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A 1.85 Ga volcanic arc offshore the proto-continent Fennoscandia in southern Sweden

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ABSTRACT

The Fröderyd Group forms part of the Vetlanda-Oskarshamn belt (also known as the Oskarshamn-Jönköping Belt), which is a piece of Palaeoproterozoic crust that is completely encapsulated by 1.81–1.77 Ga granitoids of the Transscandinavian Igneous Belt in the southern part of the Fennoscandian Shield. New U-Pb zircon data from a felsic metavolcanic rock in the Fröderyd Group have been acquired using LA-ICP-MS single collector. The age is determined to 1853 ± 11 Ma. The Fröderyd Group is interpreted to represent a volcanic arc that was located southwest of the margin to the proto-continent Fennoscandia. Tonalitic magma, identified in the Eksjö-Bäckaby regions, formed the middle crust in this arc complex and intruded the volcanic arc rocks at ca. 1.83–1.82 Ga. When this arc complex gradually approached the margin to the proto-continent Fennoscandia, parts of it were uplifted above sea level and initiated lacustrine sedimentation in restricted basins, which now are found in the Vetlanda region. Parallel with the development of this arc complex, 1.86–1.85 Ga granitoids intruded the margin to the proto-continent Fennoscandia and 1.87–1.86 Ga clastic metasedimentary rocks in the Västervik area in an Andean-type active continental margin.

It can be concluded that the Vetlanda and Västervik sedimentary basins formed in two completely different geological environments during two separate events. The Västervik sediments formed along the margin to the proto-continent Fennoscandia before the Fröderyd arc system had developed while the Vetlanda sediments formed in a post-arc environment outboard to the southwest of the margin to the proto-continent Fennoscandia. It is suggested that the mafic volcanic rocks close to the lake Nömmen should be excluded from the Vetlanda supergroup and instead be related in time to the Fröderyd Group. This paper presents an interpretation of the tectonic evolution including volcanic arc and rifted volcanic arc during the 1.87 to 1.77 Ga time span with relevance to the evolution of the active southwestern margin of the proto-continent Fennoscandia depicted as a sequence of schematic profiles.

1. Introduction

It is acknowledged that the continental crust is a collage of orogenic belts, generated as island arcs welded and amalgamated together and in several instances succeeded by continent–continent collision. Volcanic arcs can be built on continental lithosphere producing Andean-type arcs or oceanic lithosphere forming intra-oceanic island arc systems (Stern, 2010). Being produced on a thin mostly mafic crust, intra-oceanic arcs represent thickened ridges of juvenile crust less contaminated by felsic material relative to Andean-type arcs. This makes island arcs important targets for studying crustal evolution from a single terrane to continents. Although intra-oceanic island arcs are identified both in modern environments (e.g. the Izu-Bonin Mariana arc and the Philippine island arc; Stern et al., 1996; Yumul et al., 2008) and in ancient crustal terranes (e.g. Flin Flon Belt; DeWolfe et al., 2009), modern island arcs represent an intermediate stage in the tectonic evolution while ancient arcs show the entire evolution from the immature island arc to the tectonic collage accreted to the craton.

The significance of plate tectonics in the formation of the Palaeoproterozoic Svecofennian crust was first recognized in 1975, when a model, involving island arcs, was presented by Anna Hietanen (1975) for the entire Svecofennian Domain. Plate tectonic models soon followed

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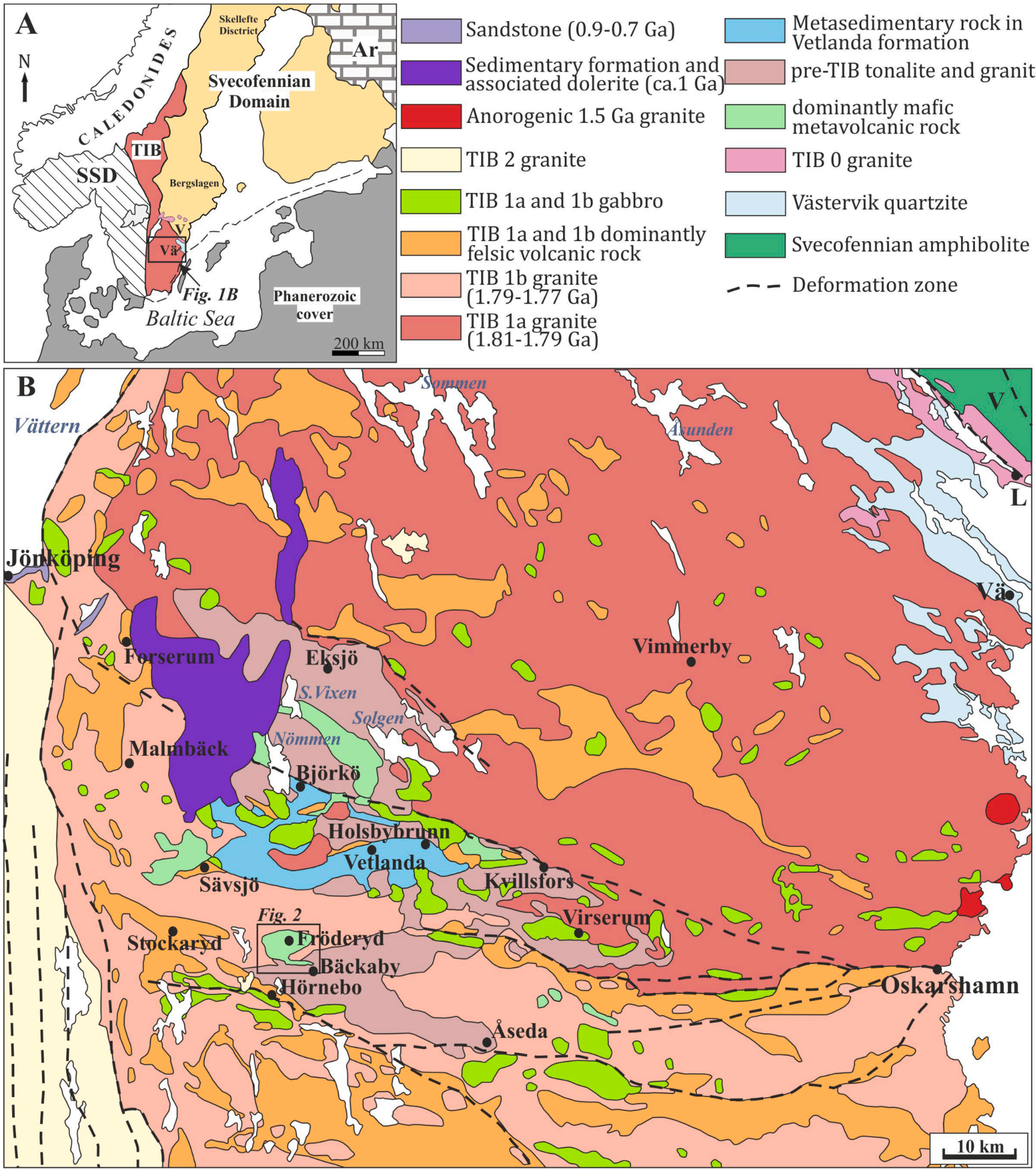

Fig. 1. **A.** Simplified geological map of the Fennoscandian Shield. Map and nomenclature are based on Gaál and Gorbatschev (1987). Ar – Archaean Domain, SSD – Southwest Scandinavian Domain, TIB – Transscandinavian Igneous Belt, grey dashed line – northern border of the Phanerozoic cover. **B.** Geological map of southeastern Sweden, modified after Bergman et al. (2012). Vä – Västervik, V – Valdemarsvik area, L – Loftahammar.

for individual supracrustal Svecofennian successions in the two specific regions that Hietanen (1975) had identified as island arcs: the Skellefte district (Rickard and Zweifel, 1975) and Bergslagen (Löfgren, 1979; Vivallo and Rickard, 1984). These concepts, however, have been rejected in later literature. Thus, Allen et al. (1996a) inferred that the character of the volcanic rocks in the Skellefte district contradicts an island arc setting and proposed continental margin volcanic arc magmatism. Furthermore, subduction-related successions formed along an active continental margin have also been proposed for the Bergslagen region (Allen et al., 1996b; Hermansson et al., 2008). Plate tectonic models for the plutonic successions within the post-Svecofennian Transscandinavian Igneous Belt were first presented by Nyström (1982) and Wilson (1982), both suggesting Andean-type active continental margins and Ahl et al. (1999), who also emphasized the back-arc aspect. A plate tectonic model for the Transscandinavian Igneous Belt presented by Andersson et al. (2004) suggests that large volumes of magma were generated due to massive post-accretional reworking of the juvenile Svecofennian crust along a newly established continental margin. Revised models of the pioneering work of Hietanen have been presented by e.g. Park (1985), Korja and Heikkinen (2005), Hermansson et al. (2008), Stephens and Andersson (2015).

The Vetlanda-Oskarshamn belt is the southernmost igneous-sedimentary complex for which a Svecofennian age has been suggested. However, insufficient geochemical and geochronological data available for this belt have led to poorly constrained age frames and vaguely defined plate tectonic models (Beunk and Valbracht, 1991; Sundblad et al., 1997; Beunk and Page, 2001; Mansfeld et al., 2005). In this contribution, we present new geochemical and geochronological data from the metavolcanic rocks of the Fröderyd Group and suggest that it represents a volcanic arc. Based on these and previously published data, we clarify the relationships between the different geological units in the Vetlanda-Oskarshamn belt with relevance to the evolution of the southwestern margin of the proto-continent Fennoscandia. We also present an interpretation of the tectonic evolution including volcanic arc and rifted volcanic arc during the 1.87 to 1.77 Ga time span.

2. Geological setting

2.1. Regional geological setting

The Fennoscandian Shield can be subdivided into three crustal domains (the Archaean Domain, the Svecofennian Domain and the Southwest Scandinavian Domain; Fig. 1A) which formed and consolidated between 3.5 and 0.9 Ga (Gaál and Gorbatschev, 1987). The Svecofennian and Southwest Scandinavian Domains are separated by a prominent array of intrusive and associated volcanic rocks, Transscandinavian Igneous Belt (Fig. 1A). The formation of the Svecofennian Domain started with the development of accretionary orogenic activity including generation of the Skellefte and Pyhäsalmi volcanic arcs and the Bergslagen active continental margin, southwest of the Archaean craton at 1.96 to 1.89 Ga (Lahtinen, 1994; Kähkönen, 2005; Kathol and Weihed, 2005).

The Svecofennian Domain is composed of metamorphosed granitoids, volcanic and sedimentary rocks and, according to Gaál and Gorbatschev (1987), can be divided into three parts: the Northern and Southern provinces are dominated by igneous rocks, and the Central province is dominated by sedimentary rocks. The Bergslagen district constitutes a major part of the Southern province, where the predominantly felsic metavolcanic successions and associated metasedimentary rocks are interpreted to represent an active continental margin (Vivallo and Rickard, 1984; Allen et al., 1996b). The southernmost parts of the Svecofennian crust are found in the coastlands of Valdemarsvik, where basaltic to andesitic metavolcanic rocks dominate. The supracrustal sequences in the Bergslagen-Valdemarsvik regions were intruded by a voluminous suite of 1.91–1.87 Ga plutonic rocks consisting of granitoids, diorites and gabbros (Stephens et al., 2009; Stephens and Andersson, 2015; Johansson and Stephens, 2017).

