U-Pb zircon age of c. 1 440 Ma syenogranite within the protogine zone at Värpeshult

– map sheet 4E Tingsryd NV, Kronoberg county

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december 2019

SGU-rapport 2019:19

Sveriges geologiska undersökning

Cover: Outcrop of syenogranite at Värpeshult and image from microscope with crossed nicols.
Photo: Dick Claeson

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SAMMANFATTNING

Syftet med SGUs dateringar är att skapa goda geologiska underlag för intressenter inom prospekteringsindustrin, gruvnäringen, länsstyrelser, kommuner och andra. Kunskap om åldersrelationerna mellan olika bergartsled, är en del av att förstå hur berggrunden bildats och omformats. Dessutom bidrar dateringarna till att utöka de akademiska kunskaperna om regionens berggrundsgeologi.

Denna rapport presenterar en ny radiometrisk datering av en bergart med uran-bly-metoden på zirkon. Dateringen utfördes i samband med SGUs regionala berggrundskarteringsprojekt ”Småland” som pågick från 1999 till 2005. Projektet resulterade bland annat i tre kartor med beskrivningar, över Kalmar län (Wik m.fl. 2005a), Jönköpings län (Wik m.fl. 2006) och Kronobergs län (Wik m.fl. 2009).

U-Pb zirkonåldern av syenograniten från Värpeshult visar att den bildades för 1 441 ± 15 Ma sedan. Syenograniten är opåverkad av deformation och höggradig metamorfos, endast låggradig ses i det undersökta materialet. Den välbevarade syenogranitens position mitt i den regionala deformationszonen, Protoginzonen, gör den till en utmärkt markör för när deformation och höggradig metamorfos av omgivande bergarter har skett. Även tre andra mycket välbevarade bergarter undersöks och beskrivs, två bedöms vara ca 1,45–1,44 Ga och en pyroxensyenit som allokeras till 1,22–1,20 Ga generationen. Dessa bergartsprover kommer dels från lokaler inom Protoginzonen,dels inom den västra delen av Blekinge-Bornholm provinsen. Genom undersökningarna framkommer ett mönster av höggradig metamorf överprägling av den berggrund som dessa bergarter intruderat i och som orsakats av händelser äldre än ca 1,45 Ga. För bergartsbildningen i denna del av Sverige, innebär det att Protoginzonen söder om Vättern, inte först och främst är en Svekonorvegisk deformationszon, utan har varit en svaghetszon under mycket lång tid. Indikationerna som diskuteras här visar på att den kan ha varit aktiv redan vid ca 1,70 Ga och definitivt före ca 1,45 Ga.

INTRODUCTION

During the regional bedrock mapping project "Småland", presentation scale 1:250 000, at the Geological Survey of Sweden (SGU), the well-preserved syenogranite at Värpeshult was chosen for age determination work, because of its controversial stratigraphic position. The rocks were in earlier work interpreted as an undeformed Smålandsgranite of the Transscandinavian belt (TIB) and thus 1.7 or 1.8 Ga in age, situated well within the Protogine Zone (Kornfält & Bergström 1991). The rocks at Värpeshult and the eastern part of the intrusion at Röckla were preliminary reinterpreted as belonging to a syenite to quartz syenite generation formed at 1.22–1.20 Ga ago (e.g. Jarl 2002 and references therein), since parts have similar compositions and because of their undeformed nature (Wik et al. 2005b). The result of the age determination from Värpeshult was reported very briefly in Wik et al. (2009) and implemented in the resulting map and database. The intrusion was interpreted as a coeval intrusion of the Karlshamn-Eringsboda granite intrusions further to the east that formed around c. 1.45 Ga ago (e.g. Čečys A. & Benn 2007, Brander & Söderlund 2009 and references therein).

The conceptual map of some tectonic units (Fig. 1), the bedrock map (Fig. 2), and the map of the filtered magnetic field (Fig. 3), are presented in order to familiarize readers of the geology of the area.

In this contribution, the collected data and a more complete description is reported for the syenogranite at Värpeshult and Röckla. Additional outcrops of interpreted coeval rocks within the Protogine Zone, as well as in the westernmost part of the Blekinge-Bornholm province outside of the Protogine Zone, are described. An outcrop of interpreted 1.22–1.20 Ga pyroxene syenite to quartz syenite close to Värpeshult is described. Lithogeochemical data is presented for the syenogranite at Värpeshult, the c. 1.22–1.20 Ga pyroxene syenite at Virestadsjön, and the c. 1.45 Ga old granite at Bastön in the Blekinge-Bornholm province. All presented rocks are used in the discussion since these rocks are eminent structural markers for the development and tectonic framework of this part of southern Sweden. Once their ages are determined one may start to unravel the ancient history of these rocks.

GEOLOGICAL SETTING

The Protogine Zone is regarded as a 20–30 km wide belt of discrete N–S trending, Sveconorwegian shear zones (Fig. 1). To some extent, it defines the eastern border of the deformation and metamorphism of the Sveconorwegian orogen in southern Sweden (Fig. 1–3). The westernmost delineation of the Protogine Zone separates strongly deformed and metamorphosed rocks of the parautochthonous Eastern Segment to the west (Fig. 1–3, cf. Brander & Söderlund 2009, Ulmius et al. 2015). The Precambrian rocks of the southernmost part of Sweden consists of rocks that formed and was subsequently metamorphically overprinted during at least four orogens: 1.92–1.66 Ga Svecokarelian orogen, 1.47–1.38 Ga Hallandian orogen, the 1.14–0.90 Ga Sveconorwegian orogen, and possibly the Caledonian (e.g. Brander & Söderlund 2009, Ulmius et al. 2015 and references therein). Whatever portion of the rocks west of the Protogine Zone that were affected by the Hallandian orogen, is for the most part severely overprinted by the later Sveconorwegian orogen. Thus, the true extent of the Hallandian orogen in that area is probably futile to try to reconstruct. To the east of the Protogine Zone, there are evidence of the extent and degree of the Hallandian orogen, a tectonometamorphic and magmatic event, seen in the Blekinge-Bornholm province (Fig. 1–3, e.g. Ulmius et al. 2015 and references therein).

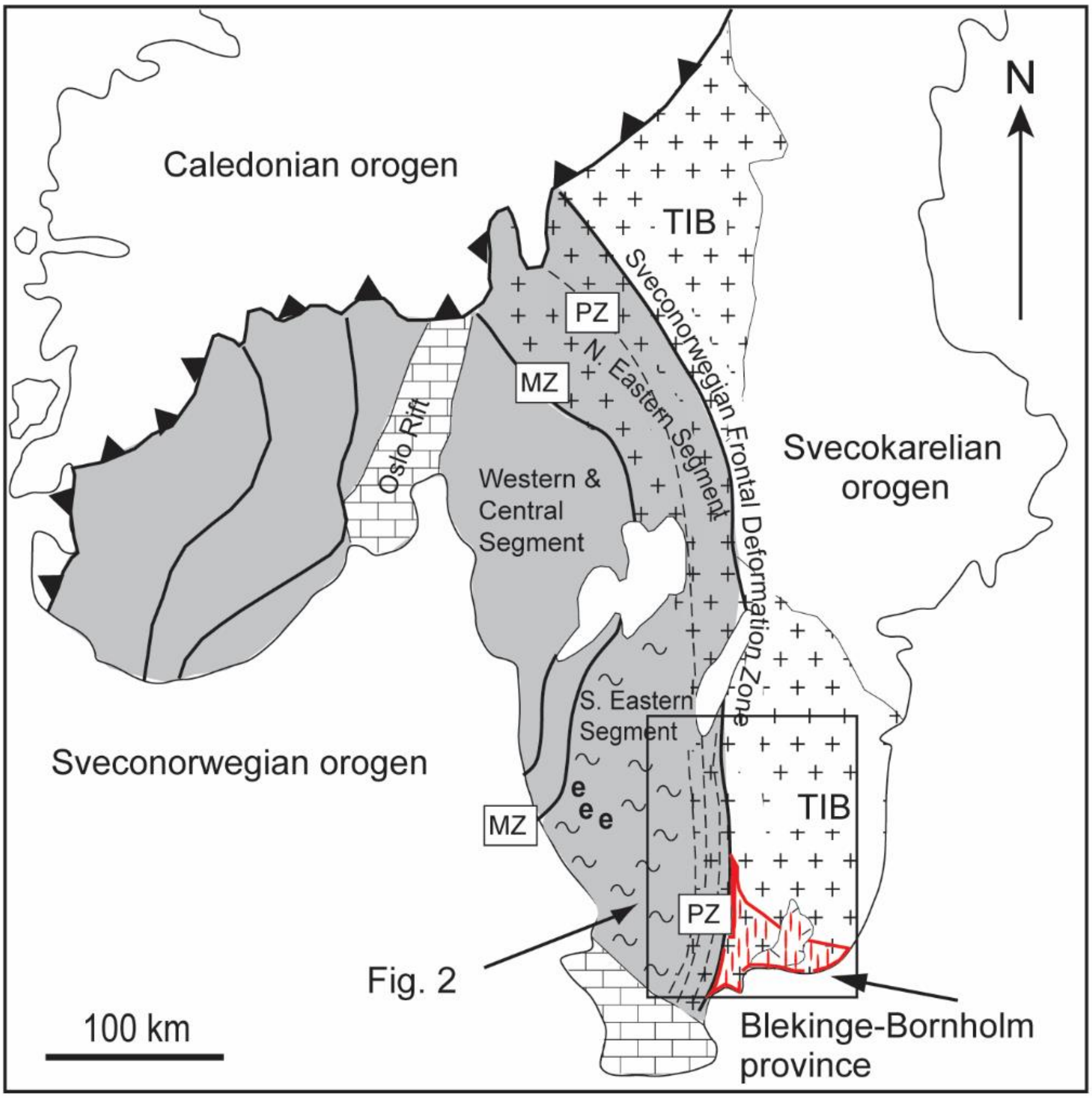

Figure 1. Some tectonic units in southern Scandinavia. TIB = the Transscandinavian Igneous Belt, PZ = the Protogine Zone, MZ = the Mylonite Zone, e = eclogite. Location of the Sveconorwegian Frontal Deformation Zone north of Lake Vättern follows Stephens et al. (1996).

