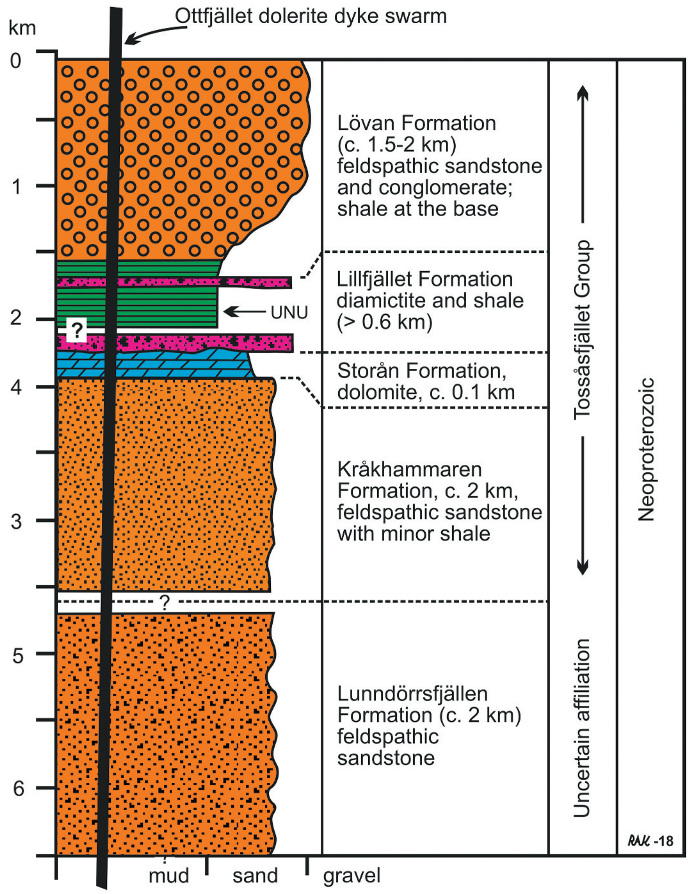

Figure 4. Stratigraphy of the Tossåsfjället Group. Modified from Kumpulainen (2011)

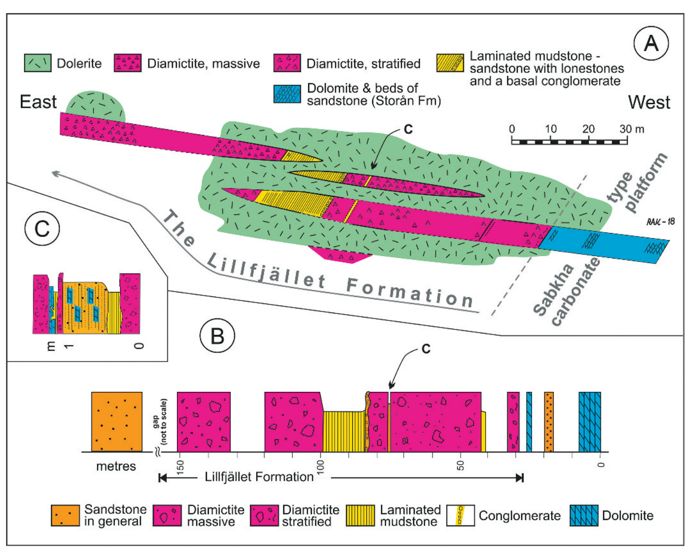

Figure 5. The Lillfjället Formation type locality. **A**. Sketch map, the side view of the steep north-facing Lillfjället hillside displaying the exposed parts of this glaciogenic formation and the thick dolerite dyke in which parts of this unit are embedded. **B**. A traditional sedimentary log displaying the various sedimentary characteristics, i.e., grainsizes, sedimentary structures and bed thicknesses. **C**. The ca. 1 m thick stratified interval between two massive diamictite beds. Note that this glaciogenic unit rests on a sabkha-type carbonate-platform deposit. This locality displays the lower diamictite-dominated member of the formation. The middle and upper members are exposed in the Stor-Lövsjön area, see Figure 2. Figure modified from Kumpulainen (2011)

(Figs. 2 and Figs.4). A provisional age of ca. 596 Ma for this dyke was reported by Kumpulainen et al. (2016). The dyke trends roughly 015°, with a dip of approximately 60° to the WNW. Contact relationships with the host feldspathic sandstones are sharp, with chilled margins. The dolerite at this locality is rich in phenocrysts up to ca. 7 mm in size surrounded by a fine- to medium-grained dark matrix, with a phenocryst:matrix ratio of approximately 1:1 (Fig. 8). Several