The first metamorphic event in Bergslagen is recorded at 1.87–1.85 Ga (Andersson et al., 2006; Hermansson et al., 2008; Stephens and Andersson, 2015; Johansson and Stephens, 2017). A second, and more intense metamorphic event, under low-P greenschist to upper amphibolite and locally granulite facies conditions, took place at 1.83–1.80 Ga and was related to the northward subduction resulted in pervasive reworking of the newly formed crust (Gaál and Gorbatschev, 1987; Andersson et al., 2006).

The Transscandinavian Igneous Belt (TIB) is a major batholith complex that can be followed along the southwestern margin of the Svecofennian Domain both within the shield and under the Caledonian nappes (Gorbatschev, 1980; Högdahl et al., 2004). It has also been followed under the Baltic Sea to the coastal areas of Latvia and Lithuania (Salin et al., 2019). It is characterized by potassium-rich, coarse-grained felsic intrusive rocks and comagmatic terrestrial felsic volcanic rocks that were emplaced periodically between 1.85 Ga and 1.67 Ga. Four main pulses can be distinguished: TIB 0 (1.86–1.85 Ga), TIB 1a (1.81–1.79 Ga), TIB 1b (1.79–1.77 Ga) and TIB 2 (1.71–1.67 Ga); Larson and Berglund, 1992; Ahl et al., 2001; Gorbatschev, 2004; Salin et al., 2019. TIB 0 as well as TIB 1a and TIB 1b have I-type characteristics while TIB 2 has both I- and A-type characteristics. TIB 0 exclusively intruded into the Svecofennian crust (along the southwestern margin of the Bergslagen district and in the Valdemarsvik region) and the Västervik quartzites (see below). Locally, TIB 0 granites have been strongly affected by deformation and metamorphism. TIB 1 rocks are affected by ductile deformation and low-grade metamorphism predominantly along ductile shear zones. The TIB 2 generation occurs as I-type continental margin intrusions west of the TIB 1 granitoids and as A-type within plate intrusions east of the TIB 1 (Ahl et al., 1999).

2.2. Pre-TIB 1 rocks around Västervik and along the Vetlanda-Oskarshamn belt

Two large areas of pre-TIB 1 units are enclosed within the TIB 1 units (Västervik sedimentary basin and Vetlanda-Oskarshamn belt; Fig. 1B). The Västervik sedimentary basin is intruded by TIB 0 and TIB 1a units, immediately to the south of the Svecofennian metabasalts and orthogneisses in the Valdemarsvik region (Fig. 1B). The Västervik basin is a km-thick metamorphosed succession of fluvial, tidal and turbiditic quartz-dominated sedimentary rocks, which accumulated in tide-dominated estuaries, river-dominated deltas and wave-dominated shallow-water environments along a continental margin (Russell, 1967; Sultan and Plink-Björklund, 2006). The Västervik succession contains a wide age range of Archaean to Palaeoproterozoic detrital zircons, the youngest of which suggest a maximum age for the sedimentation of 1.87 Ga (Claesson et al., 1993; Sultan et al., 2005). The intrusion ages of TIB 0 granitoids, 1859 ± 9 Ma (Bergström et al., 2002) and 1845.6 ± 10 Ma (Kleinhanns et al., 2015), can be considered as minimum estimates for the deposition of the Västervik sediments. Even if the age of the sedimentation is not precisely defined, it can thus be concluded that the Västervik sedimentary rocks were deposited at ca. 1.87 to 1.86 Ga.

The most extensive area of pre-TIB 1 units in southeastern Sweden was recognized already by Holst (1885) and Svedmark (1904) who first documented metasedimentary rocks in the Vetlanda region and gneissic granitoids between the towns Vetlanda and Oskarshamn. On modern maps (Bergman et al., 2012), the belt of pre-TIB granitoids is distributed between the towns Eksjö and Virserum, while pre-TIB 1 mafic volcanic units, first recognized by Röshoff (1975) in the Nömmen area, can be followed from Sävsjö to Virserum (Fig. 1B). Even if the exact distribution of these pre-TIB 1 units have changed through the years, the site names Vetlanda and Oskarshamn (first used by Holst in 1885 and Svedmark in 1904) were kept in use as the geographical end members for this belt for a long time (Magnusson et al., 1960; Röshoff, 1975; Lundqvist, 1979; Beunk and Valbracht, 1991; Beunk et al., 1992) until the term Oskarshamn-Jönköping Belt (OJB) was introduced by Mansfeld (1996) for these pre-TIB 1 units. The OJB term is, however, very inappropriate since Jönköping is located far to the west and Oskarshamn far to the east of the presently known distribution of this rock complex. For that reason, the original name, Vetlanda-Oskarshamn belt, will be used in this paper, and it is suggested that the Oskarshamn-Jönköping Belt concept is abandoned.

2.3. Lithostratigraphic units in the Vetlanda-Oskarshamn belt

The Vetlanda-Oskarshamn belt is dominated by a continuous belt of calc-alkaline tonalites to granodiorites extending between the two batholiths of TIB 1a and TIB 1b from Eksjö and Vetlanda to Virserum. Emplacement ages of the tonalites have been reported from Bäckaby (1834 Ma; Mansfeld, 1996), Eksjö (1823 Ma; Åhäll et al., 2002) and Virserum (ca. 1830 Ma; Wik et al., 2003). The supracrustal units of the Vetlanda-Oskarshamn belt are particularly well known in three separate areas: Vetlanda, Nömmen-Björkö and Fröderyd. A shear zone extending for about 150 km from the lake Vättern to the Baltic Sea, separates the tonalites of the Eksjö section from the Vetlanda-Virserum tonalites and separates the succession of mafic volcanic rocks in the Nömmen group from the metasedimentary units in the Björkö and Vetlanda groups (Fig. 1B). Both ductile and brittle strain components are present along the shear zone.

The metasedimentary Vetlanda formation south of the shear zone is

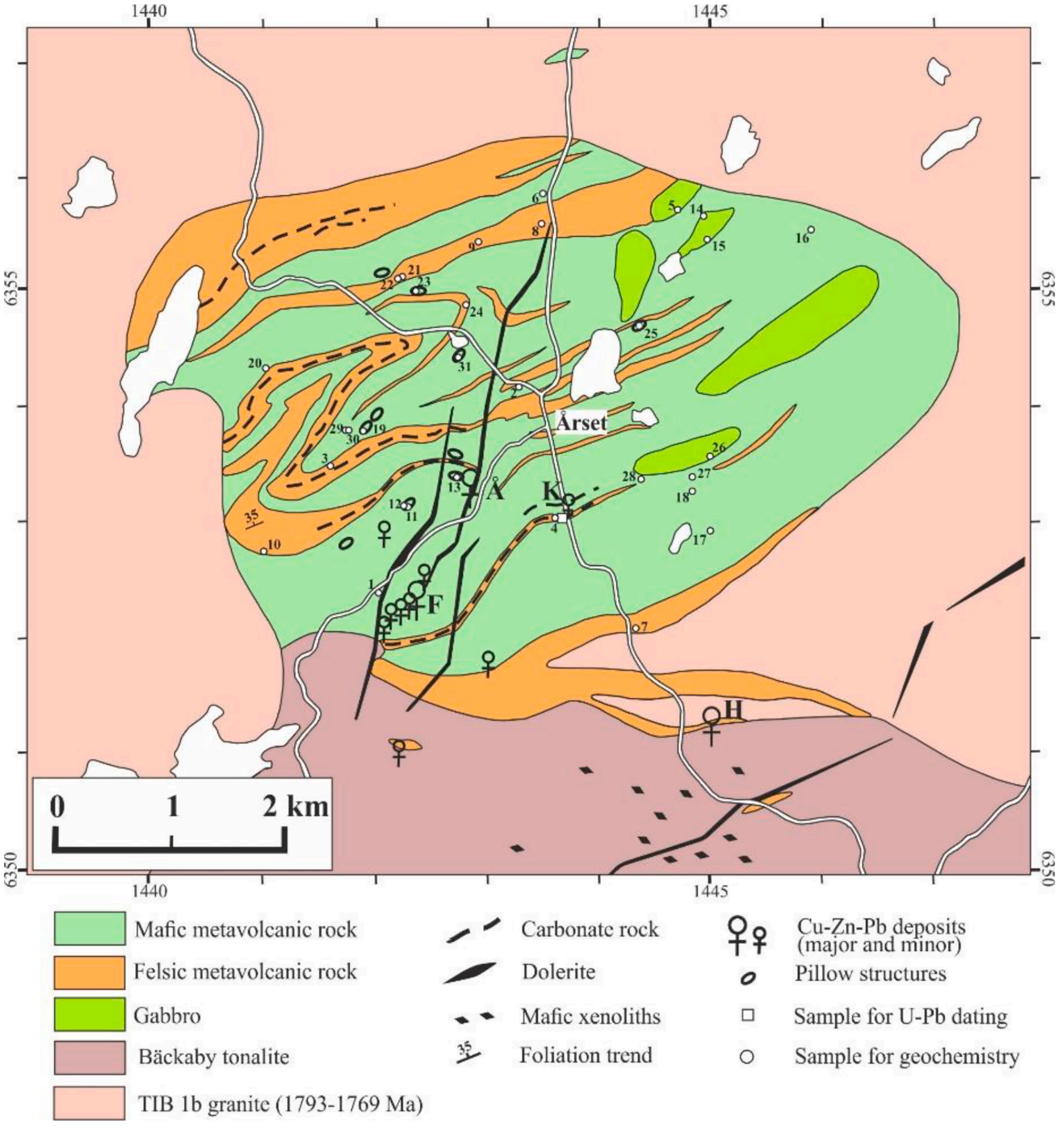

Fig. 2. Geological map of the Fröderyd area. Modified after Sundblad et al. (1997), coordinates in Swedish national grid RT 90. Sulphide deposits: F – Fredriksberg and Krongruvan, Å – Årset, K – Karl XV, H – Hökhult. Samples labelled F0001-F0031 are indicated on a map with only last figures.

dominated by quartz-plagioclase arkoses and conglomerates (Persson, 1989), clearly indicating a shallow water (and not necessarily marine) environment; the absence of limestone may suggest a lacustrine environment. Thin layers of phyllites and felsic volcanic rocks are locally abundant. The conglomerate clasts are dominated by rhyolitic volcanic rocks, but several dm-sized granitoid fragments have also been identified. A granodioritic clast in these conglomerate beds yielded a U-Pb age of 1829 ± 8 Ma (Mansfeld et al., 2005) providing a maximum age for the Vetlanda formation.