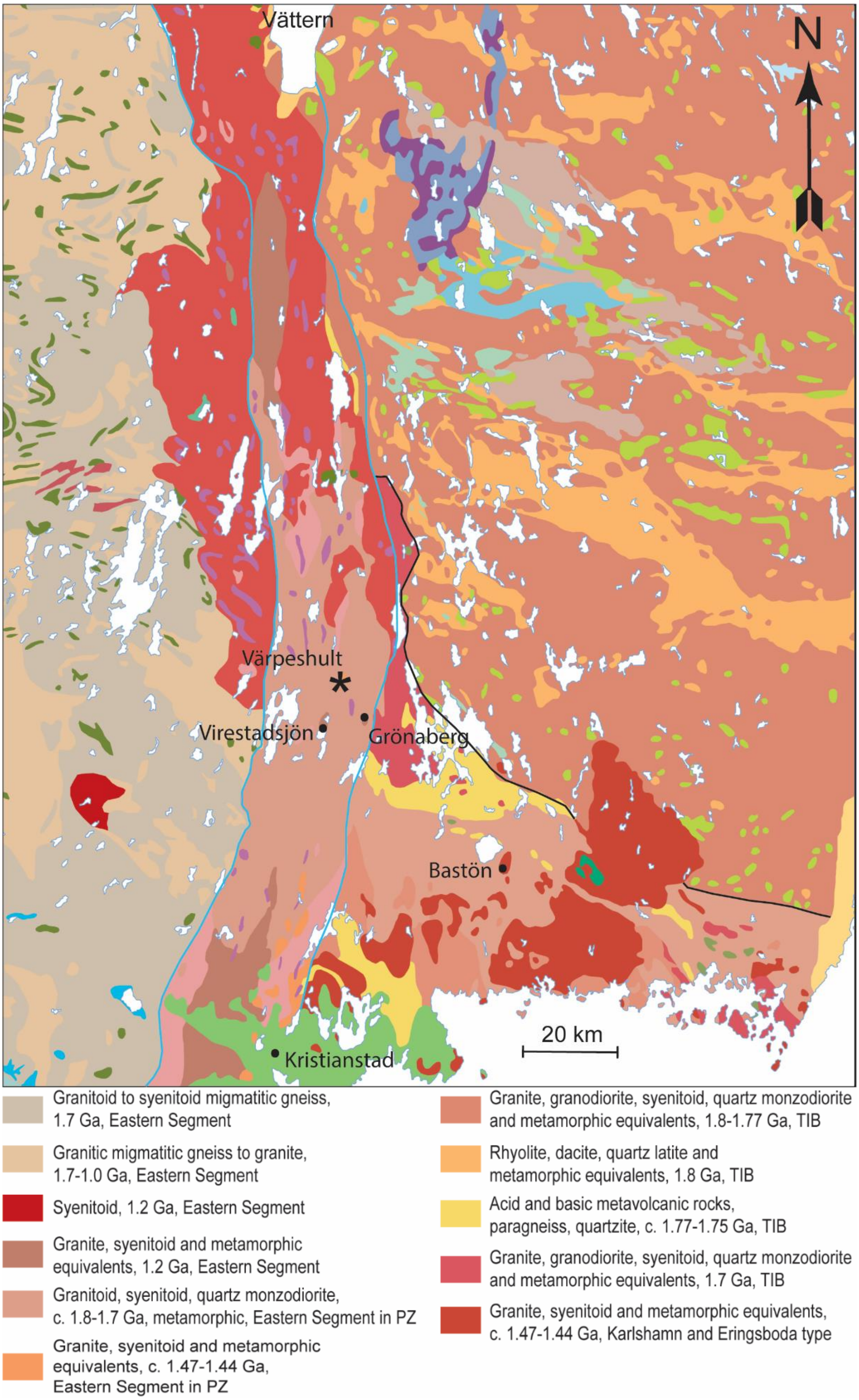

Figure 2. Bedrock map of the study area with some of the rocks near the sampling location for the age determination in the legend, marked with a black star, and the Grönaberg, Virestadsjön, and Bastön localities with black dots. The Protogine Zone delimited by blue lines and the Blekinge-Bornholm province by black lines. The legend is simplified and lacks rocks not discussed in the report.

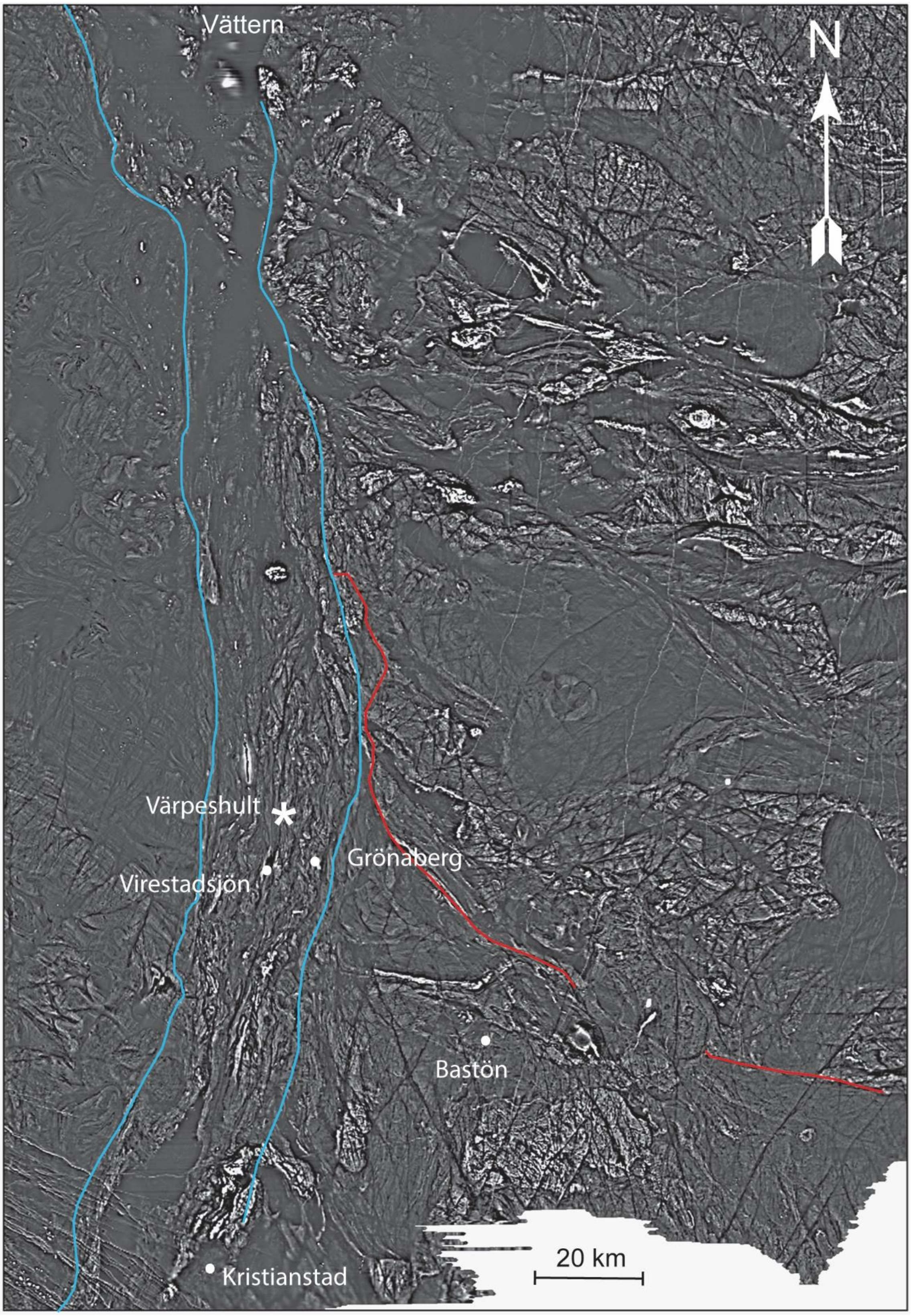

Figure 3. The magnetic field after filtering to enhance short-wavelength variations and thus enhancing the differences within the bedrock structures of the area. Locations as in figure 2. The Protogine Zone delimited by blue lines and the Blekinge-Bornholm province by red lines.

