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New zircon data supporting models of short-lived igneous activity at 1.89 Ga in the western Skellefte District, central Fennoscandian Shield

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Abstract. New U-Th-Pb zircon data (SIMS) from three intrusive phases of the Palaeoproterozoic Viterliden intrusion in the western Skellefte District, central Fennoscandian Shield, dates igneous emplacement in a narrow time interval at about 1.89 Ga. A locally occurring quartz-plagioclase porphyritic tonalite, here dated at 1889 ± 3 Ma, is considered the youngest of the intrusive units, based on the new age data and field evidence. This supports an existing interpretation of its fault-controlled emplacement after intrusion of the dominating hornblende-tonalite units, in this study dated at 1892 ± 3 Ma. The Viterliden magmatism was synchronous with the oldest units of the Jörn type early-orogenic intrusions in the eastern part of the district (1.89–1.88 Ga; cf. Gonzàles Roldán, 2010). A U-Pb zircon age for a felsic metavolcanic rock from the hanging-wall to the Kristineberg VMS deposit, immediately south of the Viterliden intrusion, is constrained at 1883 ± 6 Ma in this study. It provides a minimum age for the Kristineberg ore deposit and suggests contemporaneous igneous/volcanic activity throughout the Skellefte District. Furthermore, it supports the view that the Skellefte Group defines a laterally continuous belt throughout this "ore district". Tentative correlation of the 1889 ± 3 Ma quartz-plagioclase porphyritic tonalite with the Kristineberg "mine porphyry" suggests that these units are coeval at about 1.89 Ga. Based on the new age determinations, the Viterliden intrusion may equally well have intruded into or locally acted as a basement for the ore-hosting Skellefte Group volcanic rocks.

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1 Introduction

The Skellefte District (Fig. 1) is one of the most important mining districts in northern Europe with numerous VMS deposits and a large potential for future discoveries (Carranza and Sadeghi, 2010). The Kristineberg mine is located in the western part of the district. It is the largest past and present VMS mine in the district, with a total production of 26.5 Mt ore, grading 1.05 Cu %, 3.56 Zn %, 0.24 Pb %, 1.31 g t^{-1} Au, 38 g t^{-1} Ag, and 25.6 % S, from the start of production in 1940 to the end of 2010. The deposit is hosted by felsic to intermediate metavolcanic rocks suggested to be part of the ore hosting, 1.89–1.88 Ga Skellefte Group that occurs throughout the Skellefte District (cf. Allen et al., 1996; Kathol and Weihed, 2005). The ore-hosting metavolcanic rocks structurally overlie the composite, pre-tectonic ∼1.90 Ga Viterliden intrusion (Bergström et al., 1999; Skyttä et al., 2010), both occurring in the core of a regional-scale antiformal structure (Fig. 1; Skyttä et al., 2009). Previous geochronological work in the Skellefte District has been focused on the metavolcanic and granitoid rocks of the eastern and central parts (Billström and Weihed, 1996; Lundström and Antal, 2000; Weihed et al., 2002; Gonzàles Roldán, 2010). Apart from imprecise U-Pb zircon data from the composite Viterliden intrusion dated at 1907 ± 13 Ma by Bergström et al. (1999), age data from the western part of the Skellefte District is lacking and the time scale of volcanic activity is unknown. Correlation of the Kristineberg volcanic and intrusive units in the West with the ore-bearing Skellefte Group volcanic and early-orogenic, calc-alkaline, intrusive units in the other parts of the Skellefte District, requires control over the timing of magmatism across the district. Furthermore, temporal relationships between intrusive and volcanic events

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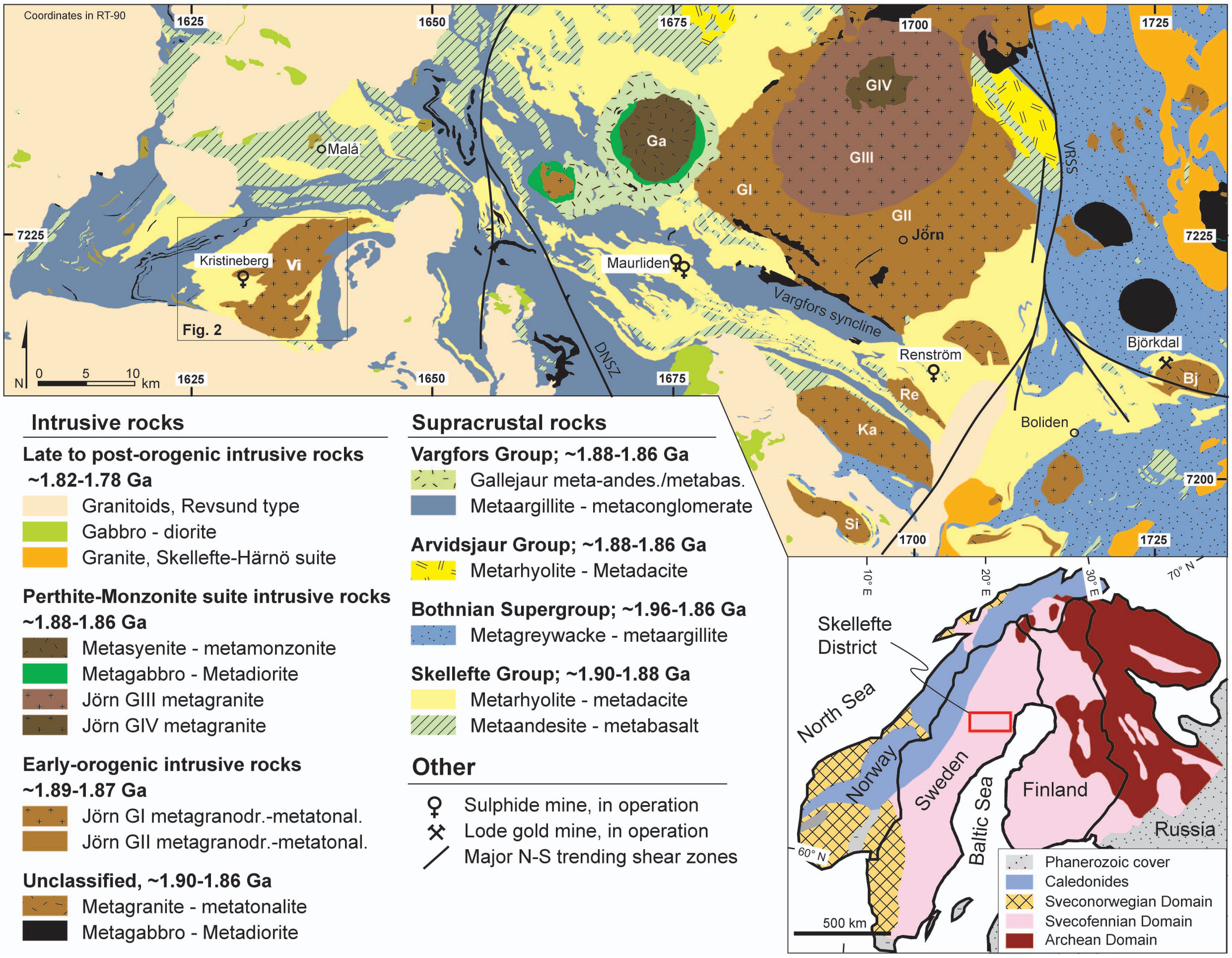

Fig. 1. Inset: geological overview of the Fennoscandian Shield. SD = Skellefte District. Main map: DNSZ = Deppis-Näsliden shear zone; VRSS = Vidsel-Röjnöret shear system; Intrusions: Vi = Viterliden; Re = Rengård, Ka = Karsträsk, Si = Sikträsk, Bj = Björkliden, Ga = Gallejaur, GI, GII, GIII, GIV = Jörn type intrusions phases I–IV. Geology modified after Kathol and Weihed (2005) and Bergman Weihed (2001).

are needed to indirectly constrain the age of the VMS mineralization, and to better understand the crustal scale accretionary processes during the Svecokarelian orogeny.

This study presents new U-Th-Pb zircon data from four different igneous units in the Kristineberg area in the western part of the Skellefte District: three compositionally different intrusive units of the composite Viterliden intrusion and one volcanic unit within the stratigraphic hanging-wall to the Kristineberg deposit. Besides constraining the emplacement history of the composite intrusion, dating several intrusive units from a geographically small area aims at investigating the consistency of igneous zircon crystallization ages within different magmatic components of this plutonic complex. The latter is especially important because of the relatively old published age of the Viterliden intrusion with respect to the other early-orogenic intrusive units in the district (Wilson et al., 1987; Weihed and Schöberg, 1991; Lundström et al., 1997; Bergström et al., 1999; Weihed et al., 2002; Gonzàles Roldán, 2010). The 1907 ± 13 Ma igneous zircon crystallisation age of the Viterliden intrusion presented by Bergström et al. (1999) was, however, constrained from regression of highly discordant, large multi-grain zircon fractions. The intercept age is defined with a high MSWD of 7.6 and a high lower intercept at about 400 Ma, factors indicative of an unconformable data set and a possibly unreliable age (cf. Metzger and Krogstad, 1997).

