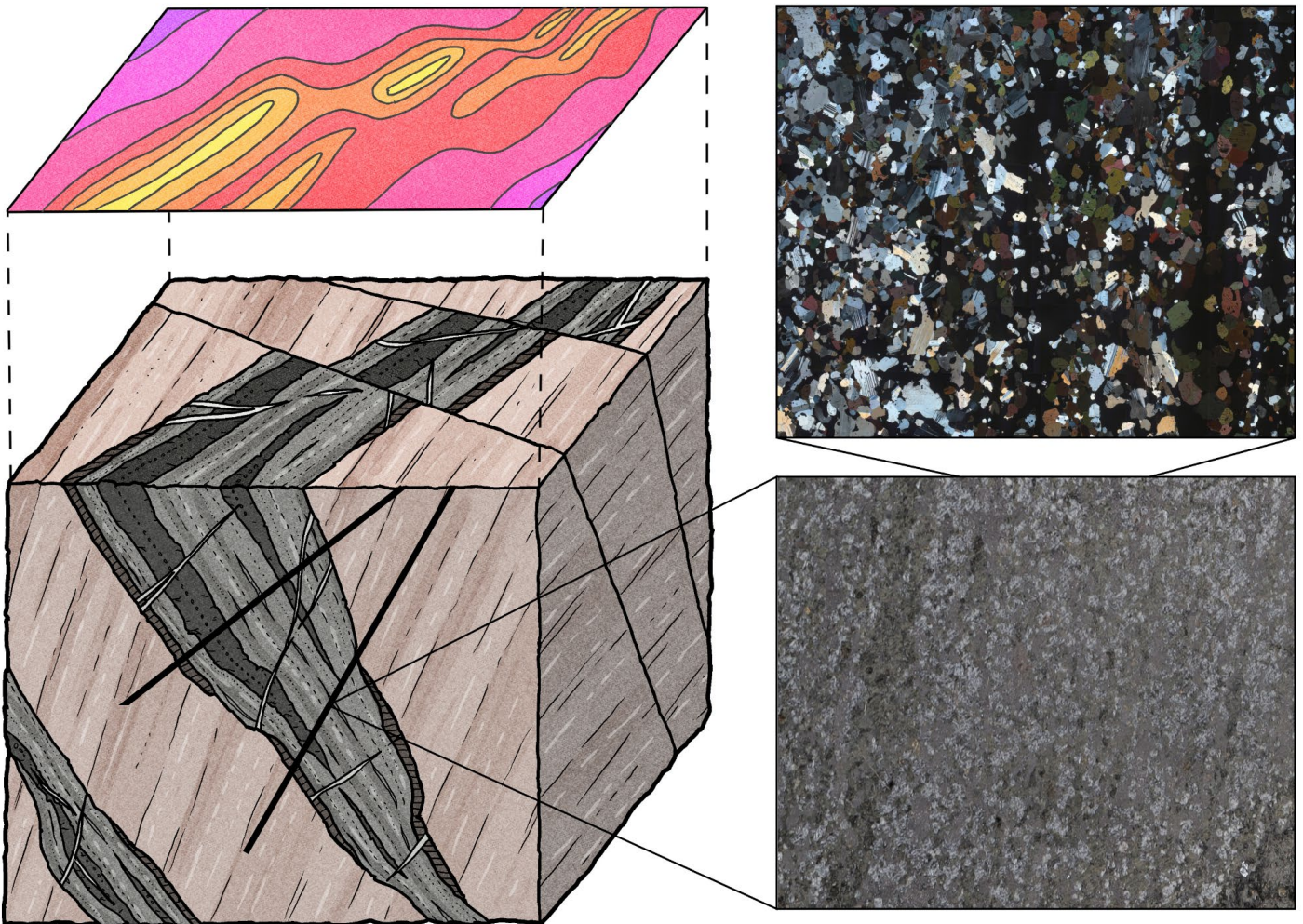


Mafic intrusion-hosted Fe-Ti-V mineralisations in the Ljusdal lithotectonic unit, Sweden



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Cover illustration: A schematic illustration of a Fe-Ti-V deposit (left) together with its associated magnetic response. A photo of image of a thin section (upper right) and a drill core (lower right) from Fe-Ti-V intrusions investigated within this study.

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Summary

The Geological Survey of Sweden (SGU) has carried out a project with the aim of providing information about vanadium, titanium and iron mineralisation, associated with mafic intrusions in Gävleborg County, Sweden. Vanadium and titanium are both so-called critical raw materials according to the EU's latest assessment (Grohol & Veeh 2023). The project is part of SGU's current mapping programme.

The project's survey area is located in the so-called Ljusdal lithotectonic unit (Högdahl & Bergman 2020) within the Svecokarelian orogen. The bedrock in this lithotectonic unit is dominated by the Ljusdal batholith (1.87–1.84 billion years old), which mainly consists of metamorphosed, gneissic and deformed rocks with granitic to granodioritic compositions. Within the Ljusdal lithotectonic unit there are a number of mafic intrusions containing iron-titanium-vanadium mineralisation.

In magmatic iron-titanium-vanadium mineralisations, also called orthomagmatic or mafic Fe-Ti-V mineralisations, vanadium is most often concentrated in the mineral magnetite, while titanium can be associated with ilmenite, ulvöspinel, or titanomagnetite. This type of mineralisation is the most important primary source of vanadium globally, where China is the largest producer (USGS 2025).

Within this project, SGU has carried out a detailed study of mafic intrusions with Fe-Ti-V mineralisation in the Ljusdal lithotectonic unit. The study includes a detailed review of existing information and digitisation of analogue data. In addition, large amounts of new data have also been collected, including 239 new petrophysical samples, 199 geochemical samples, 133 thin sections, 12 ground magnetic surveys, 1,906 ground gravity point measurements, new radiometric dating and a variety of geological observations from drill cores and outcrops. Based on these data, we have performed a detailed characterisation of more than 20 mafic intrusions, which includes updated bedrock maps, descriptions and interpretations. All of the intrusions with Fe-Ti-V mineralisation which were studied exhibit layering to a varying degree. This can be observed at the macro- and microscale, in outcrops and under the microscope. Geochemical data and magnetic properties support this interpretation. Magmatic textures that are common in layered mafic intrusions are observed in thin sections, for example cumulate textures, and poikilitic texture. Magmatic layering is exemplified by modal variations of different minerals, which are observed in both drill cores and in outcrops. A parallel orientation of the elongated minerals (most often plagioclase, but also hornblende and biotite) can be observed in connection with modal layering. This is interpreted to be a result of magmatic processes and not regional deformation.

Vanadium is included as a solid solution in magnetite. Among the studied intrusions, the fine-grained variants are usually the richest in magnetite (and thus vanadium), while coarser, amphibole-rich variants are usually magnetite-poor. The vanadium-rich layers are often dark grey and fine-medium grained.

The vanadium-bearing mafic intrusions have significantly higher density and magnetic susceptibility than the surrounding foliated and metamorphosed granitoids. This means that magnetic and gravimetric measurements can provide valuable information for mapping this type of intrusion. The petrophysical properties show a strong correlation between the concentration of vanadium, iron, and titanium. A clear correlation is observed (not unexpectedly) between the degree of Fe-Ti-V mineralisation and magnetic susceptibility. Results in this project show that magnetic susceptibility measured on drill cores, properly calibrated, can be used to directly assess the concentration of vanadium, iron, and titanium.

Intrusions of Fe-Ti-V-bearing gabbros within the Ljusdal lithotectonic unit have previously been interpreted to be older than the surrounding granitoids in the area (Lundegårdh 1967). However, alternative hypotheses have been proposed where these gabbros are proposed to be younger, intruding into the granitoids and supracrustal rocks, and that many of the textures observed are magmatic and can be explained by fractional crystallisation instead of deformation (Edberg *et al.* 1978).