SAMPLE DESCRIPTION OF THE SYENOGRANITE AT VÄRPESHULT

The syenogranite at Värpeshult was sampled in a former, small quarry well within the Protogine Zone (Fig. 2, 3). The rock is red to whitish red, massive, and fine-grained to medium-grained (Fig. 4). The odd euhedral phenocryst of potassium feldspar is seen up to 10 mm size and most feldspar crystals are euhedral (Fig. 4, 5). The quartz appears as sugary aggregates and as larger single crystals interstitially (Fig. 4, 5). The textures and sparse mineralogical changes show that there has only been a low-grade metamorphic overprinting of the rock (Fig. 5). Parts of the syenogranite are leucocratic, containing much less mafic minerals. Other parts of the outcrop, possibly dykes or just more developed portions with a different composition, show a rock with quartz syenite to syenite composition with much less quartz and a dominantly dark-coloured, grey potassium feldspar (Fig. 4B). The latter rock is most often medium-grained to coarse-grained, dark grey to grey, and massive. Their contacts are most easily seen as difference in colour, where the syenogranite and quartz syenite to syenite show no signs of chilled margins and are thought to be comagmatic (Fig. 4B). A red coloured pegmatite dyke occurs, and it is most probably comagmatic with the syenogranite and formed from late-crystallising magma. A smaller occurrence at the quarry of a gneiss with granitic composition that is the host rock, is interpreted to belong to the TIB rocks that formed at 1.7 or 1.8 Ga. Ductile deformation of the gneiss is evident as a well-developed foliation. Petrophysical measurements of the syenogranite sample show density at 2 643 kg/m^3, magnetic susceptibility 2 621 × 10^{-5} SI, remanent magnetization intensity of 240 mA/m, and Q-value of 0.226.

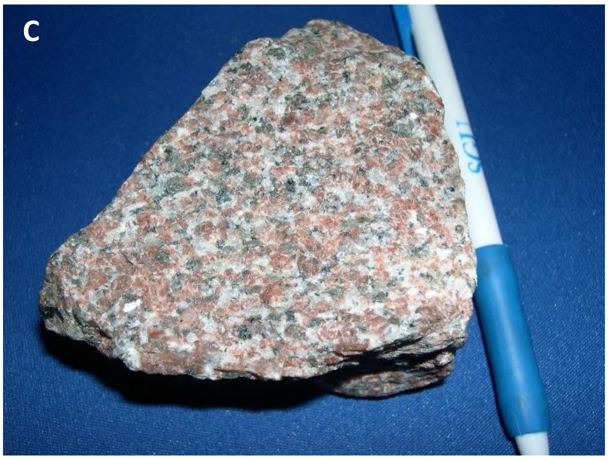

Figure 4. The age determined syenogranite at Värpeshult. **A.** Quarried slab of syenogranite (6286819/461282). **B.** Quartz syenite to syenite in contact with syenogranite (6286819/461282). **C.** Hand specimen of the age determined syenogranite (6286819/461282). All photos: Dick Claeson.

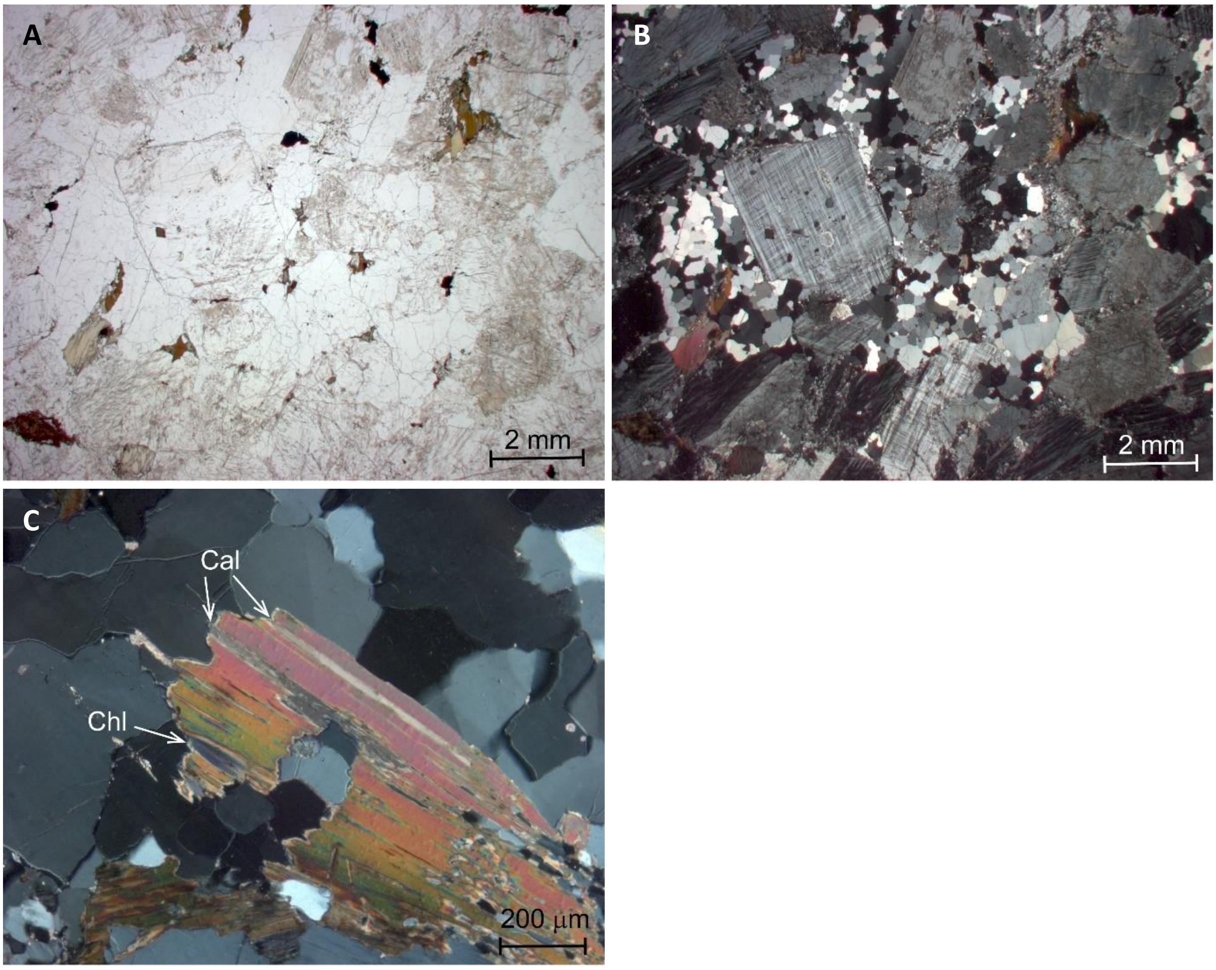

Figure 5. Groundmass of the age determined syenogranite at Värpeshult (6286819/461282), **A.** plane-polarized light and **B.** crossed nicols. **C.** Biotite displaying alteration as lamellae of chlorite (Chl) showing anomalous blue and violet interference colours and of calcite (Cal). Micrographs: Dick Claeson.

The outcrop of syenogranite at Röckla

South of Röckla, c. 1.85 km east-northeast of Värpeshult, the same syenogranite occurs as a clearly intrusive rock shown as straight and ptygmatic dykes of varying size, others showing box-shapes (Fig. 6). In the field of view at the outcrops these fold-shapes are symmetric in width and the intruding rock shows no sign what so ever of deformation (Fig. 6). Some of the dykes are pegmatitic. Occasional xenoliths of metamorphic mafite and metagabbroid occur in the syenogranite (Fig. 6D, E). The syenogranite has intruded a deformed, ductile foliated gneiss of granodioritic composition. One might argue that the dykes are the result of significant veining and formed from melting of the TIB gneiss itself, but the dykes are considered to be injections into an already foliated and deformed gneiss and coeval with the rocks at Värpeshult, but not the earlier high-grade event registered by the host TIB rock. Orientation of the foliation is 295/62 (RHR).

Figure 6. A. Several dykes of different size of syenogranite in granodioritic gneiss, mostly straight and conform with the foliation in the gneiss (6287662/462954). **B.** Mostly straight dykes, some just ½ cm wide, but to the right in the image a box-shaped part of a dyke can be seen between two straight (6287662/462954). **C.** A ptygmatic dyke of the syenogranite, positioned between two straight dykes (6287662/462954). **D.** A xenolith of metamafite that show cuspate contacts with the syenogranite and partly dissolved (6287662/462954). **E.** A xenolith of metagabbroid that is more competent and show no sign of dissolution (6287662/462954). All photos: Dick Claeson.