Dating the metavolcanic rock aims at correlating the volcanic units in different parts of the Skellefte District, and at providing an estimate for the minimum age of the mineralization of the Kristineberg deposit. The obtained age data will be interpreted and discussed with respect to the evolution of igneous activity in the Skellefte District, with special emphasis on the timing of VMS mineralization at Kristineberg.

2 Geological overview

2.1 Geological and structural setting

The bedrock of the Skellefte district is composed of ∼1.90–1.86 Ga Palaeoproterozoic Svecofennian supracrustal and associated intrusive rocks that were deformed and metamorphosed during the Svecokarelian orogeny at 1.87–1.80 Ga (Weihed et al., 2002). The majority of models for the crustal evolution of the Skellefte district suggest that it is a remnant of a volcanic arc accreted towards the Karelian craton in the NE (Hietanen, 1975; Gaál, 1990; Weihed et al., 1992). However, an alternative interpretation (Rutland et al., 2001a, b; Skiöld and Rutland, 2006) suggests that the Skellefte district was deposited in a rift setting on the Bothnian Basin metasedimentary rocks (their Robertsfors Group). Other suggestions for the basement are 2.0–1.9 Ga granitoids south of the Skellefte district (Billström and Weihed, 1996) and the Bothnian Basin rocks beneath a north-dipping crustal-scale reflector in the Kristineberg area (Malehmir et al., 2007).

The structural evolution of the Skellefte District is controlled by a complex fault pattern developed during early crustal extension, later followed by fault inversion (Allen et al., 1996; Bauer et al., 2011) during the main compressional deformation at around 1.87–1.82 Ga (Bilström and Weihed, 1996; Rutland et al., 2001b; Weihed et al., 2002). This event reflects approximately N-S shortening and is characterized by reverse south-side-up faults and upright folds in the central part of the district (Bergman Weihed, 2001; Bauer et al., 2011), whereas a regional-scale west-plunging antiform was formed in the Kristineberg area. Another episode of crustal shortening took place at ∼1.80 Ga, and was characterized by approximately E-W bulk compression (Bergman Weihed, 2001; Weihed et al., 2002; Skyttä et al., 2010). Metamorphic peak conditions reached partial melting in the south-eastern part of the district, whereas sub-solidus PT-conditions at ∼3 kbars and ∼600 °C prevailed in the Kristineberg area at ∼1.85–1.80 Ga (cf. Kathol and Weihed, 2005).

2.2 Lithology

The Skellefte District comprises three main groups of supracrustal rocks and four generations of intrusive rocks (Fig. 1; Weihed et al., 2002 and references therein). The calc-alkaline, early-orogenic intrusive rocks (∼1.89–1.87 Ga; Fig. 1) form the oldest group of intrusives in the Skellefte District and its immediate surroundings. The tonalitic Sikträsk intrusion (1878 ± 12 Ma; Weihed et al., 2002) and the oldest phases of the Jörn intrusive complex (GI and GII; ∼1.89–1.88 Ga; Wilson et al., 1987; Weihed and Schöberg, 1991; Lundström et al., 1997; Gonzàles Roldán, 2010) are coeval with the Skellefte Group volcanism, and considered co-magmatic, whereas the younger phases of the complex (GIII-IV; 1.88–1.86 Ga; Wilson et al., 1987; Weihed and Schöberg, 1991; Lundström et al., 1997; Gonzàles Roldán, 2010) post-date the Skellefte Group. Even though the Viterliden intrusion at Kristineberg (1907 ± 13 Ma; Bergström et al., 1999) is supposed to be older than most of the other intrusions, its marginal phase, the "mine-porphyry", contains xenoliths of altered Skellefte Group metavolcanic rocks and, consequently, post-dates the ore-related alteration (Årebäck et al., 2005). Late- to post-Svecokarelian 1.82–1.78 Ga intrusive rocks occur to the west and south of the Kristineberg antiform (Weihed et al., 2002 and references therein).

The predominantly felsic, volcanic Skellefte Group is attributed to a stage of extensional continental margin arc volcanism (Allen et al., 1996), and constitutes the lowermost supracrustal unit in the Skellefte District stratigraphy (Figs. 2 and 3). It is the main host to the VMS deposits, the majority of which are located within the upper part of the unit (Allen et al., 1996). Age of the Skellefte Group volcanism has been dated at ∼1.89–1.88 Ga by U-Pb data on zircons from the central part of the Skellefte District (Welin, 1987; Billström and Weihed, 1996; Montelius, 2005). The dominantly metasedimentary Vargfors Group (1875 ± 4 Ma; Billström and Weihed, 1996) lies stratigraphically above the Skellefte Group rocks and is coeval with deposition of the sub-aerial Arvidsjaur Group occurring further to the north (Skiöld et al., 1993). The Bothnian Basin metasedimentary rocks occur to the south of the Skellefte district and range in age from >1.95 to 1.87 Ga (Lundqvist et al., 1998).

2.3 The Viterliden intrusion and the Kristineberg hanging-wall rhyolite

The Viterliden intrusion and the Kristineberg VMS deposit occur in the core of the Kristineberg antiform, where the greatest strains were localised into sub-vertical, curviplanar faults which led to large variations in strain and structural geometry both across and along the regional antiformal structure (Malehmir et al., 2007, 2009; Skyttä et al., 2009; Dehghannejad, 2010). Contacts between the different intrusive phases, as well as contacts between the intrusion and the bounding volcanic rocks are generally sheared. For this reason, initial relative age relationships are inaccessible.

The Viterliden meta-intrusion comprises hornblende-tonalites (Fig. 4a), plagioclase porphyritic tonalites (Fig. 4b), granites, quartz-plagioclase porphyritic tonalites (Fig. 4d and e; "mine porphyry" by Årebäck et al., 2005). It also hosts high-strain zones characterized by boudinaged intrusives embedded in a mica-rich, mylonitic matrix. The hornblende-tonalites are volumetrically dominating, whereas the other lithologies are clearly subordinate, in particular the quartz-plagioclase porphyritic tonalites that are associated with E-W to NE-SW trending fault zones only (Fig. 2). The hornblende-tonalites are medium- and even-grained, and are composed of quartz (qtz), plagioclase (plg), hornblende (hbl), biotite (bt), magnetite (mt), pyrite (py) and sphalerite (sph) (± chlorite (chl), ± titanite (tita); totally ∼30 % mafic