Data presented in this study indicate that the mafic intrusions originate from a water-rich tholeiitic magma formed in a continental island arc during the Svecokarelian orogeny. The observed interaction between these gabbros and the surrounding metamorphosed granitoids, as well as the absence of tectonic foliations indicate that the intrusions of Fe-Ti-V mineralised gabbros postdate the first deformation phase (D1) of the Ljusdal lithotectonic unit and indicate that they intruded at a late stage in the orogenic development. This interpretation is consistent with radiometric dating performed on two samples in this project from the Kramsta intrusion. These gave an age of $1,851 \pm 8$ million years, which is younger than D1, dated at 1.87–1.86 billion years (Högdahl & Bergman 2020). Later deformation and metamorphic overprinting are very minor in the investigated area.

The intrusion depth of the layered intrusions was inferred from the minerals observed, where the maximum depth is thought to occur at the Storåsen intrusion, based on the occurrence of magmatic, interstitial garnet. These observations show that already around 1,850 million years ago this part of the Earth's crust was located in the lower parts of a volcanic arc, which had previously seen severe deformation and metamorphic overprinting, something that the layered Fe-Ti-V intrusions do not show. The Fe-Ti-V intrusions, which formed at depth, are interpreted to have been carried upwards into the Earth's crust during the predominant extension of the Ljusdal lithotectonic unit, where they can today be observed at many locations at the surface.

It is likely that in this study we have identified the majority of the Fe-Ti-V mineralised mafic intrusions found at the surface within the Ljusdal lithotectonic unit. In this study, new data and analyses of several of the larger intrusions that have not previously been investigated in detail, such as Storåsen, Kullberget, Skälberget, and Kramsta-north, are presented. However, there is still good potential to find additional Fe-Ti-V-bearing intrusions (similar to those observed at the surface) at depth within the Ljusdal lithotectonic unit. Ground gravity data and magnetic data from airborne measurements can be a valuable tool for locating potential intrusions at depth. In this study, several additional potential intrusions have been identified in the Järvsö field using such data. The regional gravity anomaly observed within the Ljusdal lithotectonic unit could indicate the presence of a large mafic intrusion at depth, which could potentially be the source of the Fe-Ti-V-bearing intrusions observed at the surface. This potential large-scale deeper intrusion could be a potential target for further investigation and exploration efforts.

Sammanfattning

Sveriges geologiska undersökning (SGU) har genomfört ett projekt med syfte att ta fram prospekteringsintressant information över mafiska intrusioner i berggrunden i Gävleborgs län med avseende på främst vanadin, men även titan och järn. Vanadin och titan är båda så kallade kritiska råmaterial enligt EU:s senaste bedömning (Grohol & Veeh 2023). Projektet ingår i SGU:s plan för kartläggning 2020–2027.

Projektets undersökningsområde är lokaliserat till den så kallade Ljusdals litotektoniska enhet (Högdahl & Bergman 2020) inom den svekokarelska orogenen. Berggrunden i denna litotektoniska enhet domineras av Ljusdalsbatoliten (1,87–1,84 miljarder år) som huvudsakligen utgörs av omvandlade, gnejsiga och deformerade bergarter med granitiska till granodioritiska sammansättningar. I Ljusdals litotektoniska enhet förekommer dessutom ett antal mafiska intrusioner som innehåller järn-titan-vanadinmineraliseringar, bland annat i området Sumåssjön–Dellen–Ljusdal, vilket utgör ett så kallat metallogenetiskt område (Hallberg m.fl. 2012) för denna typ av mineraliseringar.

I magmatiska järn-titan-vanadinmineraliseringar, också kallade ortomagmatiska eller mafiska Fe-Ti-V-mineraliseringar, är vanadin oftast koncentrerat i mineralet magnetit, medan titan kan vara knutet till ilmenit, ulvöspinel eller titanomagnetit. Denna typ av mineralisering är den viktigaste primära källan till vanadin globalt och Kina är det största producentlandet (USGS 2025).

Inom projektet har SGU genomfört en detaljerad studie av mafiska intrusioner med Fe-Ti-V-mineraliseringar i Ljusdals litotektoniska enhet. I studien ingick en detaljerad genomgång av befintlig information och digitalisering av analoga data. Vi har samlat in en stor mängd nya data, inkluderande 239 nya petrofysikprov, 199 bergartskemiska prov, 133 tunnslip, 12 yttäckande magnetiska markmätningar, 1 906 gravimetriska punktmätningar, en ny radiometrisk datering och en mängd geologiska observationer av borrhärdar och hållblottningar. Baserat på dessa data har vi utfört en detaljerad karakterisering på fler än 20 mafiska intrusioner, vilket inkluderar uppdaterade berggrundskartor, beskrivningar och tolkningar.

Samtliga av de studerade Fe-Ti-V-mineraliserade intrusionerna är i varierande grad lagrade. Detta kan observeras i makro- och mikroskala, i hållblottningar och i mikroskop. Bergartskemiska data och magnetiska egenskaper understöder denna tolkning. Magmatiska texturer som är vanliga i lagrade mafiska intrusioner observeras i tunnslip, till exempel kumulat-texturer, och poikilitisk textur. Magmatisk lagring exemplifieras av modalvariationer av olika mineral, vilket observeras i både borrhärdar och i håll. En parallellorientering av de avlånga mineralen (oftast plagioklas, men också hornblände och biotit) kan observeras i samband med modal lagring. Detta tolkas som ett resultat av magmatiska processer och inte regional deformation.

Vanadin ingår som fast lösning i magnetit och bland de studerade intrusionerna är som regel de finkorniga varianterna de som är rikast på magnetit (och därmed vanadin), medan grövre, amfibolrika varianter oftast är magnetitfattiga. De vanadinrika lagren är ofta mörkgrå, fint medelkorniga och har hög magnetisk susceptibilitet.

De vanadinförande mafiska intrusionerna har betydligt högre densitet och magnetisk susceptibilitet än de omkringliggande folierade och omvandlade granitoiderna. Detta betyder att magnetiska och gravimetriska mätningar kan ge värdefull information för kartering av denna typ av intrusioner. De petrofysiska data visar ett starkt samband mellan koncentrationen av vanadin, järn och titan. Det observeras (inte oväntat) ett tydligt samband mellan graden av Fe-Ti-V-mineralisering och magnetisk susceptibilitet. Resultat i detta projekt visar att magnetisk susceptibilitet mätt på borrhärdar, förutsatt korrekt kalibrering, kan användas för att bedöma koncentration av vanadin, järn och titan.

Intrusioner av Fe-Ti-V-förande gabbroider inom Ljusdals litotektoniska enhet har tidigare tolkats att vara äldre än de omgivande, dominerande granitoiderna i området (Lundegårdh 1967), även om alternativa hypoteser föreslagits med en betydligt enklare förklaring avseende en fraktionerad kristallisation inom en basisk magma som intruderat såväl ögongnejsen som de suprakrustala bergarterna och därmed är yngre (Edberg m.fl. 1978).

Data som presenteras i denna studie indikerar att de mafiska intrusionerna härstammar från en vattenrik tholeiitisk magma bildad i en kontinental öbåge under den svekokarelska orogenesisen. De intrusiva fältrelationerna med omkringliggande och omvandlade granitoiderna och avsaknad av tektoniska foliationer visar att intrusionerna av Fe-Ti-V-mineraliserade gabbroider postdaterar första deformationsfasen (D1) i Ljusdals litotektoniska enhet samt indikerar att de intruderade i ett sent skede i den orogena utvecklingen. Detta scenario stämmer överens med resultaten från en radiometrisk datering i detta projekt av två prov från Kramstaintrusionen som gav en intrusiv ålder på $1\,851 \pm 8$ miljoner år, vilket är yngre än D1 som är daterad till 1,87–1,86 miljarder år (Högdahl & Bergman 2020). Senare deformation och metamorf överprägling är mycket underordnad i det undersökta området.