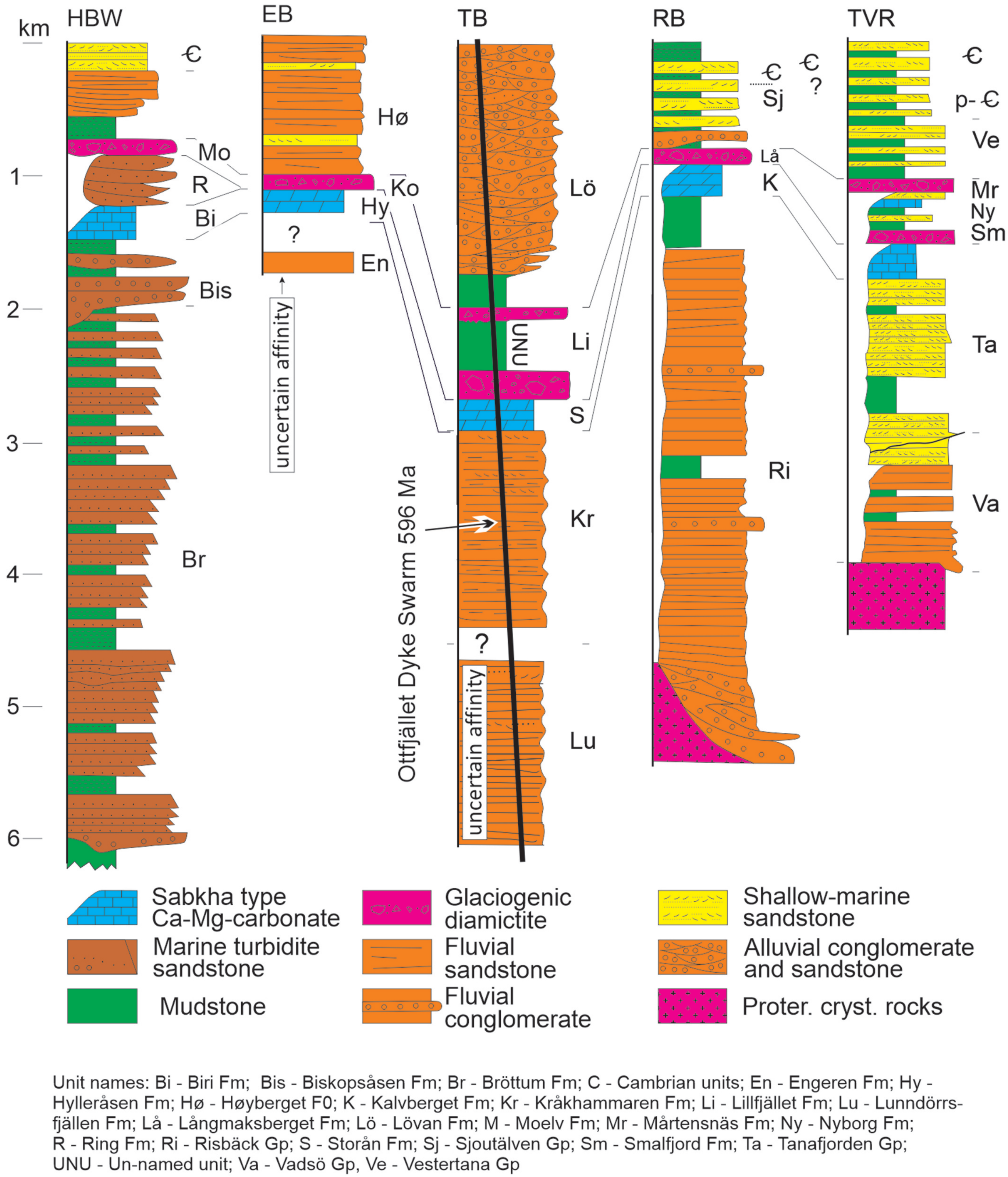

Figure 6. Correlation between Neoproterozoic successions in the Varangerfjorden-Tanafjorden Region (TVR), Risbäck Group in the Risbäck Basin (RB), Tossåsfjället Group in the Tossåsfjället Basin (TB), Engerdalen Group in the Engerdalen Basin (EB) and the Hedmark Group in western part of the Hedmark Basin (HBW), modified from Nystuen et al. (2008); stratigraphy of the Engerdalen Group from Nystuen (1980). For location of the basin areas, see Figure 1.

samples were taken from the coarsest central portions of the dyke in order to isolate a sufficient amount of baddeleyite grains for U-Pb geochronology.

Approximately 100–200 g per sample were processed at the Department of Geology, Lund University, following the procedures by Söderlund and Johansson (2002). Each sample was

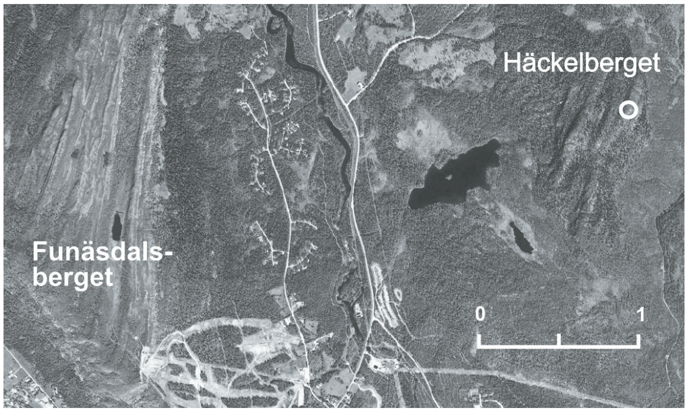

Figure 7. Vertical aerial photograph of part of the Funäsdalen ski resort with a system of ski slopes. The Ottfjället dykes on Mt. Funäsdalsberget, on the left of the photo, were described and reported by Törnebohm (1873, 1877). Compared to some other mafic dykes in Sweden, these dykes had their own characteristic features and for this reason Törnebohm named this *rocktype* "ottfjällsdiabas" (the Ottfjället diabase). Mt. Häckelberget with two prominent ridges are located on the right of the photo. The baddeleyite dating sample site is marked with a white circle on the eastern of the two ridges. The SWEREF 99 TM coordinates of the sample site are northing 6 939 811 and easting 376 586. The scale bar is 1 km. Photo: © Lantmäteriet Avtalsnummer: I2018/00134.