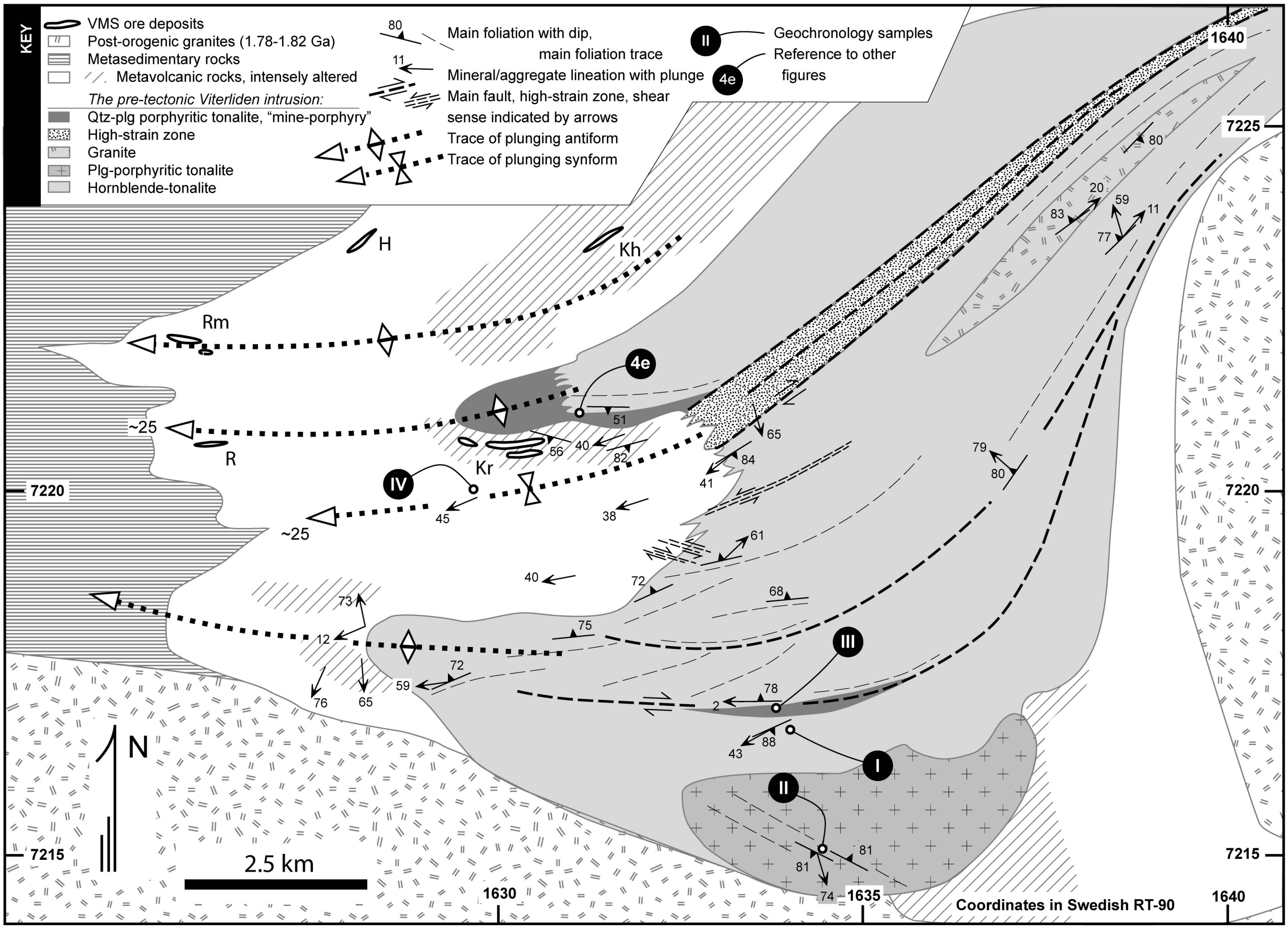

Fig. 2. Geological map of the Viterliden intrusion with locations for the geochronology samples. Modified after Skyttä et al. (2010). Ore deposits: Kr = Kristineberg, Kh = Kimheden, H = Hornträsk, Rm = Rävlidmyran, R = Rävliden.

minerals). Plagioclase porphyritic tonalites are characterized by large plg-megacrysts surrounded by finer-grained matrix composed of qtz, plg, bt (± muscovite (ms); totally ∼15 % mafic minerals). Granites display qtz-plg-kfs-rich domains separated by thinner, discontinuous domains of bt, ms, and chl (totally ∼10 % mafic minerals), which gives the rock a streaky appearance. Opaque minerals include mt, py and chalcopyrite (cpy). Quartz-plagioclase porphyritic tonalites contain phenocrysts of qtz and plg in a finer-grained matrix composed of qtz, feldspars (fsp), ms, bt and chl (totally ∼10 % mica content). The matrix grain size in the southern quartz-plagioclase porphyritic tonalite is significantly larger compared to the "mine porphyry" in the North.

The Kristineberg hanging-wall rhyolite (Fig. 4c) is fine-grained, contains up to 0.2 mm large qtz- and plg-phenocrysts in a fine-grained matrix of qtz, fsp and bt (totally <10 % mafic minerals), and has a well developed a SW-plunging lineation defined by elongate bt-aggregates. The hanging-wall rhyolite is associated with the stratigraphically lower of the two ore horizons in the Kristineberg area, i.e. the Kristineberg-Kimheden ore horizon (Figs. 2, 3). The stratigraphically higher, Hornträsk-Rävlidsmyran-Rävliden ore horizon is located in the upper part of the Skellefte Group volcanic rocks, which is the most common stratigraphic position for VMS deposits in the Skellefte District. Based on alteration patterns, the mine porphyry vs. the ore-hosting metavolcanic rock cross-cutting relationship, and geochemical modelling, Galley and Bailes (1999) suggested that the development of the lower of the Kristineberg ore horizons was associated with a pre-Viterliden subvolcanic intrusion at depth. In contrast, the upper ore horizon was considered coeval with the emplacement of the Viterliden intrusion into the volcanic pile (Galley and Bailes, 1999).

3 Geochronology

3.1 Sampling and analytical procedures

A total of seven samples were selected for geochronological analyses from the Kristineberg area. The samples were

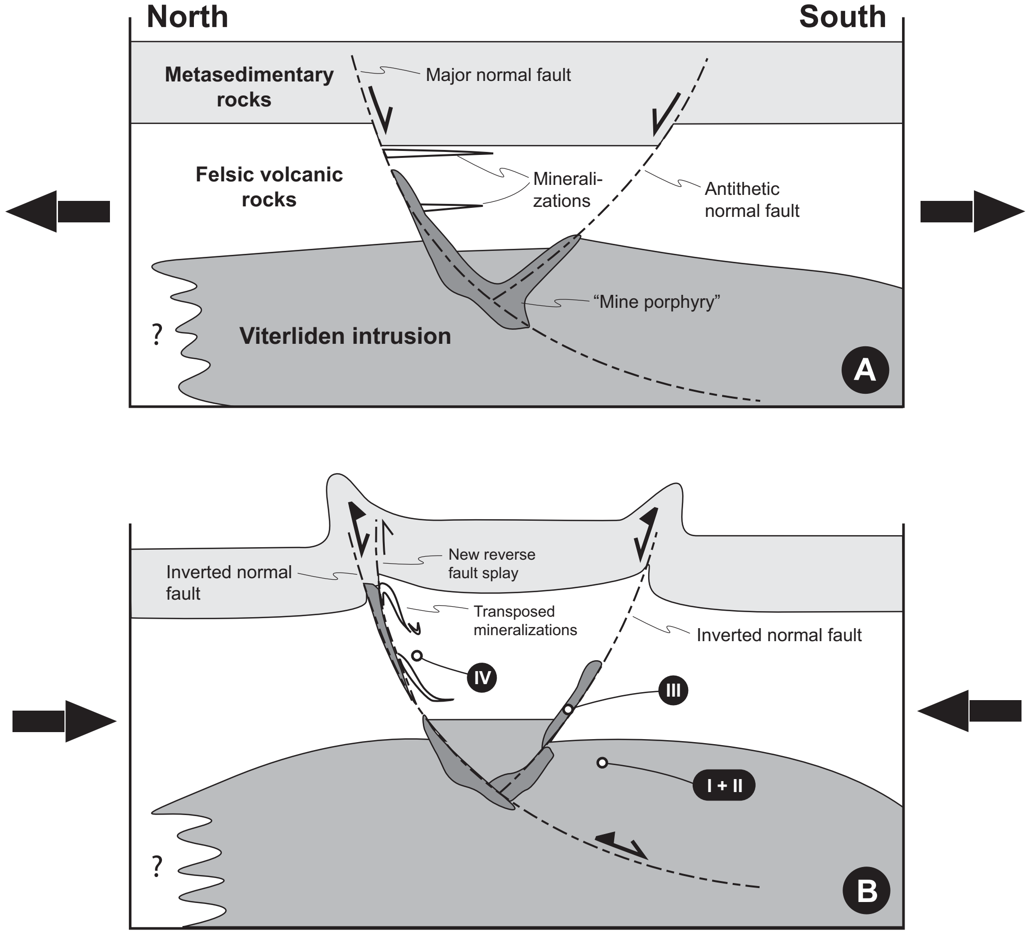

Fig. 3. Schematic stratigraphic profile across the Kristineberg area including the location of the geochronology samples. Upper mineralized horizon = Hornträsk-Rävlidsmyran-Rävliden, lower mineralized horizon = Kristineberg-Kimheden. Metasedimentary and metavolcanic rocks belong to the Vargfors and the Skellefte Groups, respectively. **(A)** Syn-extensional volcanism, mineralization sedimentation ± intrusive activity at ∼1.89–1.87 Ga. **(B)** Subsequent crustal shortening leading to basin inversion and related transposition of the mineralized horizons.

taken both at the surface and from drill cores available in the Boliden Mineral AB drill core archives. They were milled into fine-grained powder using a swing-mill. Heavy mineral separates were obtained using a full size Wilfley water panning table. Magnetic mineral fractions were removed with a hand-magnet. Zircon grains selected for further analytic work were hand-picked using a stereomicroscope. Since all samples are rather poor in zircon, as much as about 10 kg of rock were processed for most samples. Of all seven samples, zircon was obtained from one metavolcanic and three meta-intrusive rocks, while no zircon was found from one hornblende-tonalite, one hanging-wall rhyolite, and one "mine porphyry" sample.

Zircons selected for analytical work were mounted on double faced tape and embedded in transparent epoxy resin together with the 1065 Ma Geostandards zircon 91 500 (Wiedenbeck et al., 1995). The epoxy mount was polished to expose the central parts of the crystals and potentially older cores.

Back scattered electron (BSE) imaging was used for selection of the location of analytical spots and subsequent reexamination of spot sites after analysis. The overall analytical quality of the zircon populations was low, and most crystals contained cracks and inclusions. Areas large enough to host the spot without including these features were hard to find, and therefore several of the analytical spots also hit inclusions and cracks (cf. Description of spot location in Table 1 and representative zircon crystals shown in Fig. 5). A much larger number of analyses were obtained from the samples with a high abundance of cracks and inclusions to match problems with low analytical quality of analysed areas. The problem with low analytical quality of the grains was more accentuated for samples with a low yield of zircon in which the selection of grains was limited, e.g. sample IV, the Kristineberg hanging-wall rhyolite.

