The Paleoproterozoic Hedesunda granite complex, east-central Sweden, a composite intrusion

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Abstract

The Hedesunda granite complex covers a rectangular area of ca 800 km² within the Bergslagen lithotectonic unit of the Paleoproterozoic Svecofennian orogen in east-central Sweden. It is dominated by coarse porphyritic and generally undeformed granitoids whose position within the Svecofennian orogenic evolution has been controversial. New U–Pb SIMS dating of zircon confirms earlier TIMS results, showing that it is a composite intrusion made up of an older phase at ca 1865 Ma, forming the bulk of the massif, and a younger phase at ca 1785 Ma, forming a circular intrusion in the north-central area and an elongated body further west. The two generations have very different geochemistry. The older Hedesunda I intrusion ranges from diorite through tonalite and granodiorite to granite in composition, is dominantly metaluminous, calc-alkaline, magnesian, I-type and volcanic arc-related, and probably formed by melting of juvenile Svecofennian lower crust due to basaltic underplating during an extensional ‘intra-orogenic’ phase shortly after the main subduction-related early-orogenic Svecofennian magmatism. The younger Hedesunda II intrusions are purely granitic, dominantly peraluminous, alkali-calcic, K-rich, and ferroan, with A-type and within-plate-type characteristics, and formed penecontemporaneously with post-collisional shoshonitic intrusions in southern Finland, again presumably by crustal melting due to basaltic underplating in an extensional setting towards the end of the Svecofennian orogeny.

Keywords Hedesunda granite massif · Bergslagen · Svecofennian · Sweden · U–Pb dating · Granite geochemistry

Introduction and geological background

The Paleoproterozoic Hedesunda granite complex in east-central Sweden is straddling the boundary between Uppsala and Gävleborg counties along the lower part of the Dalälven river ca 120 km north of Stockholm (Fig. 1). In geological terms, it is located in the Bergslagen lithotectonic unit of the Svecofennian (also known as Svecokarelian) orogenic province (cf. Stephens et al. 2009; Stephens and Andersson 2015; Stephens and Jansson 2020). The Bergslagen region is well known for its iron and sulphide ore deposits, formed in close connection with felsic volcanism around 1900 Ma

ago, and mined continuously from the Middle Ages (and possibly earlier) to present time.

Modern and exhaustive descriptions of the geology of the Bergslagen region are found in Stephens et al. (2009) and Stephens and Jansson (2020), including summaries of geochemical and geochronological data. Most of the currently exposed crust formed in connection with subduction-related magmatism at 1.91–1.87 Ga, including ore-bearing felsic to intermediate metavolcanic rocks and associated metasediments, as well as early-orogenic intrusive rocks [the 1.91–1.87 Ga Granitoid–Dioritoid–Gabbroid (GDG) suite of Stephens et al. (2009)]. This was followed closely by pervasive deformation and low-pressure metamorphism, dominantly in amphibolite facies, with associated migmatization at 1.87–1.85 Ga (Stephens et al. 2009; Stephens and Andersson 2015; Johansson and Stephens 2017; Stephens and Jansson 2020). After an apparently quieter ‘intra-orogenic’ period, there was a second period of metamorphism at 1.82–1.75 Ga, more prevalent further south than in the Hedesunda area (Stephens and Andersson 2015), and intrusion of late-orogenic granites [Granite–Pegmatite (GP) suite

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Fig. 1 Geological bedrock map of the Hedesunda area from the digital map service of the Geological Survey of Sweden (SGU; <https://apps.sgu.se/kartvisare/kartvisare-berggrund-1-miljon.html>), with location of analysed samples [labelled symbols=this study; unlabelled symbols=samples from the SGU database; mafic rock samples 1, 3a, and 3 from Rutanen and Andersson (2009)]. Also shown are obtained U-Pb ages from the area (references: 1=Persson and

Persson 1997; 2=Bergman et al. 2004; 3=Stephens et al. 2009; 4=Johansson and Stephens 2017; 5=This study). GDG Granite–diorite–gabbro suite of Stephens et al. (2009), GP Granite–pegmatite suite of Stephens et al. (2009). Inset map of Sweden shows the location of the Hedesunda area and the recent subdivision of the Svecofennian province (aka Svecokarelian province) in Sweden into different lithotectonic units by the Geological Survey of Sweden

of Stephens et al. (2009)], at least in part considered to be of crustal anatectic origin.

In addition to the early-orogenic GDG magmatism and the late-orogenic GP magmatism, Stephens et al. (2009) also introduced the term Granitoid–Syenitoid–Dioritoid–Gabbroid (GSDG) magmatism for rocks following a more alkali-rich trend. Such rocks formed during three periods, at 1.87–1.84 Ga, 1.81–1.78 Ga, and 1.70–1.67 Ga, with the last two periods confined to rocks belonging to the Transscandinavian Igneous Belt (TIB) west of the Bergslagen region proper (TIB-1 and TIB-2 rocks, respectively), and the first period encompassing rocks in the border zone to the Transscandinavian Belt (TIB-0 rocks), but also including the older phase of the Hedesunda granite complex.

While the early-orogenic phase is generally considered to be accretionary and subduction-related, the late-orogenic phase has traditionally been regarded as collision-related. In more recent plate tectonic interpretations, it is often associated with oblique collision between Fennoscandia and Sarmatia from the present southeast (e.g. Bogdanova et al. 2015). However, Hermansson et al. (2008) presented a purely accretionary scenario involving tectonic switching between compressional and extensional episodes during the whole orogenic evolution, a model also favoured by Stephens et al. (2009) and Stephens and Jansson (2020). The latter divide the evolution into three overlapping tectonic cycles, at approximately 1.91–1.86 Ga, 1.87–1.81 Ga, and 1.82–1.75 Ga, each involving magmatism and at least the two first also involving deformation and metamorphism.

The Hedesunda granite complex

The Hedesunda granite complex has the shape of a somewhat skewed rectangle extending E–W for about 40 km and N–S about 20 km, i.e. covering a surface area of ca 800 square kilometres (Fig. 1). It is surrounded by orthogneisses belonging to the early-orogenic 1.91–1.87 Ga GDG suite of Stephens et al. (2009), plus smaller areas with gneisses presumed to be of volcanic origin, ‘migmatite granite’, and mafic intrusions. The rocks of the Hedesunda complex vary from grey to pink or red in colour and are dominantly coarse-grained and porphyritic with large rectangular feldspar megacrysts. They show little or no signs of deformation, apart from some shearing along the northern boundary of the massif, with alignment of elongated feldspar megacrysts instead being of magmatic origin. The Hedesunda granite massif thus stands out from the surrounding early-orogenic Svecofennian granitoids, which are pervasively deformed. However, it is also different from the late-orogenic (1.82–1.75 Ga) Svecofennian Granite–Pegmatite (GP) suite, since its rocks have more varied intermediate to felsic compositions.

This has led to considerable uncertainty about the age and tectonic position of the Hedesunda granite within the Svecofennian orogenic evolution. U–Pb dating (by TIMS) has given two sets of ages. A quartz monzodioritic sample close to the southern rim of the massif has given a U–Pb zircon age of 1869 ± 9 Ma (Bergman et al. 2004), and a granitic sample close to its eastern rim a zircon + titanite age of 1863 ± 16 Ma (Stephens et al. 2009). On the other hand, Persson and Persson (1997) obtained a U–Pb zircon + titanite age of 1782 ± 5 Ma from a granite sample from the central part of the massif. This has led to a division of the granite complex into two different intrusions (Stephens et al. 2009), an older phase with an age of 1.87–1.86 Ga (Hedesunda I), only marginally younger than the surrounding GDG granitoids, but referred to as having a more alkali-rich GSDG geochemistry, and a younger phase with an age of ca. 1.78 Ga (Hedesunda II), tentatively assigned to the GP (Granite–Pegmatite) suite.

However, the geographic subdivision of the Hedesunda granite complex into these two different granite intrusions remains uncertain, at least in part reflecting bad exposure in this flat-lying and forested area. In their overview map of Bergslagen, Stephens et al. (2007) assigned almost the whole northwestern part of the massif (NW of Dalälven) to the younger GP phase, and the southeastern part to the older GSDG phase. However, on the more detailed 1:50,000 maps (Delin and Söderman 2005a, b; Bergman and Söderman 2005a, b), the younger phase is more restricted to two areas in the north-central and northwestern parts, largely based on geophysical interpretation, especially the aeromagnetic pattern. In the north-central part, there is a low-magnetic circular area with an outer diameter of 9–11 km, interpreted as young Hedesunda II granite (dated in this area to 1782 ± 5 Ma), which is surrounded by a high-magnetic rim (interpreted as old Hedesunda I granite) and has a high-magnetic area in its centre (also interpreted as old Hedesunda I granite; cf. Fig. 1). Further west, there is an elongated (ca 11 km long) low-magnetic area straddling the western boundary of the Hedesunda I massif, which was also interpreted as Hedesunda II granite.

To the east of the Hedesunda complex in Fig. 1, there are other granite massifs, such as the Månkarbo granite, which have also been assigned to the late-orogenic GP suite on geological maps, although they have not been dated or studied in any detail. Around Sevallbo at the southern margin of the Hedesunda complex, a special foliated granite variety, referred to as ‘migmatite granite’, was recognized during mapping by Delin and Söderman (2005a). Johansson and Stephens (2017) described it as a ‘diffusely gneissic granodiorite’, and dated it to 1880 ± 4 Ma.

The purpose of the present study is to make a petrographic and geochemical investigation of the whole Hedesunda granite complex, and if possible use geochemical

discrimination to help in delineating the two generations on the map, as well as determine their geochemical variation and discuss their petrogenesis and tectonic setting. Twenty-eight samples covering most of the area in question, as far as the restricted outcrop allowed, have been obtained during field work. These have been studied petrographically and analysed geochemically for major and trace elements. Eighteen of these samples have also been analysed for their whole-rock Sr and Nd isotope composition, in order to determine the origin of their magma. In addition, selected zircons from the three previously dated rock samples have been reanalysed by SIMS (U–Th–Pb) in order to ascertain their age, and by LA-ICP-MS (Lu–Hf) in order to further clarify the magma origins. The new major and trace element data were complemented by earlier data obtained from the geochemical database of the Geological Survey of Sweden (SGU) from the same area, including samples assigned to one or the other of the two Hedesunda granite generations, as well as a few samples from neighbouring granitoid units.

Field observations and sampling

Differences in field appearance between the two granite generations are very subtle, and it is not strange that they were not separated in earlier mapping of the area (Sandegren and Asklund 1948; Sandegren and Lundegårdh 1949). Furthermore, no contacts have been observed, neither between the two granite generations nor with the surrounding bed-rock units.

Rocks assigned to the older Hedesunda I generation on more recent maps (Bergman and Söderman 2005a, b; Delin and Söderman 2005a, b) are grey to pink in colour, mostly coarse and porphyritic with elongated rectangular K-feldspar megacrysts, sometimes displaying magmatic alignment (Fig. 2a–c). The variation in colour reflects a variation in composition, from intermediate to felsic. Mafic enclaves are sometimes observed (Fig. 2b). Smaller bodies with mafic compositions enclosed within the Hedesunda I granitoids have also been assigned to the same magmatic event (Sandegren and Asklund 1948; Rutanen and Andersson 2009) but have not been included in the present study. Pegmatitic and aplitic dykes are sometimes observed cutting the Hedesunda I rocks (Fig. 2d, e; cf. Sandegren and Lundegårdh 1949) and are believed to represent a late-stage phase of the same magmatic event.

Rocks assigned to the younger Hedesunda II generation are also mostly coarse grained and porphyritic, with pink to reddish colour (Fig. 2f, g, h). They are invariably of felsic composition. Felsic members of the Hedesunda I suite may however look very similar to Hedesunda II rocks, and so may more fine-grained and even-grained varieties of the two suites. A possible distinction between the porphyritic

varieties of the two suites could be that the feldspar megacrysts in the Hedesunda I rocks are more distinct with a regular rectangular shape, whereas the Hedesunda II megacrysts seem to be more irregular in shape and thus be less distinct in appearance, at least in the circular body northeast of Ölbo. The Hedesunda II granite also lacks mafic enclaves as well as aplitic or pegmatitic dykes (Bergman and Söderman 2005a, b; Delin and Söderman 2005a, b).