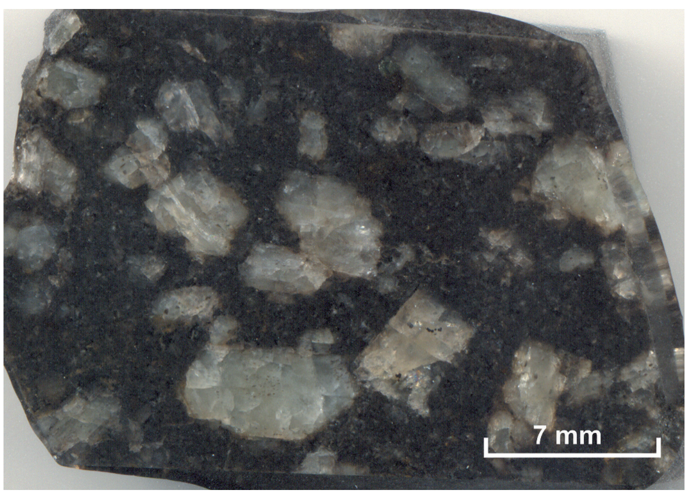

Figure 8. Polished slab of the analyzed dolerite sample from Mt. Häckelberget, northeast of Funäsdalen. The common phenocrysts include plagioclase, augite and olivine.

manually crushed to cm-size pieces before processing in a swing mill to produce a <300 μm coarse powder. The milled sample was suspended in water before loading onto a Wilfley table in small portions (~30 g). After ca. 1 minute the smallest and densest grains remaining on the deck were collected. Magnetic minerals were removed from the sample using a pencil magnet. Although zircon was not observed in the heavy mineral concentrate, rare and very fine grains of pale to medium-brown baddeleyite were present. The typical yield was only ca. 10 grains of baddeleyite on average from ca. 100 grams of milled sample, thus several batches from each sample were processed. Further details of the procedures are given by Söderlund and Johansson (2002).

All fractions except one were analyzed at the Jack Satterly Geochronology Laboratory (JSGL) at the University of Toronto. Only best quality baddeleyite grains (clearest, most euhedral, lacking attached phases, and with fresh, optically-reflective faces – i.e., lacking zircon overgrowths or dullness related to alteration, where possible) were selected for analysis. Most grains recovered and analyzed were thin, medium-brown blade-like crystals less than 60 microns in maximum dimension; many grains averaged roughly 30 × 20 microns in length vs. width, while some reached only 5 microns in width. The analytical procedures at JSGL broadly followed those described by Hamilton and Buchan (2010, 2016). Selected baddeleyite fractions (Bd1-Bd7), comprising between 4 and 50 blades and blade fragments each, were dissolved together with a mixed ^{205}Pb-^{235}U spike and analyzed on a VG354 mass spectrometer, with isotope ratios measured using a Daly photomultiplier equipped with digital ion counting. System dead time corrections during this period were 16 ns for Pb and U. Corrections for Daly mass bias were 0.07%/AMU, and thermal mass discrimination was 0.10%/AMU. Procedural blanks in the JSGL during the analytical period averaged less than 0.5 pg for Pb and 0.1 pg for U. The total common Pb measured in each analysis at JSGL was calculated assuming the isotopic composition of laboratory blank: ^{206}Pb/^{204}Pb – 18.221; ^{207}Pb/^{204}Pb – 15.612; ^{208}Pb/^{204}Pb – 39.360 (errors of 2%).

One fraction of baddeleyite was analyzed at the Swedish Museum of Natural History (NRM) in Stockholm. The analytical protocol broadly followed those described in Söderlund et al. (2019). Best quality grains were handpicked under a binocular microscope, as above. Baddeleyite fraction BdA, comprising eight medium-brown blades and blade fragments, was analyzed on a Finnigan Triton thermal ionization mass spectrometer equipped with Faraday cups and a Secondary Electron Multiplier (SEM). Intensities of ^{204}Pb, ^{205}Pb, ^{206}Pb and ^{207}Pb were analyzed in dynamic (peak-switching) mode using the SEM detector. Procedural blank levels at the NRM at the time of analysis were approximately 1.0 pg for Pb and 0.1 pg for U. Initial Pb isotopic compositions in all analyses reported here are estimated from Stacey and Kramers (1975), and U decay constants used are those reported by Jaffey et al. (1971).

Results

U-Pb isotopic analyses for eight fractions of baddeleyite from the Ottfjället dolerite are presented in Table 2 and Figure 9. They show low to moderate abundances of U (125–220 ppm), and fairly uniform, low Th/U ratios (0.008–0.060) typical of fresh, igneous baddeleyite. Two analyses show distinctly higher Th/U (0.125, 0.150) and may reflect minor overgrowth of late-crystallizing zircon; alteration of, and subsequent Pb-loss in these domains likely responsible for the enhanced discordance recorded in fraction BdA (14%).

With the exception of two relatively discordant fractions the majority of the U-Pb data cluster near, and overlap, concordia (Fig. 9), with six fractions yielding ^{206}Pb/^{238}U ages between 589.8 and 596.3 Ma. Because of the relatively unradiogenic nature of these small, low-U grains, and the high proportion of ^{207}Pb that is common-lead, the resulting ages based on this isotope are consequently imprecise. Free

Table 2. U-Pb ID-TIMS isotopic data for baddeleyite from the Ottfjället dolerite.