BSE imaging prior to analysis was done at the Luleå University of Technology in Luleå using a Phillips XL30 electron microscope with LaB6 filament. Post-analysis BSE

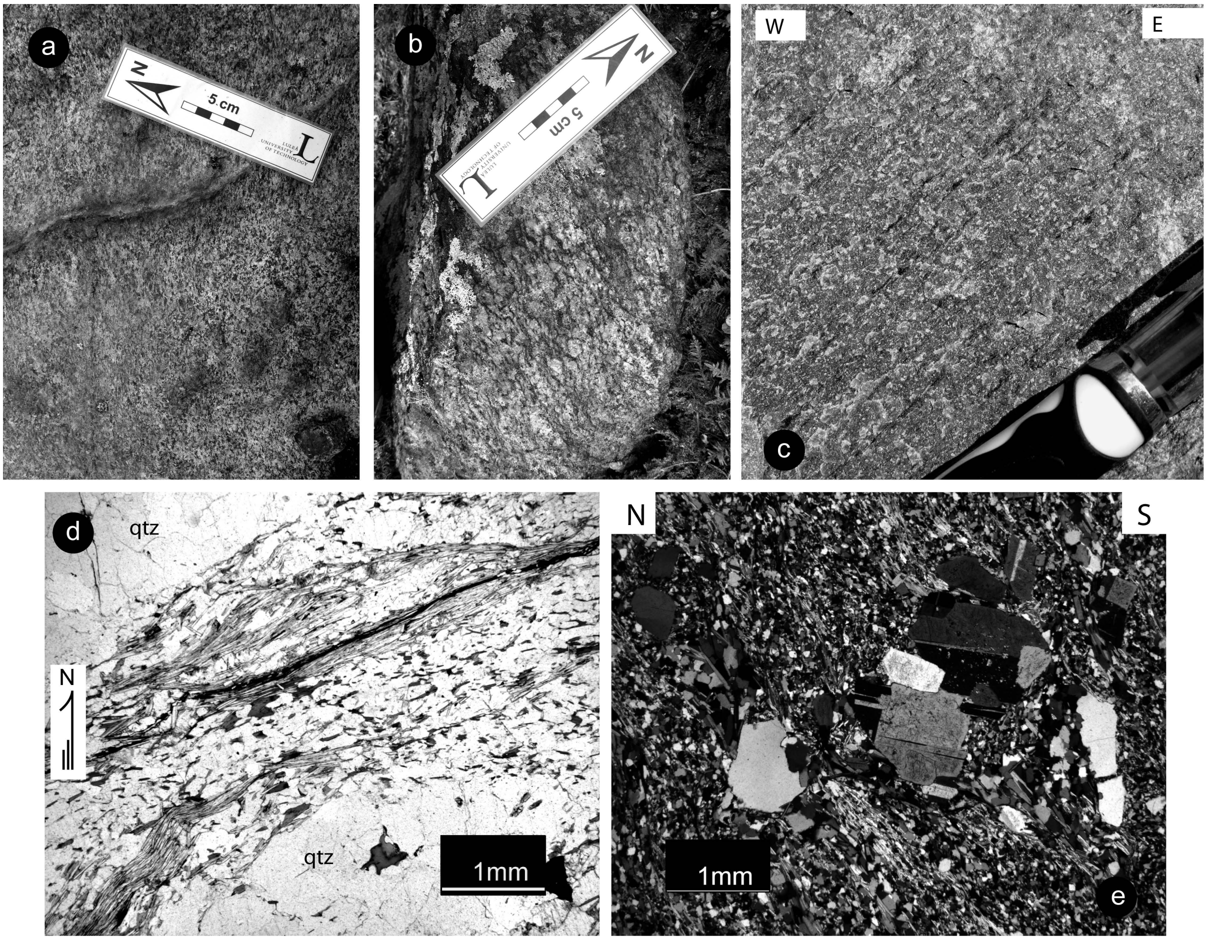

Fig. 4. Field and microphotographs of the dated rock units. See Fig. 2 for locations. **(a)** Hornblende-tonalite; geochronology sample I, **(b)** Plagioclase porphyritic tonalite; geochronology sample II, **(c)** Hanging-wall rhyolite; geochronology sample IV; vertical section, width of view ∼5 cm, **(d)** Quartz-plagioclase porphyritic tonalite (coarse "mine porphyry"); geochronology sample III and **(e)** quartz-plagioclase porphyritic tonalite ("mine porphyry").

imaging was done at the Evolutionary Biology Centre at Uppsala University using a Zeiss Supra 35-VP field emission SEM electron microscope, with a Robinson back scatter detector. Prior to U-Th-Pb analysis, the mount was coated with ca. 30 nm of gold. Secondary Ionisation Mass Spectrometry (SIMS) U-Th-Pb in situ analyses on zircon was carried out using a Cameca IMS 1280 high mass-resolution instrument, at the NORDSIM facility at the Swedish Museum of Natural History in Stockholm. The analytical and data reduction procedures closely followed Whitehouse et al. (1999) and Whitehouse and Kamber (2005). The instrument was operated using an O_2^- primary beam with a spot size less than 25 µm, high transmission secondary beam settings and a mass resolution (MRP) of ca. 5400, sufficient to resolve Pb from molecular interferences in zircon.

All isotopic data are presented in Table 1. Age calculations were done using Isoplot/Ex (Ludwig, 2003). Ages are reported with 2 sigma errors, except for sample IV (60.1-pmsk-09), which is reported with 95 %-confidence limits. In the figures and in the discussion, concordia ages are presented without decay constant errors. However, in the section below, age calculations are presented both with and without decay constant errors, for future reference.

3.2 Sample descriptions and U-Pb results

3.2.1 Sample I: Viterliden hornblende-tonalite (47.1-pmsk-09)

Zircon was quite abundant in the sample that is dominated by up to 0.6 mm long, euhedral prismatic grains with sharp terminations. The crystals have approximate width/length ratios of 1:3, and are transparent to semi-transparent and colourless to weakly yellowish (light brownish) in colour. Most grains are cracked. The sample also contains a subordinate group of small (up to 150 µm), rounded and slightly brownish grains. In BSE-images, the zircons typically show broad-banded, simple oscillatory zoning without texturally complex core-rim relationships (Fig. 5, n3448-01ab). Consequently, both

Table 1. SIMS U-Th-Pb zircon data from the Viterliden meta-igneous rocks. Zircon ion microprobe data for the intrusive and volcanic rocks dated in this study.