Intrusionsdjupet för de lagrade intrusionerna härleddes från de mineral som bildats i dem och ett maximalt djup genom förekomsten av magmatisk, interstitiell granat bildad vid Storåsens intrusion. Dessa observationer visar att redan för omkring 1 850 miljoner år sedan befann sig denna del av jordskorpan i de nedre delarna av en vulkanisk båge, som tidigare hade sett kraftig deformation och metamorf överprägling, något som de lagrade Fe-Ti-V-intrusionerna inte uppvisar. Fe-Ti-V-intrusionerna, som bildades på djupet, tolkas ha förts uppåt i jordskorpan under övervägande extension av Ljusdals litotektoniska enhet, där de idag kan observeras i många fall som berggrundsytor.

Det är troligt att vi i denna studie har identifierat majoriteten av de ytligt liggande Fe-Ti-V-mineraliserade mafiska intrusioner som finns inom Ljusdals litotektoniska enhet. I denna studie presenteras nya data och analyser över flera av de större intrusionerna som tidigare inte har undersökts i detalj, såsom Storåsen, Kullberget, Skalberget och Kramsta-norr. Det finns dock fortfarande god potential att hitta ytterligare Fe-Ti-V-förande intrusioner (liknande de som observerats vid ytan) på djupet inom Ljusdals litotektoniska enhet. Markgravitationsdata och magnetiska data från luftburna mätningar kan vara ett värdefullt verktyg för att lokalisera potentiella intrusioner på djupet. I denna studie har flera ytterligare potentiella intrusioner identifierats i Järvsöfältet med hjälp av sådana data. Den regionala gravitationsanomalin som observerats inom Ljusdals litotektoniska enhet skulle kunna tyda på förekomsten av en stor mafisk intrusion på djupet, vilken potentiellt kan utgöra källan till de Fe-Ti-V-förande intrusionerna som observerats vid ytan. Denna möjliga intrusion skulle kunna vara ett intressant mål för vidare undersökning och prospekteringsinsatser.

Introduction

Raw materials are the foundation for all industrial value chains. Technical development and innovative products that are enablers in the green and digital transitions will require increasing amounts of raw materials for their production and will put pressure on global supply chains (Bobba *et al.* 2020). Undisturbed access to increasing volumes of raw materials is vital for the European industry. As the EU is a net-importer of most metals and minerals, several actions have been taken to secure supply and strengthen resilience, e.g. the recently implemented Critical Raw Materials Act (EU 2024).

All raw materials are important for the European industry, but so-called critical and strategic raw materials are particularly important in this context (Grohol & Veeh 2023). However, even if many critical metals are indispensable constituents in modern products, they are rarely used in large quantities, and it is emphasised that the “traditional” metals such as base metals (e.g. copper, zinc and lead) and iron are also extremely important and are projected to experience increased demand because of their ubiquitous use in green energy infrastructure, construction and manufacture of industrial products. The European commission publishes a triennial list of critical raw materials in which the most recent one, published in 2023, also includes strategic raw materials. The list currently comprises 34 materials of which 16 are defined as strategic (Grohol & Veeh 2023). SGU has compiled data on worldwide production of critical and strategic raw materials that clearly illustrates the dominance of a few countries (fig. 1).

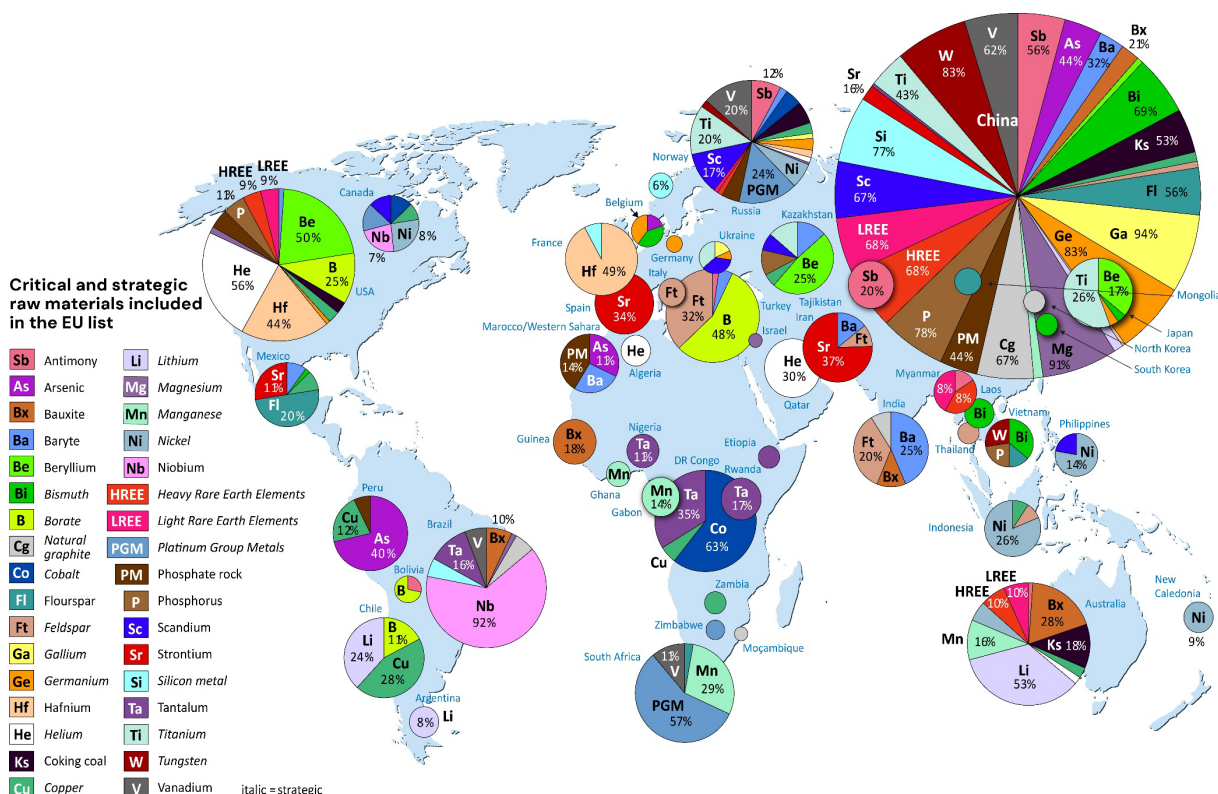


Figure 1. Map showing the global distribution of critical and strategic raw materials production. Each circle shows the percentage of the world production for each country. Source: SGU, SCREEN2/EU.

The current project “Mafic intrusion-hosted Fe-Ti-V mineralisations in the Dellen-Ljusdal area, Hälsingland, Sweden” is part of SGU's plan (2022–2027) for systematic mapping of energy-critical, battery- and innovation-critical metals and minerals. Some preliminary results of the project were presented in Reginiussen *et al.* (2023) and the current document is the final report which presents the work carried out within the project during 2022–2024.

Vanadium and titanium are both critical raw materials according to the latest EU assessment and the purpose of the project has been to produce geological and geophysical information from mafic intrusions in Gävleborg County with respect to vanadium mainly, but also titanium and iron. The aim has not been to carry out detailed exploration, but to generate a more comprehensive modern dataset that can be used to understand more about the distribution, size and genesis of these deposits which in turn may be a foundation for further exploration activities. The physical properties of the specific rocks, the content of metals and minerals and, how and when these were formed, have been investigated.

Prior to the current project, only a few modern analyses of the mafic intrusive rocks in the region had been produced during an ore inventory programme by SGU in Gävleborg County (Wik *et al.* 2009) and as part of a government assignment (Hallberg & Reginiussen 2018). To increase the knowledgebase many lithogeochemical analyses, thin sections and petrophysical measurements on newly collected field samples and existing drill cores have been produced. As well as this, detailed magnetic measurements have been undertaken over a number of mafic intrusions identified from airborne data and previous investigations.

Vanadium

The average vanadium concentration in the earth's upper crust is 97 ppm (Rudnick & Gao 2003) which makes it a rather common element, and the metal is more abundant than for example lead (17 ppm), copper (28 ppm) and zinc (67 ppm). Vanadium is rarely extracted from ore deposits as a primary product but mainly as a co- or by- product from Fe, Ti, phosphate, and bauxite mining and production. Vanadium also occurs in sandstone-hosted uranium deposits, shale-hosted deposits (incl. alum shale) as well as in coal and other fossil fuels such as crude oil and oil sands.