In the present study, twenty-six samples of Hedesunda granitoid rocks were obtained from natural outcrops and roadcuts, with as large geographical spread over the area as the limited exposure allowed. Based on their field character and position in relation to the subdivision made on the recent SGU maps (Fig. 1), they were either assigned to the Hedesunda I (13 samples) or the Hedesunda II (13 samples) generation. Two foliated samples from the Hedesunda massif close to its northern margin (ÅJ17:26 and 27) were, in spite of their deformed nature, assigned to the Hedesunda I intrusive, based on their positions and petrographic character. One additional sample (ÅJ17:07) from the southern margin of the massif was, however, based on field character and petrographic observations, considered part of the surrounding early-orogenic orthogneisses (Bergslagen GDG suite of Stephens et al. 2009), even though its location in Fig. 1 appears to be inside the Hedesunda massif. In addition, one aplitic dyke, crosscutting the Hedesunda I granite close to its eastern margin but believed to be related to it, was also sampled and analysed (ÅJ17:29), together with the surrounding coarse-grained granite (ÅJ17:28).

Sample localities are marked in Fig. 1, and a list of samples with GPS coordinates is provided in Table 1. Photographs of hand specimen from each of the twenty-eight samples are provided in Online Resource 5.

Analytical methods

Petrography and geochemistry

Polished thin sections were studied in the petrographic microscope in order to determine the mineralogy and texture of the investigated samples. In order to estimate the approximate proportions of major minerals within these samples, powdered whole-rock samples were analysed by XRD, since point counting in single 3 × 2 cm thin sections of such coarse-grained rocks are not likely to give representative results. X-ray powder diffraction data were recorded on a PANalytical X'Pert³ Powder diffractometer equipped with an X'celerator silicon strip detector and operated at 40 mA and 45 kV (Cu K α -radiation, $\lambda = 1.5406$ Å). Peak positions were determined with the X'Pert HighScore Plus 4.6 software, and Bragg peak positions (in 2θ space) were

Fig. 2 Field photographs of Hedesunda I and II rocks. **a** Typical porphyritic Hedesunda I granite of granodioritic composition in road-cut southeast of Söderfors (sample locality ÅJ17:05). Pencil 15 cm. **b** Boulder of intermediate Hedesunda I granite with mafic enclaves. **c** Close-up of Hedesunda I granite at Fäbodsjön (close to sampling locality ÅJ17:17). **d** Aplitic dyke in Hedesunda I granite (sample locality ÅJ17:28 and 29). **e** Aplitic dyke in Hedesunda I granite,

Strömsberg quarry (close to sample locality ÅJ17:30). **f** Typical red-dish coarse-porphyritic Hedesunda II granite north of Bredforsen in Dalälven (sample locality ÅJ17:09). Hammer shaft 50 cm. **g** Hedesunda II granite northeast of Ölbo, close-up of slightly weathered surface (sample locality ÅJ17:13 and LP94:1). **h** Close-up of Hedesunda II granite from the western massif (sample locality ÅJ17:21)

Table 1 List of samples with sample coordinates, Hedesunda granitoid complex, east-central Sweden

Sample no.	Map sheet	Latitude/longitude (GPS)	Rock type
ÅJ17:01	12H NO	60° 18' 59" N/17° 23' 14" E	Hedesunda I granite
ÅJ17:02	12H NO	60° 24' 34" N/17° 19' 46" E	Hedesunda I granite
ÅJ17:03	12H NO	60° 23' 45" N/17° 17' 16" E	Hedesunda I granite
ÅJ17:04	12H NO	60° 23' 32" N/17° 16' 49" E	Hedesunda I granite
ÅJ17:05	12H NO	60° 22' 21" N/17° 16' 17" E	Hedesunda I granite
ÅJ17:06	12H NO	60° 23' 03" N/17° 15' 10" E	Hedesunda I granite
ÅJ17:07	12H NO	60° 20' 11" N/17° 12' 42" E	Gneissic granite (GDG suite)
ÅJ17:08	12H NO	60° 23' 57" N/17° 12' 44" E	Hedesunda II granite
ÅJ17:09	13H SO	60° 25' 15" N/17° 11' 34" E	Hedesunda II granite
ÅJ17:10	13H SO	60° 26' 30" N/17° 11' 50" E	Hedesunda II granite
ÅJ17:11	13H SO	60° 26' 30" N/17° 11' 35" E	Hedesunda II granite
ÅJ17:12	13H SO	60° 26' 27" N/17° 11' 33" E	Hedesunda II granite
ÅJ17:13 ^a	13H SV	60° 25' 13" N/17° 03' 44" E	Hedesunda II granite
ÅJ17:16	12 N NV	60° 23' 27" N/16° 55' 53" E	Hedesunda I granite
ÅJ17:17	13H SV	60° 27' 08" N/16° 58' 00" E	Hedesunda I granite
ÅJ17:18	13H SV	60° 28' 52" N/16° 56' 56" E	Hedesunda II granite
ÅJ17:19	13H SV	60° 28' 57" N/16° 57' 45" E	Hedesunda I granite
ÅJ17:20	13H SV	60° 28' 42" N/16° 57' 14" E	Hedesunda II granite
ÅJ17:21	13H SV	60° 25' 50" N/16° 49' 08" E	Hedesunda II granite
ÅJ17:22	13H SV	60° 26' 18" N/16° 50' 14" E	Hedesunda II granite
ÅJ17:23	13H SV	60° 26' 06" N/16° 43' 58" E	Hedesunda II granite
ÅJ17:24	13H SV	60° 26' 10" N/16° 42' 58" E	Hedesunda II granite
ÅJ17:25	13H SV	60° 27' 36" N/16° 44' 11" E	Hedesunda II granite
ÅJ17:26	13H SO	60° 29' 33" N/17° 19' 02" E	Hedesunda I granite (foliated)
ÅJ17:27	13H SO	60° 28' 59" N/17° 26' 59" E	Hedesunda I granite (foliated)
ÅJ17:28	13H SO	60° 25' 01" N/17° 33' 36" E	Hedesunda I granite
ÅJ17:29 ^b	13H SO	60° 25' 01" N/17° 33' 36" E	Light red aplite dyke
ÅJ17:30 ^c	13H SO	60° 25' 00" N/17° 32' 47" E	Hedesunda I granite

^aSame locality as the dated sample LP94:1 (northeast Ölbo)^bAplite dyke cutting the ÅJ17:28 granite^cSame locality as the dated sample MBS000131A (Strömsberg quarry)

corrected against an external Si metal standard (NIST SRM 640).

The diffractograms were subsequently refined using Rietveld refinement (with X'Pert HighScore Plus 4.6 software), where the following parameters were refined: (1) scale factor, (2) background coefficients (flat background and 5 coefficients), (3) specimen displacement, (4) unit cells for all phases (to account for varying chemistry in solid-solution minerals), and 5) preferred orientations. All diffractograms were refined to residual peaks of less than 0.5%. The results are reported in Table 2.

Powdered whole-rock samples were also sent to Acme Analytical Labs. (Bureau Veritas), Vancouver, Canada, and analysed for major elements by ICP emission spectrometry and for trace elements (including rare earth elements) by

ICP mass spectrometry. The results are reported in Online Resource 2.

In order to complement my own data set, a set of samples with coordinates and geochemical data from the relevant area encompassing the Hedesunda granite complex and its closest surroundings was obtained from the rock chemistry database of the Geological Survey of Sweden (SGU). These samples consist of two subsets of data: samples obtained and analysed as part of the SGU mapping program ($n=27$), and samples obtained and analysed as part of an unpublished geochemical study of the area by Björn Öhlander (Luleå Technical University; $n=41$) that had been incorporated within the SGU database. Based on their geographic position and their classification and character, as could be deduced from the database, these samples were either assigned to the Hedesunda I type ($n=31$), the Hedesunda II type ($n=14$), or some of the surrounding rock units (early-orogenic GDG

orthogneisses, $n=5$; Sevallbo migmatite granite, $n=6$; late-orogenic granite at Månkarbo or east of Tierp, $n=4$; and mafic intrusive rocks related to the Hedesunda complex; $n=2$). The latter samples have also been plotted in some diagrams for comparative purposes. Seven of the SGU samples were discarded because of uncertainty of which rock suite they should be assigned to. The two Hedesunda mafic samples from SGU were complemented by three analyses of similar mafic rocks published by Rutanen and Andersson (2009).

Plotting of the SGU sample data on the same plots as the data obtained in the present study unfortunately caused a substantial increase in scatter which to some extent blurs the results, although the data generally agree and support each other. In part, this scatter may simply reflect that with an increased number of data points, there will be more variation and more outliers. However, it may also reflect that these samples were analysed by different laboratories at different occasions, in some cases perhaps with older and less precise methods. Not all analyses included all trace elements, so for many of the trace element plots only a smaller number of the SGU samples could be used. Furthermore, some of the SGU samples were discovered to include erroneous Eu and Yb values (identical to the Er and Lu values, respectively), so these had to be discarded from REE diagrams and other plots including those elements

Sr and Nd isotope analysis

Eighteen of the twenty-eight rock samples were selected for Sr and Nd isotope analysis, eight representing the Hedesunda I granite and ten the Hedesunda II variety. The analytical work was carried out at the Department of Geosciences of the Swedish Museum of Natural History. Between 80 and 180 mg of rock powder from each sample was dissolved in a 10:1 mixture of concentrated HF and HNO₃, together with a mixed ¹⁴⁷Sm–¹⁵⁰Nd spike, in Teflon capsules at 205°C for a few days. After evaporation and redissolution in 6 M HCl, the solutions were passed through TRU-spec columns for separation of Sr and REE as a group. Strontium was further purified using Sr-spec columns. From the REE solutions, Sm and Nd were separated using Ln-spec columns (Pin and Zalduegui 1997).

Unspiked Sr, and spiked Sm and Nd were loaded on double Re filaments and analysed on a Thermo Triton thermal ionization mass spectrometer (TIMS) in static mode. Corrections for background, spike addition (Sm and Nd), interference, and fractionation were carried out as reported in the footnotes of Tables 3 and 4. The results are reported in Table 3 (Sr) and Table 4 (Nd), together with the results on the NBS SRM987 Sr standard and the La Jolla Nd standard.

U–Th–Pb SIMS analysis

Separated zircon concentrates from the same samples previously analysed by ID-TIMS (isotope dilution thermal ionization mass spectrometry; Persson and Persson 1997; Bergman et al. 2004; Stephens et al. 2009) were obtained from Per-Olof Persson at the Department of Geosciences, Swedish Museum of Natural History. Reasonably well-shaped and clear crystals were selected by handpicking from the non-magnetic 74–106 µm size fraction of all three samples, mounted in epoxy and polished in half to reveal their inner structure. This structure was studied and documented both in reflected and transmitted light in a petrographic microscope, and in CL (cathodoluminescence) using a Philips XL30 ESEM-FEG scanning electron microscope prior to analysis. Subsequent to the SIMS analysis, the analysed zircon crystals and spot locations were documented in reflected and transmitted light (combined), CL (better quality combined SEM-CL images using the Philips scanning electron microscope), and by BSE (back-scatter electron) on a FEI Quanta 650 FEG scanning electron microscope. BSE images with spot locations and obtained ²⁰⁷Pb/²⁰⁶Pb ages and Th/U ratios of all analysed zircons are provided in Online Resources 6–8, and similar SEM-CL images in Online Resources 9–11.

The U–Th–Pb isotopic analysis (with 20 µm spots) was carried out at the Nordsim facility at the Swedish Museum of Natural History in Stockholm, using a Cameca 1280 Secondary Ion Mass Spectrometer (SIMS). The analytical procedure followed Whitehouse et al. (1999) and Whitehouse and Kamber (2005), with the calibration scheme of Jeon and Whitehouse (2015). The 91500 zircon standard with an accepted age of 1065 Ma (Wiedenbeck et al. 1995) was used as a reference. Common Pb was assumed to have been introduced principally during preparatory work and corrections were made for the present-day composition of common Pb using the values provided by Stacey and Kramers (1975). The U–Th–Pb analytical data are presented in Online Resource 1. Age calculations were carried out using the Isoplot/Ex 4.15 (Ludwig 2003). Ages are reported in the text with 2σ uncertainties, excluding decay-constant errors.