ANALYTICAL RESULTS AND INTERPRETATION OF GEOCHRONOLOGICAL DATA OF THE SYENOGRANITE AT VÄRPESHULT

U-Pb thermal ionization mass spectrometer (TIMS) analysis of zirkon was performed at the Laboratory of Isotope Geology at the Museum of Natural History in Stockholm. Common Pb corrected isotope values were calculated using modern common Pb composition (Stacey & Kramers 1975). Decay constants follow the recommendations of Steiger & Jäger (1977). The analytical results for the sampled syenogranite at Värpeshult are shown in Table 1. The zircon are colourless or light brownish-yellow coloured. They are euhedral with sharp edges and pyramid tips or slightly rounded. Even heavily rounded grains exist and many show high-index surfaces. Most are short with length to width ratios of about 1–3:1 but some longer grains are present. None of the crystals are entirely clear and inclusions are common. All crystals might be more or less metamict or it is possible that some are just impure. All the analysed grains were strongly abraded.

Fraction 1. 3 crystals. They show longitudinal zoning, black dots and elongate inclusions. Two of the grains have thin zones at the edges that do not look like overgrowth.

Fraction 2. 4 crystals. Small, elongate grains. Good quality but all have minor inclusions. Zoned.

Fraction 3. 6 crystals. Wider than the crystals of fraction 2 and therefore show greater length/width ratios. They are of good quality but all have minor inclusions.

Fraction 4. 4 crystals. Bigger than the previous fractions but of less quality. Zoned. Inclusions.

Fraction 5. 1 crystal. Short, clear, and of good quality. Somewhat more brownish than the majority.

As shown in Table 1, the zircon are uranium-rich and thus also rich in radiogenic lead. There is a large difference between the $^{206}Pb/^{204}Pb$ ratio among the different analysed fractions. Fraction 1 shows a high ratio while the others are low. No apparent explanation for these differences can be observed in the appearance of the zircon. It is unlikely that it is due to contamination in the lab because none of the other 9 samples run in the same batch of analyses were affected. In addition, the contamination must be extremely high, 200 pg Pb for fraction 2, compared to 1–2 pg as is normal. One likely explanation could be that the zircon in the three fractions contain lead-rich inclusions such as sulphides (?).

The discordance is 4–12% and they are not perfectly aligned along a discordia. A discordia of all points results in intercepts at 1 453±24 and 329±270 Ma, with a large MSWD = 25 at 2σ. If the most discordant fraction is removed (No. 4), the resulting four data points define a discordia with concordia intercepts at 1 441±15 and 88±320 Ma, and a lower MSWD = 4.7 at 2σ. The upper intercept age at 1 441±15 Ma is interpreted as the igneous crystallisation age of the syenogranite at Värpeshult (Fig. 7).

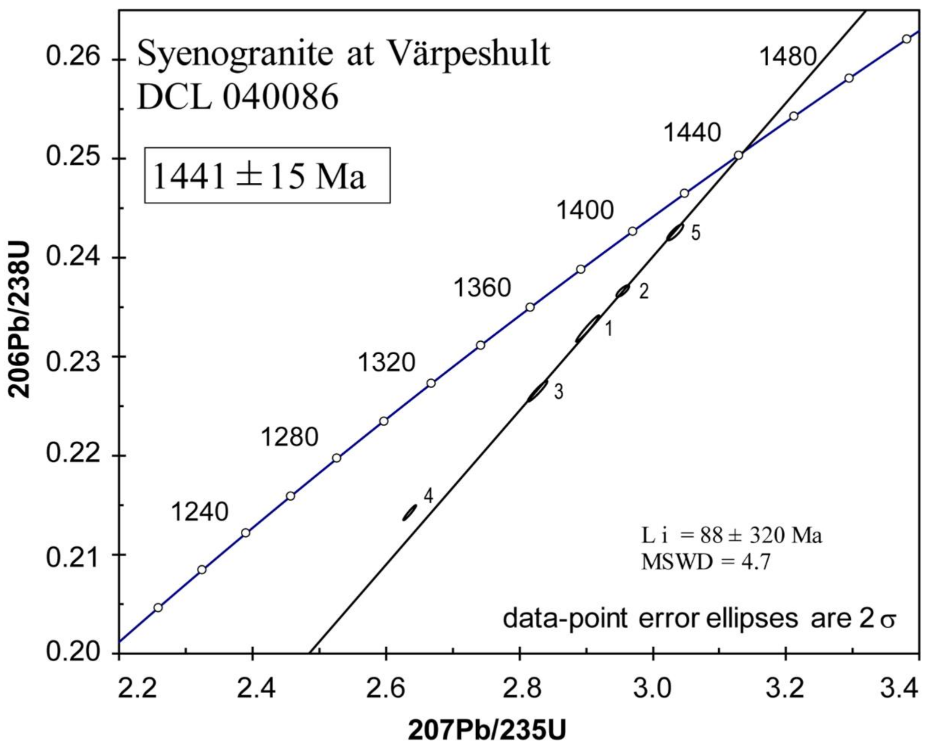

Figure 7. Concordia diagram showing U-Pb zircon data.

Table 1. U-Pb isotopic data for DCL040086, syenogranite at Värpeshult.

Analysis No	Weight (µg)	No. of crystals	U (ppm	Pb tot. (ppm)	Common Pb (ppm)	$^{206}Pb/^{204}Pb$ [a]	^{206}Pb - ^{207}Pb - ^{208}Pb Radiog. (atom %)[b]	$^{206}Pb/^{238}U$ [b]	$^{207}Pb/^{235}U$ [b]	$^{207}Pb/^{206}Pb$ age (Ma)
1	6.4	3	1 539.9	369.7	0.97	16 907	83.6 - 7.6 - 8.8	0.2328±11	2.903±14	1 434±2
2	2.6	4	1 134.7	397.6	76.74	222	72.1 - 6.5 - 21.4	0.2366±5	2.955±8	1 438±3
3	4.0	6	1 775.6	542.9	71.33	348	73.4 - 6.7 - 19.9	0.2265±9	2.828±11	1 437±2
4	5.9	4	1 713.0	413.0	19.46	1 116	80.2 - 7.2 - 12.6	0.2142±6	2.636±8	1 410±2
5	1.3	1	1 372.1	337.9	4.49	3 344	85.8 - 7.8 - 6.4	0.2425±7	3.033±10	1 440±3

[a] Corrected for mass fractionation (0.1% per a.m.u) and spike.

[b] Corrected for mass fractionation, spike, blank and common Pb.

THE SYENOGRANITE AND QUARTZ SYENITE TO SYENITE AT GRÖNABERG

North of Grönaberg, c. 10 km southeast of Värpeshult, a quartz syenite to syenite and syenogranite occur. These rocks are here interpreted as equivalent rocks to those seen at Värpeshult and Röckla, due to the more or less exact same compositional range and meta-morphic overprinting, and thus coeval (Fig. 2, 3). However, earlier work had these rocks belonging to the syenitoid intrusives in the Protogine Zone that formed around 1.22–1.20 Ga ago (Wik et al 2009). Only an age determination will decide to what generation it belongs. The quartz syenite to syenite is grey to brownish grey due to the colour of the potassium feldspar, massive, and medium-grained to coarse-grained (Fig. 8). Potassium feldspar occur as 10 to 15 mm large, euhedral phenocrysts with an estimated frequency of 0–4%. The syenogranite is red to greyish red, massive, and fine-grained to medium-grained with a blueish hue seen in quartz crystals (Fig. 8). The quartz syenite to syenite and syenogranite are interpreted to be comagmatic along with the pegmatite parts (Fig. 8). Petrophysical measurements of the quartz syenite to syenite sample show density at 2 646 kg/m^3, magnetic susceptibility 3 744 × 10^{-5} SI, remanent magnetization intensity of 1 590 mA/m, and Q-value of 1.05.

Figure 8. A. Quartz syenite to syenite from Grönaberg (6279148/466989). **B.** Quartz syenite along with granite and pegmatite at Grönaberg (6279148/466989). **C.** Quartz syenite and granite showing cuspate contacts indicative of comagmatic relation (6279148/466989). **D.** Close-up of quartz syenite with pegmatite (6279148/466989). All photos: Dick Claeson.

THE PYROXENE SYENITE TO QUARTZ SYENITE NORTH OF VIRESTADSJÖN

Pyroxene syenite to quartz syenite occurs 10.5 km south-southwest of Värpeshult, just north of Virestadsjön (Fig. 2, 3). This intrusion is well within the Protogine Zone and by us tentatively regarded as belonging to the generation of syenite rocks that formed c. 1.22–1.20 Ga ago (e.g. Jarl 2002 and references therein). No age determination has been performed at this locality, the alternative age option is that it belongs to the c. 1.45 Ga generation. However, pyroxene syenite rocks or such extreme lithogeochemical compositions as at Virestadsjön (see chapter *Litho-geochemical data*) have not been reported for the c. 1.45 Ga generation in southern Sweden. These syenitic rocks are susceptible to weathering, it is massive, medium-grained to coarse-grained, reddish brown and shows an in the field estimated content of 15 to 20% mafic minerals, mostly clinopyroxene (Fig. 9). Thus, there is no mineralogical resemblance with the syenogranite at Värpeshult and the pyroxene syenite is a much more mafic rock. The pyroxene syenite is pristine in the microscope showing only deuteric alteration and almost no low-grade metamorphism compared with the syenogranite at Värpeshult. The magmatic textures are well-preserved (Fig. 10). The groundmass is dominated by alkali feldspar, most showing simple twinning and exsolution phenomena of albite in perthite (Fig. 10). There are green, pleochroic clinopyroxene of the aegirine-augite series (Fig. 10). Some of them are deep green and other show colour zonation with darker green rims than cores. Mostly brown biotite is a late crystallising mineral and when in contact with the Fe-Ti oxide minerals it displays a spectacular, radiating growth pattern looking like a fan brush (Fig. 10) Apart from these locations, biotite is rare in the thin section. Minor amounts of magmatic green amphibole are present and minute alteration of clinopyroxene to amphibole is seen and interpreted as deuteric. Rare iron-rich olivine is seen more or less always intergrown with Fe-Ti oxide minerals. Petrophysical measurements of the pyroxene syenite sample show density at 2 832 kg/m^3, magnetic susceptibility 2 260 × 10^{-5} SI, remanent magnetization intensity of 3 040 mA/m, and Q-value of 3.31.