The world mine production amounted to approximately 100 000 tonnes (contained V metal) in 2024. China is the biggest producer, where most comes from vanadiniferous iron ore processed for steel production (USGS 2025) followed by Russia, South Africa, and Brazil. These four countries account for almost all global production (fig. 1). Anthropogenic sources of vanadium include stockpiled steel slag, fly ash, steel scrap and used catalysts.

Currently, most vanadium is used in special steels, stainless steel, superalloys, HSLA steels and as a catalyst in the chemical industry. However, much recent focus has been on the role of vanadium in the green transition due to its use as a raw material in the manufacturing of rechargeable flow batteries for grid-scale energy storage. Because these batteries require large tanks to store the energy, they are stationary. Such systems have long life cycles, large capacity and are suitable for storing electricity from intermittent renewable energy sources such as solar and wind. In this technology, vanadium is an important component because it is used as the electrolyte. This use is forecasted to grow in the future, and hence, the demand for vanadium is expected to increase.

Vanadium in Sweden

There is currently no extraction of vanadium in Sweden, although there have been recent plans for construction of a mine at Gruvberget–Sumåssjön at the so-called Brickagruvan by the company Svenska Vanadin AB. The project was granted an exploitation concession in 2010 (valid for 25 years) and also an environmental permit in 2022. However, after an appeal of the latter to a higher court (Svea Hovrätt) the decision was reversed in November 2024.

As an alternative to primary extraction, recovery of vanadium from Swedish steel-mill slag has been proposed as a viable source. The companies Neometals Ltd. and Critical materials AB had plans to process stock-piled slag from SSABs steel-mills in Luleå and Oxelösund at a new facility in Finland, but it was recently announced that this project is put on hold due to the global financial market situation (Neometals 2023).

The primary Swedish vanadium deposits are of two main types: orthomagmatic Fe-Ti-V deposits and alum shale. In terms of tonnage and contained metal the alum shale is by far the largest. Table 1 shows a compilation of the largest (>20 Mt) Swedish deposits where tonnage and grade data has been reported. The deposits that have been studied in the current project are all the orthomagmatic type.

Table 1. The largest Swedish V-deposits with resource estimates.

Deposit	Tonnage (Mt)	V (%)	Reporting code	Category	Contained V metal (t)	Reference to tonnage & grade
Smålands Taberg	150	0.12	Historic	Inferred	180 000	NODD (2023)
Gruvberget–Sumåssjön (Brickagruvan)	20.75	0.223	Historic	Inferred	47 000	Andersson (1982)
Routevare	140	0.2	JORC	Inferred	280 000	NODD (2023)
Airijoki	44.3	0.22	JORC	Inferred	100 000	Pursuit Minerals (2019)
Hörby	117	0.22	JORC	Indicated + Inferred	257 000	Scandivanadium Ltd (2019)
Häggån	2 005	0.17	JORC	Indicated + Inferred	3 400 000	Aura Energy (2023)
Viken	4 789	0.144	NI 43–101	Indicated + Inferred	6 900 000	District Metals Corp. (2025)

Layered mafic intrusions and orthomagmatic Fe–Ti–V deposits

In mafic intrusion related iron-titanium-vanadium mineralisations, also called orthomagmatic or mafic Fe–Ti–V mineralisations, vanadium is commonly contained in vanadiniferous titanomagnetite, while titanium may be tied to ilmenite, ulvöspinel, or titanomagnetite. This type of mineralisation is the main global primary source of vanadium. Examples of intrusions hosting this type are Bushveld Igneous Complex, South Africa, Panzhihua, China, Windimurra, Australia, and Lac Dore, Canada (Brough *et al.* 2019 and references therein). Subeconomic magnetite-ilmenite oxide ores occur in the Mesoproterozoic Suwalki Anorthosite Massif in the northeastern part of Poland (Mikulski *et al.* 2022).

Layered mafic intrusions typically comprise a succession of layers that may have variable grain-size, modal composition, textures or chemical composition. Studies have shown that the diversity of layering within such intrusions is not related to a single mechanism, but may involve crystal settling, in-situ crystallisation, magma pulses with replenishment, fluids percolating through semi-consolidated cumulates, mobilisation of crystal-mush and density currents moving down the sidewall of magma chambers (Maier *et al.* 2013 and references therein).

In general, orthomagmatic deposits hosted by mafic and ultramafic rocks are related to asthenospheric or lithospheric mantle-derived magmas that have experienced a high degree of partial melting. Such rocks can occur in a variety of tectonic settings. However, layered intrusions carrying commodities such as Ti, V, Ni, Cu, Co, and PGE are typically related to extensional regimes and underplating of continental crust.

Due to the diversity of elements hosted by such intrusions they have an interesting multi-commodity potential (Simandl & Paradis 2022). Fe-Ti-V enriched layers in such intrusions are often, although not always, located in the central and upper portions (Smith & Maier 2021).

Methods

Lithogeochemical analyses

Only a few modern analyses of the Fe-Ti-V mineralised mafic intrusives from the studied area were publicly available before the start of this project. Of these, only two analyses contained a complete set of elements according to SGU's routine package (Reginiussen *et al.* 2023). One of the aims of this project was to expand the knowledgebase with a new comprehensive lithogeochemical database.

In the field, samples for geochemical analyses were collected by hammer or sledgehammer from outcrops, boulders, abandoned mine workings and waste-rock heaps. A total of 2–4 kg of fresh material consisting of several smaller rock fragments and chips were collected at the location for each sample.

Historic drill core from Simesvallen, Bläckmyran, Gruvberget–Sumåssjön, Masugnsberget and Kramsta are stored at SGU's archive at Malå. The cores, which are now publicly available were previously owned by NSG and AB Statsgruvor. A total of 122 sections from 50 drill cores were selected for lithogeochemical analysis.

The selection of drill core sections for lithogeochemical analysis was based on assessments made on-site in the drill core archive, with descriptions and existing analyses in drillhole protocols and exploration reports as support. Results from hyperspectral drill core scanning data were also used where available. No drillhole protocols were available for the Kramsta drill cores.

The sampling was typically done in one-metre intervals, and the sections were marked and tagged and transported in their original drill core boxes to the ALS facility in Malå for sawing and sample preparation. All lithogeochemical analyses were performed by ALS using the analytical packages CCP-PKG01, ME-MS41 and PGM-ICP23 (ALS 2023). Three rock standards were used for quality control of each sample batch. Data can be accessed through SGU's map viewer "Rock Chemistry" which is available at the SGU website: <https://apps.sgu.se/kartvisare/kartvisare-bergartskemi.html>. The full dataset can be obtained by contacting SGU's customer service or by using SGU's download service which is described at the following link: <https://resource.sgu.se/dokument/produkter/lithogeochemistry-description.pdf>.

Plotting of geochemical data was done using the GCD-kit package (Janoušek *et al.* 2006).

Ground geophysical measurements

As part of this project new ground magnetic field measurements were done at 12 different intrusions using a GEM GSMV-19 magnetometer. The surveys were typically performed by collecting a series of parallel profiles over a given area of interest, with the objective of generating a map of the magnetic field. Whilst surveying, magnetic field measurements were made at 1 second intervals and recorded together with X and Y coordinates measured with a GPS receiver. During data collection a handheld compass was used for navigation, in order to follow a constant azimuth for the parallel magnetic profiles. During data collection it was often the case that two or three people collected data simultaneously, measuring on parallel lines. During data

collection in 2022 and 2023 repeat base station measurements were made during data collection in order to later correct for diurnal variation. However, for the surveys in 2024 a base station magnetometer was deployed to provide continuous measurements for subsequent diurnal corrections. After data collection the following processing steps were performed to generate the final total magnetic field maps presented later in this report:

1. **Filtering of X and Y coordinates:** In some areas with poor GPS signal the position information was noisy or even absent in the data. In these areas the GPS data was filtered and interpolated to provide reasonable position information for all measurement points.
2. **Base station correction:** At this stage the data was corrected to remove the effects of variations of the earth's magnetic field during the period of the survey. This was done using repeat base station measurements or data from a base station magnetometer.
3. **Removal of artefacts:** The data were then manually quality controlled and small-scale magnetic anomalies which were identified to be related to manmade materials, structures or equipment were removed. To do this the profile positions were cross-referenced with maps of infrastructure and satellite images as well as notes of observations in the field. For these surveys only a few minor artefacts were removed, such as small anomalies due to cars, drainage pipes below gravel roads or scrap metal.
4. **Gridding:** At this stage the data were gridded using a minimum curvature algorithm, typically with a 5×5 m grid spacing.