Sample[a]/ spot #	Analysed area: textural domain	Analysed area: location	[Pb] ppm	[U] ppm	Th[b]/U	$^{206}Pb/^{204}Pb$	$f^{206}Pb$[c] %	Ratios ± σ: $^{206}Pb/^{238}U$	± σ	Ratios ± σ: $^{207}Pb/^{206}Pb$	± σ	Age ± σ (Ma): $^{207}Pb/^{206}Pb$	± σ	Age ± σ (Ma): $^{206}Pb/^{238}U$	± σ	Disc. % 2σ lim.[d]
Sample I: Viterliden hornblende tonalite (47.1-pmsk-09)																
n3448-01a	wk osc zon	cracked	190	439	0.53	65 130	0.03	0.3423	1.09	0.1154	0.27	1886	5	1898	18	
n3448-01b	wk osc zon		204	462	0.55	152 518	0.01	0.3480	1.21	0.1159	0.26	1894	5	1925	20	
n3448-02a	wk osc zon		52	122	0.40	206 770	<0.01	0.3446	1.16	0.1162	0.50	1899	9	1909	19	
n3448-03a	wk osc zon		171	394	0.53	225 287	0.01	0.3418	1.15	0.1163	0.28	1899	5	1895	19	
n3448-04a	wk osc zon		163	384	0.47	47 375	0.04	0.3385	1.15	0.1157	0.29	1891	5	1880	19	
n3448-05a	wk osc zon		95	223	0.44	190 369	0.01	0.3416	1.10	0.1156	0.37	1890	7	1895	18	
n3448-06a	uz inner domain		200	467	0.51	68 717	0.03	0.3388	1.14	0.1155	0.26	1887	5	1881	19	
n3448-06b	uz outer domain	cracked	90	234	0.39	25 552	0.07	0.3115	1.10	0.1149	0.40	1878	7	1748	17	−5.1
n3448-07a	uz inner domain		273	598	0.65	218 045	0.01	0.3518	1.17	0.1159	0.23	1894	4	1943	20	0.4
n3448-08a	wk osc zon		163	374	0.48	155 575	0.01	0.3488	1.10	0.1154	0.31	1887	5	1929	18	
n3448-08b	wk osc zon		113	266	0.43	206 131	0.01	0.3427	1.16	0.1153	0.35	1885	6	1900	19	
n3448-09a	uz inner domain		163	384	0.44	249 095	0.01	0.3419	1.06	0.1154	0.33	1886	6	1896	18	
n3448-11a	wk osc zon		123	295	0.44	126 747	0.01	0.3354	1.06	0.1156	0.33	1889	6	1865	17	
n3448-12a	uz outer domain		200	457	0.54	282 209	0.01	0.3439	1.06	0.1160	0.26	1896	5	1906	18	
n3448-13a	uz sec domain	cracked	112	309	0.24	63 005	0.03	0.3032	1.08	0.1153	0.37	1884	7	1707	16	−8.1
Sample II: Viterliden plagioclase porphyritic tonalite (33.1-pmsk-08)																
n3450-01a	uz outer domain		49	121	0.27	100 267	0.02	0.3377	1.09	0.1163	0.50	1899	9	1875	18	
n3450-02a	uz outer domain		45	111	0.26	15 757	0.12	0.3361	1.11	0.1155	0.58	1887	10	1868	18	
n3450-02b	wk zon outer domain	cracked	49	128	0.24	58 176	0.03	0.3201	1.11	0.1148	0.56	1876	10	1790	17	−1.9
n3450-03a	uz outer domain		60	144	0.33	84 446	0.02	0.3412	1.11	0.1167	0.48	1907	9	1892	18	
n3450-03b	osc zon core		99	238	0.37	106 179	0.02	0.3410	1.09	0.1157	0.45	1891	8	1892	18	
n3450-04a	uz margin/osc core	crystal margin	55	140	0.30	50 501	0.04	0.3275	1.16	0.1167	0.88	1906	16	1826	18	−0.2
n3450-05a	wk zon outer domain		78	195	0.32	52 019	0.04	0.3312	1.12	0.1156	0.62	1889	11	1844	18	
n3450-06a	wk zon core		57	140	0.30	61052	0.03	0.3378	1.13	0.1155	0.51	1888	9	1876	18	
n3450-07a	uz margin	crystal margin	56	148	0.24	20 809	0.09	0.3165	1.10	0.1143	0.50	1868	9	1773	17	−2.8
n3450-07b	uz		66	163	0.34	43 894	0.04	0.3340	1.07	0.1157	0.65	1891	12	1858	17	
n3450-08a	wk zon outer domain	cracked	43	228	0.09	4580	0.41	0.1599	1.10	0.1142	0.58	1868	10	956	10	−49.4
n3450-08b	wk zon outer domain	cracked, epoxy	96	747	0.12	467	4.00	0.1070	1.21	0.1067	1.12	1744	20	655	8	−59.7
n3450-09a	wk osc zon	cracked	51	141	0.26	3166	0.59	0.3021	1.14	0.1154	0.67	1886	12	1702	17	−7.4
n3450-09b	wk osc zon		54	126	0.35	41 408	0.05	0.3509	1.16	0.1153	0.64	1884	11	1939	19	
n3450-10a	wk zon bands		43	103	0.29	73 561	0.03	0.3459	1.09	0.1157	0.58	1891	10	1915	18	
n3450-11a	wk zon bands	inclusion	56	132	0.29	48 447	0.04	0.3537	1.13	0.1159	0.49	1895	9	1952	19	0.3
n3450-11b	wk zon bands		81	195	0.35	182 975	0.01	0.3428	1.06	0.1163	0.44	1900	8	1900	18	
n3450-12a	uz core		35	85	0.25	59 478	0.03	0.3440	1.09	0.1152	0.60	1882	11	1906	18	
n3450-13a	osc zon	cracked, epoxy	141	469	0.24	2223	0.84	0.2486	1.10	0.1131	0.54	1850	10	1431	14	−22.2
n3450-14a	uz core	cracked	51	146	0.22	52 445	0.04	0.2955	1.40	0.1152	0.49	1883	9	1669	21	−9.6
n3450-15a	wk osc zon	cracked, crystal margin	156	419	0.37	15 215	0.12	0.3013	1.08	0.1146	0.38	1874	7	1698	16	−8.1
n3450-16a	osc zon	crystal margin	269	800	0.37	37 558	0.05	0.2716	1.07	0.1122	0.28	1835	5	1549	15	−15.4
n3450-17a	wk osc zon	cracked	107	264	0.37	75 986	0.02	0.3318	1.06	0.1161	0.42	1897	7	1847	17	−0.2
n3450-18a	wk osc zon	cracked	191	471	0.48	44 536	0.04	0.3209	1.06	0.1160	0.34	1895	6	1794	17	−3.6
n3450-19a	wk osc zon		65	156	0.35	68 554	0.03	0.3391	1.07	0.1160	0.50	1896	9	1883	17	
n3450-20a	wk osc zon	inclusion	58	159	0.24	8383	0.22	0.3053	1.06	0.1140	0.56	1864	10	1717	16	−5.7
n3450-21a	osc zon	cracked, inclusion	163	458	0.39	34 098	0.05	0.2857	1.24	0.1154	0.32	1886	6	1620	18	−13.4
n3450-22a	wk osc zon	cracked	103	366	0.24	12 084	0.15	0.2312	1.32	0.1150	0.49	1880	9	1341	16	−28.9
n3450-23a	wk osc zon	cracked	63	182	0.30	6926	0.27	0.2835	1.12	0.1148	0.55	1877	10	1609	16	−13.0
n3450-24a	alt core	cracked	921	2180	0.50	77 295	0.02	0.3345	1.06	0.1158	0.14	1892	2	1860	17	
n3450-25a	wk osc zon		138	326	0.40	66 439	0.03	0.3439	1.08	0.1149	0.35	1878	6	1906	18	
n3450-26a	uz core	cracked	471	1197	0.49	69 280	0.03	0.3102	1.12	0.1150	0.25	1880	5	1742	17	−6.0
Sample III: Quartz-plagioclase porphyritic tonalite (coarse “mine-porphyry”; 29.1-pmsk-08)																
n3449-01a	uz	cracked	127	343	0.21	6818	0.27	0.3147	1.11	0.1153	0.64	1884	11	1764	17	−3.7
n3449-02a	osc zon		237	573	0.27	65 615	0.03	0.3473	1.11	0.1155	0.23	1888	4	1922	18	
n3449-03a	osc zon		164	406	0.23	87 815	0.02	0.3415	1.11	0.1151	0.28	1882	5	1894	18	
n3449-04a	osc zon		159	397	0.22	33 500	0.06	0.3396	1.10	0.1160	0.30	1895	5	1885	18	
n3449-05a	uz core	cracked	237	580	0.63	4554	0.41	0.3116	1.15	0.1151	0.36	1882	6	1748	18	−5.4
n3449-06a	osc zon	cracked	287	762	0.32	9097	0.21	0.3095	1.45	0.1159	0.30	1894	5	1738	22	−6.4
n3449-07a	osc zon	epoxy	160	528	0.16	2936	0.64	0.2584	1.78	0.1138	0.47	1860	9	1481	24	−19.3
n3449-08a	osc zon	margin	303	831	0.31	7942	0.24	0.2998	1.11	0.1140	0.26	1865	5	1690	16	−8.3
n3449-08b	osc zon		253	617	0.29	62 164	0.03	0.3421	1.07	0.1154	0.26	1886	5	1897	18	
n3449-09a	wk osc zon		141	356	0.19	69 422	0.03	0.3380	1.10	0.1158	0.30	1892	5	1877	18	
n3449-10a	osc zon		239	594	0.28	17 957	0.10	0.3355	1.06	0.1156	0.35	1890	6	1865	17	
n3449-11a	alt osc zon	cracked	206	1019	0.12	1650	1.13	0.1714	1.35	0.1160	0.75	1895	13	1020	13	−46.0
n3449-12a	osc zon	cracked	216	556	0.25	12 574	0.15	0.3263	1.08	0.1155	0.29	1887	5	1820	17	−1.6
n3449-13a	osc zon	cracked	293	775	0.25	10 292	0.18	0.3177	1.07	0.1151	0.25	1882	5	1778	17	−4.0
n3449-14a	osc zon	epoxy	239	644	0.17	3173	0.59	0.3175	1.10	0.1154	0.40	1886	7	1778	17	−3.8
n3449-15a	uz	cracked	137	402	0.15	5806	0.32	0.2923	1.06	0.1151	0.44	1882	8	1653	15	−11.1
n3449-16a	osc zon	epoxy, cracked	179	639	0.13	2513	0.74	0.2392	1.32	0.1144	0.55	1871	10	1383	16	−25.8
n3449-17a	wk osc zon	cracked	201	535	0.23	79 531	0.02	0.3157	1.06	0.1150	0.27	1879	5	1769	16	−4.4
n3449-18a	osc zon	slightly cracked	235	595	0.22	10 743	0.17	0.3335	1.06	0.1160	0.34	1896	6	1856	17	
n3449-19a	osc zon	margin	268	661	0.36	12 333	0.15	0.3327	1.06	0.1152	0.32	1883	6	1851	17	
n3449-20a	wk osc zon		197	491	0.20	259 299	0.01	0.3423	1.07	0.1161	0.27	1897	5	1898	18	
n3449-21a	alt osc zon	cracked	240	626	0.25	4684	0.40	0.3216	1.66	0.1149	0.31	1879	6	1797	26	−1.5

Table 1. Continued.