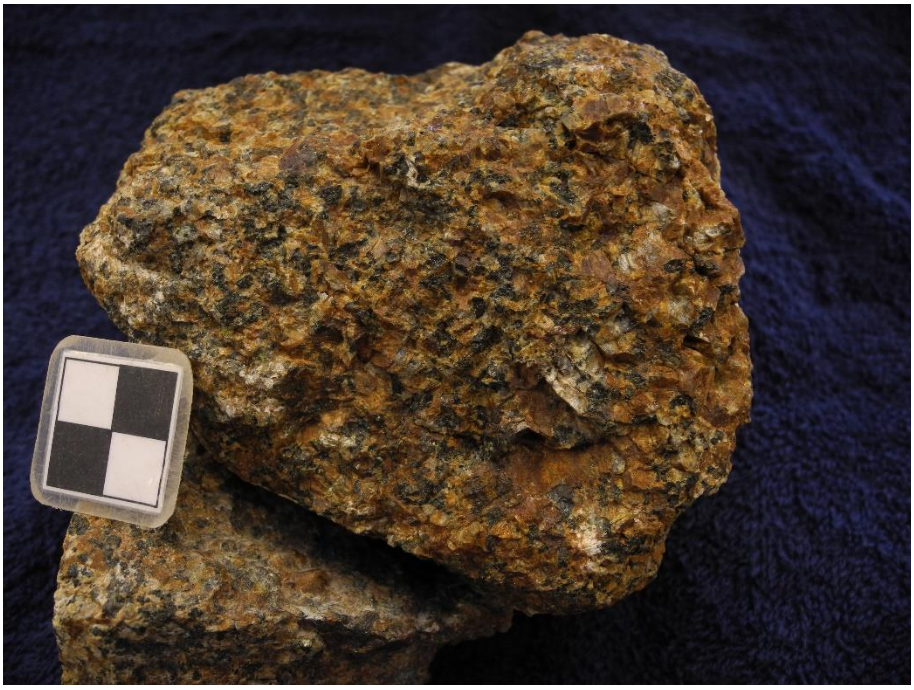

Figure 9. Pyroxene syenite north of Virestadsjön (6276837/458048). Photo: Dick Claeson.

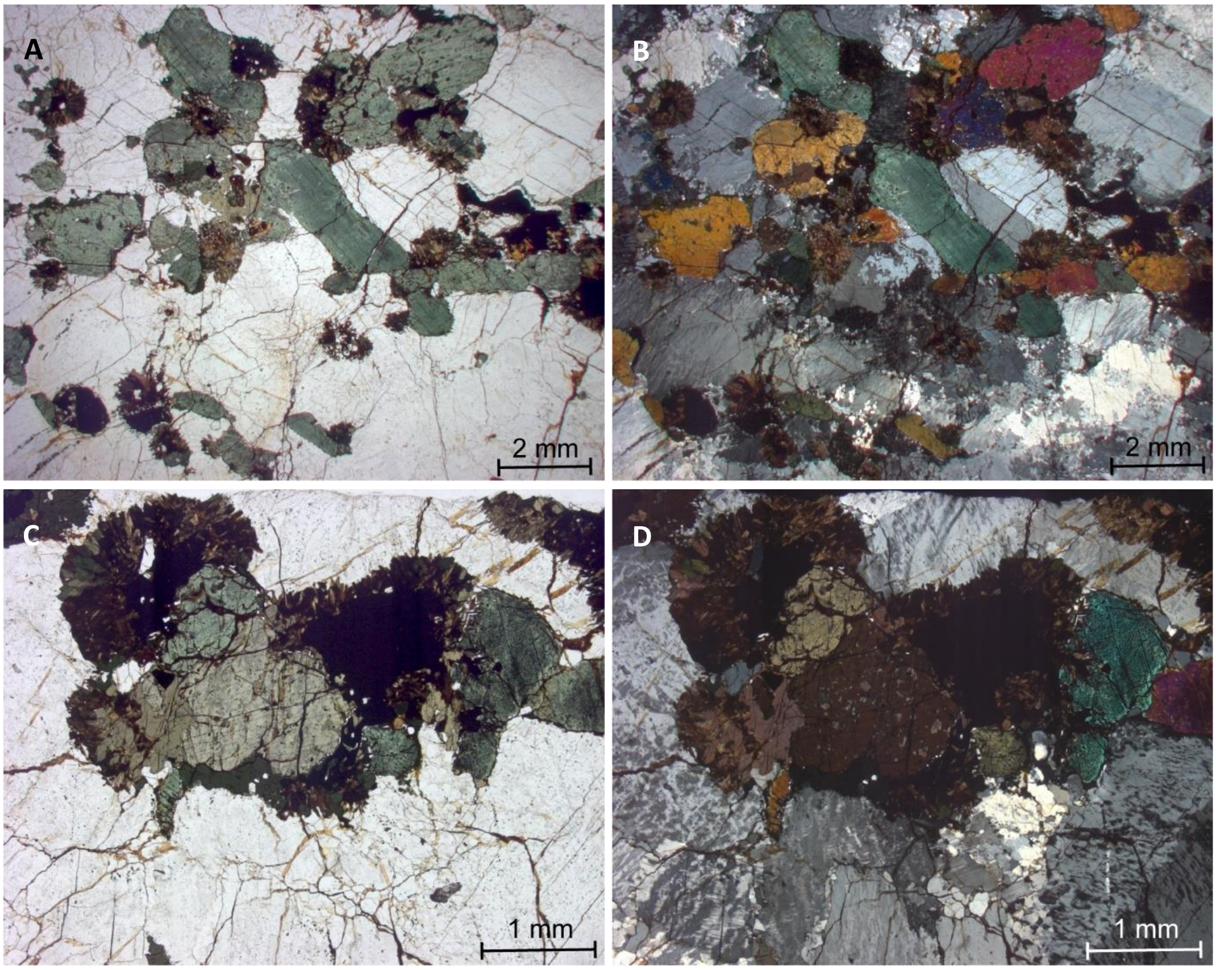

Figure 10. Groundmass of the pyroxene syenite north of Virestadsjön, green aegerin-augite clinopyroxen (6276837/458048), **A.** plane-polarized light and **B.** crossed nicols. Biotite displaying spectacular, radial growth around Fe-Ti oxides, **C.** plane-polarized light and **D.** crossed nicols. Micrographs: Dick Claeson.

THE C. 1.45 GA ERINGSBODA-TYPE GRANITE AT BASTÖN

The Bastön locality is positioned c. 50 km to the southeast of Värpeshult and the rocks here are part of the westernmost outcrops of Eringsboda-type granite (Fig. 2, 3). The granite at the northern part of the outcrops at Bastön (6248477/494460) is greyish red, massive, and medium-grained to coarse-grained (Fig. 11A–D). The granite is potassium feldspar phenocryst-bearing that are euhedral, 10 to 20 mm large and the abundance is 10–15%. Comagmatic dykes of aplite and pegmatite occur in the granite, which are fine-grained to coarse-grained, massive, light grey to light red, and in pristine magmatic appearance. Petrophysical measurements of the Eringsboda-type granite sample show density at 2 630 kg/m^3, magnetic susceptibility 2 634 × 10^{-5} SI, remanent magnetization intensity of 90 mA/m, and Q-value of 0.084.

At the southern part of the outcrops at Bastön (6248417/494397) the granite is reddish grey to greyish red, massive, and fine-grained to medium-grained (Fig. 11E–H). The granite is potassium feldspar phenocryst-bearing that are euhedral, 5 to 10 mm large and the abundance is few to 5%. Comagmatic, pristine dykes of aplite and pegmatite occur here as well that are fine-grained to coarse-grained, massive, and reddish grey to greyish red. Gneissic granodiorite of Tvings granitoid affinity (1.78–1.77 Ga old, e.g. Johansson et al. 2006 and references therein) occur as several metre large xenoliths. The strongly foliated granodiorite is uneven-grained with K-feldspar phenocryst 10–15 mm large, where few of them are rimmed by plagioclase and amphibole is seen in their groundmass along with biotite. The colour is grey to reddish grey and the granodiorite is medium-grained to coarse-grained.