As well as new ground magnetic data, we present a number of legacy ground magnetic surveys in this report. Over the previous decades the mafic deposits in Gävleborg County have been the subject of several investigations where significant amounts of ground geophysical data have been collected. Most of the available data were collected between 1978 and 1985 by SGU or LKAB. Up until recently, these data have only been available as analogue maps, graphs, and tables in paper format. However, in recent years many of these old data have been digitised as part of on-going work by SGU. Hence, ground geophysical data from the area around Gruvberget–Sumåssjön were already available digitally at the beginning of the project. During this project, all remaining datasets from the study area which remained in analogue format were digitised, this included ground magnetic data from the Järvsö Field, Kullberget, Simesvallen, Svedåsen, Bergvallåsen, and Spännarslätten. In some cases, tables of magnetic measurement values were available which were simply typed in by hand and assigned coordinates. In other situations, only scanned images of magnetic profile data were available, in a raster format. In these cases, the image was imported into digitising software, where after defining the axes on the image, the measurement values could be extracted and exported in an ASCII format.

Microscopy

A Zeiss Axioskop 40 FL microscope with ordinary objectives and a 20 times magnification Differential Interference Contrast objective was used for microscopy work.

Abbreviations for names of rock-forming minerals are according to Whitney & Evans (2010).

The method used for panoramas of entire thin-sections of Fe-Ti-V mineralised samples is described in appendix C *Thin-section panoramas of Fe-Ti-V mineralised samples*.

Radiometric dating

The methods used for age determination are given in the chapter *Age determination of mafic mineralised rocks in the Järvsö Field*.

Regional overview

Bedrock geology

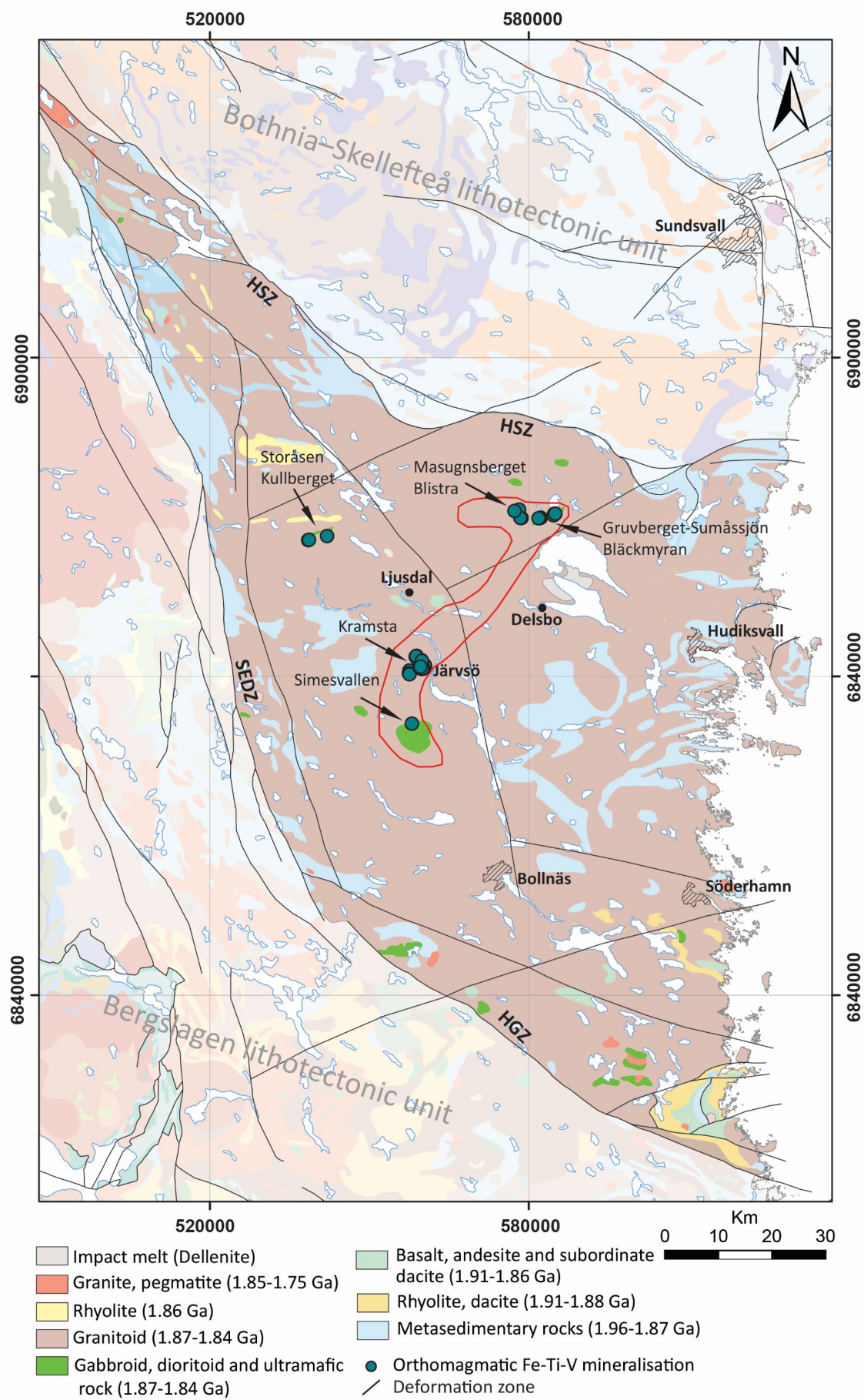
The project area is located within the so-called Ljusdal lithotectonic unit (Stephens & Bergman 2020), which comprises part of the Svecokarelian orogen in south central Sweden (fig. 2). The bedrock of the Ljusdal lithotectonic unit is dominated by the Ljusdal batholith (1.87–1.84 Ga), which consists mainly of gneisses and deformed rocks with granitic to granodioritic compositions. The regional geology of the area is described in works by, among others, Lundegårdh (1957, 1967), Bergman *et al.* (2008), Högdahl *et al.* (2008), Albrecht & Kübler (2011) and Högdahl & Bergman (2020). The description of the regional geology given below is based on these earlier works and is intended here as a general overview.

The Ljusdal lithotectonic unit is situated north of the Bergslagen lithotectonic unit and south of the Bothnia-Skellefteå lithotectonic unit (e.g. Högdahl & Bergman 2020). It is bounded by large regional shear zones; the Storsjön–Edsbyn deformation zone (SEDZ) in the west, Hassela shear zone (HSZ) in the north and Hagsta gneiss zone (HGZ) in the south (fig. 2). A U–Pb age of $1\,674 \pm 6$ Ma has been obtained by dating syn-kinematic titanite within the high-strain shear zone of the SEDZ (Bergman *et al.* 2006). Titanite from a high-strain part of the HGZ has been dated at $1\,809 \pm 2$ Ma interpreted to reflect the timing of the ductile shearing (Högdahl *et al.* 2009). The HSZ records transpressive deformation at c. 1.82–1.80 Ga (Högdahl & Sjöström 2001).