Sample III: Quartz-plagioclase porphyritic tonalite (coarse "mine-porphyry"; 29.1-pmsk-08)															
n3449-22a	*osc zon*	*cracked*	*204*	*545*	*0.23*	*12 079*	*0.15*	*0.3150*	*1.10*	*0.1160*	*0.28*	*1896*	*5*	*1765*	*17*	*−5.5*
n3449-23a	*osc zon*	*inclusion*	*254*	*875*	*0.20*	*3506*	*0.53*	*0.2432*	*1.14*	*0.1155*	*0.31*	*1888*	*5*	*1403*	*14*	*−26.4*
n3449-24a	*osc zon*	*slightly cracked*	*182*	*470*	*0.22*	*27 240*	*0.07*	*0.3283*	*1.06*	*0.1154*	*0.37*	*1886*	*7*	*1830*	*17*	*−0.7*
n3449-25a	*osc zon*	*inclusion, cracked*	*268*	*765*	*0.25*	*4358*	*0.43*	*0.2917*	*1.12*	*0.1157*	*0.29*	*1890*	*5*	*1650*	*16*	*−12.1*
n3449-26a	*osc zon*	*cracked*	*160*	*406*	*0.25*	*7382*	*0.25*	*0.3300*	*1.06*	*0.1162*	*0.38*	*1898*	*7*	*1839*	*17*	*−1.0*
Sample IV: Kristineberg hanging wall rhyolite (60.1-pmsk-09)																
n3447x-1a	*eu uz core*	*cracked, hit epoxy*	*188*	*462*	*0.41*	*13 725*	*0.14*	*0.3293*	*0.53*	*0.1147*	*0.35*	*1875*	*6*	*1835*	*9*	*−0.51*
n3447x-2a	*eu uz tip*	*cracked*	*70*	*179*	*0.24*	*49470*	*0.04*	*0.3300*	*0.53*	*0.1169*	*0.58*	*1910*	*10*	*1838*	*9*	*−1.50*
n3447x-4b	*uz core*	*cracked*	*213*	*572*	*0.37*	*21 417*	*0.09*	*0.3007*	*0.54*	*0.1161*	*0.34*	*1897*	*6*	*1695*	*8*	*−10.30*
n3447x-6a	eu wk zonedcore		137	331	0.38	66 261	0.03	0.3389	0.54	0.1149	0.38	1878	7	1882	9	
n3447x-7a	eu wk zoned core		143	349	0.36	48 080	0.04	0.3365	0.54	0.1150	0.46	1880	8	1870	9	
n3447x-8a	*broad band zon core*	*cracked*	*159*	*432*	*0.34*	*30 298*	*0.06*	*0.3005*	*0.53*	*0.1151*	*0.36*	*1882*	*6*	*1694*	*8*	*−9.46*
n3447x-9a	wk zon core		66	164	0.29	84 414	{0.02}	0.3340	0.53	0.1159	0.57	1894	10	1858	9	
n3447x-9b	wk zon tip		80	199	0.28	43 265	0.04	0.3357	0.53	0.1141	0.50	1866	9	1866	9	
n3447x-10a	eu wk osc zon		71	179	0.29	33843	0.06	0.3314	0.53	0.1144	0.52	1870	9	1845	9	
n3447x-10b	eu wk osc zon		113	275	0.33	56 280	0.03	0.3400	0.53	0.1155	0.42	1888	7	1887	9	
n3447x-11a	eu wk zon core	cracked	151	365	0.38	103 256	0.02	0.3361	0.53	0.1162	0.42	1898	8	1868	9	
n3447x-14a	eu uz core	cracked & inclusion	75	183	0.39	14 479	0.13	0.3345	0.54	0.1150	0.56	1880	10	1860	9	
n3447x-21a	*uz*	*cracked margin*	*48*	*139*	*0.21*	*2317*	*0.81*	*0.2922*	*0.53*	*0.1107*	*0.87*	*1811*	*16*	*1652*	*8*	*−5.78*
n3447x-22a	*uz core*	*cracked*	*89*	*231*	*0.25*	*55 815*	*0.03*	*0.3223*	*0.54*	*0.1157*	*0.67*	*1890*	*12*	*1801*	*9*	*−2.20*
n3447x-23a	uz core	cracked	85	216	0.26	1132	1.65	0.3311	0.53	0.1145	0.94	1873	17	1844	9	
n3447x-28a	uz core	cracked & inclusion	164	401	0.37	2006	0.93	0.3342	0.53	0.1156	0.55	1890	10	1859	9	
n3447x-32a	*osc zon core*		*228*	*545*	*0.39*	*114 640*	*0.02*	*0.3406*	*0.53*	*0.1165*	*0.30*	*1902*	*5*	*1890*	*9*	

[a] Data used for age calculation shown with normal letters; data in italics have been excluded from age calculation.
[b] Th/U ratios calculated from $^{208}Pb/^{206}Pb$ ratios corrected for Pb_{com}.
[c] % of common ^{206}Pb in measured ^{206}Pb, estimated from ^{204}Pb assuming a present day Stacey and Kramers (1975) model.
[d] Degree of discordance; positive numbers are reverse discordant. Blanks indicate that analysis is concordant within 2σ error.
Abbreviations: zon = zonation, osc = oscillatory, wk = weak, uz = unzoned, eu = euhedral crystal, alt = altered

the external morphology and the internal textures suggest a well-preserved igneous character of the zircon in this sample (cf. Corfu et al., 2003).

A total of fifteen analyses were obtained in thirteen different crystals. Two analyses are more than 5 % discordant (n3448-06b and 13a). Both hit cracks and were excluded from age calculation. The remaining thirteen concordant analyses yield a concordia age (ignoring decay constant errors) of 1892 ± 3 Ma (Fig. 6a; $MSWD_{conc.+equiv.} = 1.2$, probability $= 0.24$) identical to the weighted average $^{207}Pb/^{206}Pb$ age of 1891 ± 3 Ma (MSWD $= 0.86$, probability $= 0.59$).The concordia age including decay constant errors is 1894 ± 5 Ma ($MSWD_{conc.+equiv.} = 1.14$, probability $= 0.28$). The well-preserved igneous appearance of the zircon population and the limited spread in the U-Th-Pb data suggests negligible post-igneous crystallisation isotopic disturbance. The concordia age of 1892 ± 3 Ma is interpreted to date igneous crystallisation of the hornblende tonalite.

3.2.2 Sample II: Viterliden plagioclase porphyritic tonalite (33.1-pmsk-08)

Processing the sample gave a moderate yield of zircon. The analytical quality of the population is rather poor and cracks and inclusions (both dark and colourless) are frequent. The crystals are typically subhedral prisms, with rounded outer terminations. They are between 100–200 µm long with aspect ratios of about 1:2. Uncracked domains are clear to semi-transparent, often with a yellow/orange tint. In BSE-images, the zircons generally show a weak, broad-banded oscillatory zoning, whereas some marginal domains appear more or less unzoned (Fig. 5, n3450-03ab). Some grains display intense oscillatory zoning in specific domains, which are typically cracked and appear more altered (Fig. 5, n3450-21a). Most grains are texturally non-complex. However, some grains contain texturally older core domains, surrounded and cut by texturally younger unzoned or weakly oscillatory zoned zircon (Fig. 5, n3450-05a, 12a). Secondary alteration features in the zircon population typically occur as BSE-dark thin alteration fronts preferentially located along the outer margins of the grains, broadly following bands in the zoning of the crystal. These domains are interpreted as poorly crystalline regions, tentatively indicating progressive metamictisation of the grain.