Lu–Hf LA-ICP-MS analysis

Lu–Hf isotope composition was analysed from the majority of the zircon grains analysed for U–Th–Pb, using a Nu Plasma II Multicollector ICP-MS coupled to an ESI NWR193UC excimer laser ablation system at the Vega-center facility of the Swedish Museum of Natural History in Stockholm. Details of the analytical procedure have been outlined by Robinson et al. (2018). All ¹⁷⁶Hf/¹⁷⁷Hf ratios were normalized to the primary reference zircon Mud Tank (Woodhead and Hergt 2005). For quality control, zircon reference materials Temora, Plesovice, and FC1 were analysed

alongside the samples and the results were compared to their reported values. $^{176}\text{Hf}/^{177}\text{Hf}$ for these zircons were 0.282663 ± 0.000047 ($n = 11$, 2σ), 0.282477 ± 0.000019 ($n = 10$, 2σ), and 0.282172 ± 0.000040 ($n = 10$, 2σ), respectively.

The analytical results are reported in Online Resource 3. Positions of the analysed ca 50 μm spots and the obtained initial ε_{Hf} values have been indicated on the BSE and CL images of respective zircon in Online Resources 6–11.

U–Pb age determination results

Sample MBS000131A, Strömsberg quarry (eastern part of the Hedesunda complex)

Sample MBS000131A comes from the Strömsberg quarry in the eastern part of the Hedesunda complex northeast of Tierp (coordinates $60^\circ 25' 02'' \text{N}/17^\circ 32' 46'' \text{E}$). According to the original description, it is a coarse-grained granitic to quartz monzonitic rock, which has been intruded by fine-grained granite and pegmatite (Stephens et al. 2009). Zircon and titanite were separated and analysed by ID-TIMS at the Swedish Museum of Natural History, with the results being reported in an appendix to Stephens et al. (2009). A discordia line encompassing all three analysed zircon fractions and three titanite fractions yielded an upper intercept age of 1863 ± 16 Ma (when forced through 0 ± 400 Ma), considered to represent the magmatic crystallization age. Four additional titanite fractions plotted to the left of the discordia line with $^{207}\text{Pb}/^{206}\text{Pb}$ ages down to 1811 Ma, indicating post-magmatic disturbance.

The zircon crystals handpicked from this sample for the present SIMS analysis were of somewhat variable quality. They were dominantly prismatic but somewhat rounded, varying from relatively clear to dark, turbid, and fractured. Magmatic (oscillatory) zonation was visible in the light microscope, as well as core-like structures and overgrowths, which, however, seemed to represent different magmatic pulses when seen in CL and BSE, rather than inheritance and metamorphism, respectively.

In BSE, the investigated zircons mostly showed coarse and faint zoning in various shades of grey. Some of the zircon crystals, especially the very elongated Zr07 and Zr11, have narrow BSE-dark metamict zones (presumably U rich) parallel to the magmatic growth zonation (BSE images in Online Resource 6). In CL, the zircons show much more variation than in BSE. Textures range from homogeneous CL-grey (especially in zircon interiors), thinly CL-zoned (oscillatory magmatic zonation), striped appearance in very elongated crystals to irregular and patchy (CL images in Online Resource 9). Thin CL-dark metamict zones are sometimes seen, but less so and not as clearly as in BSE. A few

zircons (Zr24, 30, 38) have a discontinuous CL-dark outer rim that may be of metamorphic origin. In Zr02, 17, 25 and 39 (and Zr19 in BSE), this CL-dark (presumably U rich) rim grows out into larger irregular areas in part replacing the original magmatic zircon. In BSE, the corresponding areas are bright, but not as sharply delineated and well seen as in CL.

Twelve spots in twelve zircons were analysed by SIMS. Six of these spots, ranging from concordant to 10% normal discordant, form a discordia line with an upper intercept of 1862 ± 7 Ma (lower intercept at 276 ± 220 Ma, MSWD 0.77; Fig. 3a). Forcing the discordia line through the origin will change the upper intercept age only marginally to 1858 ± 6 Ma, identical to the weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of those six points (MSWD 1.7). The 1862 ± 7 Ma upper intercept age, which is almost identical to the previous U–Pb zircon + titanite TIMS age, is taken as the best estimate of the magmatic crystallization age of the Hedesunda granite in the Strömsberg quarry. It is noteworthy that this age is identical to the metamorphic U–Pb monazite age of 1863 ± 1 Ma from a highly foliated grey migmatitic gneiss along the eastern margin of the Hedesunda complex ca. 2 km east of the Strömsberg quarry reported by Johansson and Stephens (2017).

The remaining six spot analysis, however, fall to the left of the discordia with a degree of discordance ranging from -3 to -17% and $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1814 to 1701 Ma (Online Resource 1, Fig. 3a). This is similar to the pattern of the previous U–Pb titanite analyses described above, and could be taken to indicate metamorphic recrystallization. However, all of these spots are in texturally magmatic zircon and have magmatic Th/U ratios similar to the spots falling along the discordia line (Th/U of 0.40–0.82; Online Resource 1, Fig. 3a). In the Th vs. U diagram (Fig. 3a), all twelve analyses fall on a similar magmatic differentiation trend. Also, no metamorphic or magmatic activity younger than ca. 1780 Ma is known in the area, making the youngest $^{207}\text{Pb}/^{206}\text{Pb}$ ages down to 1700 Ma difficult to explain by metamorphic resetting. These apparently disturbed spots seem to have hit fractures, or in some cases (Zr11, Zr13) metamict zones, and may have undergone a combination of ancient and more recent Pb loss, that, however, left their Th–U systems intact. These spots have thus been classified as ‘magmatic/altered’ in Online Resource 1. Areas in Zr02, 17, 19, 25, and 39 that seem to consist of secondary replaced zircon in CL or BSE (cf. Zr02 and 25 in Online Resources 6 and 9) were only observed after the SIMS analysis and were hence unfortunately not analysed. Nevertheless, they are an additional sign of post-magmatic disturbance in these zircons.

Sample HLD020767A, south of Sevallbo (southern part of the Hedesunda complex)

Sample HLD020767A is a quartz monzodioritic rock (Delin and Söderman 2005a) from the lobe of the Hedesunda granite complex extending south of Sevallbo at its southern margin. Zircon was separated and analysed by ID-TIMS at the Swedish Museum of Natural History, with the results being reported in abstract form as ca. 1.87 Ga by Bergman et al. (2004). The age was subsequently specified to 1869 ± 9 Ma by Delin and Söderman (2005a) and Stephens et al. (2009), but without giving any additional analytical details. According to P-O Persson (pers. comm. 2019), this age was based on the upper intercept of a discordia through four slightly discordant zircon fractions and forced through the origin.

The zircons handpicked from this sample for SIMS analysis were generally of superior quality compared to those from the Strömsberg quarry, being prismatic and relatively clear, with oscillatory zoning visible in transmitted light.

In BSE, the analysed zircons mostly show a coarse and faint zoning in various shades of grey, similar to the previous sample (BSE images in Online Resource 7). Some fractures are seen at the surface, but less than in that sample, and no metamict bands or patches. The zircons in the HLD sample are also clearer and less turbid than the zircons in the previous sample. There are no inherited cores seen, nor any metamorphic rims or replacement structures.

As in the previous sample, much more detail is seen in the CL images than in the BSE images from the present zircons. They dominantly show magmatic oscillatory zoning in various shades of CL-grey or CL-bright, sometimes with more homogeneous CL-grey central areas of grains (probably an effect of not cutting across the centre of a crystal, but along one growth zone), and occasionally a bit more irregular and patchy appearance (CL images in Online Resource 10). In very elongated zircon crystals, the oscillatory zoning may give a striped appearance both in CL and BSE. As in BSE, there are neither any inherited cores nor any metamorphic rims or replacement structures seen, but they all seem to have a simple magmatic history.

Sixteen spots in sixteen zircons were analysed (Online Resource 1). In keeping with their simple magmatic appearance, fifteen of them plot concordantly and yield a concordia age of 1865 ± 4 Ma (MSWD 0.34; Fig. 3b), within error identical to the previously obtained TIMS age, and interpreted to date the magmatic crystallization of this rock. The Th/U ratios fall between 0.45 and 0.92, with the Th and U concentrations following a magmatic differentiation trend similar to that in the previous sample (Fig. 3b).

Sample LP94:1, northeast of Ölbo (north-central part of the Hedesunda complex)

Sample LP94:1 is a coarse-grained granite from a roadcut 1250 m NE of the village Ölbo in the north-central part of the Hedesunda complex, within the low-magnetic circular anomaly that would subsequently be designated as a separate intrusion (Delin and Söderman 2005b), here referred to as Hedesunda II granite. Zircons and titanite were separated and analysed by ID-TIMS at the Swedish Museum of Natural History, with the result being published by Persson and Persson (1997) together with major and trace element data on the sample. One concordant titanite fraction and three (out of four) discordant zircon fractions together defined a discordia with an upper intercept age at 1782 ± 5 Ma, taken by the authors as the magmatic crystallization age.

Zircons handpicked for the present SIMS analysis were prismatic but somewhat rounded, varying from relatively clear to dark and turbid, with magmatic (oscillatory) zonation visible in transmitted light. As reported by Persson and Persson (1997), cores were relatively common. Some of the cores may represent an early magmatic phase, but most of them are rounded and most likely inherited, sometimes with radiating fractures in the surrounding mantle, indicating expansion due to metamictization.

In BSE, the selected and analysed zircon grains had various shades of grey, without any very obvious zonation (BSE images in Online Resource 8). BSE-dark zones and patches were, however, observed in many of the zircons. With the exception of the core in Zr44, these areas do not show up in CL as being dark and are hence probably not metamict, but instead U-poor (none of these areas were analysed for U–Th–Pb by SIMS). The very distinct BSE-dark core in Zr44 is surrounded by radiating fractures and dark also in CL, and hence metamict.

In CL there is more variation. Some zircon grains show distinct oscillatory magmatic zonation which is mostly CL-bright (U-poor), whereas others (also of magmatic appearance) are homogeneously CL-grey. Still others have irregular and patchy CL-patterns, especially those with inherited cores, suggesting later disturbances (CL images in Online Resource 11). Several zircon grains have CL-dark (or dark grey) patches and irregular areas, but with the exception of the Zr44 core, these do not match with the BSE-dark areas in the same grains, but rather with BSE-bright areas, suggesting that these are not metamict areas, but U-rich irregular zones, possibly affected by post-magmatic alteration.

In summary, these are the texturally most complex Hedesunda zircons out of the three samples investigated, since they both contain abundant inherited cores, a dominant magmatic phase, and parts of zircon crystals that appear to have undergone some sort of post-magmatic alteration with irregular U-rich (BSE-bright and CL-dark) or U-poor

(BSE-dark) areas, even though the rock as such is non-metamorphic. None of the latter areas have been analysed, so the age of this alteration is unknown. Among the analysed spots ($n = 19$), the U and Th contents are also highly variable and in part very high, the most extreme spot (the core 44a) having almost 12,000 ppm U and more than 7800 ppm Th.

Nineteen spots in sixteen zircon crystals were analysed (Online Resource 1). Four of these spots (10a, 13a, 44a, 48a; Online Resources 1, 8 and 11) represent visible cores, out of which at least the former three were rounded and metamict and interpreted as inherited. All of these were more or less discordant due to metamictization and did not give any useful age information. A fifth spot (32) in the centre of a seemingly normal magmatic zircon yielded a reversely discordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1855 ± 9 Ma and may hence represent inheritance from the Hedesunda I phase. This spot also had a deviating, much higher Th/U ratio (0.96) than the rest of the magmatic zircon (0.26–0.55).

The remaining fourteen spots are all texturally magmatic, but still show some scatter and variable amounts of discordance, partly reflecting high Th and U concentrations. Nine out of them, however, yield a concordia age of 1787 ± 4 Ma (MSWD 1.02; Fig. 3c). An identical upper intercept age can be obtained from twelve concordant or discordant points, with lower intercept around 500 Ma and MSWD 0.83, whereas eight spots yield a weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1785 ± 3 Ma (MSWD 0.54). The concordia age of 1787 ± 4 Ma is taken as the best estimate of the crystallization age of the granite northeast of Ölbö.