The supracrustal rocks in the Nömmen-Björkö area, occurring mainly north of the shear zone, were divided into the Nömmen volcanic group and the volcano-sedimentary Björkö group by Röshoff (1975). The Nömmen volcanic group is composed of volcaniclastic rocks and amygdaloidal lavas of basaltic to andesitic composition with rare pillow lavas (Röshoff, 1975). This volcanic group was interpreted as a Svecofennian near-shore or terrestrial deposition by Röshoff (1975) and was proposed to represent Svecofennian arc magmatism by Beunk and Valbracht (1991). Only few geochemical data are available for the Nömmen volcanic rocks and it is difficult to evaluate the exact character of this proposed volcanic arc. Felsic volcanic rocks are only found on the south side of the shear zone, within the volcano-sedimentary Björkö group, which Röshoff (1975) correlated with the Vetlanda metasedimentary unit. All these supracrustal units (Nömmen, Björkö and Vetlanda) were defined as the Vetlanda supergroup by Röshoff (1975).

The Fröderyd Group is located about 15 km SW from Vetlanda town (Fig. 1B) and was defined by Sundblad et al. (1997) who considered it a distinct supracrustal formation from the Vetlanda supergroup, based on the contrasting geological environments in the Fröderyd Group and the clast-dominated Vetlanda formation. The Fröderyd Group is composed of 80% mafic rocks and 20% felsic volcanic rocks (Fig. 2). The mafic rocks include fine-grained basalts, locally with well-preserved pillow structures, and gabbros, while the felsic rocks are often quartz porphyritic (Sundblad et al., 1997). In addition, 5–10 m thick carbonate strata are common at the contacts between the mafic and felsic units and interpreted as exhalites. Cu-Zn-Pb sulphide mineralization occurs as replacements in the volcanic rocks and in the carbonate strata. The mafic rocks comprise tholeiitic basalts with MORB (mid-ocean ridge basalt) signature (Sundblad et al., 1997). Most of the volcanic rocks have a spilitic overprint, confirming the submarine character demonstrated by the pillow lavas. The Fröderyd mafic volcanic rocks also have high ε_{Nd} values (from + 5.1 to + 5.2 at 1.85 Ga; Mansfeld, 1995), and the galena in the sulphide ores have low μ values ($\sim\mu = 9.1$ to 9.2, Sundblad

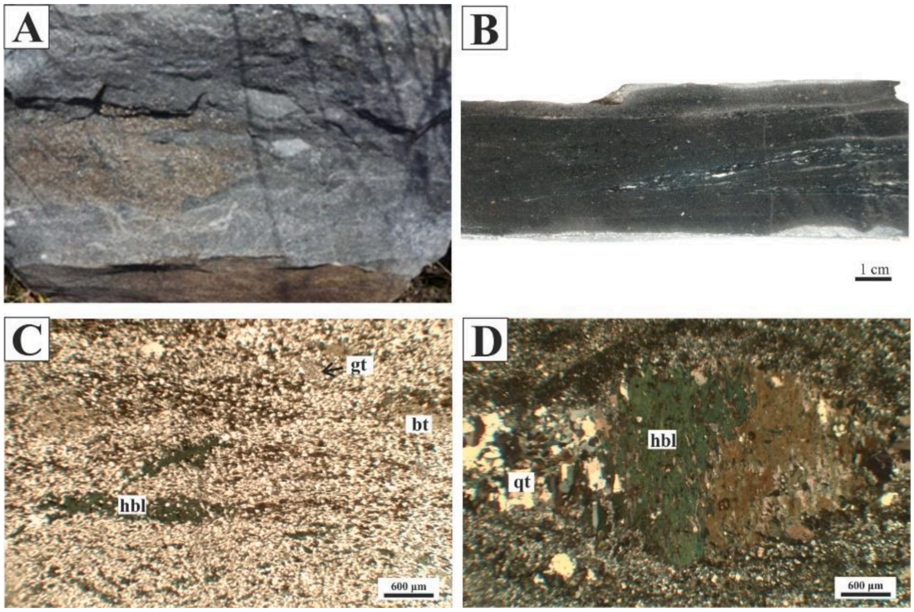

Fig. 3. **A.** Outcrop photograph of the investigated felsic volcanic rock from the Fröderyd Group; **B.** A rock piece from that outcrop with pale grey bands. C and D photomicrographs of the rock. **C.** Biotite and garnet megacrysts and curved hornblende laths in a fine-grained matrix of amphibole, biotite and quartz (plane-polarized light). **D.** Boudinaged hornblende-rich layer (crossed polars). bt – biotite, gt – garnet, hbl – hornblende, qt – quartz.

et al., 1997), confirming the primitive geochemical signature. The Fröderyd succession was intruded by tonalites belonging to the 1834 Ma Bäckaby intrusion (Mansfeld, 1996) in the south and by the 1786 ± 6 Ma TIB 1b batholith (Mansfeld, 1991) in all other directions. The Fröderyd succession was metamorphosed under lower amphibolite facies and penetratively deformed in a characteristic Z-shaped fold pattern before it was intruded by the TIB 1b granitoids. A U-Pb zircon age of 1807 ± 15 Ma of a granophyric dyke, cross-cutting the Fröderyd basalts, was considered as a minimum age for the Fröderyd Group while Sm-Nd data on the basalts suggested a maximum model age of ca. 1850 Ma (Mansfeld, 1995; Mansfeld et al., 2005).

The intrusive contact between the Fröderyd Group and the Bäckaby tonalite is shown in detail in the 1:50000 bedrock map of Wikman (2000), where numerous xenoliths of mafic volcanic rocks and gabbro are seen in the Bäckaby tonalite south of the contact.

3. Material and methods

The geochemical data from the Fröderyd Group, originally used by Sundblad et al. (1997), have been re-evaluated in this contribution. These data were based on 22 samples of mafic and nine samples of felsic rocks, which were analysed for major, minor and trace elements by SGAB Analys, Luleå, Sweden, in 1990, using the inductively coupled plasma optical emission spectroscopy (ICP-OES) method after dissolution in $LiBO_2$ and HNO_3. When the 31 data sets, used by Sundblad et al. (1997), were to be re-examined for the current contribution, data for only eleven mafic and four felsic samples were retrieved. In order to reproduce new data for the mafic rocks, where the original data had been lost, more material from the original samples labelled F90019, F90020, F90023 and F90025-F90031 was retrieved and re-analysed for geochemistry at Actlabs, Ontario, Canada, in 2020 Major, minor and trace elements (Sc, Be, V, Ba, Sr, Y and Zr) were measured using inductively coupled plasma optical emission spectroscopy (ICP-OES), while other trace and rare-earth elements (REE) were measured using inductively coupled plasma mass spectrometry (ICP-MS) methods, both combined with a fusion technique. The fusion technique employs a lithium metaborate/tetraborate fusion; the resulting molten bead is digested in a weak nitric acid solution. A general precision/accuracy is > 100x detection limit - +/- 5% for major oxides and > 100x detection limit - +/- 10% for minor and trace elements.

In order to define the age of the emplacement of the Fröderyd Group, a sample of a felsic volcanic rock was collected from a thin (~ 70 m) felsic volcanic unit, which can be followed from south of the Fredriksberg mine to south of the Karl XV mine (coordinates in the Swedish national grid RT 90: 6352937/1443716; Fig. 2). Sample F90004 was previously collected from this outcrop (Fig. 3A), and geochemical data were presented by Sundblad et al. (1997). Zircon grains from this sample were separated using conventional methods of crushing and panning with a subsequent heavy liquid and magnetic separation. The zircons were carefully handpicked from the heavy mineral concentrate and mounted into epoxy. Zircons were polished to approximately half of their thickness to reach the core of the grain. Back-scattered electron (BSE) images were prepared to study growth features and to target the spot analysis sites using JEOL TM JSM-7100F Field Emission Scanning Electron Microscope. The U-Pb age determination was performed using a Nu Plasma AttoM single collector ICP-MS connected to a Photon Machine Excite laser ablation system. All analytical procedures related to the U-Pb study were conducted at the Finnish Geosciences Research Laboratory, Geological Survey of Finland, Espoo.

The ablation conditions involved a beam diameter of 25 µm and a pulse frequency of 5 Hz with a beam energy density of 2 J/cm^2. Each U–Pb measurement included a short 10 s pre-ablation followed by 30 s of ablation with a stationary beam to integrate the signal. Mass number 204 was used as a monitor for common Pb. When the analysis showed common Pb contents significantly above the detection limit, age-related common Pb correction, according to Stacey and Kramers (1975), was used. Signal strengths on mass 206 were typically 100,000 cps, depending on the uranium content and age of the zircon. U/Pb ratios were calibrated against GJ-1 standards (609 ± 1 Ma; Belousova et al., 2006) and in-house A382 standard (1877 ± 2 Ma; Huhma et al., 2012) at the beginning and end of each analytical session, and at regular intervals during sessions (n = 10). Data for in-house standard for LA-ICP-MS are presented as a supplementary material in Appendix 1. The depth-to-diameter ratio of the ablation pit was kept low to minimize the effects

Table 1

New geochemical data[1] for mafic metavolcanic rocks in the Fröderyd area.