The low analytical quality of the zircon population made it difficult to locate areas devoid of cracks, inclusions, and BSE-dark altered domains large enough to host an analytical spot. As a consequence, 18 of the totally 32 analytical spots hit cracks, inclusions or straddled the crystal margin-epoxy interface. This resulted in a varying degree of discordance for these analyses (Table 1), which show a more or less complex pattern indicating both ancient and recent Pb-loss. The discordant data were excluded from the age calculation. The remaining 14 concordant analyses were located in domains showing a weak, broad-banded

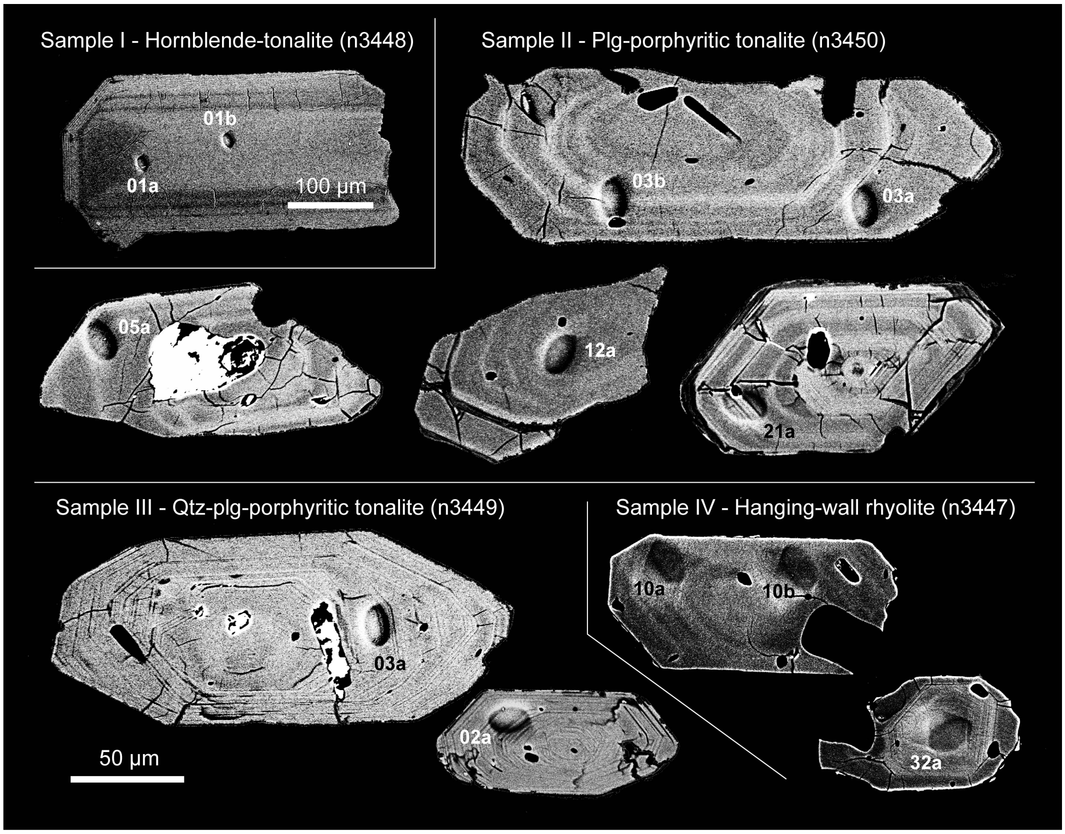

Fig. 5. BSE images for selected ion microprobe-dated zircons. Sites of analyses are indicated by analyze number, see also Table 1. Note the different scale in n3448-01ab. Qtz = quartz, plg = plagioclase.

BSE-zoning, covering both internal and marginal parts of the crystals. Together the 14 concordant analyses define a concordia age (ignoring decay constant errors) of 1891 ± 3 Ma (Fig. 6b; $MSWD_{conc.+equiv.} = 1.4$, probability = 0.082), identical to a weighted average $^{207}Pb/^{206}Pb$ age of the same analyses at 1892 ± 4 Ma (MSWD = 0.89, probability = 0.56). The concordia age including decay constant errors is 1890 ± 5 Ma ($MSWD_{conc.+equiv.} = 1.4$, probability = 0.086). The 1891 ± 3 Ma concordia age is interpreted to directly date igneous crystallisation of the plagioclase porphyritic tonalite.

3.2.3 Sample III: quartz-plagioclase porphyritic tonalite (coarse "mine porphyry"; 29.1-pmsk-08)

The zircon population is dominated by prismatic, typically between 100–250 µm long and more or less euhedral crystals with length/width ratios of 2.5–3. They are semi-transparent light-brown to nearly colourless, with slight orange shades. Cracks and inclusions are common. In BSE-imaging, the crystals typically show an intense but somewhat blurred oscillatory zoning that in most grains continues throughout the grain all the way to the crystal edge (Fig. 5, n3449-02a, 03a). This is indicative of a single, non-complex growth stage.

A total of 27 analyses were made in 25 different crystals. The analytical result is affected by the abundance of cracks and inclusions in the analysed zircon population. 18 out of 27 analyses are between 1–46 % discordant. This discordance is directly correlated to the location of the analytical spot hitting cracks or inclusions, or the crystal-epoxy interface (see location of analysed area in Table 1). U contents in un-cracked, inclusion-free domains are between 350–660 ppm. Discordant analyses, where the analytical spot has hit cracks and/or inclusions, may have up to 1000 ppm U and generally also significantly higher amounts of common Pb ($^{206}Pb/^{204}Pb$ ratios often well below 10 000, Table 1). These analyses have been excluded from the age calculation. The remaining nine analyses are concordant and give a concordia age (ignoring the decay constant errors) of 1889 ± 3 Ma (Fig. 6c; $MSWD_{conc.+equiv.} = 1.4$, probability = 0.13), identical to a weighted average $^{207}Pb/^{206}Pb$ age of the same analyses calculated at 1890 ± 4 Ma (MSWD = 1.1, probability = 0.33). The concordia age including decay constant errors is 1888 ± 6 Ma ($MSWD_{conc.+equiv.} = 1.4$, probability = 0.14). The concordia age defined by the nine concordant analyses is interpreted to date igneous crystallisation of the quartz-plagioclase porphyritic tonalite at 1889 ± 3 Ma.

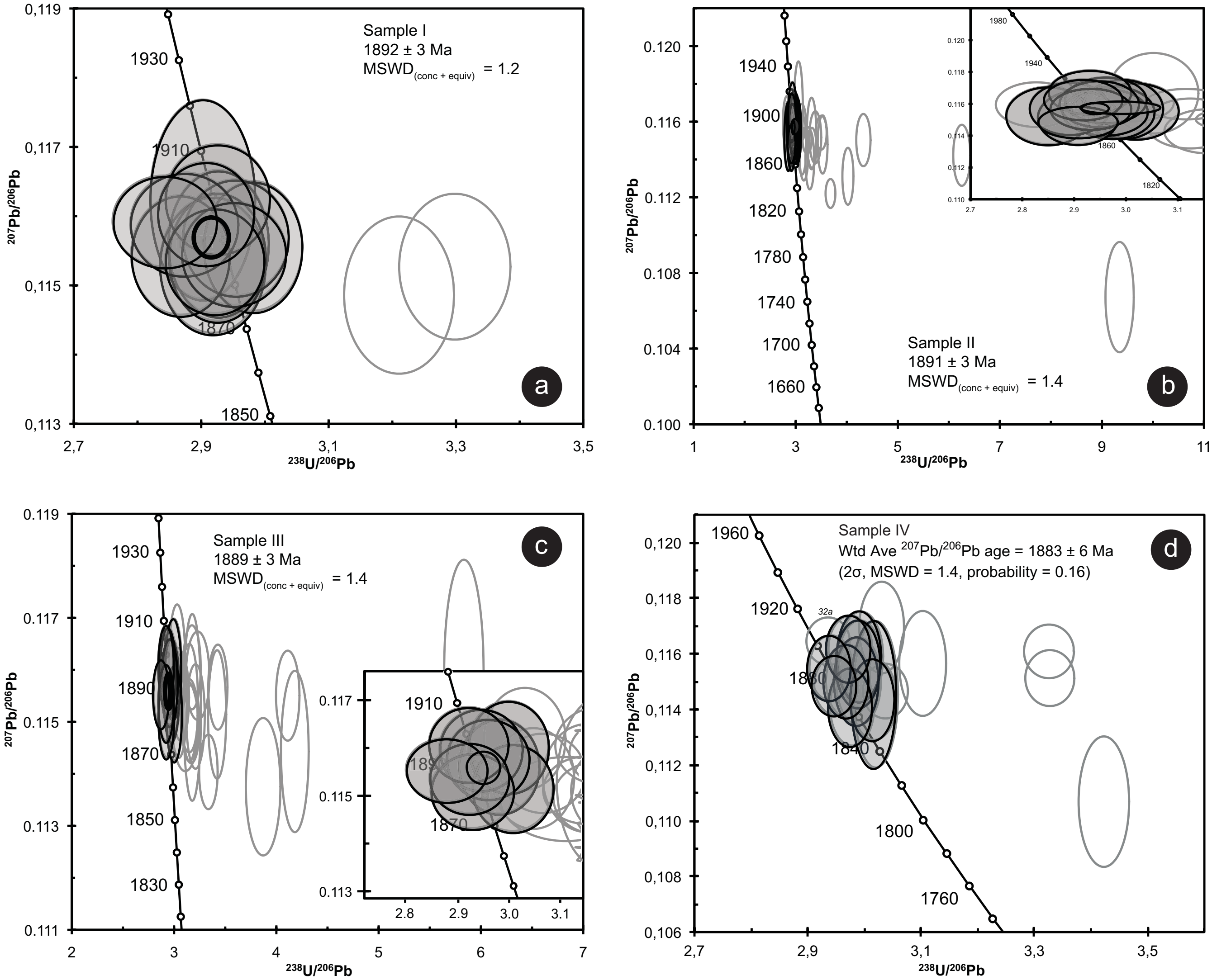

Fig. 6. Tera-Wasserburg type concordia diagrams for the dated rock units. **(a)** Sample I: Viterliden hornblende-tonalite (47.1-pmsk-09), **(b)** Sample II: Viterliden plagioclase porphyritic tonalite (33.1-pmsk-08), **(c)** Sample III: quartz-plagioclase porphyritic tonalite (coarse "mine porphyry"; 29.1-pmsk-08), **(d)** Sample IV: Kristineberg hanging-wall rhyolite (60.1-pmsk-09).