Summary of U–Pb dating

The newly obtained U–Pb SIMS ages are within error identical to the previous TIMS ages from the same samples and thus confirm the earlier ages. Both sets of age data have been inserted on the geological map shown in Fig. 1, together with recently published U–Pb zircon or monazite SIMS ages from immediately surrounding rock units (Johansson and Stephens 2017).

It is thus clear that the Hedesunda granitoid complex is a composite intrusion, consisting of an older Hedesunda I suite with an age of ca 1865 Ma, and a younger Hedesunda II granite with an age of ca 1785 Ma, i.e. an age difference of ca 80 million years. The Hedesunda I suite is only marginally younger than the surrounding ca 1.91–1.87 Ga early-orogenic GDG orthogneisses, which, however, have not been dated in the immediate vicinity. It shows little or none of the pervasive regional deformation that has affected the surrounding GDG suite, although its magmatic age overlaps with the 1875–1850 Ma range inferred for early Svecofennian metamorphism in east-central Sweden (Johansson and Stephens 2017 and references therein).

The age of the Hedesunda I suite is also marginally younger than the 1880 ± 4 Ma Sevallbo migmatite

Fig. 3 **a** U–Pb concordia diagram for SIMS analyses from sample MBS000131A from Strömsberg quarry. Shaded ellipses are included in the age calculation. In the diagrams of Th/U vs. $^{207}\text{Pb}/^{206}\text{Pb}$ age, and Th (ppm) vs. U (ppm) to the right, the dark symbols represent points included in the age calculation. **b** U–Pb concordia diagram for SIMS analyses from sample HLD020767A from south of Sevallbo. Shaded ellipses are included in the age calculation; small coloured ellipse marks the concordia age (2σ error). In the diagrams of Th/U vs. $^{207}\text{Pb}/^{206}\text{Pb}$ age, and Th (ppm) vs. U (ppm) to the right, the dark symbols represent points included in the age calculation (all but no. 01). **c** U–Pb concordia diagram for SIMS analyses from sample LP94:1 northeast of Ölbö. Shaded ellipses are included in the age calculation. In the diagrams of Th/U vs. $^{207}\text{Pb}/^{206}\text{Pb}$ age, and Th (ppm) vs. U (ppm) to the right, the dark symbols represent points included in the age calculation

granite at its southern rim, and a nearby felsic dyke dated at 1872 ± 2 Ma (Johansson and Stephens 2017). The Sevallbo migmatite granite is also more deformed and should probably be regarded as a variety of the surrounding GDG orthogneisses, rather than an early phase of the Hedesunda granitoid complex. The nearby felsic dyke, on the other hand, may be an early precursor of the Hedesunda I magmatism.

The Hedesunda II granite at 1785 Ma falls within the wide age range of late-orogenic Svecofennian GP intrusives within the Bergslagen lithotectonic unit (ca 1.85–1.75 Ga; compilation in Stephens et al. 2009, see also later discussion), as well as penecontemporaneous GSDG intrusives within the Transscandinavian Igneous Belt (1.81–1.78 Ga, op. cit.).

Petrography

The mineralogy and texture of all twenty-eight rock samples used for whole-rock geochemistry have been studied in thin section, with some representative microphotographs shown in Fig. 4. Furthermore, the approximate modal proportions of the major minerals in all samples were determined through XRD analysis of whole-rock powders. The results are listed in Table 2 and illustrated in Fig. 5, with the samples being subdivided and sorted into inferred Hedesunda I and Hedesunda II granites (13 each), plus one sample of the surrounding GDG orthogneiss (ÅJ17:07), and one aplite dyke sample (ÅJ17:29).

All Hedesunda samples are dominated by quartz, K-feldspar, and plagioclase in variable proportions, plus some amphibole and/or biotite. The Hedesunda I samples show more variation in their modal compositions, with quartz content ranging from 17 to 39%, and up to 19% mafic minerals in the intermediate members of this suite. The Hedesunda II samples are more homogeneous, with quartz ranging from 30 to 40%, and only a couple of percent of amphibole and biotite. In some Hedesunda I or Hedesunda II samples, the mafic minerals only occur as minor constituents, and in a few cases, no amphibole at all was detected in the XRD analysis, possibly due to heavy alteration, as observed in thin section.

Fig. 4 Microphotographs of selected thin sections. All photos are at the same magnification (1 mm scale bar). The photos in the left-hand column are with parallel nicols, the ones to the right show the same area with crossed nicols. **a** Sample ÅJ17:01 Hedesunda I granodiorite. **b** Sample ÅJ17:03 Hedesunda I granite. **c** Sample ÅJ17:05 Hedesunda I granodiorite. **d** Sample ÅJ17:13 Hedesunda II granite. **e** Sample ÅJ17:20 Hedesunda II granite. Mineral abbreviations: *qz* quartz, *plag* plagioclase, *kfsp* K-feldspar, *amph* amphibole, *bi* biotite, *ti* titanite, *all* allanite, *opq* opaques

The aplitic dyke sample has a modal composition similar to the more felsic Hedesunda I samples, or the Hedesunda II ones. The single GDG orthogneiss sample stands out by containing very little K-feldspar and no amphibole but only biotite (plus minor oxides) as mafic phase (Table 2, Fig. 5a).

If the proportions of quartz, K-feldspar, and plagioclase are plotted in a QAP diagram of Streckeisen (1976), the Hedesunda I samples range from granodiorite to monzogranite in composition, the Hedesunda II samples are purely monzogranitic, the aplite dyke sample is also monzogranitic, and the single sample of GDG orthogneiss plots as tonalite (Fig. 5b).

When it comes to minor or accessory constituents, titanite, apatite, and oxides were noted in most thin sections, zircon in about half of them, and pyrite in a few samples (Table 2). Titanite is a rather frequent constituent both in the Hedesunda I and in many of the Hedesunda II samples, as aggregates together with amphibole and biotite, or as 1–2 mm large euhedral single grains. Epidote is mentioned as a minor constituent in these rocks in the map descriptions by Sandegren and Asklund (1948) and Sandegren and Lundegårdh (1949) and presumably occurs in many of these samples, although it was not observed in the studied thin sections. Allanite is also mentioned by these authors, and was observed here as up to 2 mm long well-shaped euhedral brown crystals (but often heavily altered) in almost all of the Hedesunda II samples, but in only two if the rocks classified as Hedesunda I granite. Although perhaps not diagnostic in separating these granite types, it is thus more typical for the Hedesunda II variety.

The amphibole is green to blue-green in colour; biotite ranges from pale brown to brownish green under the microscope. Both minerals are variably altered, biotite more so than amphibole, and has been grouped together with secondary chlorite as shown in Table 2 and Fig. 5a. According to the map descriptions (Sandegren and Asklund 1948; Sandegren and Lundegårdh 1949), the K-feldspar megacrysts in the Hedesunda rocks consists of microcline or microcline perthite. However, in the present investigation, only limited microcline twinning was seen. It is normally quite fresh, unlike the plagioclase which appears heavily altered. In several of the Hedesunda II samples, there is a very clear distinction between fresh and unaltered K-feldspar and heavily altered plagioclase in the thin sections, the latter sometimes containing fine brown hematite dusting. The presence of hematite dusting in the plagioclase is also pointed out by Sandegren and Lundegårdh (1949). From this, it thus appears that much of the red colouring, at least in the Hedesunda II variety, is due to hematite dusting in the plagioclase rather than in the K-feldspar. In the Hedesunda I rocks, the plagioclase alteration is more patchy and irregular, leaving some areas relatively intact.

Major and trace element geochemistry

Major and trace element data, including rare earth elements, from the investigated samples are reported in Online Resource 2 and illustrated in Figs. 6, 7, 8 and 9. In most of these figures, data points from the geochemistry database of SGU from the same area have also been plotted. These include both samples classified as Hedesunda I and II, as well as some samples from the surrounding granitoids, as discussed above. Furthermore, five samples of mafic rocks believed to be related to the Hedesunda I massif, two from the SGU database and three from Rutanen and Andersson (2009), have also been included in some of these plots.

Major and trace element classification

In the Total Alkali–Silica (TAS) diagram of Middlemost (1994; Fig. 6a), the Hedesunda I samples range from diorite through tonalite and granodiorite to granite, falling on the subalkaline side of the alkaline–subalkaline division line of Irvine and Baragar (1971). The associated mafic samples plot as gabbro or gabbroic diorite. The Hedesunda II samples all plot as true granite. It is noteworthy that the Hedesunda I suite thus follows a tonalitic GDG (granite–diorite–gabbro) trend similar to the surrounding early-orogenic orthogneisses, and not the more syenitic GSDG trend that was proposed for it by Stephens et al. (2009) in their overview of the Bergslagen lithotectonic unit. However, they did not include any geochemical samples from the Hedesunda I rocks in their GSDG group. In the AFM diagram of Irvine and Baragar (1971), the Hedesunda I and II samples follow distinctly separate differentiation trends, which both, however, are calc-alkaline (Fig. 6b). In the P–Q-diagram of Debon and Le Fort (1983), the Hedesunda I samples trend from quartz monzodiorite through granodiorite and adamellite to granite, while the Hedesunda II samples are purely granitic (Fig. 6c).

In the trace element classification diagram of Winchester and Floyd (1977), there is a clear division between the Hedesunda I and Hedesunda II samples, the latter plotting at higher Zr/TiO₂ ratios (Fig. 6d). In the MALI diagram (Modified Alkali–Lime Index; Frost et al. 2001), the Hedesunda I samples mainly follow a calc-alkalic trend, while the Hedesunda II samples range from alkali-calcic to calc-alkalic or even calcic at the high-silica end of the spectrum (Fig. 6e).

In terms of K₂O versus SiO₂ (Peccerillo and Taylor 1976; see Fig. 7), the Hedesunda I samples plot as high-K calc-alkaline, whereas the Hedesunda II samples trend into the shoshonitic field. In the A/NK versus A/CNK diagram (Shand 1943; Maniar and Piccoli 1989), the Hedesunda I samples range from metaluminous to peraluminous, whereas the Hedesunda II samples are almost purely peraluminous,

Table 2 Petrographic character of the Hedesunda I and II granitoids and adjacent gneissic granitoid (GDG suite)

Sample no.	Rock type	Rock classification (QAP)	Quartz	Plagioclase	K-feldspar	Amphibole	Biotite/chlorite	Titanite	Allanite	Apatite	Zircon	Oxides	Pyrite	Other
ÅJ17:07	GDG	Tonalite	33.5	54.3	1.5		10.7			x	x	x		
ÅJ17:27	H-I	Granodiorite	17.5	46.5	17.2	5.3	13.5	X	X	x		X		
ÅJ17:04	H-I	Granodiorite	20.6	44.3	19.0	8.2	7.9	X		x	x	x		
ÅJ17:05	H-I	Granodiorite	21.1	49.8	16.6	7.9	2.4	X		x	x	X	X	cpy, cc
ÅJ17:01	H-I	Granodiorite	23.4	50.1	12.5	9.2	4.8	X		x	x	X		
ÅJ17:26	H-I	Granodiorite	25.2	46.9	16.5	9.0	4.6	X		x		X	x	
ÅJ17:19	H-I	Granite	31.5	38.7	27.0	1.8	1.0	X		x		X	X	Epidote
ÅJ17:16	H-I	Granite	32.9	36.4	28.0	1.0	1.6	X	x	x		0.1		
ÅJ17:28	H-I	Granodiorite	34.4	40.3	20.3	1.9	3.1	X		x		X		
ÅJ17:17	H-I	Granite	36.7	32.5	30.3	x*	0.5	x*				x		
ÅJ17:06	H-I	Granite	37.6	30.5	29.7	x*	2.2	X		x	x	X		
ÅJ17:03	H-I	Granite	38.4	24.7	36.4	X*	0.5					x		
ÅJ17:02	H-I	Granite	38.6	32.5	28.7	X	0.2	X		x	x	x		
ÅJ17:30	H-I	Granodiorite	39.1	39.9	18.2	0.7	2.1	X		x		x		
ÅJ17:20	H-II	Granite	30.3	29.7	36.1	X*	3.9		X			X		
ÅJ17:13	H-II	Granite	31.2	29.8	37.5	0.5	1.0	X	X	x				
ÅJ17:25	H-II	Granite	32.0	28.2	36.9	0.8	2.1	X	X*	x	x	x		
ÅJ17:21	H-II	Granite	32.4	29.6	34.5	1.1	2.4	x	x	x		x		
ÅJ17:09	H-II	Granite	32.5	30.9	35.3	0.4	0.9		X*	x	x			Epidote
ÅJ17:24	H-II	Granite	33.7	32.7	31.7	0.5	1.4	X	x	x		x		
ÅJ17:18	H-II	Granite	34.2	33.8	31.6	X*	0.4		x	x				
ÅJ17:22	H-II	Granite	34.2	30.5	32.3	1.2	1.8	X	X	x	x	x		
ÅJ17:12	H-II	Granite	35.5	27.1	35.4	0.6	1.4		x					
ÅJ17:11	H-II	Granite	36.4	24.8	37.8	0.6	0.4		X			x		
ÅJ17:23	H-II	Granite	37.3	30.1	30.5	0.5	1.6	X	x	x		x		
ÅJ17:08	H-II	Granite	37.5	30.4	28.9	X*	3.2	x*		x	x	x		
ÅJ17:10	H-II	Granite	39.9	26.0	32.9	0.5	0.7		X*		x			
ÅJ17:29	Aplite	Granite (aplite)	34.5	34.6	30.0	x*	0.9					x		