Sample/Description Fraction		U (ppm)	Pb^T (pg)	Pb_C (pg)	Th/U	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	± 2σ	$^{207}Pb/^{235}U$	± 2σ	$^{207}Pb/^{206}Pb$	± 2σ	$^{206}Pb/^{238}U$	± 2σ	$^{207}Pb/^{235}U$	± 2σ	$^{207}Pb/^{206}Pb$	± 2σ	Disc. (%)
Ottfjället dolerite																			
BdA	8 mbr blades & frags	N/A	N/A	N/A	0.124	221	0.079497	0.003208	0.64997	0.02751	0.059300	0.001040	496.6	19.2	511.4	16.9	578.2	37.9	14.1
Bd1	4 p-mbr blades & frags	196	8.52	1.08	0.013	572	0.096918	0.000261	0.80400	0.01513	0.060166	0.001041	596.3	1.5	599.1	8.5	609.5	37.6	2.3
Bd2	5 p-mbr blades & frags	154	1.47	0.60	0.009	191	0.092825	0.000700	0.76617	0.04634	0.059863	0.003354	572.2	4.1	577.6	26.8	598.6	123.6	4.6
Bd3	8 mbr blades & frags, dull	155	5.07	0.88	0.150	405	0.096529	0.000313	0.80287	0.02164	0.060323	0.001503	594.0	1.8	598.4	12.2	615.2	54.2	3.6
Bd4	8 mbr blades & frags	125	6.45	0.87	0.008	540	0.096084	0.000261	0.79958	0.01597	0.060355	0.001110	591.4	1.5	596.6	9.0	616.3	40.0	4.2
Bd5	7 mbr blades & frags	132	8.53	0.94	0.009	654	0.095831	0.000233	0.79686	0.01307	0.060308	0.000909	589.9	1.4	595.1	7.4	614.6	32.7	4.2
Bd6	50 p-mbr blades & frags	218	62.92	3.09	0.056	1431	0.095805	0.000177	0.78696	0.00612	0.059574	0.000414	589.8	1.0	589.4	3.5	588.1	15.1	-0.3
Bd7	50 p-mbr blades & frags	169	36.74	1.95	0.059	1322	0.096255	0.000180	0.79176	0.00663	0.059659	0.000448	592.4	1.1	592.2	3.8	591.2	16.3	-0.2

Notes:
Abbreviations: Bd – baddeleyite; all analyzed baddeleyite fractions represent best optical quality – fresh (least altered) grains, free of inclusions or attached phases.
p – pale; mbr – medium brown; frags – broken euhedral blade fragments; dull – comparatively dull lustre.
Pb^T is total amount (in picograms) of Pb.
Pb_C is total measured common Pb (in picograms) assuming the isotopic composition of laboratory blank: 206/204 – 18.221; 207/204 – 15.612; 208/204 – 39.360 (errors of 2%).
Pb/U atomic ratios are corrected for spike, fractionation, blank, and, where necessary, initial common Pb; 206Pb/204Pb is corrected for spike and fractionation.
Th/U is model value calculated from radiogenic 208Pb/206Pb ratio and 207Pb/206Pb age, assuming concordance.
All errors on ratios and ages are presented at the 2-sigma (absolute) level of uncertainty.
Disc. (%) – per cent discordance for the given 207Pb/206Pb age.
Uranium decay constants are from Jaffey et al. (1971).

regression of the error-weighted $^{207}Pb/^{206}Pb$ ratios for all eight analyses yields an upper intercept age of 596 ± 12 Ma, and a lower intercept of 103 ± 220 Ma (Fig. 9a; MSWD = 0.79, probability of fit = 58%;Ludwig 2012). This upper intercept age is in strong accord with the oldest, least discordant analysis, having a $^{206}Pb/^{238}U$ age of 596.3 ± 1.5 Ma (2σ error; fraction Bd1; Table 2). Given the fact that baddeleyite is widely recognized as a primary crystallizing phase in mafic magmas, with a closure temperature to Pb diffusion in excess of 900°C, we regard the $^{206}Pb/^{238}U$ age of 596.3 ± 1.5 Ma as an accurate estimate of the timing of extension, and accompanying Ottfjället dyke emplacement and crystallization.

Discussion

Analytical data

The reliability and applicability of baddeleyite as a high temperature mineral chronometer in mafic igneous rocks is well documented (e.g., Krogh et al. 1987; Heaman et al. 1992; Heaman & LeCheminant 1993), as its utility in providing accurate, high-precision age control on the timing, tempo and duration of large igneous province (LIP) events sometimes linked to supercontinent breakup (Heaman et al. 1992; Ernst et al. 2010, 2016; Hamilton & Buchan 2010; Halls et al. 2015; Söderlund et al. 2006, 2010).

U-Pb isotopic data for baddeleyite in unmetamorphosed to low-grade gabbros and dolerites occasionally yield variably discordant data, though the cause of discordance is not always clear. A number of studies have suggested that discordance in baddeleyite analyses in these instances could involve Pb-loss from secondary (late magmatic) zircon overgrowths on baddeleyite crystals, resulting from increasing Si activity in evolved magmas (e.g., Sahin & Hamilton 2019), partial transformation of baddeleyite to zircon during metamorphism (e.g., Söderlund et al. 2013) and/or alpha recoil effects due to the wafer-thin, blade-like crystal habit of baddeleyite that yield high surface area:volume ratios, particularly in very small crystals (Romer 2003; Davis & Davis 2017). Most of the baddeleyite U-Pb results presented in this study show variable degrees of discordance – 6 of 8 analyses have $^{206}Pb/^{238}U$ ages within approximately 1% of (younger than) of the oldest fraction – with the majority of the data clustered on or near concordia, convergent on an age of 596 Ma. We conclude that the Pb-loss mechanisms responsible for the dispersion in Pb/U ages is likely due to one or more of the hypothesized mechanisms mentioned above.