The oldest rocks in the Ljusdal lithotectonic unit are metasedimentary rocks originally deposited in the submarine Bothnian basin. This basin extended from central Sweden to eastern Finland (Welin *et al.* 1993). The metasedimentary rocks are subordinate to the igneous rocks of the Ljusdal batholith and occur as inclusions of migmatites. Felsic metavolcanic rocks also occur within the batholith. In the Hamrånge area in the southeastern part of the Ljusdal unit, the supracrustals are better preserved due to lower strain and metamorphic grade.

The main constituents of the Ljusdal batholith are metamorphic rocks with granitic to granodioritic composition. The granitoids are typically variably porphyritic and carry K-feldspar, megacrysts (typically 1 cm, but up to 8 cm in some areas), although even-grained granite is also present. The K-feldspar megacrysts are sometimes mantled with plagioclase (Albrecht & Kübler 2011, Högdahl & Bergman 2020). Subordinate mafic intrusive rocks, mainly gabbroids, occur at several locations in the Ljusdal lithotectonic unit.

► **Figure 2.** Simplified map from the SGU bedrock database in scale 1:1 000 000 (Bergman *et al.* 2012). The Ljusdal lithotectonic unit is constrained by large ductile structures; HSZ: Hassela shear zone (Sjöström *et al.* 2000), SEDZ: Storsjön–Edsbyn deformation zone (Bergman *et al.* 2006), HGZ: Hagsta gneiss zone (Bergman & Sjöström 1994). The area is dominated by 1.87–1.84 Ga granitoids (brown colour) belonging to the Ljusdal batholith. Red polygon outlines the Dellen–Ljusdal Fe–Ti–V metallogenic area (Hallberg *et al.* 2012). Important Fe–Ti–V mineralisations and deposits are indicated by arrows. Note that the so called Järvsö Field, sometimes referred to in the text includes the Kramsta, Storsveden and Järvsö–Gruvberget deposits.



The rocks in the Ljusdal lithotectonic unit underwent polyphase, ductile deformation and metamorphism during the Svecokarelian orogeny. The tectonic evolution is manifested by structures related to shortening events which are separated by a period of regional extension that is reflected by the preserved metasedimentary sequence in the Hamrånge area. The metamorphic evolution in the Ljusdal lithotectonic unit is characterised by low-P and high-medium T conditions. Granulite facies was attained locally as shown by the occurrence of metamorphic orthopyroxene in the northeastern and western parts.

In detail, three compressive, ductile deformation phases (D1–D3) and two high grade, low pressure metamorphic episodes (M1–M2) are recognised. D1 is related to M1 and D2 to M2. D1 has been dated to 1.87–1.86 Ga and D2–D3 to c. 1.83–1.80 Ga. Ductile fabric development during D1 has been suggested to relate to compressive shortening and the accretion of an older arc–basin complex to an active continental margin (Högdahl & Bergman 2020). This compressive phase was followed by an intra-orogenic period characterised by regional extension, basin formation and sedimentation. (Bergman *et al.* 2008).

Due to variations in metamorphic grade within the unit, there appears to be differences in the development and preservation of structures. In the southeastern Hamrånge area where the lowest grade areas are found, it has been possible to separate three distinct fold phases (Ogenhall *et al.* 2010). In the high-grade areas on the other hand, it is more difficult to distinguish between individual deformation and fold phases.

The geochemical similarities between the rocks of the Ljusdal batholith and magmatic arcs have supported an interpretation in which the formation is associated with subduction along a continental plate during the Svecokarelian orogeny (Högdahl & Bergman 2020). Similarities between the Ljusdal lithotectonic unit and lithotectonic units in southern Finland have led some authors to correlate across the Baltic Sea to southern Finland (e.g. Luth *et al.* 2024).

Petrophysics

Before interpreting and analysing geophysical data, it is crucial to have a good understanding of the physical properties of the different rock types in the area of investigation. Hence, in this section we present a compilation of pre-existing and newly acquired petrophysical data from the study area. We use these data to investigate the typical properties of the vanadium-bearing mafic intrusions both regionally, and on a deposit-by-deposit basis. Furthermore, in order to better understand the controls on the physical properties, we relate the petrophysical data to mineralogical observations and geochemical data.

Previous work

Over the past 100 years significant geological, mineralogical, and geochemical investigations have been conducted on data from the different gabbro intrusions in Gävleborg County. In addition, a range of petrophysical samples have been collected, which includes a limited number of orientated samples, for measurement of the inclination and declination of remanent magnetisation.

Mineralogical descriptions of samples taken from the different gabbro intrusions show strong similarities in the types of minerals present. Magnetite is commonly observed and occurs in significant amounts in the parts of the gabbro intrusions which have been mineralised (Edberg *et al.* 1978, Persson & Holdar 1982, AB Statsgruvor 1984). Hence, the amount of magnetite can be considered the primary control of the magnetic response of the mineralisation. Ilmenite also occurs as grains or as lamellae within magnetite grains within the mineralised parts. Hence, the presence of ilmenite can also contribute to the magnetic response, however its effect is thought to be subordinate to that of magnetite. Pyrrhotite is observed in some of the deposits but only in

trace amounts (Persson & Holdar 1982, AB Statsgruvor 1984). The presence of paramagnetic minerals such as biotite, orthopyroxene, clinopyroxene and amphibole is also documented within the gabbro intrusions (Edberg *et al.* 1978, AB Statsgruvor 1984).

Vanadium is thought to occur within the magnetite grains and hence, there is a correlation between the amount of vanadium and the strength of the magnetic response (Edberg *et al.* 1978; Persson & Holdar 1982). As a result, during the investigations by SGU during the 1970s and 1980s the relative strength of the magnetic anomaly was used as a measure of the prospectivity of the different deposits prior to drilling (Persson 1983). Similarly, a clear relationship between the density and iron content within the deposits can be observed (Lagergren 1983). In some cases, such as the Kramsta deposit, the gabbro can be classified as a layered intrusion with cryptic layering, igneous lamination, and potentially rhythmic layering. In these cases, the amount of magnetite can be observed to vary between individual layers (Lundegårdh 1957, 1967; Ahlin & Larson 1985).

New petrophysical data and analysis

Although a significant amount of data has been collected previously, additional data was required to provide a better statistical basis for the petrophysical analysis. Hence, as part of this study 239 new petrophysics samples were collected and analysed in SGU's petrophysics laboratory, where density, magnetic susceptibility and natural remanent magnetisation were measured. In SGU's petrophysics lab density is measured by comparing measurements of the weight of a sample both in air and submerged in water. A FX-3200 precision scale was used to measure the weight of the samples. A GTK K4/GSF-93 instrument was used to measure the magnetic susceptibility of the samples and the remanent magnetisation was measured using a Remanence Meter R4. Both instruments for performing the magnetic measurements were manufactured by the Geological Survey of Finland (GTK). In order to obtain an inclination and declination for the remanent magnetisation, the samples collected in the field must be orientated. In this study this was done using a sun compass. When collecting orientated samples, in order to reduce the effect of anomalous measurements, efforts were made to collect three samples at any given location. However, fewer than three samples were collected at some locations due to limitations in the field. The new data collected in this study are listed in appendix A.

Of the new samples collected, 117 were taken from outcrops and from waste-rocks produced during previous mining activity. Although some of these new samples were collected from known gabbro intrusions, efforts were made to investigate and collect data from deposits (or suspected deposits), with little or no available petrophysical data. Efforts were also made to increase the number of orientated samples, to better understand the remanent magnetisation. Hence, several of the samples taken at outcrop (34) were orientated using a sun compass. The remaining 122 were sampled from drill cores at SGU's drill core archive in Malå. When sampling the drill cores, efforts were made to collect petrophysical samples adjacent to geochemical samples, to investigate the relationship between the petrophysical and geochemical properties.

As the main focus of the project is to investigate vanadium-bearing mafic intrusions, the majority of the new petrophysical samples were taken from gabbros with varying degrees of mineralisation. However, a number of samples were taken from the rocks surrounding the intrusions, often granitic rocks with varying intensity of foliation. These new petrophysical data were then combined with pre-existing data from SGU's petrophysical database. The following section describes the analysis of these data.