The Karlshamn-Eringsboda granite intrusions formed around c. 1.45 Ga ago (e.g. Čečys A. & Benn 2007, Brander & Söderlund 2009 and references therein) and are thus coeval with the Värpeshult syenogranite. The former rocks are not regarded to be affected by the Sveconorwegian orogeny since being part of the Blekinge-Bornholm province (Fig. 1–3) and for the most part igneous structure and texture are well-preserved (e.g., Johansson et al. 2006). At Bastön, strongly foliated TIB-rocks of the Tvings granodiorite are observed as large xenoliths within pristine granite (Fig. 11). The relationship between these rocks shows that the regional deformation found in the area's TIB-rocks, granitoids and syenitoids, can be interpreted as much older or just older than the Karlshamn-Eringsboda intrusions in the Blekinge-Bornholm province. The results of Johansson et al. (2006) point towards a deformation event between 1.75 and 1.77 Ga but they also register a major tectonothermal event with possible migmatization at 1.45–1.40 Ga. Nothing in their data suggests that the Sveconorwegian orogeny reset or grew titanite or rims on zircon, since these are of a 1.45–1.40 Ga generation.

The Eringsboda-type granite at Bastön shows only minor signs of alteration and low-grade metamorphism and a thin section from an outcrop 1 km north of the two above described locations displays this well (6249364/494133). Studying the rock in the microscope, the magmatic textures are pristine (Fig. 12). Both the groundmass and phenocrysts of potassium feldspar show minor signs of any alteration. Plagioclase is occasionally completely altered to saussurite, especially when plagioclase rim phenocrysts of potassium feldspar in a rapakivi texture (Fig. 12). The rapakivi texture seems to only occur in a single, outer position in the studied thin section. Groundmass plagioclase show less saussuritization but most are effected (Fig. 12). Saussuritization is a common alteration of granite that is ascribed to hydrothermal activity and it might be deuteric in origin in these rocks. Biotite is to a minor degree altered to chlorite and prehnite in lamellae (Fig. 12C). The estimated metamorphic overprinting, part from deuteric alteration, would thus be prehnite-pumpellyite facies for the Eringsboda-type granite at Bastön.

▶**Figure 11.** Eringsboda-type granite at Bastön. **A.** Potassium feldspar phenocryst-bearing Eringsboda-type granite (6248477/494460). **B.** Aplite dyke (6248477/494460). **C.** Close-up of dyke with multiple, strike-parallel, alternating aplite and pegmatite (6248477/494460). **D.** Close-up of dyke with mostly pegmatite at the boarder of the dyke and aplite in the centre (6248477/494460). **E.** Gneissic granodiorite of Tvingsgranite occur as several metre large xenoliths (6248417/494397). **F.** Close-up of contact between xenolith of gneissic granodiorite and Eringsboda-type granite (6248417/494397). **G.** Close-up of xenolith of gneissic granodiorite with plagioclase rimmed potassium feldspar phenocrysts in Eringsboda-type granite (6248417/494397). **H.** Close-up of contact between xenolith of gneissic granodiorite and Eringsboda-type pegmatite (6248417/494397). All photos: Dick Claeson.


A
B
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D
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G
H

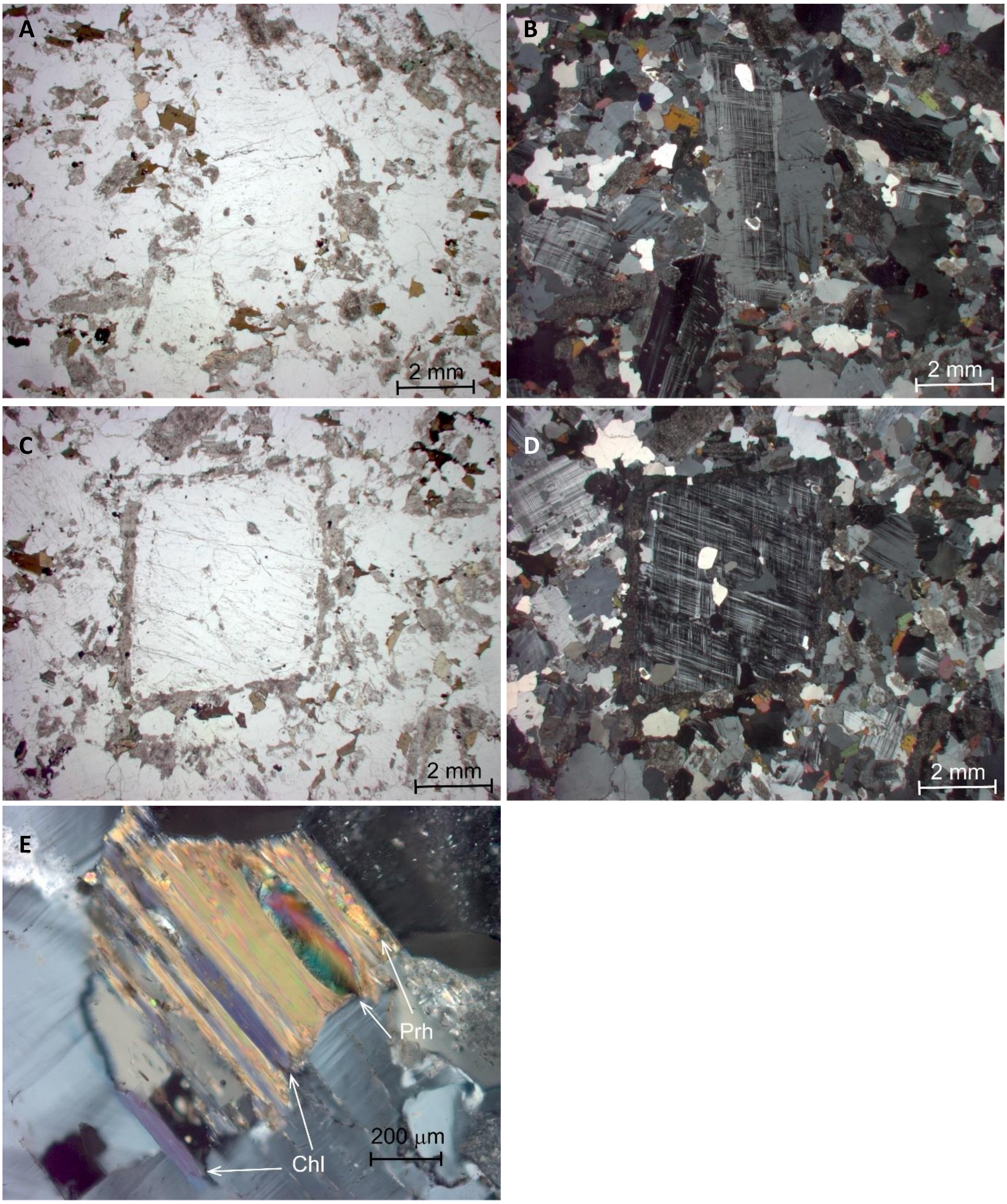

Figure 12. Groundmass of the Eringsboda-type granite at Bastön (6249364/494133), **A.** plane-polarized light and **B.** crossed nicols. In the centre of the image is a plagioclase rimmed phenocryst of potassium feldspar, where saussuritization is evident of the plagioclase, **C.** plane-polarized light and **D.** crossed nicols. **E.** Biotite displaying alteration as lamellae of chlorite (Chl) showing anomalous blue and violet interference colours and of prehnite (Prh). Micrographs: Dick Claeson.

LITHOGEOCHEMICAL DATA

Three samples, from the Värpeshult (6286819/461282), Bastön (6249364/494133), and Virestadsjön (6276837/458048) localities, were analysed at ACME Analytical Laboratories, Canada using their 4A+B, ICPMS analyses packages in 2005 and the results are shown in Table 2. Both samples of the 1.45–1.44 Ga generation, Värpeshult and Bastön, show very similar behaviour in the REE and multielement diagrams, even though their appearance is very different (Fig. 13). This shows that the rocks have had similar petrogenesis and source rocks from where they originated. They both display strong negative anomalies for Nb and Ti, a trough for Sr and P, but dissimilar strength in the positive Pb anomaly (Fig. 13). The LREE fractionation that these rocks have seen is evident from the steep inclination and the negative Eu anomaly they display resulting from plagioclase fractionation through early crystallisation of their magma (Fig. 13).

The pyroxene syenite north of Virestadsjön displays very low Sr content as evident in the multielement diagram as a negative anomaly (Fig. 13). This is not due to plagioclase fractionation from the initial magma because no Eu anomaly is seen in the REE diagram (Fig. 13). Instead this should be attributed to the petrogenesis of syenitic rocks, where a low degree of melting of a granitic source precludes the melting of minerals like plagioclase, where a lot of the Sr is allocated. The pyroxene syenite displays a strong negative anomaly for Ti, troughs for U and Nb as well as for Sr and P, and a distinct negative Pb anomaly (Fig. 13). The LREE fractionation of the pyroxene syenite is not pronounced and even though there is no plagioclase but possibly for some albite, it shows a small positive Eu anomaly. This indicate that not much fractionation through earlier crystallisation of the syenite magma en route to the emplacement position have taken place (Fig. 13).

All three rocks plot in the classification diagrams in accordance with the field estimate (Fig. 14).