What is absent or highly unlikely in gabbroic or doleritic magmas, particularly those intruding felsic or siliciclastic crustal rocks, is inheritance in baddeleyite. This lies in stark contrast to issues often present in zircon-based studies of similar rocks, where xenocrysts of this phase may be ubiquitous; indeed, magmatic zircon can be comparatively rare, especially in thinner, less fractionated mafic dykes – compared to baddeleyite – which is typically omnipresent, although often small in grainsize. In a CA-ID-TIMS study of metagabbro and contemporaneous metagranitoid from the Kebne Dyke Complex of the structurally higher Seve Nappe Complex by Baird et al. (2014), both samples show clear evidence for inheritance in single grain zircon analyses,

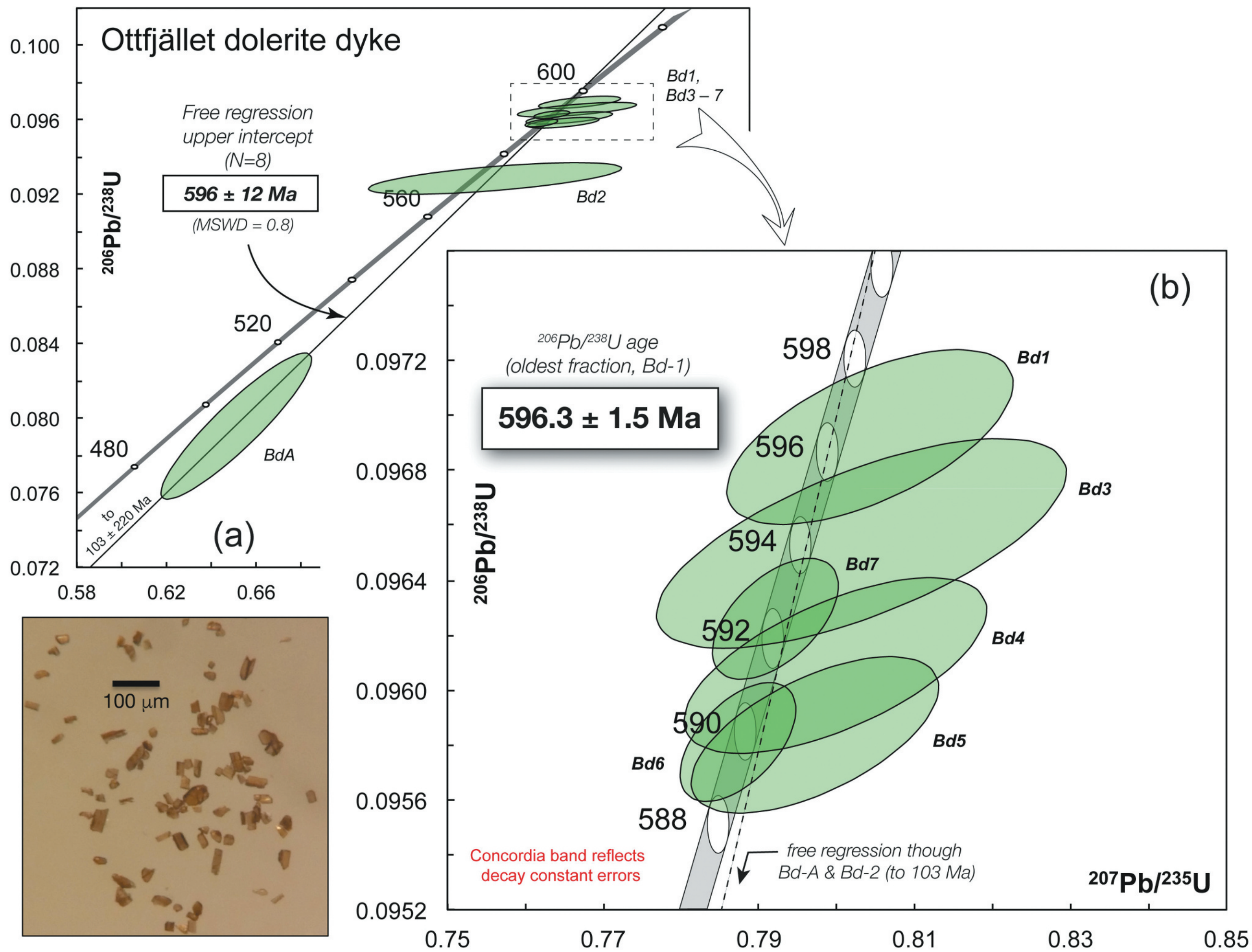

Figure 9. U-Pb Concordia diagram showing results for eight baddeleyite analyses from the Ottfjället dolerite at Mt. Häckelberget. Inset image shows representative baddeleyite grains from the sample. See text for discussion.

despite a lack of obvious optical signs of cores. Within the metagabbro, the youngest zircon analysis yielded an age of 598.4 ± 1.4 Ma, with five others giving older Ediacaran ages of ca. 603–608 Ma (all $^{206}Pb/^{238}U$ ages), and one most discordant grain analysis (~6%) projecting to a xenocrystic inheritance age of 968 Ma (early Tonian). Likewise, results from the metagranitoid yielded two discordant Mesoproterozoic $^{207}Pb/^{206}Pb$ ages (ca. 1440 and 1485 Ma, respectively), and five younger, Ediacaran ages of ca. 604–596 Ma ($^{206}Pb/^{238}U$) – with the youngest two overlapping with a weighted average $^{206}Pb/^{238}U$ age of 596.6 ± 0.8 Ma (MSWD = 0.54). Baird et al. (2014) concluded from their data that the results could support an interpretation of ca. 596 Ma magmatism with variable contamination from older Proterozoic crustal sources.