Rock type: *GDG* Synorogenic gneissic granitoid of the GDG suite, *H-I* Hedesunda I granitoid, *H-II* Hedesunda II granitoid, *Aplite* Aplite dyke

Rock classification according to the QAP triangle based on XRD data (Fig. 5a)

Samples sorted after rock type, and then after quartz content within each group

Minerals in digits (approximate volume percent): major or minor constituents based on XRD analysis of whole rock powders

X minor constituent observed in thin section, x accessory constituent observed in thin section, * heavily altered

Other: *cpy* chalcopyrite, *cc* calcite

Fig. 5 a Modal mineral composition calculated from XRD analyses of powdered whole-rock samples. For each rock group, the samples have been ordered from the lowest to the highest quartz content. GDG = one sample of the surrounding GDG suite orthogneisses (ÅJ17:07); Apl = one sample of an aplite dyke (ÅJ17:29) cutting the Hedesunda I granite (sample ÅJ17:28). **b.** The same modal data plotted in the QAP (quartz—alkali feldspar—plagioclase) diagram of Streckeisen (1976). The Hedesunda I samples range from granodiorite to monzogranite in composition; the Hedesunda II samples are purely monzogranitic

but still mainly I type ($A/CNK < 1.1$; Fig. 6f). In terms of $FeO/(FeO + MgO)$ versus SiO_2 (Frost et al. 2001), the Hedesunda I samples are magnesian and the Hedesunda II samples are ferroan (Fig. 6g).

Differentiation trends in Harker diagrams

When it comes to major elements versus silica (Fig. 7), the Hedesunda I and II granitoids follow similar differentiation

trends, although the Hedesunda II granitoids have a much more narrow range of SiO_2 (70–78 wt%) than the Hedesunda I granitoids (55–76 wt%, SGU samples included). Most of the major elements decrease with the increasing SiO_2 as normal, Na_2O follows a slightly curved trend, and K_2O increases, but with substantial scatter. However, there are subtle differences in the trends for FeO , MgO , CaO , Na_2O , and K_2O between Hedesunda I and II samples that are more clearly seen in Fig. 6e and g. It is noteworthy that the five

Fig. 6 Rock classification diagrams from chemical analyses. **a** Total alkali–silica (TAS) diagram after Middlemost (1994). **b** AFM diagram after Irvine and Baragar (1971). **c** P–Q diagram after Debon and Le Fort (1983). **d** Classification diagram after Winchester and Floyd (1977). **e** Modified alkali–lime index (MALI) after Frost et al. (2001). **f** A/NK (molar $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$) vs. A/CNK (molar $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) plot after Shand (1943) and Maniar and Piccoli (1989).

g $\text{FeO}/(\text{FeO} + \text{MgO})$ vs. SiO_2 diagram after Frost et al. (2001). In most diagrams, both samples analysed in this study (symbols with solid outlines) and samples from the SGU database plus three mafic rock samples from Rutanen and Andersson (2009) (symbols without outlines) have been included; in diagrams **b** and **c** (AFM and P–Q diagrams) only the samples analysed in this study are plotted for clarity. In diagram **a** (TAS diagram), the gneissic GDG sample and the two gneissic Hedesunda I samples have been labelled with the last digits in their sample number

Fig. 7 Major elements versus SiO_2 for all studied samples from the Hedesunda complex and immediately surrounding rock units [this study, SGU database samples, and mafic rock samples from Rutanen

and Andersson (2009)]. Division lines in the K_2O vs. SiO_2 diagram after Peccerillo and Taylor (1976)

Fig. 8 Selected trace elements versus SiO_2 for all samples from the Hedesunda complex as well as immediately surrounding rock units [this study, SGU database samples, and mafic rock samples from Rutanen and Andersson (2009)]. Some outliers have been labelled with the last digits in their sample number

mafic samples (SiO_2 47–54 wt%), assumed to be related to the Hedesunda I granitoids, plot totally off the Hedesunda I differentiation trend, at least when it comes to Al_2O_3 , TiO_2 , and P_2O_5 , and thus appear not to be co-magmatic with the Hedesunda I granitoid suite.

For trace elements versus silica (Fig. 8), examples both of increasing and decreasing trends, as well as scatter, can be seen. In many cases, however, clear differences are seen between the Hedesunda I and II samples. For Zr and Hf, and to some extent Ga (not shown), the Hedesunda II samples follow a parallel but higher trend (at any given SiO_2 value) compared to the Hedesunda I samples, whereas the opposite is true for Sr and V. For many of the trace elements depicted, the Hedesunda II samples scatter without any well-defined trend, but fall at consistently higher trace element concentrations at the high-silica end of the spectrum than do the Hedesunda I samples. This is true for Rb, Th, U, Y, Nb, La, and Yb as well as for the Rb/Sr ratio.

Trace and rare earth element variation diagrams

Trace and rare earth element variation diagrams for the different sets of samples are plotted in Fig. 9, with the trace element concentrations normalized to N-MORB (Sun and McDonough 1989) and the rare earth element concentrations normalized to chondrite values (Sun and McDonough 1989).

From the older GDG orthogneisses immediately surrounding the Hedesunda granite complex, only four samples (sample ÅJ17:07 and three of the SGU samples) with appropriate trace and rare earth element analysis were available (much more data are available in the SGU database if a wider geographic area would be considered). These four samples are plotted in Fig. 9a1 and a2. They show marked enrichment in LILE (Large Ion Lithophile Elements, i.e. K, Rb, Ba, and Th), and negative spikes in Nb, P, and Ti, as is typical for crustal, subduction-related rocks. In the REE diagram, they show moderate REE enrichment, with variably steep slopes ($(\text{La}/\text{Yb})_N$ 7.2–32) and small to moderate negative Eu anomalies ($(\text{Eu}/\text{Eu}^*)_N$ 0.59–0.86).

The six SGU samples from the Sevallbo migmatite granite at the southern rim of the Hedesunda granite complex did not contain a full set of trace and rare earth element analysis and could thus not be plotted in the above diagrams. One sample from this intrusion, collected, analysed, and dated (to 1880 ± 4 Ma) by Johansson and Stephens (2017), however, has similar trace and rare earth element patterns as

the GDG gneisses as well as the Hedesunda I granitoids (Fig. 9a1 and a2).

From rocks classified as Hedesunda I granitoids, twenty-two samples (13 from this study and 9 SGU samples) with full trace element data were available and are plotted in Fig. 9b1 and b2. The trace and rare earth element patterns for most of the samples are similar to the surrounding GDG orthogneisses, with marked enrichment in LILE, negative spikes for Nb, P, and Ti, moderate enrichment in REE, $(\text{La}/\text{Yb})_N$ varying between 6.8 and 50 (with two outliers at higher values; cf. Online Resource 2), and slightly positive to moderately negative Eu anomalies ($(\text{Eu}/\text{Eu}^*)_N$ 0.52–1.11).

Four highly fractionated siliceous Hedesunda I samples (SiO_2 = 75.0–76.3 wt%), however, stand out with markedly lower REE concentrations. ÅJ17:07 and 17 are low both in LREE and HREE, whereas ÅJ17:02 and 03 are low in HREE only. Three of these samples have anomalous positive Eu anomalies with $(\text{Eu}/\text{Eu}^*)_N$ between 2.0 and 3.9 (cf. diagram in Fig. 8). These positive Eu anomalies are due to strong depletion in the other rare earth elements, normally contained in various accessory minerals, whereas the concentration of plagioclase-hosted Eu is in the same range as in the other samples.

The aplite sample ÅJ17:29 with 74.5 wt% SiO_2 has been plotted in the same diagrams and shows similar characteristics as the normal Hedesunda I samples. K, Rb, and Th are a bit higher, Ba shows a negative spike, and HFSE (High Field Strength Elements) are a bit less enriched, compared to most other Hedesunda I samples, with the negative P, Ti, and Eu anomalies being more marked ($(\text{Eu}/\text{Eu}^*)_N$ 0.52).

Among the rocks classified as Hedesunda II granite, fourteen samples with full and reliable trace element data were available (13 from this study and only one of the SGU samples). These are plotted in Fig. 9c1 and c2. As for most granitoids, the patterns are generally similar, but some differences can be discerned compared to the Hedesunda I rocks. The Hedesunda II rocks are even more strongly enriched in Rb and Th but show a negative spike in Ba, and the negative P and Ti anomalies are much more strongly marked. They also tend to be more strongly enriched in REE, but with more marked negative Eu anomalies ($(\text{Eu}/\text{Eu}^*)_N$ 0.14–0.50) and generally less steep slopes ($(\text{La}/\text{Yb})_N$ 4.6–30).

In the SGU database, there were also four samples from similar young (not dated, but considered late-orogenic) granites to the east of the Hedesunda granite complex, three from the Månkarbo massif southeast of Tierp and one from the area east of Tierp also marked as late-orogenic GP granite on the SGU map, which are plotted for comparative purposes in Fig. 9d1 and d2. Two of the Månkarbo samples have identical trace and rare earth element patterns as the Hedesunda II granitoids, while the third Månkarbo sample and the sample east of Tierp have more or less deviating patterns.

A more general comparison of the surrounding granitoid massifs with the Hedesunda I and II granitoids using all available diagrams shows that the GDG orthogneisses and the Sevallbo migmatite granite in most respects are geochemically similar to the Hedesunda I granitoids and form similar trends in most plots. The late-orogenic Mångarbo granite seems to be more similar to the Hedesunda II granite, as may be expected, and as far as can be deduced from the limited data.

Sr and Nd isotope geochemistry

Eight of the Hedesunda I and ten of the Hedesunda II whole-rock samples were analysed for their Sr and Nd isotope composition, with the results reported in Tables 3 and 4 and illustrated in Fig. 10a and b, respectively.

Given the difference in Rb/Sr ratios between the Hedesunda I and II granitoids noted above, the Hedesunda I samples have substantially lower $^{87}\text{Rb}/^{86}\text{Sr}$ ratios, with one exception below 1. Their initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, calculated at 1865 Ma, fall between 0.7023 and 0.7037 except for in one sample, corresponding to $\varepsilon_{\text{Sr}}(i)$ between 0 and +19, at or slightly above the mantle evolution line (UR in Fig. 10a). The mafic Hedesunda I rock analysed by Rutanen and Andersson (2009) shows a similar initial isotope composition. The somewhat more Rb-rich and Sr-poor sample ÅJ17:03 with $^{87}\text{Rb}/^{86}\text{Sr}$ of 1.644 is somewhat disturbed in its Rb–Sr systematics and yields an anomalously low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.6995, corresponding to $\varepsilon_{\text{Sr}}(i)$ of –40.