Sample #}	F90019[2]}	F90020}	F90023}	F90025}	F90026}	F90027}	F90028}	F90029}	F90030}	F90031}	Detection limit}	Sample #}	F90019[2]}	F90020}	F90023}	F90025}	F90026}	F90027}	F90028}	F90029}	F90030}	F90031}	Detection limit}
Major and minor elements (wt %)																							
SiO_2	51.34	50.76	49.25	49.97	48.74	51.61	49.27	44.57	44.9	47.29	0.01	Mo	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	2
Al2O$_3$	15.72	14.77	16.52	15.24	17.1	14.38	16.53	15.86	14.84	15.91	0.01	Ag	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	1	< 0.5	0.5
Fe_2O_3(T)	12.8	12.77	11.51	12.74	10.08	14.18	11.28	14.02	15.07	15.55	0.01	In	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.2
MnO	0.173	0.148	0.179	0.179	0.162	0.276	0.178	0.19	0.219	0.212	0.001	Sn	1	1	< 1	1	< 1	2	1	1	3	1	1
MgO	5.84	5.84	7.44	5.98	9.04	5.01	7.15	4.79	2.35	5.52	0.01	Sb	< 0.5	0.5	< 0.5	0.5	0.5	0.5	< 0.5	0.6	0.9	0.9	0.5
CaO	9.46	8.29	10.91	10.06	10.44	9.49	8.69	13.15	13.55	10.59	0.01	Cs	< 0.5	< 0.5	< 0.5	< 0.5	1.1	< 0.5	< 0.5	0.8	2.4	< 0.5	0.5
Na_2O	3.36	3.82	2.94	2.68	1.93	2.66	3.86	2.71	0.56	2.75	0.01	Hf	2.1	3	1.5	2.8	0.9	2.4	1.9	2.9	8	3	0.2
K_2O	0.22	0.58	0.23	0.36	0.83	0.39	0.45	0.66	2.83	0.25	0.01	Ta	0.2	0.6	0.2	0.4	0.1	0.3	0.3	0.3	1	0.3	0.1
TiO_2	1.36	1.559	0.861	1.653	0.591	1.496	1.273	1.77	2.867	1.748	0.001	W	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1
P_2O_5	0.15	0.23	0.08	0.22	0.07	0.18	0.13	0.24	0.49	0.23	0.01	Tl	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.3	< 0.1	0.1
LOI	0.36	0.62	0.65	0.57	1.55	0.33	0.62	2.67	3.08	0.8		Pb	< 5	< 5	< 5	< 5	< 5	9	< 5	15	52	< 5	5
Total	100.8	99.38	100.6	99.66	100.5	100	99.43	100.6	100.8	100.8	0.01	Bi	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4	0.4
Trace elements (ppm)												Th	0.5	1.3	0.4	0.8	0.3	0.9	0.2	0.8	5	0.9	0.1
Sc	44	42	39	45	36	49	37	47	57	46	1	U	0.2	0.5	0.2	0.4	0.1	0.3	0.1	0.4	2	0.4	0.1
Be	< 1	< 1	< 1	< 1	< 1	2	< 1	< 1	1	< 1	1	*Rare-earth elements (ppm)*											
V	290	260	233	308	206	377	238	325	505	326	5	La	5.8	15.9	4.5	8.1	3.6	6.7	5.6	9.8	35.8	9.5	0.1
Ba	58	139	99	83	133	108	1085	1173	210	77	2	Ce	14.5	37.7	10.8	20.2	8.2	15.5	13.6	22.9	77.6	22.7	0.1
Sr	192	289	236	194	180	162	266	294	189	223	2	Pr	2.11	5.2	1.55	2.77	1.17	2.23	1.99	3.21	9.98	3.28	0.05
Y	26	28	20	31	13	22	22	32	63	32	1	Nd	10.5	22.8	7.3	13.5	5.5	10.6	9.9	15.1	41.5	15.2	0.1
Zr	74	121	53	104	32	92	73	107	298	109	2	Sm	3.3	5.6	2.3	4.2	1.6	3.2	3	4.4	10.3	4.5	0.1
Cr	130	120	190	110	140	50	110	110	< 20	110	20	Eu	1.11	1.73	0.83	1.43	0.65	1.37	1.2	1.62	2.81	1.58	0.05
Co	52	40	50	50	52	41	61	54	49	54	1	Gd	4.4	5.6	3.2	5.7	2.1	4.2	3.8	5.6	11.9	5.7	0.1
Ni	60	30	110	60	170	30	120	60	< 20	60	20	Tb	0.8	0.9	0.6	0.9	0.4	0.7	0.6	1	2.1	1	0.1
Cu	30	40	30	50	< 10	50	10	50	50	30	10	Dy	5.1	5.6	3.8	6.1	2.5	4.6	4.2	6.1	13.2	6.4	0.1
Zn	100	200	90	90	70	170	70	140	210	110	30	Ho	1.1	1.1	0.8	1.3	0.5	0.9	0.9	1.2	2.7	1.3	0.1
Ga	19	20	16	19	14	20	18	21	30	21	1	Er	3	3.2	2.3	3.7	1.6	2.6	2.5	3.6	7.8	3.8	0.1
Ge	2	1	1	2	1	2	2	2	2	1	1	Tm	0.45	0.46	0.33	0.52	0.24	0.38	0.36	0.52	1.13	0.54	0.05
As	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	8	< 5	5	Yb	2.9	3	2.3	3.5	1.6	2.5	2.4	3.5	7.6	3.8	0.1
Rb	3	10	4	8	34	4	10	16	65	4	2	Lu	0.45	0.48	0.35	0.55	0.27	0.37	0.37	0.53	1.14	0.57	0.01
Nb	3	8	2	5	1	4	4	4	14	5	1	Zr/Y	2.85	4.32	2.65	3.35	2.46	4.18	3.32	3.34	4.73	3.41	2.00

[1] See Appendix 2 for all the raw data.

[2] All analyses are conducted at Actlabs, Canada.

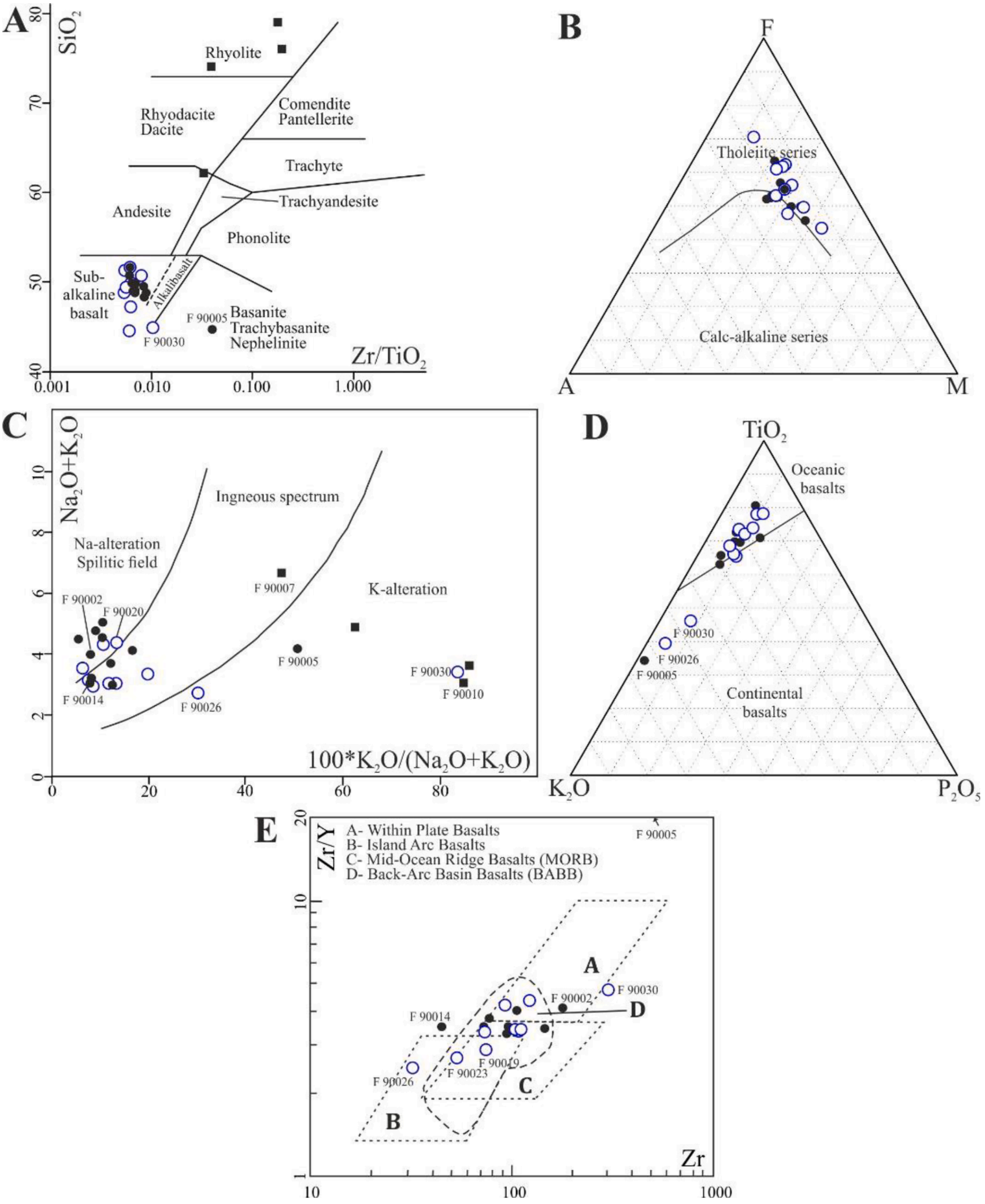

Fig. 4. **A.** SiO_2 vs. Zr/TiO_2 diagram after Winchester and Floyd (1977); **B.** AFM diagram after Irvine and Baragar (1971). A = $Na_2O + K_2O$, F = FeOt, M = MgO in wt. %. **C.** Alkali alteration diagram after Hughes (1972); **D.** K_2O-TiO_2-P_2O_5 discrimination diagram after Pearce et al. (1975); **E.** Zr/Y vs. Zr diagram after Pearce and Norry (1979) with a back-arc basin basalt field after Floyd et al. (1991). MORB – mid-ocean ridge basalt, BABB – back-arc basin basalt. Filled circles – mafic rocks, filled squares – felsic rocks, both data from Sundblad et al. (1997), empty blue circles – mafic rocks, data from this paper (Table 1).

of laser-induced elemental fractionation. Only homogeneous or exhibiting little fractionation segments of a time-resolved signal for each isotope ratio were calibrated against the corresponding time interval for each mass in the reference zircon using the program Glitter (van Achterbergh et al., 2001). All age calculations were performed using the Isoplot program (Ludwig, 2003) with 2σ uncertainties and without uncertainties of decay constants.

4. Results

4.1. *Petrography*

The sample chosen for geochronological analysis is a fine-grained, equigranular, slightly foliated felsic metavolcanic rock. Banded appearance is defined by pale grey to greenish grey layers which

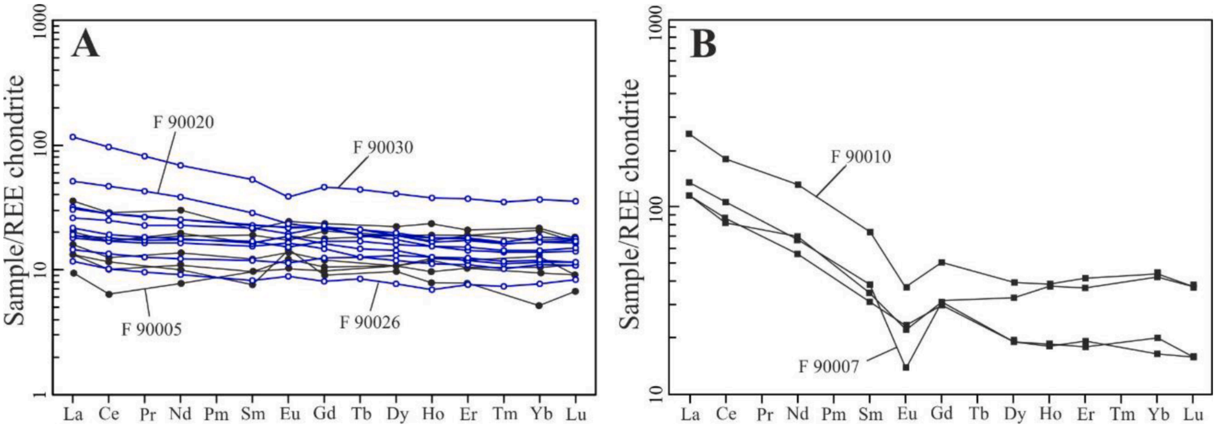

Fig. 5. Chondrite-normalized REE patterns for the volcanic rocks from the Fröderyd Group after Boynton (1984). **A.** Mafic volcanic rocks. **B.** Felsic volcanic rocks. Symbols and data sources are as for Fig. 4.

sometimes occur as lenses (Fig. 3B). The rock is mainly composed of plagioclase, hornblende, biotite and quartz with accessory garnet, ilmenite, titanite, pyrite and zircon. Calcite occurs as a secondary mineral. Anhedral grains of garnet, biotite and hornblende occur in a fine-grained groundmass of amphibole, biotite and quartz (Fig. 3C). Hornblende-rich layers are boudinaged (Fig. 3D), as a result of ductile deformation affected the rock. All grains have subhedral to anhedral shapes and contain numerous inclusions of groundmass minerals.