A similar conclusion was reached by Kirsch and Svenningsen (2016) in a parallel study of oxide-apatite gabbronorite from the same Kebne(kaise) Intrusive Complex. Air abrasion ID-TIMS results for one single grain and nine multigrain zircon fractions yielded only Tonian and older, Mesoproterozoic, dates (810–1281 Ma $^{206}Pb/^{238}U$ ages; 914–1482 Ma $^{207}Pb/^{206}Pb$ ages). This clearly shows that the variably discordant gabbronorite zircon analyses are fully mixtures of inherited and magmatic components, a conclusion supported by SEM imaging of representative grains showing partially resorbed cores and igneous overgrowths. Moreover, SIMS analyses in the same study, based upon 14 ion probe spot analyses in structurally distinct zircon growth domains, gave a spread of common Pb-corrected $^{206}Pb/^{238}U$ ages between 507 and 844 Ma confirming the presence of xenocrystic cores. Kirsch & Svenningsen (op. cit.) identified a coherent subgroup of seven analyses yielding a mean $^{206}Pb/^{238}U$ age of 578 ± 9 Ma, which they interpreted to represent the best crystallization age of the gabbronorite. It is unclear, however, whether several of the youngest SIMS ages, determined on zircon rims and surface/veneer analyses might alternatively reflect late hydrothermal growth during the end stages of magmatism within the complex (with or without Pb-loss), a possibility conceded by the authors. Both the Baird et al. (2014) and Kirsch and Svenningsen (2016) studies raise renewed concern regarding the complexities of interpreting zircon ages in mafic igneous rocks, particularly in the BDS swarm where these dykes have intruded thick successions dominated by Neoproterozoic clastic sediments.

The new U-Pb baddeleyite age reported here for an Ottfjället dolerite dyke at 596.3 ± 1.5 Ma avoids the clouding issues of xenocrystic inheritance plaguing a number of other BDS studies, and thus represents a significant revision to the long-standing ^{40}Ar-^{39}Ar age of 665 ± 10 Ma (Claesson & Roddick 1983). The new result also confirms that most modern U-Pb-based age estimates for BDS-related magmatism fall within a narrow time interval (e.g., ca. 610–595 Ma; Tegner et al. 2019), consistent with a relatively large LIP (see below). Due to the possibility of zircon inheritance in some published studies, we suspect that the magmatic pulse during this event may have been even more restricted in time of duration.

Age constraints of the Baltoscandian Dyke Swarm and the Baltoscandian Large Igneous Province

The Baltoscandian Dyke Swarm formed at the western margin of Baltica during break up of Rodinia, with the separation of Baltica from Laurentia and Amazonia in the west and southwest, respectively, and, finally, the opening of the Iapetus Ocean. The full span of U-Pb ages for the dyke swarm appears to comprise an intrusion period of about 40 million years, beginning with the Egersund Dyke Swarm in the southwest as the oldest one at 616 ± 3 Ma (Bingen et al. 1998, 2005) to the 578 ± 9 Ma age recorded in the Kebne Dyke Complex in the northeast (Kirsch & Svenningsen 2016). The age presented here for the Ottfjället Dyke Swarm, at 596.3 ± 1.5 Ma, fits well within the broader range of intrusive ages for all Baltoscandian dykes, as well as within the narrower 610–595 Ma span for the majority of modern analyses (Table 1).

Andréasson et al. (2005) suggested the Baltoscandian Dyke Swarm represented a large igneous province. Tegner et al. (2019) discussed the characteristics of the BDS as a LIP and concluded that the Baltoscandian Dyke Swarm fulfills both duration and estimated magmatic volume as criteria for a LIP, as those proposed by Bryan and Ernst (2008, p. 175). The Baltoscandian Large Igneous Province (BLIP) has been supposed to be the Baltoscandian part of the Central Iapetus Magmatic Province (CIMP) that comprises both mafic and granitic plutonic and volcanic rocks, besides carbonatites, occurring along the margins of Baltica and Laurentia (Andréasson et al. 2005; Ernst & Bell 2010; Tegner et al. 2019). The CIMP, representing a very large LIP, was suggested by Tegner et al. (2019) to have been formed from several plumes rising from a plume generation zone (PGZ) at the edge of one of the two stationary Large Low Shear-wave Velocity Provinces (LLSVP) at the core-mantle boundary.

As pointed out by Andréasson (1994) and Bingen et al. (1998), the rifting of Baltica was diachronous, not only between the plate margins of Baltica, Laurentia and Amazonia (Bingen et al. 1998), but also within the Baltoscandian margin itself, as reflected by the spread in high-resolution ages from the BDS referred above. In western Baltica, aborted attempts of early break-up of the Rodinia supercontinent may be represented by: (1) 850–900 Ma magmatism represented by granites in the Seve Nappe Complex (Paulsson & Andréasson 2002), (2) the ca. 850 Ma mafic Hunnedalen Dyke Swarm in southwestern Norway (Walderhaug et al. 1999) and (3) basalt volcanism predating Neoproterozoic glaciation in the Hedmark Basin in the Caledonian Lower Allochthon of South Norway (Furnes et al. 1983; Lamminen et al. 2014). The diachronous rifting indicates that the Iapetus Ocean initially formed a series of narrow, segmented seaways in the rift zones between Baltica, Laurentia and Amazonia, including a series of large and small Cryogenian-Early Cambrian rift basins and marginal marine platforms in western Baltica.