The Hedesunda II samples all have $^{87}\text{Rb}/^{86}\text{Sr}$ ratios above 3, with one extreme sample (ÅJ17:18) being as high as 16.6. As is often the case with Rb-rich rocks, their Rb–Sr systematics have been disturbed so that their initial Sr isotope values (calculated at 1785 Ma) scatter widely on both sides of the mantle evolution line, from $^{87}\text{Sr}/^{86}\text{Sr}$ 0.6783 ($\varepsilon_{\text{Sr}}(i)$ –343) to $^{87}\text{Sr}/^{86}\text{Sr}$ 0.7079 ($\varepsilon_{\text{Sr}}(i)$ +78; Fig. 10a).

Normally, more felsic rocks with high Rb/Sr ratios, as the Hedesunda II granitoids, would be expected to have low Sm/Nd ratios. However, in the case of the Hedesunda rocks, the Hedesunda II samples instead mostly have higher Sm/Nd ratios than the Hedesunda I samples, with a dividing line around $^{147}\text{Sm}/^{144}\text{Nd}$ of 0.100.

The Hedesunda I samples thus have $^{147}\text{Sm}/^{144}\text{Nd}$ ratios between 0.0587 and 0.1005. Initial ε_{Nd} (at 1865 Ma) fall in a very narrow range between 0 and +1 (with ÅJ17:03 also here standing out as the lowest value), suggesting a juvenile origin with no variation between intermediate and felsic members of the Hedesunda I suite (Fig. 10b). The mafic Hedesunda I sample analysed by Rutanen and Andersson (2009) plots at a slightly more depleted initial value of +1.4. In terms of Nd model ages, the Hedesunda I granitoid

samples have T_{CHUR} of 1.79 to 1.85 Ga, and T_{DM} (De Paolo 1981) of 2.04–2.11 Ga.

The Hedesunda II samples have systematically higher $^{147}\text{Sm}/^{144}\text{Nd}$ ratios between 0.1005 and 0.1483. Initial ε_{Nd} (at 1785 Ma) fall between +0.4 and +1.8, overlapping or slightly higher than the Hedesunda I samples (Fig. 10b). However, at 1785 Ma, the Hedesunda I samples would have evolved to ε_{Nd} values between 0 and –1. The Sm–Nd systematics thus show that the Hedesunda II granitoids did not originate from remelting of surrounding Hedesunda I rocks, or similar rocks at depth, but their magmas must have contained an additional, more juvenile component. In terms of Nd model ages, the Hedesunda II samples have T_{CHUR} from 1.63 to 1.74 Ga, and T_{DM} (De Paolo 1981) of 1.95–2.06 Ga, with one sample (ÅJ17:18) at 2.17 Ga.

If initial ε_{Nd} is plotted against initial ε_{Sr} (not shown) for the apparently undisturbed samples (seven of the eight Hedesunda I samples, but only one Hedesunda II sample, ÅJ17:22), the data points fall in the upper right quadrant of the diagram, at ε_{Nd} between 0 and +2 and ε_{Sr} between 0 and +20, similar to mafic Svecofennian rocks in the same region in east-central Sweden (Johansson et al. 2012; Johansson and Hålenius 2013; Dahlin et al. 2014; Johansson and Karlsson 2020).

Hf isotope systematics

In order to get further information on the petrogenesis and magma origin of the Hedesunda I and II granitoids, the Lu–Hf isotope composition was analysed by LA-ICP-MS in almost all zircon crystals previously dated by U–Pb in samples MBS000131A, HLD020767A, and LP94:1. Analytical data are listed in Online Resource 3, analytical spots with obtained initial ε_{Hf} values have been marked on the BSE and CL images of the zircons in Online Resources 6–11, and the data are summarized in Fig. 10c. Areas with magmatic-looking zircon was selected for the Hf isotope analysis, avoiding the inherited and highly metamict cores in sample LP94:1.

Since some of the Hf isotope analyses nevertheless are from zircons in samples MBS000131A and LP94:1 that have yielded discordant and younger ages than the accepted crystallization age, the question arises whether to use the average crystallization age for each sample, or the $^{207}\text{Pb}/^{206}\text{Pb}$ age obtained for each individual zircon which is sometimes younger, when calculating its initial ε_{Hf} value. Given that the areas with younger $^{207}\text{Pb}/^{206}\text{Pb}$ ages appear to consist of magmatic zircon, based on their texture and high Th/U ratios, that has been disturbed in its U–Pb systematics, and not newly crystallized metamorphic overgrowths with low Th/U, it was considered appropriate to use the average crystallization age for each rock for all Hf analysis, also those from disturbed zircons, assuming that the more robust

Fig. 9 Trace element variation (left column) and rare earth element variation (right column) diagrams for the Hedesunda complex and immediately surrounding rock units. Normalizing N-MORB and chondrite values from Sun and McDonough (1989). **a** GDG orthogneiss and Sevallbo migmatite granite. **b** Hedesunda I granitoids, plus

one aplite dyke sample. Low REE (and HFSE) samples are marked with the last digits in their sample number in the REE diagram. **c** Hedesunda II granite. **d** Late Svecofennian granite at Månkarbo and east of Tierp (SGU samples only)

Lu–Hf system remained intact during the later disturbance, so that the measured $^{176}\text{Lu}/^{177}\text{Hf}$ ratio can be extrapolated back to the time of original zircon crystallization.

Following that logic, the zircons from the two Hedesunda I samples ($n = 13 + 15$) have moderately depleted initial ε_{Hf} values between +1.1 and +4.4 at 1865 Ma (Fig. 10c). Assuming an average crustal $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0015 (cf.

Table 3 Rb–Sr isotope data for the Hedesunda granitoid complex

No.	Sample no.	Type ^a	Rock classification ^b	Rb (ppm) ^c	Sr (ppm) ^c	⁸⁷ Rb/ ⁸⁶ Sr ^c	⁸⁷ Sr/ ⁸⁶ Sr ± 2σ _m ^d (corrected)	Age (Ma)	⁸⁷ Sr/ ⁸⁶ Sr(<i>t</i>) ^e	ε _{Sr} (<i>t</i>) ^e	T _{UR} (Ga) ^e	f _(Rb/Sr) ^f
1	AJ17-01	HI	Tonalite	66	994	0.1910	0.707490 ± 4	1865	0.70245	2	1.95	1.31
2	AJ17-02	HI	Granite	48	858	0.1615	0.707236 ± 6	1865	0.70297	9	2.44	0.95
3	AJ17-03	HI	Granite	117	206	1.6445	0.742951 ± 5	1865	0.69954	−40	1.74	18.89
4	AJ17-04	HI	Tonalite	50	1257	0.1144	0.705890 ± 5	1865	0.70287	8	3.07	0.38
5	AJ17-08	HII	Granite	210	101	6.0951	0.848326 ± 7	1785	0.69440	−114	1.69	72.70
6	AJ17-09	HII	Granite	178	105	4.9515	0.824434 ± 6	1785	0.69939	−43	1.74	58.87
7	AJ17-10	HII	Granite	160	70	6.7034	0.860130 ± 6	1785	0.69085	−165	1.66	80.06
8	AJ17-12	HII	Granite	172	99	5.0729	0.828588 ± 4	1785	0.70048	−28	1.76	60.34
9	AJ17-13	HII	Granite	171	141	3.5484	0.786206 ± 5	1785	0.69660	−83	1.67	41.91
10	AJ17-16	HI	Granite	78	705	0.3207	0.710805 ± 4	1865	0.70234	0	1.87	2.88
11	AJ17-18	HII	Granite	257	46	16.6175	1.097954 ± 8	1785	0.67830	−343	1.68	199.94
12	AJ17-19	HI	Granodiorite	82	709	0.3343	0.712481 ± 4	1865	0.70365	19	2.23	3.04
13	AJ17-21	HII	Granite	212	180	3.4326	0.793968 ± 6	1785	0.70728	69	1.89	40.51
14	AJ17-22	HII	Granite	184	156	3.4543	0.790399 ± 7	1785	0.70317	11	1.80	40.77
15	AJ17-23	HII	Granite	165	110	4.3779	0.815906 ± 5	1785	0.70535	42	1.83	51.94
16	AJ17-25	HII	Granite	181	109	4.8604	0.830652 ± 4	1785	0.70791	78	1.87	57.77
17	AJ17-28	HI	Granodiorite	54	615	0.2541	0.709697 ± 4	1865	0.70299	10	2.14	2.07
18	AJ17-30	HI	Granite	89	386	0.6698	0.720639 ± 4	1865	0.70295	9	1.94	7.10

^aHedesunda I or Hedesunda II granite^bRock classification according to the Total Alkali—Silica (TAS) diagram^cRb and Sr contents and ⁸⁷Rb/⁸⁶Sr ratio from chemical analyses done by Acme Analytical Laboratories, Vancouver, Canada^d⁸⁷Sr/⁸⁶Sr ratios measured on a Thermo Triton thermal ionization mass spectrometer in static mode, corrected for Rb interference and normalized to ⁸⁶Sr/⁸⁸Sr = 0.1194. Four runs of the NBS SRM 987 Sr-standard during the measurement periods gave ⁸⁷Sr/⁸⁶Sr ratios of 0.710206 ± 5, 0.710212 ± 6, 0.710194 ± 6 and 0.710185 ± 6 (2σ_m), respectively. Because of the systematically low NBS 987 standard values (not only during these analyses), an additional correction of +0.000046 was added to all measured ⁸⁷Sr/⁸⁶Sr ratios, in order to normalize them to a NBS 987 value of 0.710245. Error given as 2 standard deviations of the mean from the mass spectrometer run in the last digits^eε_{Sr}-values (at the given age), and T_{UR} Sr model ages according to McCulloch and Chappell (1982); present-day ⁸⁷Rb/⁸⁶Sr mantle ratio = 0.0827, present-day ⁸⁷Sr/⁸⁶Sr mantle ratio = 0.7045. Initial Sr ratios, ε_{Sr}-values and T_{UR} model ages calculated using newly revised decay constant for ⁸⁷Rb of 1.3972 × 10^{−11} (Villa et al. 2015)^ff_(Rb/Sr) = ((⁸⁷Rb/⁸⁶Sr)_{sample} − (⁸⁷Rb/⁸⁶Sr)_{UR}) / (⁸⁷Rb/⁸⁶Sr)_{UR}, where (⁸⁷Rb/⁸⁶Sr)_{UR} = 0.0827

Table 4 Sm–Nd isotope data for the Hedesunda granitoid complex

No.	Sample	Type ^a	Rock classification ^b	Sm (ppm) ^c	Nd (ppm) ^c	¹⁴⁷ Sm/ ¹⁴⁴ Nd ^c	¹⁴³ Nd/ ¹⁴⁴ Nd ± 2σ _m ^d (corrected)	Age (Ma)	ε _{Nd} (present) ^e	ε _{Nd} (initial) ^e	T _{CHUR} (Ga) ^f	T _{DM} (Ga) ^g	f _(Sm/Nd) ^h
1	AJ17-01	HI	Tonalite	6.42	40.3	0.0962	0.511455 ± 2	1865	−23.1	1.0	1.79	2.06	−0.51
2	AJ17-02	HI	Granite	2.37	24.4	0.0587	0.510998 ± 2	1865	−32.0	1.0	1.81	2.01	−0.70
3	AJ17-03	HI	Granite	4.96	29.9	0.1005	0.511469 ± 3	1865	−22.8	0.2	1.85	2.11	−0.49
4	AJ17-04	HI	Tonalite	5.56	38.1	0.0882	0.511357 ± 3	1865	−25.0	1.0	1.80	2.04	−0.55
5	AJ17-08	HII	Granite	13.5	66.3	0.1232	0.511818 ± 2	1785	−16.0	0.8	1.70	2.06	−0.37
6	AJ17-09	HII	Granite	27.7	154.2	0.1086	0.511696 ± 2	1785	−18.4	1.8	1.63	1.95	−0.45
7	AJ17-10	HII	Granite	18.4	110.7	0.1005	0.511574 ± 1	1785	−20.8	1.3	1.68	1.97	−0.49
8	AJ17-12	HII	Granite	19.5	113.8	0.1034	0.511592 ± 1	1785	−20.4	0.9	1.71	2.00	−0.47
9	AJ17-13	HII	Granite	12.2	69.7	0.1055	0.511617 ± 1	1785	−19.9	0.9	1.70	2.00	−0.46
10	AJ17-16	HI	Granite	5.62	38.6	0.0880	0.511347 ± 1	1865	−25.2	0.8	1.81	2.05	−0.55
11	AJ17-18	HII	Granite	10.1	41.3	0.1483	0.512109 ± 3	1785	−10.3	0.8	1.67	2.17	−0.25
12	AJ17-19	HI	Granodiorite	6.58	41.1	0.0968	0.511461 ± 2	1865	−23.0	0.9	1.79	2.06	−0.51
13	AJ17-21	HII	Granite	19.6	117.6	0.1008	0.511558 ± 2	1785	−21.1	0.9	1.71	2.00	−0.49
14	AJ17-22	HII	Granite	17.0	86.3	0.1190	0.511791 ± 1	1785	−16.5	1.3	1.66	2.01	−0.39
15	AJ17-23	HII	Granite	11.8	61.4	0.1162	0.511728 ± 3	1785	−17.8	0.7	1.72	2.05	−0.41
16	AJ17-25	HII	Granite	14.1	76.0	0.1118	0.511665 ± 1	1785	−19.0	0.4	1.74	2.06	−0.43
17	AJ17-28	HI	Granodiorite	7.95	52.7	0.0913	0.511389 ± 1	1865	−24.4	0.9	1.80	2.05	−0.54
18	AJ17-30	HI	Granite	5.70	38.6	0.0893	0.511356 ± 3	1865	−25.0	0.7	1.82	2.06	−0.55