The mafic metavolcanic rocks are fine-grained (0.1–1 mm) slightly foliated metabasalts with actinolite, plagioclase, ilmenite and biotite, which was metamorphosed under lower amphibolite facies conditions. The rock contains well-preserved pillows (5–30 cm thick) with locally developed elongated and rounded amygdales (2 mm – 1 cm thick).

4.2. Geochemistry

The major, minor and trace element contents of the ten samples of mafic metavolcanic rocks analyzed in 2020 are shown in Table 1. These data are plotted together with previously unpublished raw data from Sundblad et al. (1997) in Figs. 4 and 5, and all data are presented in the electronic supplementary material in Appendix 2. Old and new data are treated as one dataset which will be used for comparison with mafic and felsic volcanic rocks from the Flin Flon Belt presented in the discussion.

The mafic rocks from the Fröderyd Group mostly plot in the sub-alkaline basalt field (Fig. 4A), whereas two samples show alkali basalt and basanite affinity in the classification diagram after Winchester and Floyd (1977). Almost all mafic rocks belong to the tholeiite series (Fig. 4B). Almost half of the samples plot outside the primary igneous spectrum defined by Hughes (1972); (Fig. 4C) suggesting alkali

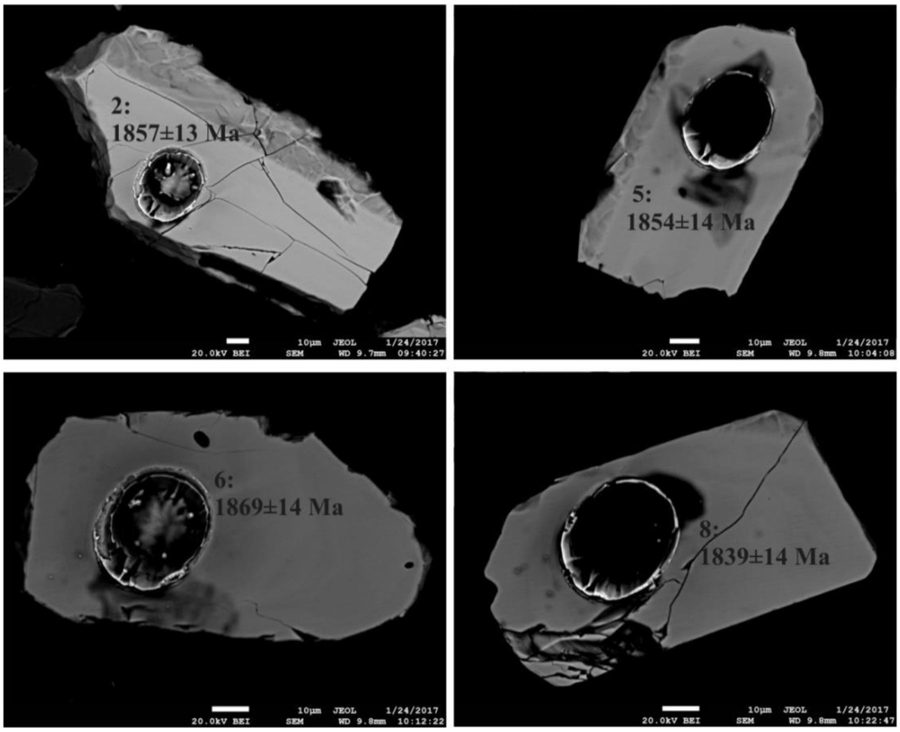

Fig. 6. BSE images of selected analyzed zircon grains in the felsic metavolcanic rock from the Fröderyd Group. Spot sites, number of the analysis and the ^{207}Pb/^{206}Pb age are indicated (individual U-Pb data are in Table 2).

Table 2
LA-ICP-MS U-Pb zircon dating of the felsic metavolcanic rock from the Fröderyd Group.

Sample/ Analysis#	$^{206}Pb_c$ [1] (%)	Concentration (ppm)			Isotopic ratios[3]						Rho.[4]	Concor.[5] (%)	Ages & 1σ errors (Ma)						Th/U meas.
		Pb[2]	Th	U	$^{207}Pb/^{206}Pb$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ			$^{207}Pb/^{206}Pb$	±1σ	$^{207}Pb/^{235}U$	±1σ	$^{206}Pb/^{238}U$	±1σ	
1	1.70	99	165	189	0.1134	0.0009	5.0937	0.1259	0.3258	0.0067	0.95	98	1854	14	1835	21	1818	33	0.9
2	0.10	97	227	183	0.1135	0.0008	5.2283	0.1150	0.3340	0.0068	0.94	100	1857	13	1857	19	1858	33	1.2
3*	0.20	71	177	139	0.1124	0.0008	4.9157	0.1092	0.3171	0.0065	0.94	97	1839	13	1805	19	1775	32	1.3
4*	0.00	151	464	328	0.1086	0.0011	4.2794	0.1039	0.2859	0.0059	0.91	91	1775	19	1689	20	1621	29	1.4
5	0.76	55	75	113	0.1134	0.0009	5.1346	0.1127	0.3285	0.0067	0.94	99	1854	14	1842	18	1831	32	0.7
6	0.01	70	120	136	0.1143	0.0009	5.2654	0.1176	0.3341	0.0068	0.94	99	1869	14	1863	19	1858	33	0.9
7	0.24	60	101	119	0.1134	0.0009	5.1423	0.1190	0.3289	0.0068	0.94	99	1854	14	1843	19	1833	33	0.8
8	0.69	52	86	103	0.1124	0.0009	5.1238	0.1128	0.3306	0.0067	0.94	100	1839	14	1840	19	1841	33	0.8
9*	0.01	138	379	278	0.1112	0.0012	4.8609	0.1129	0.3170	0.0065	0.89	98	1796	19	1796	19	1775	32	1.4

1. $^{206}Pb_c$ (%) – percentage of common lead (^{206}Pb) in measured ^{206}Pb value calculated from the ^{204}Pb signal (if distinct from background) using age-related common lead after model by Stacey and Kramers (1975).
2. Corrected for background, common lead and Pb/U fractionation, normalized to reference zircon GJ1 using Glitter data reduction (Longerich et al., 1996).
3. Common lead correction applied if ^{204}Pb count > 50 cps.
4. Rho. is the error correlation between Pb/U errors.
5. Concordance (%) = (age($^{206}Pb/^{238}U$) / age($^{207}Pb/^{206}Pb$))*100.

* Analysis excluded from the age calculation.

mobilization. Three samples are characterized by potassic alteration, while other samples record high sodium contents (>3 wt%) due to interaction of the magma with seawater and plot within the spilitic field. The purpose of the above mentioned diagram is to distinguish "primitive" basalts, because as stated by Pearce et al. (1975), the K_2O-TiO_2-P_2O_5 discrimination diagram cannot be effectively used for fractionated or alkaline rocks. In this tectonic discrimination diagram, mafic rocks plot within the field of oceanic basalt field except three samples characterized by potassic alteration (Fig. 4D). In the Zr/Y vs. Zr diagram (Fig. 4E), most of the data plot within the BABB field suggesting that the Fröderyd volcanic rocks represent back-arc basin basalts. Deviating samples are mainly affected by potassic (F 90005, F 90,026 and F 90030) or sodic (F 90002) alteration as well as one sample plotting within the igneous spectrum (Fig. 4C).

The mafic rocks show a flat to modestly enriched in LREE pattern in the chondrite-normalized REE diagram after Boynton (1984). Four samples (F 90005, F 90020, F 90,026 and F 90030) affected by alkali alteration deviate from the general trend (Fig. 5A).

The felsic metavolcanic rocks plot within the rhyolite and andesite fields (Fig. 4A) and are mostly affected by potassic alteration (Fig. 4C). They show a stronger enrichment in LREE relative to the mafic rocks and have a negative Eu anomaly (Fig. 5B), which is most pronounced in a sample belonging to the primary igneous spectrum (F 90007; Fig. 4C). This unaltered sample shows enrichment in HREE relative to samples affected by the potassic alteration.

4.3. *U-Pb zircon geochronology*

Zircons in the felsic metavolcanic rock from the Fröderyd Group selected for geochronology are scarce and euhedral grains are rare. Mostly, they range from subhedral, with preserved prismatic shapes (Fig. 6), to anhedral. The grains are transparent and the colour varies from pink and orange to dominating colourless. Their sizes vary from 90 to 140 μm in length and from 35 to 60 μm in width. The grains are usually cracked and broken which could be caused by the magma eruption or later deformation. The zircon grains contain various inclusions of different sizes and with unknown compositions. In the back-scattered electron images (BSE), some zircon grains show a weak growth zoning.

A total of nine zircon domains were analysed using LA-ICP-MS. The results from the U-Pb age determination are presented in Table 2 and plotted on concordia diagram in Fig. 7. Six zircon grains form a tight cluster with a concordia age of 1853 ± 11 Ma (2σ, MSWD = 0.44; MSWD and probability are calculated for combined concordance and equivalence). The weighted average $^{207}Pb/^{206}Pb$ age is 1855 ± 11 Ma (2σ, MSWD = 0.48). The concordia age is suggested to record the time of emplacement of the felsic metavolcanic rocks within the Fröderyd Group. If data point 3 is included into calculations, the concordia age is 1849.5 ± 9.8 Ma, and the weighted average $^{207}Pb/^{206}Pb$ age is 1852 ± 10 Ma. These ages are rather close to the ages obtained without this data point. However the probability of both concordia and weighted average ages is significantly lower (0.59 and 0.74 respectively), while the MSWD is higher (0.86 and 0.58 respectively). For this reason, data point 3 was excluded from the age calculations. Data points 4 and 9 have higher U contents (328 and 278 respectively) relative to the other 7 analyses and plot along the discordia line with a younger age (1777 ± 18 Ma) and a rather high MSWD = 2.6.