Figure 3 shows the distribution of density and magnetic susceptibility for a range of different rock types in the study area. In this case we differentiate between mafic intrusions which are vanadium bearing (such as those in Gruvberget–Sumåssjön, the Järvsö Field, Simesvallen, Kullberget, and Storåsen (see fig. 2)) and those which are not (for example those located in the northernmost or southern part of the Ljusdal lithotectonic unit). The magnetic susceptibilities and densities of the vanadium-bearing gabbros are typically significantly higher than those from the vanadium-poor gabbros. The magnetic susceptibility and density data for the vanadium-bearing gabbros appear to lie within the “Magnetite trend” as described by Henkel (1991). This is consistent with previous observations from thin sections which suggest that magnetite is the primary control on the magnetic response for these gabbros (Edberg *et al.* 1978, Persson & Holdar 1982, AB Statsgruvor 1984). For the non-vanadium-bearing gabbros, extrusive mafic rocks and to a lesser extent the granodiorites a bimodal distribution is observed in the magnetic susceptibility. In this case the samples belonging to the group with a higher magnetic susceptibility likely contain ferromagnetic minerals. The concentration of paramagnetic minerals such as biotite and amphibole is likely to be the controlling factor in the group with lower magnetic susceptibility values. In this case one can observe a more or less systematic decrease in magnetic susceptibility and density moving from more mafic rocks to more felsic rocks. Table 2 describes the average petrophysical properties for the different lithologies from the study area.

Table 2. Summary of the average petrophysical properties of the different rock types in the study area. Note that the susceptibility data includes both susceptibility measurements made in the lab and at outcrop using a hand-held susceptibility meter. Data from SGU’s petrophysical database and samples collected in this study.

Rock type	Density (kg/m ³)			Susceptibility (10 ⁻⁶ SI)				Q			
	Samples	Mean	Std. Dev.	Samples	Min	Max	Median	Samples	Min	Max	Median
Vanadium-bearing gabbro	244	3 260	271	1 428	233	6 900 000	87 900	244	0.07	84.7	1.37
Gabbro	18	2 980	79	203	200	150 000	16 800	18	0.09	2.13	0.7
Mafic extrusive	36	2 910	90	80	39	67 800	2 070	36	0.03	25.4	0.47
Granodiorite	130	2 700	38	438	10	71 800	3 000	117	0.08	46.1	0.66
Granite	413	2 660	36	8 331	1	200 000	2 000	386	0.05	111	0.55

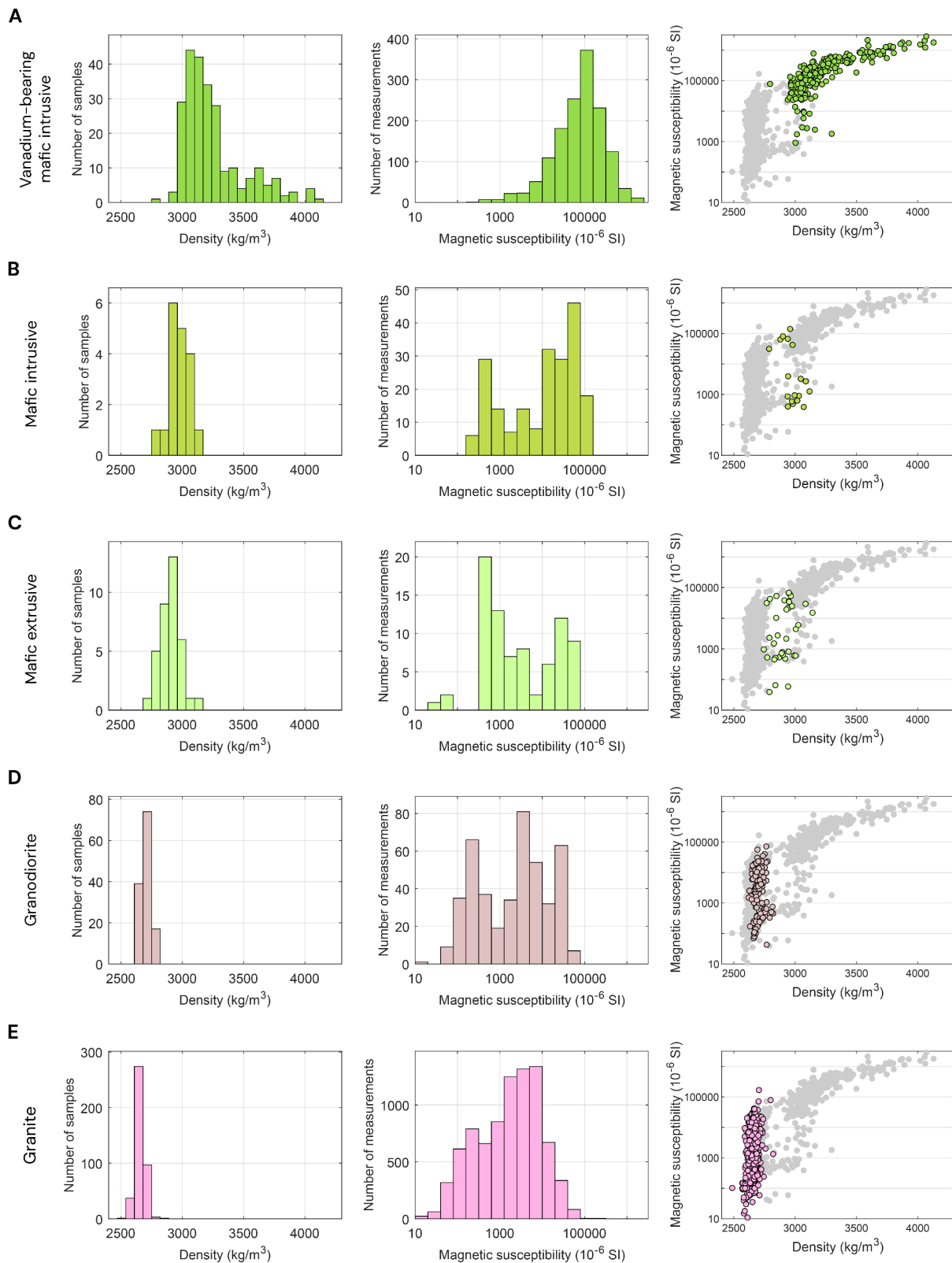


Figure 3. Variation of petrophysical properties with rock type. Histogram plots of density and magnetic susceptibility can be observed in the left hand and central positions, respectively. In the right-hand position a cross plot of magnetic susceptibility and density is shown. On the cross plot the light grey dots show all data, while the coloured dots indicate data from that specific lithology. The different rows show plots for different lithologies, where rows A, B, C, D and E shows data for vanadium-bearing mafic intrusive, mafic intrusive, mafic extrusive, granodiorite and granitic rocks, respectively. Source: SGU's petrophysical database and samples collected in this study.

Figure 4 and Table 3 shows petrophysical data from vanadium-bearing gabbro intrusions, grouped by the different deposits (fig. 2). Note that more detailed maps and descriptions of the different deposits can be found later in the report under the investigated areas section. Note that in this section we use the term “Gruvberget–Sumåssjön area” to refer to data from Masugnsberget, Blistra, Gruvberget–Sumåssjön, Bläckmyran and Gråsjön. Similarly, we refer to “The Järvsö Field” which includes data from the Kramsta, Kramsta-north, Storsveden and Järvsö–Gruvberget intrusions. Before considering the results, it is important to consider the variation in number and type of samples included in the analysis. A greater number of samples are available from the Gruvberget–Sumåssjön area and the Järvsö Field compared to the other areas (Table 3). Furthermore, most samples taken from drill cores were also from these deposits. This means that it was possible to obtain samples from strongly mineralised parts of these deposits, which may often be inaccessible when only taking surface samples. As a result, the statistics from these two deposits are likely to be more representative than for the other deposits.