Abdelmalak et al. (2015) and Jakob et al. (2017) compared the dolerite dyke swarms in the Scandinavian Caledonides with the Cenozoic rifting and magmatic record in the present mid-Norwegian margin and suggested the Ediacaran dyke swarms in the Caledonides were related to a hyperextended pre-Caledonian margin within a magma-rich, thinned continental crust outside a necking zone containing non-magmatic Neoproterozoic basins (Jakob et al. 2019). The age constraints and crustal development discussed above are of crucial importance to the sedimentary history and timing of the western Baltoscandian Neoproterozoic basins.

Age constraint of the Neoproterozoic glaciation in Scandinavia

The Ottfjället Dyke Swarm cuts the Tossåsfjället Group of the Särv Nappe of the Caledonian thrust belt. Consequently, it also cuts the glaciogenic Lillfjället Formation. So far, no fossils have been found in the Tossåsfjället Group. The Lillfjället Formation has been correlated with the glaciogenic Moelv and Koppang formations in southern Norway, the glaciogenic Långmarkberg Formation in northern Jämtland, and the Neoproterozoic glaciogenic units in Finnmark of Northern Norway (Kumpulainen & Nystuen 1985; Nystuen et al. 2008; Nystuen & Lamminen 2011; Kumpulainen 2011; Kumpulainen & Greiling 2011). The Moelv and Långmarkberg formations, diamictites similar to the Lillfjället Formation, rest with erosional disconformity on various older rocks, but characteristically also on thick platform carbonate formations, probably also sabkha deposits, within allochthonous basin successions (Kumpulainen & Nystuen 1985). Similar "*carbonate platform-glacial diamictite couples*", i.e., warm to cold climate change recorders, have been described in the Tanafjorden-Varangerfjorden Region in Eastern Finnmark of northern Norway, in the Engerdalen Group in the middle allochthonous Kvitvola Nappe Complex in southern Norway, in the Nijak Formation (Svenningsen 1994a) in the Seve Nappe in the Sarek area (Kjøll 2020), as well as in East and North-East Greenland and Nordaustlandet and Ny Friesland in Svalbard (Nystuen et al. 2008). It is highly probable that this archive of dramatic climate change preserved in the rock record in the middle-late Neoproterozoic represents a major shift in the Earth's climate history, to which continental-wide glaciation in Baltica and adjacent Laurentian plates can be correlated.

The Moelv Formation and the glaciogenic Koppang Formation in the Kvitvola Nappe Complex in South Norway (Nystuen 1980) have generally been correlated with the younger of the two glacial units in Finnmark, the Mortensnes Formation (e.g., Bjørlykke & Nystuen 1981; Kumpulainen &

Nystuen 1985; Siedlecka et al. 2004; Nystuen et al. 2008). The lower and upper glacial units in Finnmark, the Smalfjord and Mortensnes formations, respectively, have traditionally been referred to the *Varanger Ice Age*, a name introduced by Kulling (1951). Halverson et al. (2005) correlated, on the basis of $\delta^{13}C$ values in carbonate beds, the Smalfjord Formation with the 635 Ma world-wide and hypothetical "Snowball Earth-type" Marinoan glaciogenic succession, and the Mortensnes Formation with the 580 Ma glaciogenic Gaskiers Formation in Newfoundland. From this chemostratigraphical correlation, Rice et al. (2011) concluded that the concept of a "Varanger Ice Age" was no longer valid and should be discarded. The Gaskiers glaciation in Newfoundland is constrained between 580.90 ± 0.40 and 579.24 ± 0.17 Ma, giving the duration of the Gaskiers glacial event of just 340 ky (Pu et al. 2016). The Gaskiers glaciation was limited to coastal mountains at mid-latitude positions (34° ± 8°S) in a humid temperate climate (Retallack 2013). No robust high-resolution radiometric age determination exists from the Finnmark succession, hence the correlation of the Mortensnes Formation with the Gaskiers event remains uncertain.

Bingen et al. (2005) suggested that Late Neoproterozoic glaciation on Baltica corresponds to the Gaskiers glaciation, as inferred from two clastic zircons in the Rendalen Formation, the correlative to the Brøttum Formation (Nystuen 1987; Nystuen & Lamminen 2011) beneath the glacial Moelv Formation, of a pooled ^{238}U-^{206}Pb age of 620 ± 14 Ma. Lamminen et al. (2014) found at the same locality another four concordant detrital zircons with a ^{238}U-^{206}Pb age of 624 ± 10. In the Brøttum Formation (Fig. 6), also underlying the Moelv Formation in the same region of the Lower Allochthon in South Norway, Lamminen et al. (2014) found another 7 concordant detrital zircons with a ^{238}U-^{206}Pb age of 618 ± 8 Ma. The combined data for these 13 youngest analyses from three samples yield an average age of 620 ± 6 Ma. The 620 Ma zircon grains recorded by Lamminen et al. (2014) were part of the youngest population of clastic zircons in the Hedmark Group beneath the Moelv Formation, up 700 Ma in age. Nevertheless, the majority of clastic zircons reported by Lamminen et al. (2014) from sandstones and conglomerates beneath the Moelv Formation reveal ^{238}U-^{206}Pb ages ranging from ca. 960–1680 Ma, all with well-known provenances in the Sveconorwegian domain and the Transscandinavian Igneous Belt (TIB) of Baltica. Lamminen et al. (2014) obtained individual detrital zircon ages within the range 800–600 Ma in sandstone formations beneath the Moelv Formation, including the zircons of about 620 Ma, all of unknown provenance, but hypothetically from peri-Gondwana terranes, unless the ages are the consequence of post-depositional, metamorphic resetting.