^aHedesunda I or Hedesunda II granite^bRock classification according to the Total Alkali—Silica (TAS) diagram^cSm and Nd contents and ¹⁴⁷Sm/¹⁴⁴Nd ratio from isotope dilution analysis with combined ¹⁴⁷Sm/¹⁵⁰Nd tracer. Estimated analytical uncertainty of ¹⁴⁷Sm/¹⁴⁴Nd ratio is ±0.5%^dAll Sm and Nd samples measured with a Thermo Triton thermal ionization mass spectrometer in static mode. ¹⁴³Nd/¹⁴⁴Nd ratios calculated from ID run, corrected for Sm interference and normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219. Five runs of the La Jolla Nd-standard during the measurement periods gave ¹⁴³Nd/¹⁴⁴Nd ratios of 0.511872 ± 3, 0.511871 ± 4, 0.511862 ± 3, 0.511862 ± 3 and 0.511859 ± 3 (2σ_{sp}), respectively. Because of the systematically high La Jolla standard values (not only during these analyses), an additional correction of −0.000013 was subtracted from all measured ¹⁴³Nd/¹⁴⁴Nd ratios, in order to normalize them to a La Jolla standard value of 0.511852. Error given as 2 standard deviations of the mean from the mass spectrometer run in the last digits^ePresent-day and initial ε_{Nd} values (at the given age) calculated using a present-day chondritic ¹⁴⁷Sm/¹⁴⁴Nd ratio of 0.1966, and a present-day chondritic ¹⁴³Nd/¹⁴⁴Nd ratio of 0.512638 (cf. Dickin 1995)^fModel age calculated relative to the chondritic uniform reservoir (CHUR) of Jacobsen and Wasserburg (1984) (recalculated as in Dickin 1995)^gModel age calculated relative to the depleted mantle curve (DM) of De Paolo (1981)^hf_(Sm/Nd) = ((¹⁴⁷Sm/¹⁴⁴Nd)_{sample} − (¹⁴⁷Sm/¹⁴⁴Nd)_{CHUR}) / ((¹⁴⁷Sm/¹⁴⁴Nd)_{CHUR} − 0.1966)

Spencer et al. 2020) in the protolith material of the Hedesunda I magma, this would correspond to T_{DM2} model ages in the 2.2–2.4 Ga range, a bit higher than the Nd T_{DM} model ages calculated above.

The zircons analysed from Hedesunda II sample LP94:1 ($n = 15$) have similar to slightly more positive initial ε_{Hf} values at 1785 Ma of +2.5 to +4.8 (Fig. 10c). Using a similar protolith $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0015, this would correspond to T_{DM2} model ages of 2.1 to 2.3 Ga, again a bit higher than the Nd T_{DM} model ages for the Hedesunda II granite calculated above.

Using the Lu and Hf concentrations in the new whole-rock samples of both types, average $^{176}\text{Lu}/^{177}\text{Hf}$ ratios and Hf isotope evolution lines that the Hedesunda I and II samples would have followed after their crystallization can be calculated. The Hedesunda I granitoids then yield a rather low $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0064 ± 0.0027 , whereas the Hedesunda II granitoids yield a more normal crustal $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0152 ± 0.0067 , albeit with considerable scatter around the average value. If whole-rock Hf evolution trends based on these averages are drawn for the Hedesunda I and II granitoids in Fig. 10C, it can be seen that the Hedesunda II magma cannot have formed by pure remelting of Hedesunda I rocks but must contain some more juvenile depleted component, similar to what was deduced based on the Nd isotope data above.

Discussion

Distribution of Hedesunda I and II rocks within the Hedesunda complex

The assignment of samples to the Hedesunda I or II intrusions was based on their location relative to the recent SGU bedrock map (Fig. 1), and their character as observed in the field or deduced from the SGU database. A relatively straightforward and clear geochemical division was then found to exist between the two sample groups, as outlined above. The geochemical subdivision largely confirms the subdivision made between the two granitoid types on the SGU maps (Delin and Söderman 2005a, b; Bergman and Söderman 2005a, b), based on field mapping and aeromagnetics, with a circular Hedesunda II massif in the north-central part and an elongated Hedesunda II massif in the northwestern part, as shown in Fig. 1.

However, a few samples within the Hedesunda I areas have Hedesunda II petrographic and geochemical characteristics, necessitating slight revisions of the map pattern (cf. Fig. 1). This is true for the northwest corner of the Hedesunda I massif close to highway 56, and along the Dalälven river northwest of Söderfors in the central area. However, it

is beyond the scope of this paper to do any actual revision of the geological map.

Tectonic setting and petrogenesis

In Fig. 11, some additional geochemical diagrams are shown, in order to illustrate the differences between the Hedesunda I and II granitoids, as well as adjacent rock units (GDG orthogneisses, Sevallbo migmatite granite, Månkarbo granite, and mafic rocks included within and presumed to be related to the Hedesunda I intrusion).

In Fig. 11a–e, selected major and trace elements have been plotted relative to the immobile trace element Zr, illustrating the different fractionation trends displayed by the two generations of Hedesunda granites. From these diagrams, it is also clear that the above-mentioned mafic rocks do not fall on the same differentiation trend as any of the Hedesunda granitoids. Although they may still be co-genetic with the Hedesunda I granitoids, they do not appear to be co-magmatic but must have originated from a separate magma.

In Fig. 11f–h, the separation between Hedesunda I and II samples when it comes to their concentrations of various large ion lithophile elements, such as Rb, Sr, Ba, and Th, is clearly visible.

In Fig. 11i, j, a compatible element (V and Sr, respectively) has been plotted versus an incompatible (Rb), on a logarithmic scale. In such diagrams, rock suites that have formed by fractional crystallization will dominantly follow steep trends, and rock suites whose variation is mainly due to different degrees of partial melting of their sources will follow flat trends (Cocherie 1986). These diagrams again indicate the differences between the Hedesunda I and II granitoids, and between the former and the related mafic rocks. The mafic rocks display flat trends, suggesting that they formed by different degrees of partial melting of a mantle source, whereas the two granitoid suites display separate steep trends, suggesting fractional crystallization of magmas that may have originated in the lower crust.

In Fig. 12, the investigated rocks have been plotted in various discrimination diagrams. In the diagram of Whalen et al. (1987), the Hedesunda I samples dominantly plot as unfractionated to fractionated I-, S- or M-type granites, although straddling into the A-type field (Fig. 12a). The Hedesunda II samples plot as A-type granite. In the Rb vs. Y + Nb diagram of Pearce et al. (1984), the Hedesunda I samples dominantly plot as volcanic-arc granites, and the Hedesunda II samples as within-plate granites (Fig. 12b). However, the latter samples also fall within the overlapping circular field of post-collisional granites added by Pearce (1996).

Väisänen et al. (2012b) showed that some magmatism in southern Finland towards the end of the synorogenic accretionary stage of the Svecofennian orogeny at ca 1.87 Ga had

Fig. 10 **a** Initial ϵ_{Sr} versus age for the Hedesunda I (H-I) and Hedesunda II (H-II) granitoids, plus one mafic rock sample related to the Hedesunda I intrusion analysed by Rutanen and Andersson (2009). The Hedesunda II samples show considerable scatter due to disturbances of their Rb–Sr systems. **UR** Uniform (mantle) reservoir. **b** Initial ϵ_{Nd} versus age for the Hedesunda I (H-I) and Hedesunda II (H-II) granitoids, plus one mafic rock sample related to the Hedesunda I intrusion analysed by Rutanen and Andersson (2009). **CHUR** Chondritic uniform reservoir, **DM** Depleted mantle according to De Paolo (1981). **c** Initial ϵ_{Hf} for Hedesunda I (H-I) and Hedesunda II (H-II) zircons. **CHUR** chondritic uniform reservoir, **DM** depleted mantle according to Griffin et al. (2000). For the time prior to crystallization and back to the DM curve, evolution lines for the magma sources assuming an average crustal $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.015 (Spencer et al. 2020) are drawn. For the time after crystallization, average evolution lines for the Hedesunda I and II granitoids with $^{176}\text{Lu}/^{177}\text{Hf}$ of 0.006 and 0.015, respectively, based on the average whole-rock Lu/Hf values for each rock unit, are drawn

Fig. 11 **a–e** Selected major and trace elements versus Zr, illustrating the different fractionation trends for the Hedesunda I and II granitoids, as well as the deviation of the mafic Hedesunda I samples from the Hedesunda I granitoid trend, suggesting different magma sources. **f–h** Rb/Sr vs. Th, Th vs. Ba, and Th vs. Sr diagrams, illustrating the separation in large ion lithophile element concentrations and ratios between the Hedesunda I and II granitoids. **i, j** Logarithmic V vs. Rb and Sr vs. Rb diagrams, showing the different trends for the mafic Hedesunda I samples (flat trends caused by different degrees of partial melting in the source), and the intermediate to felsic Hedesunda I and II granitoids (steep trends caused by fractionation; cf. Cocherie 1986; De Souza et al. 2007)

an adakitic character (Defant and Drummond 1990). In the Sr/Y vs. Y diagram, the Hedesunda I samples mainly plot as typical arc rocks, but with a somewhat adakitic tendency (Fig. 12c). However, the two samples plotting highest up in the adakitic field with highly elevated Sr/Y ratios (ÅJ17:02 and 06) have anomalous Sr concentrations, possibly due to some cumulate plagioclase, plotting above the Sr vs. SiO₂ trend shown in Fig. 8. Disregarding those two outliers, the Hedesunda I granitoid cannot really be considered adakitic.

In the ternary Hf–Rb–Ta diagram of Harris et al. (1986), the Hedesunda I samples fall in the volcanic arc granite field (Fig. 12d). The Hedesunda II samples fall in an area where volcanic arc and collision-related granites overlap.

In summary, the Hedesunda I granitoids may be considered I-type, calc-alkaline, magnesian granites formed in a continental arc setting, shortly after the main stage of Svecofennian accretionary magmatism and deformation, possibly during an extensional episode with magmatic underplating triggering melting of the newly formed Svecofennian crust. The Hedesunda II intrusions are A-type high-K calc-alkaline to shoshonitic ferroan granites, formed 80 million years later in a late- to post-orogenic setting.

The Hedesunda I and II granitoids seen in a wider regional context

The new U–Pb SIMS data confirm the earlier U–Pb TIMS ages, indicating that the Hedesunda granitoid massif is a composite intrusion, composed of an early Hedesunda I phase with an age around 1865 Ma, and a much younger Hedesunda II phase with an age at ca. 1785 Ma.