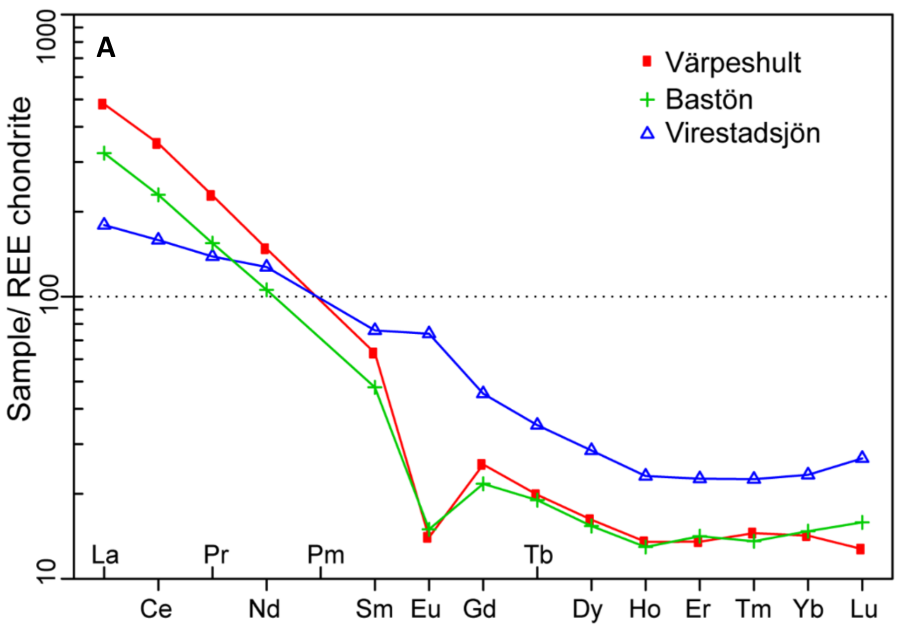

Figure 13A. REE-diagram with data from Värpeshult, Bastön, and Virestadsjön. Normalizing values for chondrite from Boynton (1984).

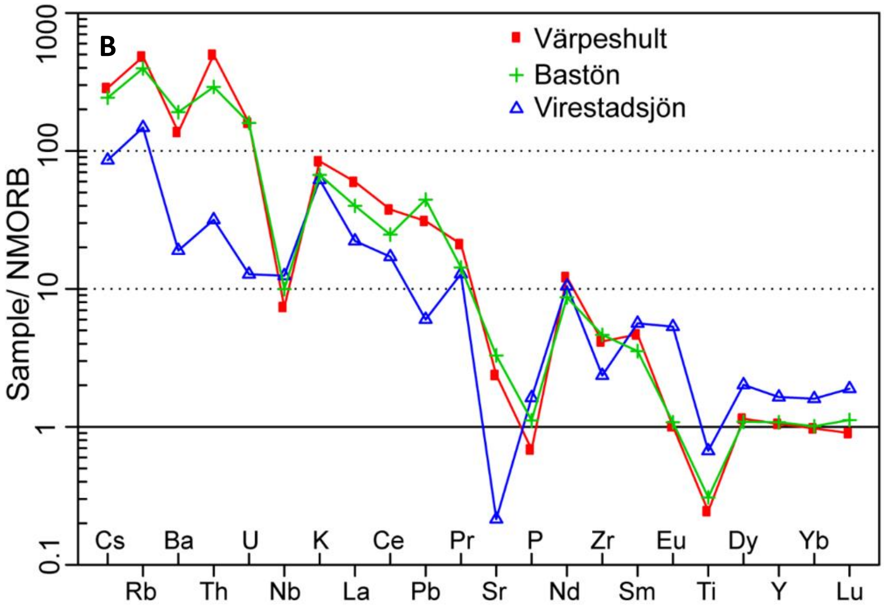

Figure 13B. Multi-element diagram, rocks as in A. Normalizing values for N-MORB from Sun & McDonough (1989).

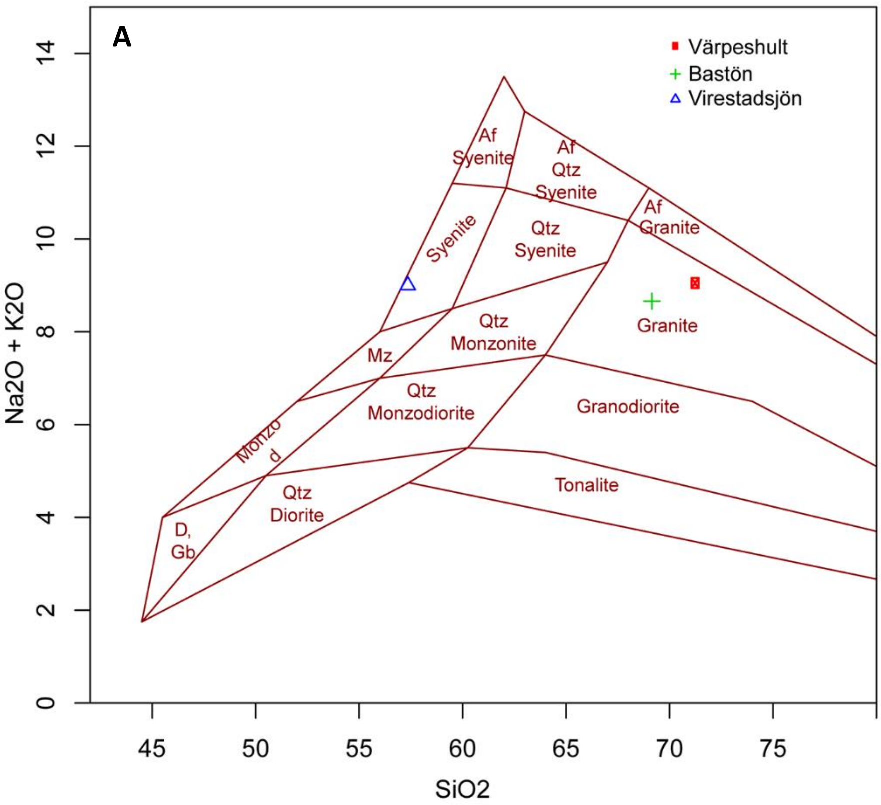

Figure 14A. Classification diagram. TAS diagram variation according to Middlemost (1994).

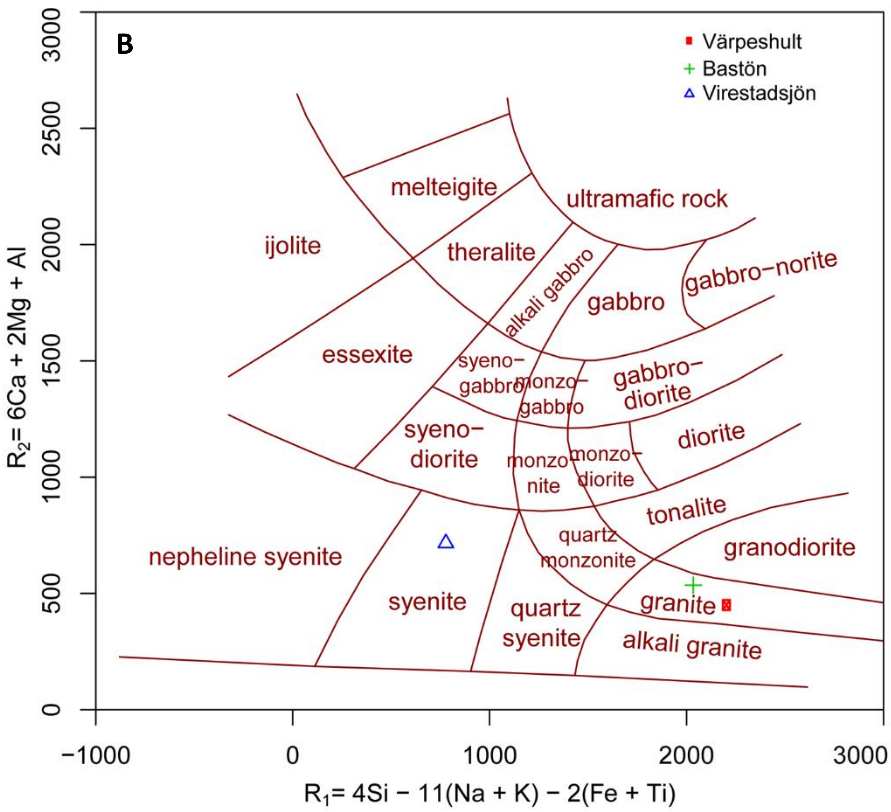

Figure 14B. Classification diagram. R1-R2 plot (De la Roche et al. 1980).

Table 2. Litogeochemical data for syenogranite at Värpeshult, pyroxene syenite north of Virestadsjön, and Eringsboda-type granite at Bastön.