5. Discussion

5.1. *Timing of geological events in the Vetlanda-Oskarshamn belt*

Even if the Fröderyd Group was considered by Sundblad et al. (1997) to be a distinct formation from the metasedimentary rocks in the Vetlanda group, Mansfeld et al. (2005) linked the Fröderyd Group to the tonalites and the sedimentary rocks in the Vetlanda region and proposed

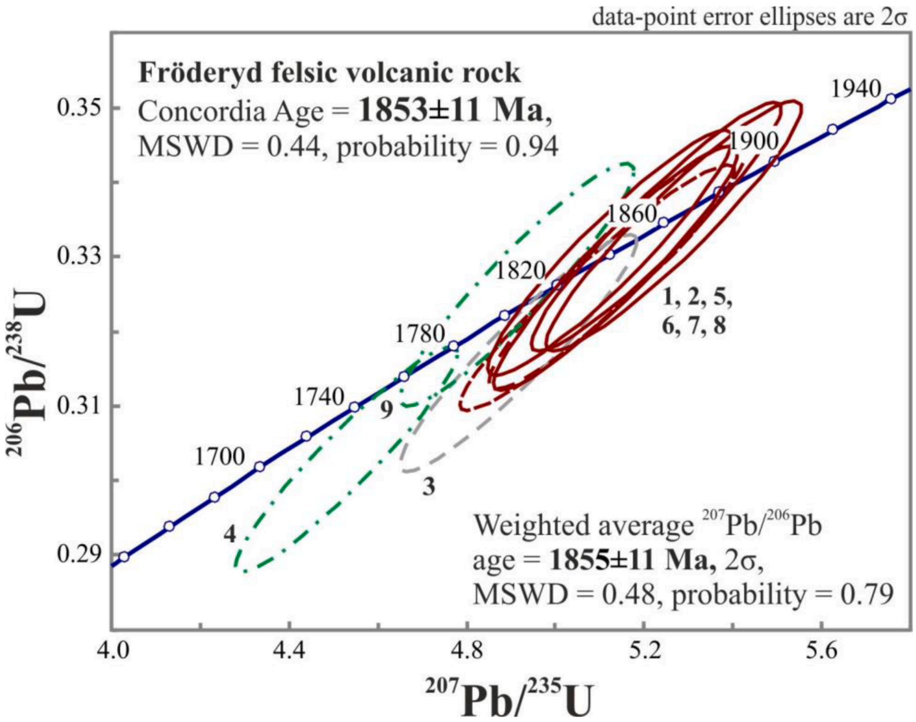

Fig. 7. Concordia diagram of the analyzed zircon grains from the felsic metavolcanic rock from the Fröderyd Group. Error ellipses are at the 2σ level. MSWD and probability are calculated for combined concordance and equivalence. Red solid line – data points used for age determination; green dot-and-dashed line – younger points, grey dashed line – point excluded from the age calculations.

that they all formed in a short time interval between 1.83 and 1.82 Ga. However, the 1.85 Ga age of the felsic components in the Fröderyd Group presented in this paper shows that the Fröderyd volcanic rocks are significantly older and the oldest recognized rocks in the entire area southwest of the Svecofennian Domain (and the Västervik quartzite). With the age of 1.85 Ga, the Fröderyd Group is 20–30 m.y. older than the Eksjö-Bäckaby tonalites, but still at least 20 m.y. younger than the crust in the Svecofennian Domain. The recognition of the 1.85 Ga age for the Fröderyd Group also suggests that the formation of the Fröderyd volcanic rocks was coeval with the emplacement of the TIB 0 continental margin felsic intrusive rocks.

The presence of a sedimentary succession consisting of metamorphosed arkose, mica schist and conglomerate beds led Röshoff (1975) to propose a near-continental environment for the Vetlanda formation. The 1.83 Ga age of a granodiorite clast in the Vetlanda formation (Mansfeld et al., 2005) shows that the tonalites in the Vetlanda-Oskarshamn belt were an important source for these sediments. Furthermore, based on the ε_{Nd} values of the metasedimentary rocks, Mansfeld et al. (2005) claimed that it was likely that the erosional products in the Vetlanda formation were derived from the tonalites in the Vetlanda-Oskarshamn belt rather than from the Svecofennian crust.

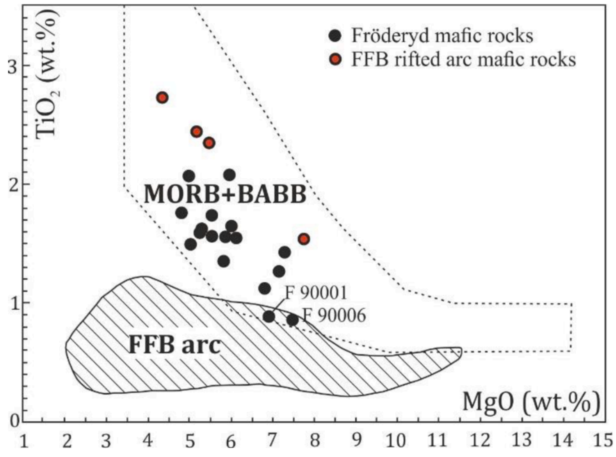

Fig. 8. TiO_2 vs. MgO diagram after Stern et al. (1995) for the mafic rocks in the Fröderyd Group in comparison with the mafic rocks in the Flin Flon Belt (FFB) volcanic arc and rifted volcanic arc. MORB – mid-ocean ridge basalt, BABB – back-arc basin basalts. Data for the Fröderyd Group are from Sundblad et al. (1997) and this publication (Table 1). Data for the FFB mafic rocks are from Syme et al. (1999).

Based on the youngest age estimate for the proposed provenance rocks to the Vetlanda formation (the 1.82 Ga Eksjö tonalite) and the rapid character of the 2.0–1.8 Ga orogenic activity in eastern Sweden it is likely that cooling, uplift and erosion of the tonalites and subsequent sediment deposition within the Vetlanda basin occurred around or shortly after 1.82 Ga. This means that this succession must be at least 40 m.y. younger than the Västervik quartzites. It is unclear whether the 1.81 Ga TIB 1a granitoids cut the Vetlanda succession, but the 1.79 Ga TIB 1b granitoids in the Sävsjö region (Mansfeld, 1991) provide a minimum age for the end of the Vetlanda sedimentation.

5.2. *Tectonic affinity of the Fröderyd Group and other volcanic units in the Vetlanda-Oskarshamn belt*

The tectonic affinity of the Fröderyd volcanic rocks was first discussed by Sundblad et al. (1997), based on field investigations as well as geochemical and isotopic data. The occurrence of spilitised pillow structures led Sundblad et al. (1997) to suggest that the volcanic activity took place in a subaquatic environment while the geochemical and lead isotopic data from mafic metavolcanic rocks convincingly showed a primitive magma generation without any influence of older crustal components, which is supported by the Sm-Nd data presented by Mansfeld (1995). However, as the Fröderyd succession contains an unusually large volume of felsic volcanic rocks and lacks sheeted dykes and ultramafic components, an ophiolitic setting was not considered as a realistic geotectonic environment for the Fröderyd Group. Instead, an

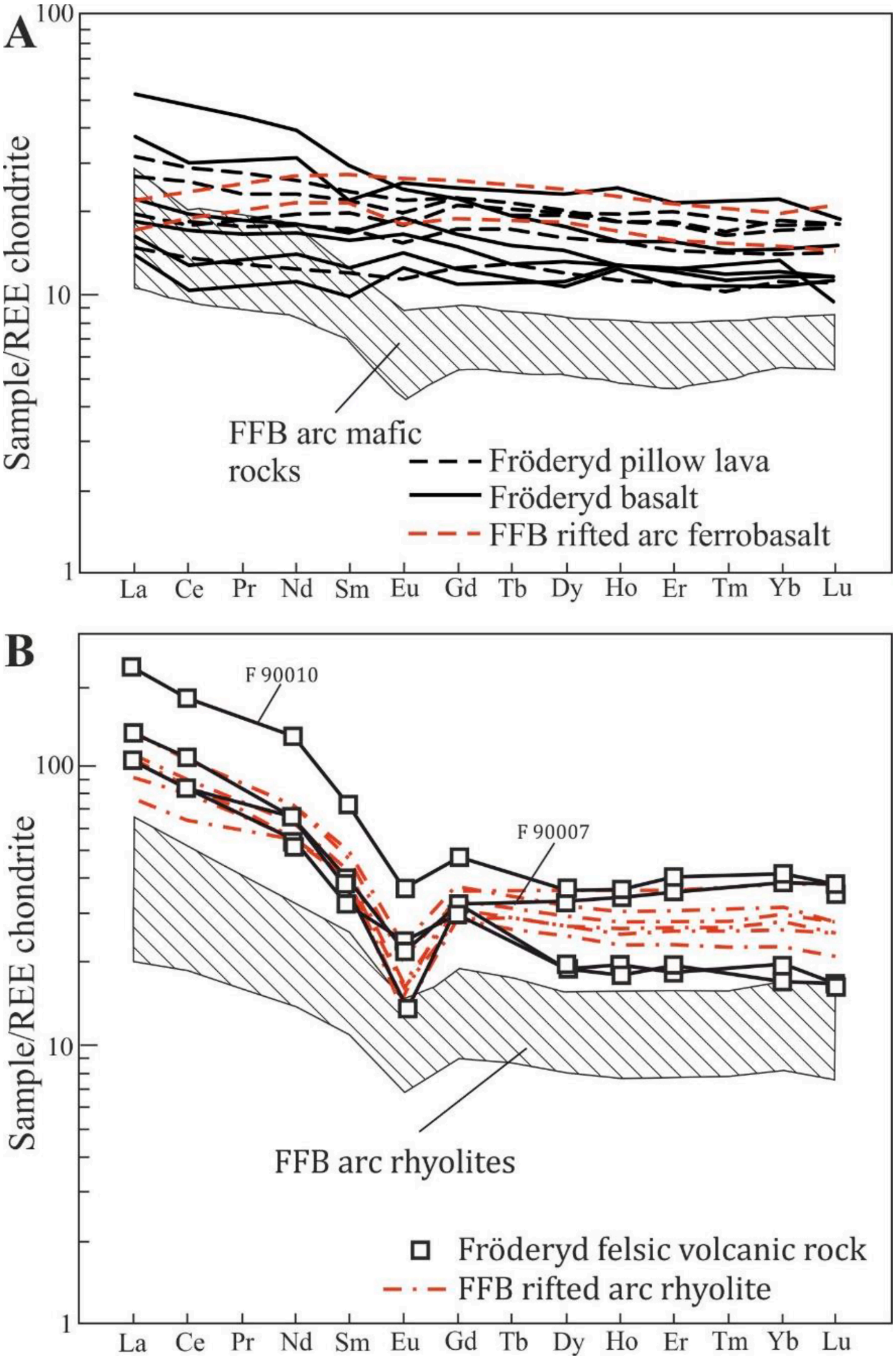

Fig. 9. Chondrite-normalized REE patterns (Boynton, 1984) for the volcanic arc and rifted volcanic arc rocks within the Flin Flon Belt (FFB) and rocks in the Fröderyd Group. **A.** mafic volcanic rocks. **B.** felsic volcanic rocks. Sources as for Fig. 8.

undefined marine rift event in the final stage of the Svecofennian crust-forming period along the southwestern margin of the Svecofennian Domain was proposed by Sundblad et al. (1997), while a forearc or back-arc spreading scenario at 1.83–1.82 Ga (or even 1.81 Ga) was suggested by Beunk and Page (2001) and Mansfeld et al. (2005), respectively.