In Fig. 13, the newly obtained Hedesunda I and Hedesunda II ages have been inserted in a diagram of all magmatic U–Pb zircon ages (with an uncertainty less than ± 20 million years) within the whole Bergslagen lithotectonic unit, obtained from the age database of the Geological Survey of Sweden (SGU). The underlying data are shown in Online Resource 4. This may be seen as an update of the diagrams published by Stephens et al. (2009) and follows the same division of rock types: felsic volcanic rocks, GDG (granite–diorite–gabbro) intrusives, GSDG intrusives, and GP (granite–pegmatite) intrusives. In addition, shaded bands

outlining the ranges of metamorphic ages within the Bergslagen lithotectonic unit, as summarized in Johansson and Stephens (2017), have been added.

In this diagram, the narrow range in ages for felsic meta-volcanic rocks in Bergslagen between 1.91 and 1.88 Ga is seen, as well as the overlapping age range for the GDG intrusives, which however extends all the way down to 1.85 Ga. Intrusives assigned to the GSDG group by Stephens et al. (2009) largely overlaps with the younger GDG intrusives at 1.88–1.84 Ga, including intrusions along the southwest margin of the Bergslagen lithotectonic unit (TIB-0), but disregarding much younger intrusives further west (TIB-1). The new Hedesunda I ages have been placed within the GSDG group, following Stephens et al. (2009), but according to the geochemical data presented above they should rather be moved left into the tail of the GDG group, as indicated by the horizontal arrows in the diagram. These emplacement ages overlap with the first group of metamorphic ages from Bergslagen (Metamorphism 1), although most of the regional deformation in the Hedesunda area clearly occurred prior to the intrusion of the Hedesunda I granitoids at around 1865 Ma.

The GP intrusive rocks cover a very wide age range from 1.85 to 1.75 Ga, possibly with some gaps, and largely overlap with the second metamorphic episode in Bergslagen. However, most of the published ages for GP rocks are TIMS ages and should thus be taken with some caution, since they may be affected by inheritance or later disturbances. The Hedesunda II age at around 1785 Ma fall in the middle of this age group. However, just as with the Hedesunda I granitoids, the assignment of the Hedesunda II granite within the GP group may be disputed. Although it has a purely granitic composition, its geochemical characteristics are not those of a typical low-temperature crustal anatectic granite, but rather akin to high-temperature A-type granites.

The Ljusdal lithotectonic unit occurs immediately north of the Bergslagen lithotectonic unit (see inset map in Fig. 1), separated by a system of crustal-scale shear zones that were initiated at 1.87–1.86 Ga and remained active to at least 1.81 Ga (Högdahl et al. 2009), during oblique Sarma-tia–Fennoscandia convergence and collision from the south-east (e.g. Lahtinen et al. 2005, Bogdanova et al. 2015). The Ljusdal unit is dominated by pervasively deformed synorogenic GDG intrusive rocks (Ljusdal batholith) with ages of 1.87–1.86 Ga (Högdahl et al. 2008, SGU geochronological database), younger than the dominant synorogenic magmatism within the Bergslagen unit (1.91–1.87 Ga Bergslagen GDG suite, Stephens et al. 2009), but contemporaneous with the intrusion of the Hedesunda I granitoids within the northern part of the Bergslagen lithotectonic unit, only some 20–30 km south of the tectonic boundary between the two units. However, the distance between the two lithotectonic units may have been much larger at that time, prior to the

Fig. 12 Tectonic discrimination diagrams. **a** Diagram by Whalen et al. (1987), showing the I-type character of the Hedesunda I granitoids, and the A-type character of the Hedesunda II granitoids. *OGT* unfractionated I-, S- and M-type granites, *FG* fractionated granites. **b** Tectonic discrimination diagram for granites by Pearce et al. (1984). *ORG* ocean ridge granites, *VAG* volcanic arc granites, *syn-COLG*

syn-collisional granites, *WPG* within-plate granites, *post-COLG* (Pearce 1996) post-collisional granites. **c** Sr/Y vs. Y diagram from Defant and Drummond (1990), separating adakites from typical arc rocks. **d** Ternary Hf-Rb-Ta discrimination diagram by Harris et al. (1986). *ORG* ocean ridge granites, *VAG* volcanic arc granites, *WPG* within-plate granites, *ColG* collision granites

late Svecofennian oblique convergence and collision with Sarmatia, which displaced the crustal blocks in the southern part of the Svecofennian orogen in a northwestward direction. At 1.87–1.86 Ga, the Ljusdal and Bergslagen lithotectonic units were apparently under different tectonic regimes, with the Ljusdal unit still undergoing synorogenic magmatism and deformation, while the Bergslagen unit had entered an extensional intra-orogenic stage.

In southern Finland, recent research has revealed a phase of bimodal magmatism following shortly after, but clearly separate, from the dominant synorogenic magmatism in that area, including the 1865 ± 9 Ma Rauma diorite and the ca 1850 Ma Korpo diorite and granite (Väisänen et al. 2012a), the 1860 ± 5 Ma Moisio gabbro (Nevalainen et al. 2014), and ca. 1.86 Ga post-kinematic mafic dykes (Kara et al. 2016). This magmatism is referred to as intra-orogenic by Väisänen et al. (2012a) and considered to be caused by basaltic underplating during extension of the newly formed Svecofennian

crust. Similarly, the Herräng mafic dykes in east-central Sweden, although not precisely dated, are considered intra-orogenic and having formed through north–south extension at some time during the 1.87–1.85 Ga period (Johansson and Karlsson 2020, and references therein). Also amphibolitic bodies within the east–west trending Avesta-Östhammar belt (Johansson and Hålenius 2013) and the basic to ultrabasic cumulate rocks in southern Roslagen (Johansson et al. 2012) may be part of the same episode of extensional magmatism, although they have not been dated. The Herräng mafic dyke swarm, the Avesta-Östhammar mafic intrusions, and the southern Roslagen cumulate rocks all occur in the same general area within the Bergslagen lithotectonic unit in east-central Sweden as the Hedesunda granitoid massif. Seen in that perspective, the Hedesunda I intrusion may be the most voluminous example exposed at the present surface of the 1.87–1.85 Ga bimodal intra-orogenic magmatism in east-central Sweden and southern Finland. It is also remarkably

Fig. 13 Summary diagram of magmatic U–Pb ages with an uncertainty less than ± 20 million years within the Bergslagen lithotectonic unit from the geochronological database of the Geological Survey of Sweden (SGU). Data are listed in Online Resource 4. The data points have been subdivided according to rock type, following Stephens et al. (2009): felsic volcanic rocks, granite–diorite–gabbro (GDG) suites, granite–syenite–diorite–gabbro (GSDG) suites, and granite–pegmatite (GP) suites. Green symbols are gabbroic or dioritic rocks within the respective rock suite. The old (TIMS) and new (SIMS) ages from the Hedesunda I and II intrusions have been encircled and marked with red arrows. *TIB-0 intrusives*: rock units with ages around

1.85 Ga along the southwest margin of the Bergslagen lithotectonic unit that are sometimes assigned to the TIB-0 phase of the adjacent Transscandinavian Igneous Belt (TIB). *TIB-1 intrusives*: rock units with ages around 1.8 Ga along the western margin of the Bergslagen lithotectonic unit that are similarly assigned to the TIB-1 phase of the Transscandinavian Igneous Belt. Younger TIB-2 rocks are not included in this diagram. The two shaded bands outline the ranges of metamorphic U–Pb ages (in zircon, titanite or monazite) within the Bergslagen lithotectonic unit, as found in the SGU database and summarized by Johansson and Stephens (2017)

well preserved and little deformed, perhaps not only due to its size but also due to the fact that the Bergslagen area apparently acted as a relatively stable block during the subsequent late Svecofennian tectonism, unlike the situation in southern Finland.

As stated above, the ca 1785 Ma Hedesunda II granite, although falling within the timeframe of the late-orogenic anatectic GP rock suite within the Bergslagen lithotectonic unit, rather has A-type geochemical characteristics. Similar characteristics, however, have been found among a number of late Svecofennian granites in the Bergslagen region, such as the small Mo–W-bearing Pingstaberg, Skålhöjden, Bispbergs klack, and Högberget intrusions (Billström et al. 1988; Sundblad et al. 1993; Bergman et al. 1995; Sundblad and Bergman 1997). Also the larger 1.77–1.78 Ga Lisjö and Fellingsbro granites have similar A-type and within-plate type characteristics and are believed to have formed in an extensional environment above an east–west-trending gravity low (Öhlander and Zuber 1988; Öhlander and Romer 1996).

Through southern Finland, stretching from the Åland archipelago in the west to the lake Ladoga region in Russian

Karelia in the east, there is a belt of relatively small shoshonitic intrusions, referred to as post-collisional (Eklund et al. 1998; Eklund and Shebanov 2005; Andersson et al. 2006; Rutanen et al. 2011), with ages around or somewhat below 1.8 Ga and ranging in composition from ultramafic lamprophyres to peraluminous granites. One of the most well-studied examples is the 1.79–1.76 Ga Åva ring complex in the Åland archipelago (Eklund and Shebanov 2005, and references therein), with a diameter of ca 7 km. Other shoshonitic post-collisional intrusions in the Åland archipelago are the Seglinge, Mosshaga, and Lemland intrusions (Eklund et al. 1998; Eklund and Shebanov 2005). The central Hedesunda II intrusion is also ring-shaped with a comparable diameter (9–11 km) and of similar age, but is solely granitic in composition, whereas the Åland examples contain both granitic and monzonitic rocks and crosscutting lamprophyric dykes. In spite of this difference, the Hedesunda II intrusions may tentatively be considered a Swedish counterpart of this mantle-induced magmatism, although the Hedesunda II magma itself is probably dominantly of crustal origin.

It may be that the oblique Fennoscandia–Sarmatia collision (Lahtinen et al. 2005; Bogdanova et al. 2015), with

dextral displacement of large crustal blocks, such as the Bergslagen lithotectonic unit, in a northwesterly direction (present-day coordinates) caused alternating zones of compression and extension, or transpression and transtension, giving rise to penecontemporaneous magmatism having different character. Penecontemporaneous with this oblique collision, renewed subduction-related 1.81–1.76 Ga magmatism along the western continental margin of Fennoscandia created the TIB-I intrusions of the Transscandinavian Igneous Belt, about 120 km west of the Hedesunda area, attesting to the very complex tectonic situation during this time period.

Summary and conclusions

- New U–Pb SIMS zircon ages confirm earlier TIMS ages, indicating that the Hedesunda granite complex within the Bergslagen lithotectonic unit in east-central Sweden is a composite intrusion consisting of an older Hedesunda I granite at ca. 1865 Ma, and a younger Hedesunda II granite at ca. 1785 Ma, i.e. having an age difference of ca 80 million years.
- The two granitoid generations have very similar field appearances but can be separated geochemically into two groups. This separation largely confirms the geographic division between them made on recent SGU maps, based on field mapping and aeromagnetics.
- The Hedesunda I granitoids are I-type calc-alkaline intrusions ranging in composition from diorite via tonalite and granodiorite to granite (GDG trend, not GSDG as previously inferred). They are magnesian and dominantly metaluminous and formed in a continental margin setting during the 1.87–1.85–(1.83) Ga extensional, intra-orogenic phase that immediately followed the early Svecofennian synorogenic magmatism and deformation in east-central Sweden and southern Finland.
- While related mafic rocks may have formed directly from mantle-derived magma, the intermediate to felsic Hedesunda I rocks probably formed by fractional crystallization of melts generated in the juvenile Svecofennian lower crust by extension-related basaltic underplating and heating. Initial Sr, Nd, and Hf isotope compositions are near-chondritic to mildly depleted, compatible with formation from juvenile Svecofennian mafic lower crust.
- The Hedesunda II granitoids have a purely granitic composition. However, they are not low-temperature crustal anatectic melts, but rather high-temperature, ferroan, dominantly peraluminous, and high-K calc-alkaline to shoshonitic granites having an A-type and within-plate-type character. Initial Sr is disturbed, but initial Nd and Hf are mildly depleted, indicating a slightly more juvenile source than for the Hedesunda I intrusion.
- The Hedesunda II granites form part of a belt of late Svecofennian post-collisional intrusions across east-central Sweden and southern Finland. Their magma may have formed by melting of juvenile deep crustal rocks due to renewed basaltic underplating in an extensional within-plate environment during the later stages of the Svecofennian orogeny.

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Compliance with ethical standards

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