	SiO2	**Al2O3**	**Fe2O3**	**CaO**	**MgO**	**Na2O**	**K2O**	**TiO2**	**MnO**	**P2O5**	**LOI**	**TOT/C**	**TOT/S**	**SUM**	**Ag**	**As**
Värpeshult	71.34	14.25	2.14	1.36	0.5	2.97	6.08	0.31	0.04	0.08	1.1	0.07	0.02	100.19	<0.1	<0.5
Virestadsjön	57.35	13.31	14.64	4.19	0.14	4.53	4.47	0.85	0.48	0.19	0.1	0.02	0.01	100.25	<0.1	<0.5
Bastön	69.15	15.12	2.91	1.85	0.83	3.82	4.84	0.39	0.07	0.13	1	0.03	0.02	100.13	<0.1	<0.5
	Au	**Ba**	**Be**	**Bi**	**Cd**	**Co**	**Cr**	**Cs**	**Cu**	**Ga**	**Hf**	**Hg**	**Mo**	**Nb**	**Ni**	**Pb**
Värpeshult	<0.5	862	2	<0.1	<0.1	3.1	75	2	7.3	16.8	9.1	<0.01	4	17.2	2.5	9.3
Virestadsjön	<0.5	119	2	<0.1	0.1	0.8	21	0.6	5.1	28.4	5.1	<0.01	3.2	29	0.5	1.8
Bastön	<0.5	1203	4	<0.1	<0.1	4.8	82	1.7	9.4	19.3	9.3	<0.01	4.5	23.2	5.3	13.3
	Rb	**Sb**	**Sc**	**Se**	**Sn**	**Sr**	**Ta**	**Th**	**Tl**	**U**	**V**	**W**	**Y**	**Zn**	**Zr**	
Värpeshult	270	<0.1	4	<0.5	2	213	1.5	59.7	0.2	7.5	27	0.3	29.4	41	308	
Virestadsjön	82.7	<0.1	26	<0.5	1	19.3	1.7	3.8	0.1	0.6	6	0.6	46	119	174	
Bastön	222	<0.1	6	<0.5	2	296	1.6	34.9	0.2	7.5	40	1	30.2	57	344	
	La	**Ce**	**Pr**	**Nd**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**		
Värpeshult	149.2	282.1	27.86	88.7	12.3	1.03	6.58	0.94	5.21	0.97	2.84	0.47	2.97	0.41		
Virestadsjön	55.6	128.2	16.93	76.4	14.8	5.43	11.7	1.66	9.17	1.66	4.75	0.73	4.88	0.86		
Bastön	100	185.5	18.87	63.4	9.3	1.1	5.62	0.9	4.95	0.93	2.97	0.44	3.08	0.51		

DISCUSSION AND CONCLUSION

The igneous age of the 1 441±15 Ma massive and well-preserved syenogranite at Värpeshult is evidence that the rocks formed prior to the Sveconorwegian orogeny, within parts of the Protogine Zone that were already overprinted by high-grade amphibolite facies prior to c. 1.45 Ga. This has also been shown for the area around the southern part of Lake Vättern within the Protogine Zone (e.g. Lundqvist 1996, Brander & Söderlund 2009). The particular part of the Protogine Zone that the syenogranite at Värpeshult is located in is designated to the Sveconorwegian orogen, upper part of the Eastern segment (Fig. 2). However, the lack of deformation and metamorphic overprinting of the syenogranite and associated rocks suggest that the imprint of the Sveconorwegian orogeny is only minor, despite the typical Protogine Zone orientation of the foliation seen in the granodioritic gneiss. The structures related to high-grade, ductile deformation is sometimes only assigned to Sveconorwegian deformation or at least seen as the most important event for their development, even south of Lake Vättern (e.g., Stephens et al. 1996, Wikström 2003). This view has earlier been challenged by several workers (e.g., Claeson 2003, Gorbatschev & Bogdanova 2004, Bogdanova et al. 2008), where it was advocated that the Protogine Zone has been a major zone of crustal weakness and where deformation occurred, long before the Sveconorwegian orogeny took place.

The rocks at Grönaberg is reinterpreted and stated above to belong to the same generation as those at Värpeshult, due to the more or less exact same compositional range and metamorphic over-printing. In fact, there are several intrusions within the Protogine Zone assigned to a c. 1.45 Ga age, from Grönaberg towards the south at least as far as south of Kristianstad (Fig. 2), which are well-preserved and show no sign of high-grade metamorphism or ductile deformation. This is also the case for the area around the southern part of Lake Vättern within the Protogine Zone, where the gneissosity is cut by undeformed intrusions (e.g. Lundqvist 1996, Brander & Söderlund 2009).

The pristine pyroxene syenite to quartz syenite north of Virestadsjön is assigned to the 1.22–1.20 Ga generation on mineralogical and lithogeochemical differences with the Värpeshult syenogranite, is just one of several intrusions of this generation of well-preserved rocks that continues towards the south at least as far as south of Kristianstad. To the north within the Protogine Zone, the Vaggeryd syenite is the most prominent 1.22–1.20 Ga intrusion (e.g. Jarl 2002 and references therein).

The rocks at Bastön do have distinct appearance but similar lithogeochemical composition and are coeval with the syenogranite at Värpeshult. The pristine nature precludes any high-grade metamorphism and the xenoliths of strongly foliated Tvings granodiorite show amphibolite facies metamorphism occurred prior to their incorporation in the Eringsboda-type granite.

At all four locations, three well inside the Protogine Zone (Värpeshult-Röckla, Grönaberg, and Virestadsjön) and one well outside (Bastön) but in the regionally deformed Tvings granitoids in the Blekinge-Bornholm province, these c.1.45 Ga rocks show subgreenschist and prehnite-pumpellyite facies, respectively. The syenite at 1.22–1.20 Ga shows deuteric and almost no low-grade metamorphism. This is proof that the Sveconorwegian orogeny may not be inferred to have had a significant impact in this area. Still there is the presence of local, relatively narrow deformation zones but none of the amphibolite facies metamorphism. The high-grade metamorphism seen in the host rocks are the result of older orogenesis than the age c. 1.45–1.44 Ga. Most probably, the amphibolite facies metamorphism is older than 1.45 Ga and several events might have produced the high-grade rocks. An earlier study at Kullaskog and Åboda, c. 40 km north of Värpeshult, a migmatitic gneiss mega-xenolith at Kullaskog recorded a magmatic age of 1 770±12 Ma (Möller et al. 2005). Two generations of metamorphic rim overgrowth on the magmatic zircon were reported, inner rims formed at 1 685+11/-10 Ma Ga and outer rims at 1 414±21 Ma, respectively (Möller et al. 2005). At the Åboda locality a K-feldspar megacryst-bearing granitoid, with up to 50 mm tabular megacrysts was suggested to have formed at c. 1.45 Ga but has since been dated at c. 1.70 Ga (SGU unpublished SIMS data).

This data show that within the southern part of the Protogine Zone, at least from the area of Kullaskog-Åboda to within Skåne, the high-grade metamorphism and ductile deformation are the result of older orogenic events than the Sveconorwegian orogeny. Probably several orogenic events, the 1.47–1.38 Ga Hallandian orogen (e.g. Ulmius et al. 2015 and references therein) and an older tectonometamorphic and magmatic event at c. 1.70 Ga are the causes of the high-grade metamorphism and ductile deformation in this part of the Protogine Zone. The well-preserved c. 1.45 Ga intrusions in south-central and eastern Scania, e.g. the Romele granite 1 445±8 Ma (Ulmius et al. 2015), the Beden granodiorite to quartz monzonite 1 464±9 Ma (Petersson et al. 2015), the Stenshuvud intrusion 1 458±6 Ma and the Tåghusa granites 1 442±9 Ma (Čečys et al. 2002), all within the Protogine Zone with N-S dominated older ductile deformation lack high-grade Sveconorwegian overprinting. The area might be better designated to belong to the Hallandian orogen instead of the upper part of the Eastern Segment and that the Protogine Zone is acknowledged as a structural zone of weakness prior to both the Sveconorwegian and Hallandian orogens (cf. Ulmius et al. 2015). This is also in accordance with the results of earlier work for the area around the southern part of Lake Vättern within the Protogine Zone (e.g. Lundqvist 1996, Brander & Söderlund 2009). However, the appearance, orientation and width of the Protogine Zone south of Lake Vättern today, is due to both Sveconorwegian orogenesis and possibly even later once, but the high-grade imprint must be older than c. 1.45–1.44 Ga for the most part. Not recognizing this will lead to misconceptions regarding the older high-grade events within the Protogine Zone, as well as the nature of the imprint that the Sveconorwegian orogeny de facto had in the easternmost part south of Lake Vättern. The efforts for reconstruction of e.g. positions of subduction zones, paths of indenters, tectonic geometries, and extensional versus compressional (where and when) of the Sveconorwegian orogen, need that its boundary problems are recognized and in fact solved prior to a comprehensive model can be trusted. How wide and the nature of the Protogine Zone will most certainly be unattainable since most of it disappeared by erosion when the Eastern Segment rose from the abyss.

Table 3. Summary of sample data.

Rock type	Syenogranite
Lithotectonic unit	Eastern Segment, upper unit of the Sveconorwegian orogen
Lithological unit	
Sample number	DCL040086
Lab_id	NRM TIMS
Coordinates	6286819/461282 (Sweref99TM)
Map sheet	4E Tingsryd NV (RT90)
Locality	Värpeshult
Project	Småland (1101803)

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