In order to shed light on this problem, the Fröderyd Group has been compared with the Palaeoproterozoic Flin Flon Belt (FFB) in the Trans-Hudson Orogen, Canada. The FFB is characterized as a tectonic collage of oceanic terranes, including volcanic and rifted volcanic arcs, back-arc, ocean floor and younger arc successions ranging from 1.9 to 1.74 Ga (Stern et al., 1995; Syme et al., 1999; DeWolfe et al., 2009). The Flin Flon rifted arc assemblage encompasses volcanic rocks composed of subaqueous erupted pillowed and massive mafic volcanic rocks, interstratified with rhyolite tuffs and flows. Pillowed flows are intercalated with volcaniclastic material; locally abundant synvolcanic mafic dykes and sills define fluid pathways for volcanogenic massive sulfide (VMS) mineralization (DeWolfe et al., 2009).

The Fröderyd Group consists of pillowed and massive mafic volcanic rocks intercalated with felsic volcanic rocks, associated with thin marble horizons and occasional gabbroic bodies (Fig. 2). Abundant, but small sulphide deposits occur in all these rock units except gabbro. Although fine-grained, banded felsic volcanic units were suggested to represent ash falls, other volcaniclastic sedimentary rocks were not observed within the area (Sundblad et al., 1997). However, as pointed out by

Table 3
Geological events along the southwestern active margin of the Fennoscandia proto-continent at 1.87–1.77 Ga.

Time (Ga)	Events
1.87–1.86	Accretionary processes along the margin to the Fennoscandia proto-continent when the 1.91–1.87 Ga crustal components in Bergslagen and Valdemarsvik areas were metamorphosed for the first time. Sedimentation in the Västervik area started slightly after this
1.86–1.85	A double subduction scenario: 1. The TIB 0 granitoids intruded into the margin to the Fennoscandia proto-continent and the Västervik sediments in an Andean-type active continental margin. 2. A volcanic arc (Nömmen) and a rifted volcanic arc (Fröderyd) formed further outboard along the active continental margin
1.83–1.82	Intrusion of tonalitic plutons (Eksjö-Bäckaby style) into the volcanic arc complex, still outboard along the active continental margin
ca. *1.82*	Uplift and rapid erosion of the volcanic arc complex, forming rapidly accumulating sediments in narrow lacustrine basins (Vetlanda style), during start of accretionary processes
1.82–1.81	Ductile deformation and metamorphism in connection with accretionary processes along the margin to the Fennoscandia proto-continent
1.81–1.79	Accretion to the margin to the Fennoscandia proto-continent and initiation of continental margin igneous activity (TIB 1a)
1.79–1.77	Continuous continental margin igneous activity (TIB 1b)

Stern (2010), significant sediment accumulations only occur close to the volcanic front and reflect prevailing wave direction which controls deposition of volcanic ash and dispersal of eroded material. Furthermore, island arc systems are characterized by a slow sedimentation rate and relatively thin sediments (Stern, 2010).

Geochemical data for mafic and felsic volcanic rocks in the Fröderyd Group are plotted in Fig. 8, together with corresponding data from the FFB volcanic arc and rifted volcanic arc rocks (Syme et al., 1999). Most of the data for the Fröderyd mafic volcanic rocks plot within the mid-ocean ridge and back-arc basin basalt field (MORB + BABB), two analyses enter marginally the volcanic arc field inferred for the FFB mafic rocks. The three samples that were shown to be affected by potassic alteration and plotted within the field of continental basalts in Fig. 4D were not used for comparison. In general, the mafic rocks in the Fröderyd Group have lower TiO_2 contents compared to the FFB rifted volcanic arc mafic rocks, which however show higher TiO_2 content relative to the FFB volcanic arc mafic rocks (Fig. 8).

Basalts and basaltic pillow lavas in both the Fröderyd Group and the FFB rifted arc are mostly characterized by flat MORB-like chondrite-normalized REE patterns, two Fröderyd samples show slight LREE fractionation. The FFB volcanic arc mafic rocks are slightly enriched in LREE and have a distinct negative Eu anomaly not shown in the Fröderyd pattern (Fig. 9A). The REE patterns for the rhyolites in the Fröderyd Group and the FFB volcanic rift have the same features with LREE enrichments, variable HREE abundances and a negative Eu anomaly. In general, the REE patterns are similar to those of the FFB volcanic arc, but the FFB volcanic arc rhyolites show comparatively lower concentrations (Fig. 9B).

Mafic volcanic rocks have also been observed elsewhere in the Vetlanda region, at e.g. Nömmen (Fig. 1B), for which Röshoff (1975) reported basalts and andesites. Although concrete geochemical evidence is missing in the literature, the presence of abundant amygdaloidal lavas and scarce pillow structures in the basaltic-andesitic Nömmen group (Röshoff, 1975) indicates a volcanic arc environment, which also was proposed by Beunk and Valbracht (1991) and Beunk and Page (2001). This contrasts from the bimodal basaltic-rhyolitic character of the Fröderyd Group, where spilitized pillow lavas are common (Sundblad et al., 1997), which may suggest that the Nömmen group represents a true volcanic arc, while the Fröderyd Group may represent a rifted volcanic arc. The geological environments for other mafic volcanic units within the Vetlanda-Oskarshamn belt, e.g. at Sävsjö and lake Solgen (Fig. 1B), are uncertain, but each of them may represent similar arc fragments as have been suggested for the Nömmen and Fröderyd areas.

5.3. Rise and fall of the Vetlanda supergroup concept

Röshoff (1975) proposed that all supracrustal rocks in the Nömmen and Vetlanda areas constituted one single supergroup, which was assumed to record a coherent geological evolution in the area. The idea of close geological and temporal relations between the members in this supergroup was adapted by Mansfeld et al. (2005), who also included the Fröderyd Group in the same geological scenario. This led them to conclude that the age frame inferred for the metasedimentary rocks in the Vetlanda formation (1.83–1.82 Ga) also was applicable for the volcanic formations in the Nömmen and Fröderyd areas. However, based on current information on the area in a larger perspective (Bergman et al., 2012), the fault that Röshoff (1975) documented in the Nömmen area is now known to be a part of a major deformation structure, running for 170 km from lake Vättern to the Baltic Sea (Fig. 1B), and any correlation across this structure must be done with caution.

An alternative counterpart for the mafic volcanic rocks in the Nömmen area is the Fröderyd Group. From the geochemical and geochronological data presented by Mansfeld (1996), Mansfeld et al. (2005) and in this contribution, it is now evident that a rifted volcanic arc formed in Fröderyd at 1.85 Ga, ca. 20–30 m.y. before the Eksjö-Bäckaby tonalites provided erosion products to the Vetlanda sediments. Although there is no clear geochronological evidence, it is possible that the 1.85 Ga rifted volcanic arc in the Fröderyd Group formed close in time to or shortly after the basaltic-andesitic volcanic arc in Nömmen and mafic volcanic rocks at other sites in the Vetlanda-Oskarshamn belt. It is thus suggested that the mafic volcanic rocks in the Nömmen group are excluded from the Vetlanda supergroup and instead included into the volcanic arc/rifted arc concept to which the Fröderyd Group belongs. In turn, the Vetlanda formation should be restricted to the metasedimentary and felsic volcanic rocks in the Vetlanda and Björkö areas. Consequently, the Vetlanda supergroup concept has lost its meaning and should be abandoned.

6. Plate tectonic evolution at 1.87–1.77 Ga along the southwestern margin of the Fennoscandia proto-continent

After the first simplistic plate tectonic model for the Fröderyd Group was presented by Sundblad et al. (1997), suggesting an undefined marine rift event in the final stage of the Svecofennian crust-forming period, two subsequent models have been presented for the Vetlanda-Oskarshamn belt. Beunk and Page (2001) concluded that this belt constituted a $\geq$ 1.80–1.84 Ga magmatic arc at the same time as the supracrustal rocks in the Västervik and Valdemarsvik areas formed in a back-arc environment along the > 1.85 Ga Svecofennian orogen. Mansfeld et al. (2005) proposed a forearc (or back-arc spreading) scenario at 1.83–1.82 Ga (or even 1.81 Ga).

Based on results obtained from the present study, an improved schematic sequence of the geological evolution along the southwestern active margin of the Fennoscandia proto-continent at 1.87–1.77 Ga is presented in Table 3 and Fig. 10.

The oldest crustal components southwest of the 1.96–1.86 Ga Svecofennian Domain consist of 1.87–1.86 Ga Västervik quartzites as well as 1.86–1.85 Ga continental margin intrusions of the TIB 0 granitoids and arc-related rocks in the Vetlanda-Oskarshamn belt. These contrasting crustal components were formed during and shortly after the first deformation and metamorphic event at 1.87–1.86 Ga in Bergslagen, but were deformed and metamorphosed at a later event (<1.85 Ga), which must have taken place prior to the emplacement of the TIB 1 generations (1.81–1.77 Ga).

7. Conclusions

The felsic metavolcanic rocks in the Fröderyd Group formed at 1853 ± 11 Ma in a rifted volcanic arc zone that was located outboard to the southwest of the Fennoscandia proto-continent which had amalgamated