It could be argued that the presence of ca. 620 Ma detrital zircon beneath the Neoproterozoic glacial diamictite in southern Norway indicates an Ediacaran glaciation younger than 620 Ma, but older than 596 Ma, in the North Atlantic region. However, no Ediacaran glaciation, neither local, nor continental-wide, of this age interval is hitherto known from any part of the world (Arnaud et al. 2011; Young 2017). A maximum age constraint on the Neoproterozoic glaciation of Scandinavia may perhaps be revealed from a basalt bed directly beneath the Moelv Formation in the same region as the 620 Ma zircons (Nystuen & Lamminen 2011). No radiometric age has yet been published from this basalt formation, which is altered to greenstone due to Caledonian metamorphism (Furnes et al. 1983).

We consider the geological interpretation of detrital zircon ages in the time range 800–600 Ma, including those of about 620 Ma, to be too uncertain for proposing an additional Ediacaran glaciation between 620 and 596 Ma.

The stratigraphy of the Lillfjället Formation (Fig. 4), with a lower diamictite unit followed by the more than 600 m thick unnamed mudstone-sandstone unit (UNU) and another diamictite unit on the top, is very similar to the Smalfjord Fm (diamictite)-Nyborg Fm (siltstone/sandstone)-Mortensnes Fm (diamictite) succession in Finnmark, referred to above. This similarity additionally strengthens the correlation between the Neoproterozoic glacial succession in Finnmark and those in the central and southern Scandinavia (Fig. 6).

Neoproterozoic diamictites located on wide carbonate platform formations in the Lower and Middle Allochthons of the Scandinavian Caledonides, cut by the ca. 600 Ma Baltoscandian Dyke Swarm, and on Baltica basement (e.g., Andréasson 1994; Nystuen & Lamminen 2011; Stodt et al. 2011) testify to a continental glaciation of Baltica, predating the 580 Ma Gaskiers glaciation. Kjøll (2020), taking into consideration our Ottfjället dolerite age of 596 ± 12 Ma from the preliminary announcement of this age (Kumpulainen et al. 2016) and a U-Pb age of 698 ± 15 Ma for detrital zircon in sandstone overlying the glaciogenic diamictite in the Nijak Member in the Sarek area, constrained the age of the Neoproterozoic glaciation in Scandinavia between 596 Ma and 698 Ma, excluding the possibility of Gaskiers glaciation, and suggested a Marinoan 635 Ma age as most likely.

The complete Neoproterozoic succession in the Tossåsfjället Basin, now in the Särv Nappe, as well as other Neoproterozoic outboard basin successions, i.e., the Seve-Kalak Nappe Complex which are cut by the Baltoscandian Dyke Swarm, must have subsided and lithified well before the 578–608 Ma time of intrusion of the dykes. From the lithostratigraphic correlation of the Scandinavian Neoproterozoic glaciogenic units, their extent and localization within the denudated Baltica and its marginal rift and shelf basins, we find it most likely, in accordance with the conclusion of Kjøll (2020), that the Late Neoproterozoic glacial deposits on Baltica belong to the ca. 635 Ma Marinoan (Varangerian) glacial period which was of worldwide extent (Li et al. 2013).

Conclusions

The mafic Baltoscandian Dyke Swarm is part of a large igneous province comprising the Ediacaran-early Cambrian Baltoscandian and Laurentian rifted Iapetus margins. U-Pb age-determinations on baddeleyite from the Ottfjället Dyke Swarm in the southern Swedish Caledonides, have given an intrusion age of 596.3 ± 1.5 Ma. The age of the dolerite in Härjedalen represents the first, precise, modern age-determination of a Baltoscandian dyke from the Särv Nappe, and correlates with a narrow range of other recent U-Pb ages determined for intrusives of the Baltoscandian Dyke Swarm intruded into their sedimentary host rocks, occurring now in nappes higher than the Särv Nappe of the Swedish Caledonides (Svenningsen 2001; Root & Corfu 2012; Baird et al. 2014; Kirsch & Svenningsen 2016; Kjøll 2020). The entire Baltoscandian Dyke Swarm comprises a series of dyke swarms ranging in age from the ca. 616 Ma Egersund Dyke Swarm in autochthonous Precambrian basement in southwestern Norway to the youngest age of ca. 578 Ma in the Kebne Dyke Complex in the northeast in the Seve-Kalak Nappe Complex of the Swedish Caledonides. In consideration of the best constrained data, however, we speculate that the vast majority of rift-related mafic magmas were likely emplaced into the Baltoscandian margin in a more limited span of time, between approximately 610–595 Ma.

The Ottfjället Dyke Swarm cuts the glaciogenic Lillfjället (diamictite-sandstone-shale) and sabkha-type Storån (carbonate) formations of the Tossåsfjället Group. Similar facies couplets are described from many parts of Scandinavia. Consequently, we interpret this change from dry, arid conditions to one of glaciation to have been simultaneous across much of the Neoproterozoic western Baltica. Hence, the new age of 596 Ma for the Ottfjället Dyke Swarm establishes a minimum age for Neoproterozoic glaciation in Scandinavian (Baltica) region. This event demonstrably predates the 580 Ma Gaskiers glaciation, and implies that Neoproterozoic glaciogenic units in Scandinavia represent the "Snowball-Earth"-type Marinoan (Varangerian) glaciation, at ca. 635 Ma.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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