3.2.4 Sample IV: Kristineberg hanging-wall rhyolite (60.1-pmsk-09)

Only about 50 zircons were retrieved from a 10 kg sample of the Kristineberg hanging-wall rhyolite, and all crystals were selected for analytical work. The crystals are rather small in size, typically short prismatic and more or less euhedral with aspect ratios between 1:2 and 1:3 and maximum lengths of about 150 µm. They are turbid to semi-transparent and cracks and inclusions are common in all crystals. In BSE-images the zircons are mostly texturally uniform, typically showing a weak broad-banded zoning or are unzoned, suggesting a non-complex single stage of zircon growth (Fig. 5, n3447-10a and b). A couple of grains have BSE-brighter inner domains with a narrow-banded oscillatory zonation surrounded by unzoned or weak broad-banded zoned zircon that dominates the sample (estimated >90 vol-% of the sample).

17 analyses were obtained from the sampling. Some of the spots hit cracks and inclusions (Table 1), of which six analyses are discordant and discarded from age calculation. Eleven analysis are concordant (Fig. 6d, Table 1). The data set does not allow calculation of a Concordia age, but together these analysis define a common weighted average ^{207}Pb/^{206}Pb age of 1883 ± 7 Ma (MSWD = 2.4, probability = 0.01). One of the concordant analysis (n3447x-32a) hit a BSE-brighter oscillatory zoned core surrounded by unzoned BSE-darker zircon that dominates the sample (analysis marked in Fig. 6d). This texturally older domain also gives a slightly higher ^{207}Pb/^{206}Pb age (Table 1) and may potentially be a xenocrystic domain. If this analysis is excluded

from age calculation, the remaining 10 concordant analyses define a weighted average $^{207}Pb/^{206}Pb$ age of 1883 ± 6 Ma (MSWD = 1.4, probability = 0.16). This age is interpreted to date igneous crystallisation of the Kristineberg Rhyolite at 1883 ± 6 Ma.

4 Discussion

The new ∼1.89 Ga U-Pb ages for the three different phases of the composite Viterliden intrusion demonstrate that it was emplaced synchronously with the majority of the pre- to early-orogenic granitoids further east in the Skellefte District (Wilson et al., 1987; Weihed and Schöberg, 1991; Lundström et al., 1997; Weihed et al., 2002; Gonzàles Roldán, 2010). Exceptions are the ∼1.91 Ma Björkdal intrusion (Lundström and Antal, 2000) and the younger phases of the Jörn intrusive complex (Gonzàles Roldán, 2010). Of these two, the Björkdal intrusion has a complex history including several zircon-forming events (Lundström and Antal, 2000), and for this reason, it is not clear if it may be classified into the group of Jörn type intrusives. According to recent petrological investigations of the younger phases of the Jörn intrusive complex (GIII-IV; 1.87 Ga), it is not likely that they are cogenetic with the older 1.89–1.88 Ga GI-phase (Gonzàles Roldán, 2010). The 1.89–1.88 Ga age for the Kristineberg hanging-wall rhyolite shows that not only intrusive, but also felsic volcanic activity was synchronous throughout the whole Skellefte District, culminating at around 1.89 Ga (cf. Welin, 1987; Billström and Weihed, 1996). This also supports the idea that the Skellefte District was originally a laterally (sub)continuous volcanic belt (Carranza and Sadeghi, 2010) that was later split and transposed by tectonic events (Skyttä et al., 2010). The new geochronology data presented here highlight the importance of the 1.89 Ga igneous activity in the build-up of the Skellefte District. The synchronous timing of the igneous events allows for geological correlations throughout the Skellefte District.

The relationship between the intrusive and volcanic units in the Skellefte District is important, since it affects interpretations on the mineralization processes. Because nearly all early-orogenic intrusions within the district (e.g. Karsträsk, Sikträsk, Rengård; Fig. 1) experienced high degrees of tectonic transposition, often including development of shear zones along their margins (Bergman Weihed, 2001), it is not possible with the available data to constrain their stratigraphic position relative to the surrounding metavolcanic rocks. Not even from the now reasonably well-dated Kristineberg area is it possible to satisfactorily determine the temporal relationship between all the intrusive phases and the structurally overlying volcanic sequence. The regionally overlapping ages of the early-orogenic intrusives (Wilson et al., 1987; Weihed and Schönberg, 1991; Lundström et al., 1997; Weihed et al., 2002; Gonzàles Roldán, 2010) and the Skellefte Group metavolcanic rocks (Welin, 1987; Billström and Weihed, 1996) are in agreement with the idea that the Viterliden complex intruded into the succession of the Skellefte Group metavolcanic rocks (Galley and Bailes, 1999). This is also supported by the xenoliths of altered ore-hosting metavolcanic rocks in the "mine porphyry" at Kristineberg (Årebäck et al., 2005). The new data presented here show that the volumetrically largest phases of the Viterliden intrusion probably are slightly older than the Kristineberg hanging-wall rhyolite. For this reason, it is possible that these parts of the intrusive complex acted as a basement for the overlying volcanic rocks. This interpretation agrees with Billström and Weihed (1996), who considered the Sm-Nd signature of the Skellefte Group metavolcanic rocks to indicate the presence of an intrusive basement, not much older than the metavolcanic rocks themselves. However, the new data does not exclude the possibility that the whole complex is intrusive into the volcanic sequence, since it only constrains the relationship between the intrusion and the hanging-wall rhyolite. The age of the volcanic footwall rocks still remains unknown. Furthermore, the interpretation, which considers part of the intrusive complex to be the basement to the volcanic sequence, would require some time for erosion and uplift between the crystallisation of the intrusion and the onset of volcanism. This may have been accomplished by normal faulting-related footwall uplift prior to, or in the early stages of extension-related volcanism. Regionally, pre-compressional uplift and unroofing of the Jörn GI-type granitoids are attributed to major dip-slip faulting along the intrusive-volcanic contact in the central part of the Skellefte District (Bauer, 2010). However, uplift-related granitoid clast-conglomerates, similar to those in the central Skellefte District area, are lacking in the Kristineberg area.

The "mine porphyry" is considered the youngest of the Viterliden intrusive phases (Galley and Bailes, 1999; Årebäck et al., 2005), but no geochronological evidence has been provided. The overlapping or perhaps slightly younger age of the qtz-plg-porphyritic tonalite presented in this paper (1889 ± 3 Ma), with respect to the other tonalite types (1892 ± 3 Ma; 1891 ± 3 Ma), may support this interpretation. Such a relative timing is also supported by Skyttä et al. (2010), who proposed that the qtz-plg-porphyritic tonalites were emplaced along fault zones truncating the hornblende-tonalites. However, since no zircon was obtained from the "mine porphyry proper" the possibility still remains that it is even younger than the 1889 ± 3 Ma age for its coarser equivalent. This would imply that successive pulses of magma were intruded along the fault zones, after the volumetrically largest phases of the intrusion. Considering the narrow time interval of the dated intrusive units and the lack of further evidence on the age of the "mine porphyry proper", we tentatively estimate that it was emplaced 1889 ± 3 m.y. ago. If correct, this sets a minimum age for the VMS deposition, which is in agreement with the more loosely-defined minimum age constrained by the hanging-wall rhyolite.

5 Conclusions

The early-orogenic magmatism within the Kristineberg area occurred at ∼1.89 Ga when the Viterliden composite intrusion was emplaced during a period of ∼5 Ma. The intrusion was coeval with the emplacement of the earliest phases of the Jörn GI -type intrusions further east. The oldest phase of the Viterliden intrusion is a hornblende-tonalite (1892 ± 3 Ma) and the youngest is a quartz-plagioclase porphyritic tonalite ("mine porphyry"; 1889 ± 3 Ma). The emplacement of the latter was controlled by major faults. Volcanism in the Kristineberg area took place at 1.89–1.88 Ga and was contemporaneous with volcanism in the other parts of the Skellefte District. Furthermore, it defines the minimum age for the Kristineberg VMS deposit at ≥1.88 Ga. However, if the tentative correlation between the dated quartz-plagioclase porphyritic tonalite and the "mine porphyry proper" is correct, the minimum age is constrained even further, at 1889 ± 3 Ma. The age relationships between the volcanic and intrusive units within the Kristineberg area are compatible with the Viterliden intrusion being both the local basement for, and/or intruding into, the ore-hosting Skellefte Group volcanic rocks.

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