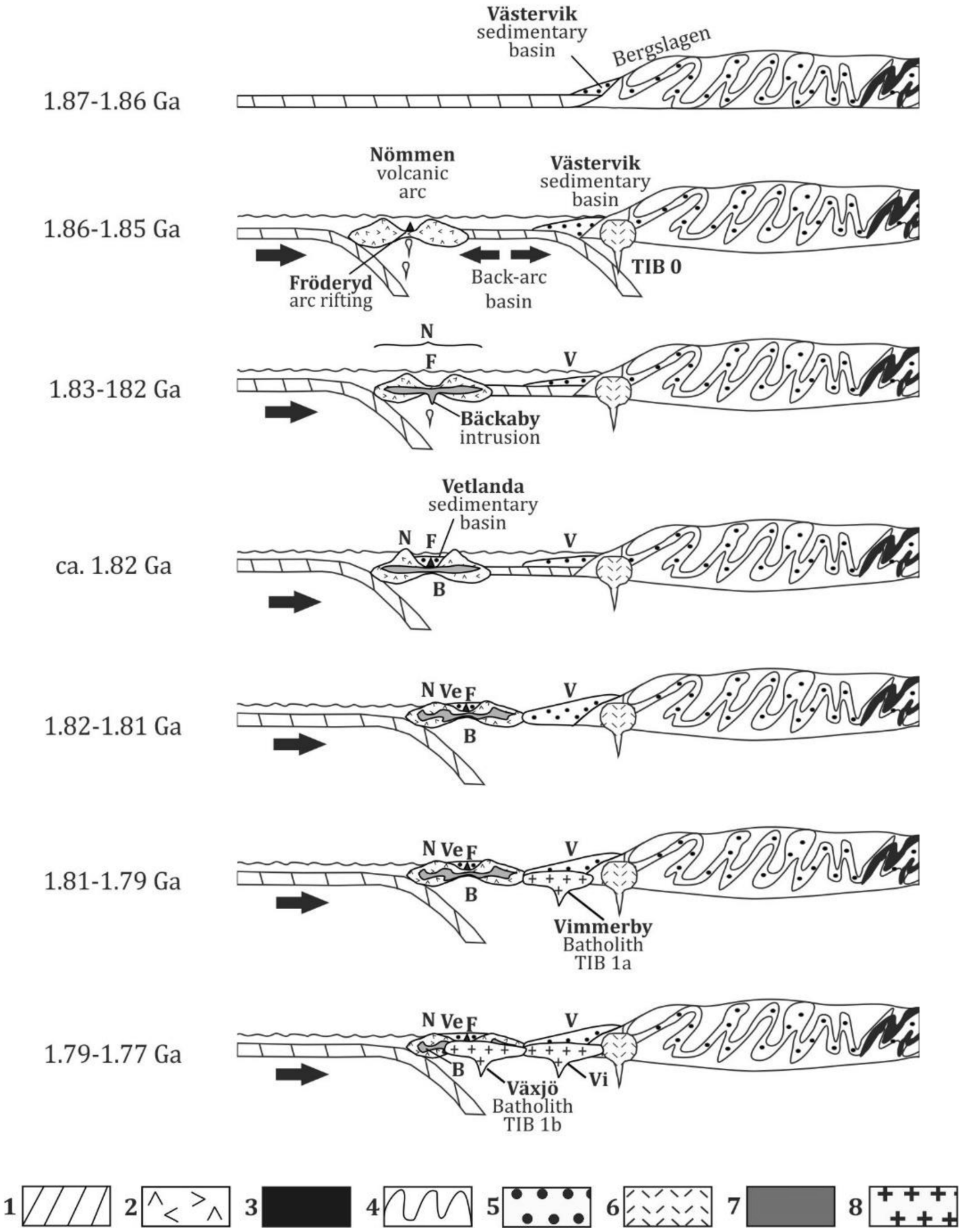

Fig. 10. Schematic profiles depicting the 1.87–1.77 Ga evolution of the southwestern active margin to the Fennoscandia proto-continent (not to scale). 1 – oceanic crust, 2 – andesitic and basaltic volcanic rocks and amygdaloidal lavas, 3 – basaltic volcanic rocks and/or pillow lavas, 4 – metamorphosed and affected by polyphase ductile deformation crust, 5 – sedimentary rocks, 6 – TIB 0 granitoids, 7 – Bäckaby tonalite, 8 – TIB 1 granitoids. B – Bäckaby tonalite, F – Fröderyd volcanic arc rifting, N – Nömmen volcanic arc, TIB – Transscandinavian Igneous Belt, Ve – Vetlanda sedimentary rocks, V – Västervik quartzites, Vi – Vimmerby Batholith. See text for a description.

at 1.87–1.86 Ga. When this arc complex gradually approached and started to accrete to the Fennoscandia proto-continent, parts of it were uplifted above sea level and gave rise to a lacustrine sedimentation in restricted basins, now found in the Vetlanda region. Parallel with the development of this arc complex, 1.86–1.85 Ga TIB 0 granitoids intruded the Fennoscandia proto-continent in an Andean-type active continental margin subduction.

As a result, the Vetlanda and Västervik sedimentary basins formed in two completely different geological environments and during two separate events. The Västervik sediments formed along the Fennoscandia proto-continent before the arc system had developed, while the Vetlanda sediments formed in a post-arc environment outboard to the southwest of the Fennoscandia proto-continent. It is suggested that the mafic volcanic rocks in the Nömmen group are included into the volcanic arc/rifted arc complex to which the Fröderyd Group belongs. In practice, this means that the lithostratigraphic unit “Vetlanda supergroup” has lost its meaning. It is also recommended that the term “Oskarshamn-Jönköping belt” is abandoned and replaced by the original term “Vetlanda-Oskarshamn belt”.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. In-house standard for the LA-ICP-MS analyses on zircon.

Name	^{206}Pbc (%)	*Concentration (ppm)*			*Isotopic ratios*						Rho.	Concor. (%)	*Ages & 1σ errors (Ma)*					
		Pb	Th	U	^{207}Pb/^{206}Pb	±1σ	^{207}Pb/^{235}U	±1σ	^{206}Pb/^{238}U	±1σ			^{207}Pb/^{206}Pb	±1σ	^{207}Pb/^{235}U	±1σ	^{206}Pb/^{238}U	±1σ
A382	0.53	77	91	137	0.1156	0.0006	5.4869	0.1214	0.3443	0.0070	0.97	98	1889	10	1899	19	1907	34
A382	0.76	55	68	100	0.1120	0.0006	5.2862	0.1193	0.3422	0.0070	0.97	99	1833	10	1867	19	1897	34
A382	1.47	74	46	124	0.1145	0.0007	5.9527	0.1410	0.3770	0.0078	0.98	102	1872	10	1969	20	2062	36
A382	0.67	62	66	117	0.1133	0.0006	5.3041	0.1188	0.3397	0.0070	0.97	98	1852	10	1870	19	1885	33
A382	0.08	2850	5330	5763	0.1145	0.0006	4.9449	0.1056	0.3133	0.0064	0.97	93	1872	9	1810	18	1757	31
A382	0.15	86	76	167	0.1170	0.0007	5.5388	0.1196	0.3435	0.0070	0.97	99	1910	10	1907	18	1903	34
A382	0.23	29	35	53	0.1207	0.0008	6.0034	0.1312	0.3607	0.0074	0.96	100	1967	11	1976	19	1985	35
A382	0.70	27	53	51	0.1121	0.0012	5.1975	0.1251	0.3364	0.0069	0.90	98	1833	19	1852	20	1869	33
A382	1.08	48	87	87	0.1116	0.0012	5.3126	0.1316	0.3452	0.0071	0.91	98	1826	19	1871	21	1912	34
A382	1.09	73	139	128	0.1126	0.0012	5.4178	0.1343	0.3489	0.0072	0.91	99	1842	19	1888	21	1929	34

Appendix 2. Chemical compositions of mafic and felsic metavolcanic rocks in the Fröderyd area (Sundblad et al., 1997).

Rock type	Mafic volcanic rocks											Felsic volcanic rocks			
Sample #	F 90001[1]	F 90002	F 90005	F 90006	F 90011	F 90012	F 90013	F 90014	F 90015	F 90016	F 90017	F 90003	F 90004	F 90007	F 90010
Major elements (wt.%)															
SiO_2	76.8	48.30	44.60	48.70	50.70	51.6	49.8	48.7	48.90	49	49.8	62.20	74.10	79.00	76.10
TiO_2	0.26	2.09	1.14	0.88	1.61	1.57	1.64	0.65	1.42	1.55	2.08	0.77	0.47	0.21	0.25
Al_2O_3	12.3	15.4	18.2	17.5	14.4	13.6	15.0	19.3	15.8	15.9	12.8	16.5	9.7	11.3	10.4
Fe_2O_3	1.88	14.40	14.90	11.70	12.40	12.60	12.30	9.57	12.50	13.10	16.70	8.12	5.29	2.57	1.26
MnO	0.02	0.18	0.10	0.18	0.37	0.46	0.26	0.16	0.23	0.22	0.26	0.18	0.30	0.21	0.02
MgO	0.13	5.95	6.80	7.62	5.30	5.54	5.34	7.16	7.28	6.12	5.00	3.83	2.01	0.70	0.43
CaO	0.14	9.80	9.40	10.40	9.29	9.73	11.30	11.50	8.85	9.14	9.15	2.92	4.62	0.55	6.44
Na_2O	3.6	3.65	2.08	3.00	4.55	4.36	4.27	2.88	3.40	4.08	3.27	1.83	0.50	3.49	0.46
K_2O	4.81	0.30	2.12	0.25	0.52	0.42	0.24	0.23	0.67	0.47	0.45	3.05	3.11	3.12	2.62
P_2O_5	0.02	0.29	0.06	0.08	0.17	0.14	0.15	0.06	0.16	0.20	0.39	0.23	0.10	0.03	0.08
Tot	100	100	99	100	99	100	100	100	99	100	100	100	100	101	98
LOI	0.5	0.2	1.7	0.8	0.7	0.7	0.7	0.9	0.7	0.8	0.4	1.8	0.5	0.3	1.1
Trace elements (ppm)															
Ba	119	89	251	126	519				164			599	925	874	401
Be	1.7	1.8	2.2	1.8	1.2				1.2			1.1	1.1	1.5	1.6
Co	51	46	50	49	46				42			22	9	6	6
Cr	218	159	46	215	258	246	253	86	197	168	62	147	64	16	6
Cu	38	27	11	117	17	123	290	55	13	14	91	5	25	7	11
Mo	8	9	11	9	6				6			5	6	9	6
Ni	133	56	125	137	72	70	72	99	74	51	21	41	19	6	8
Pb	17	18	22	18	12				12			44	29	12	12
Sc	42	57	35	41	43				39			19	10	4	4
Sn	8	9	11	9	6				6			5	6	6	17
Sr	331	241	138	230	252				182			210	58	62	68
V	255	410	260	251	280				262			117	57	6	6
Y	21	44	19	21	29	28	31	13	29	27	43	35	41	78	57
Zn	167	159	82	98	279	674	257	186	224	183	116	142	103	77	42
Zr	73	179	463	78	98	97	105	45	95	107	147	252	182	373	488
W	31	37	29	35	24				22			30	19	16	21
Nb	8	9	11	9	6				6			5	508	8	15
Rare earth elements (ppm)															
La	4.2	11.2	3.0	5.0	5.9			4.2	6.4			35.6	35.5	41.7	75.7
Ce	8.3	23.5	5.2	10.2	14.1			9.5	13.9			66.2	69.7	86.2	145.0
Pr															
Nd	6.6	18.2	4.8	8.3	11.5			6.1	12.0			41.3	33.6	40.3	78.6
Sm	1.9	4.2	1.9	2.4	3.8			1.5	3.3			6.8	6.1	7.5	14.2

(*continued on next page*)

(*continued*)

Rock type	Mafic volcanic rocks											Felsic volcanic rocks			
Sample #	F 90001[1]	F 90002	F 90005	F 90006	F 90011	F 90012	F 90013	F 90014	F 90015	F 90016	F 90017	F 90003	F 90004	F 90007	F 90010
Eu	0.9	1.8	0.8	1.0	1.3			1.1	1.4			1.6	1.7	1.0	2.7
Gd	2.8	6.2	2.6	3.2	5.4			2.4	4.7			8.0	7.7	8.2	12.8
Tb															
Dy	3.5	7.3	3.5	3.4	6.3			3.2	6.1			6.1	6.2	10.5	12.6
Ho	0.9	1.7	0.7	0.9	1.4			0.6	1.3			1.3	1.3	2.7	2.8
Er	2.6	4.4	2.2	2.2	4.1			1.7	4.0			4.0	3.8	7.7	8.6
Tm															
Yb	2.7	4.6	2.0	2.2	9.2			1.1	4.4			3.4	4.2	8.8	9.2
Lu	0.3	0.6	0.3	0.4	0.6			0.2	0.6			0.5	0.5	1.2	1.2
Zr/Y		4.07				3.46	3.39	3.46	3.28	3.96	3.42	7.20	4.44	4.78	8.56

[1] Analyses are conducted at SGAB Analys, Sweden.

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