When comparing the data from the Gruvberget–Sumåssjön area and the Järvsö Field, where relatively large amounts of data are available, it can be observed that the gabbros from the Järvsö Field typically have slightly higher densities. The magnetic susceptibilities from these two deposits appear to have quite similar average values, however the degree of variation is greater for the data from the Gruvberget–Sumåssjön area (fig. 4). On inspection of the cross plot between magnetic susceptibility and density one can observe that for a given density value, the magnetic susceptibility values from the Järvsö Field appear to typically be lower than those from the Gruvberget–Sumåssjön area (i.e. the susceptibility-density trend is shifted to slightly lower susceptibility values).

When considering the average values in Table 3, it appears that the average densities for the Järvsö Field and the Gruvberget–Sumåssjön area deposits are higher than those from the other deposits. It also appears that the median average magnetic susceptibilities for the Gruvberget–Sumåssjön area, the Järvsö Field, and Simesvallen are higher than those from the remaining deposits.

Table 3. Summary of the average petrophysical properties of gabbro rocks from the different deposits. Source: SGU’s petrophysical database and samples collected in this study.

Deposit	Density (kg/m ³)			Susceptibility (10 ⁻⁶ SI)				Q			
	Samples	Mean	Std. Dev.	Samples	Min	Max	Median	Samples	Min	Max	Median
The Gruvberget–Sumåssjön area	128	3 250	247	417	991	2 140 000	99 100	128	0.07	84.7	1.32
The Järvsö Field	54	3 400	321	437	1 600	6 900 000	125 000	54	0.35	27.9	2.57
Simesvallen	13	3 170	179	77	5 810	441 000	128 000	13	0.69	10	3.37
Kullberget–Storåsen	19	3 140	208	206	1 170	1 410 000	50 100	19	0.09	29.8	0.83
Other deposits	30	3 130	226	291	233	1 780 000	57 900	30	0.2	2.85	0.85

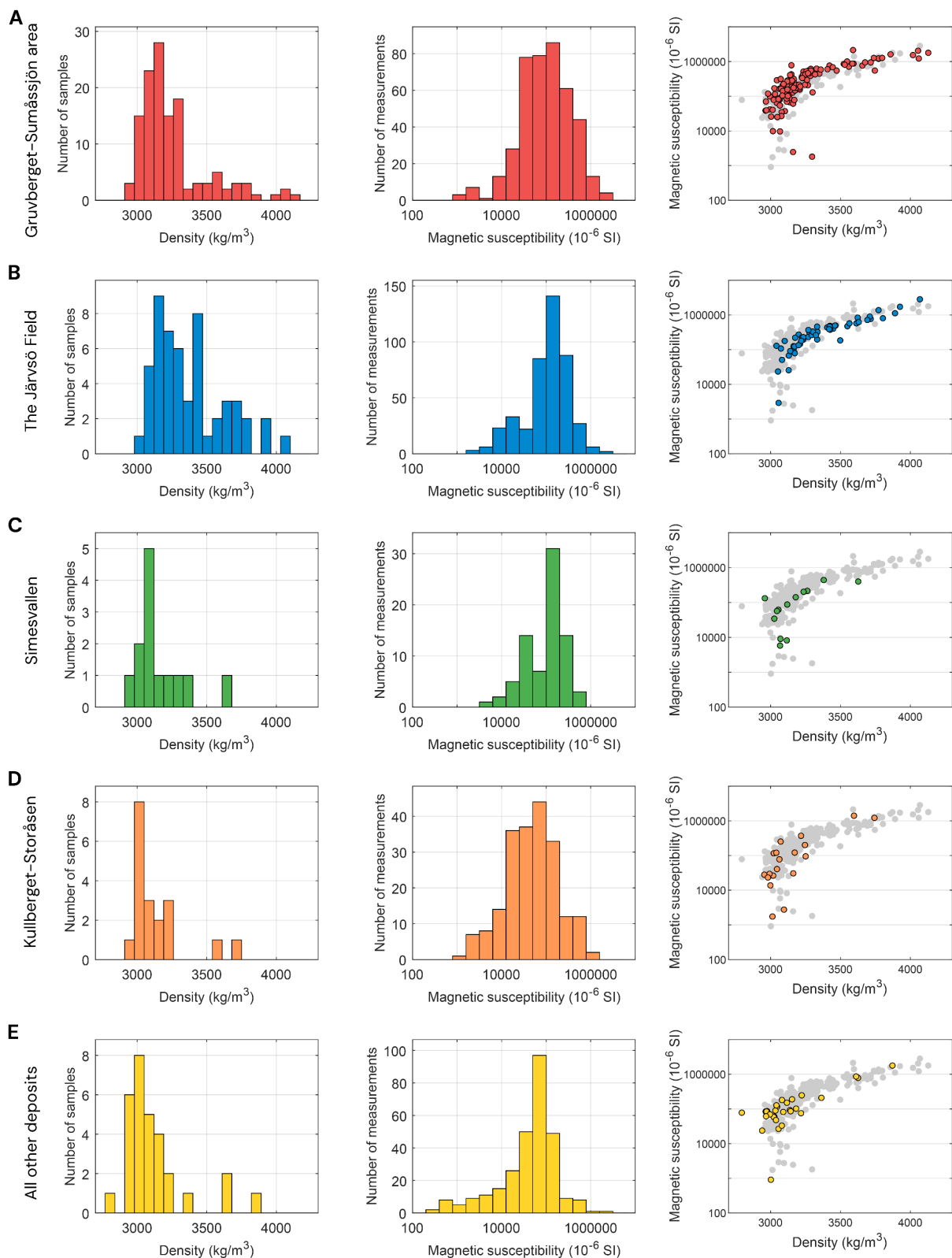


Figure 4. Variation of petrophysical properties of vanadium-bearing gabbro intrusions grouped by deposit. See figure 2 for the locations of the different deposits. Histogram plots of density and magnetic susceptibility can be observed in the left hand and central positions, respectively. In the right-hand position a cross plot of magnetic susceptibility and density is shown. On the cross plot the light grey dots show all data, while the coloured dots indicate data from that specific deposit. The different rows show plots for different deposits, where rows A, B, C, D, and E shows data for the Gruvberget-Sumåssjön area, the Järvsö Field, Simesvallen, Kullberget-Storåsen, and all other deposits, respectively. Source: SGU's petrophysical database and samples collected in this study.

As part of the petrophysical analysis the remanent magnetisation of the different samples was measured. Figure 5 shows cross plots of the Q value and remanent magnetisation (J) versus magnetic susceptibility for samples taken from vanadium-bearing gabbro intrusions. The data in the figure are grouped by deposit. The Q value describes the ratio between the remanent and induced components of the magnetisation, where a Q value above 1 indicates that the remanent component of the overall magnetisation is greater than the induced component. Here it can be observed that the remanent magnetisation is significant for all of the deposits, where a significant proportion of the samples exhibit a Q value above 1. However, it appears that the average remanent magnetisation for the samples from the Järvsö Field and Simesvallen are higher than the other deposits (see Table 3). Figure 6 shows plots of the inclination and declination of the remanent magnetisation measured from oriented petrophysical samples, grouped by deposit. While Table 4 shows average values for the inclination and declination of the remanent magnetisation for the different deposits. It is clear from the results that there is quite a large degree of variability in the orientation of the remanent magnetisation for the different deposits. However, the majority of the deposits appear to have a median average inclination of about 55°. An exception to this is the Järvsö Field which appears to have a relatively low average inclination of about 22°. It also seems to be the case that the deposits from the Gruvberget–Sumåssjön area, Simesvallen, and the other deposits have a median average declination towards the southeast (around 125°). While the Järvsö Field and Kullberget–Storåsen appear to have an average declination towards the southwest (around 220°).

Table 4. Summary of the average inclination and declination of the remanent magnetisation, measured from orientated samples collected in this study from vanadium-bearing gabbro intrusions grouped by deposit.

Deposit	Number of samples	Median declination (degrees)	Median inclination (degrees)
Gruvberget–Sumåssjön area	25	120	53
The Järvsö Field	10	208	22
Simesvallen	3	148	55
Kullberget–Storåsen	7	235	59
Other deposits	11	105	50

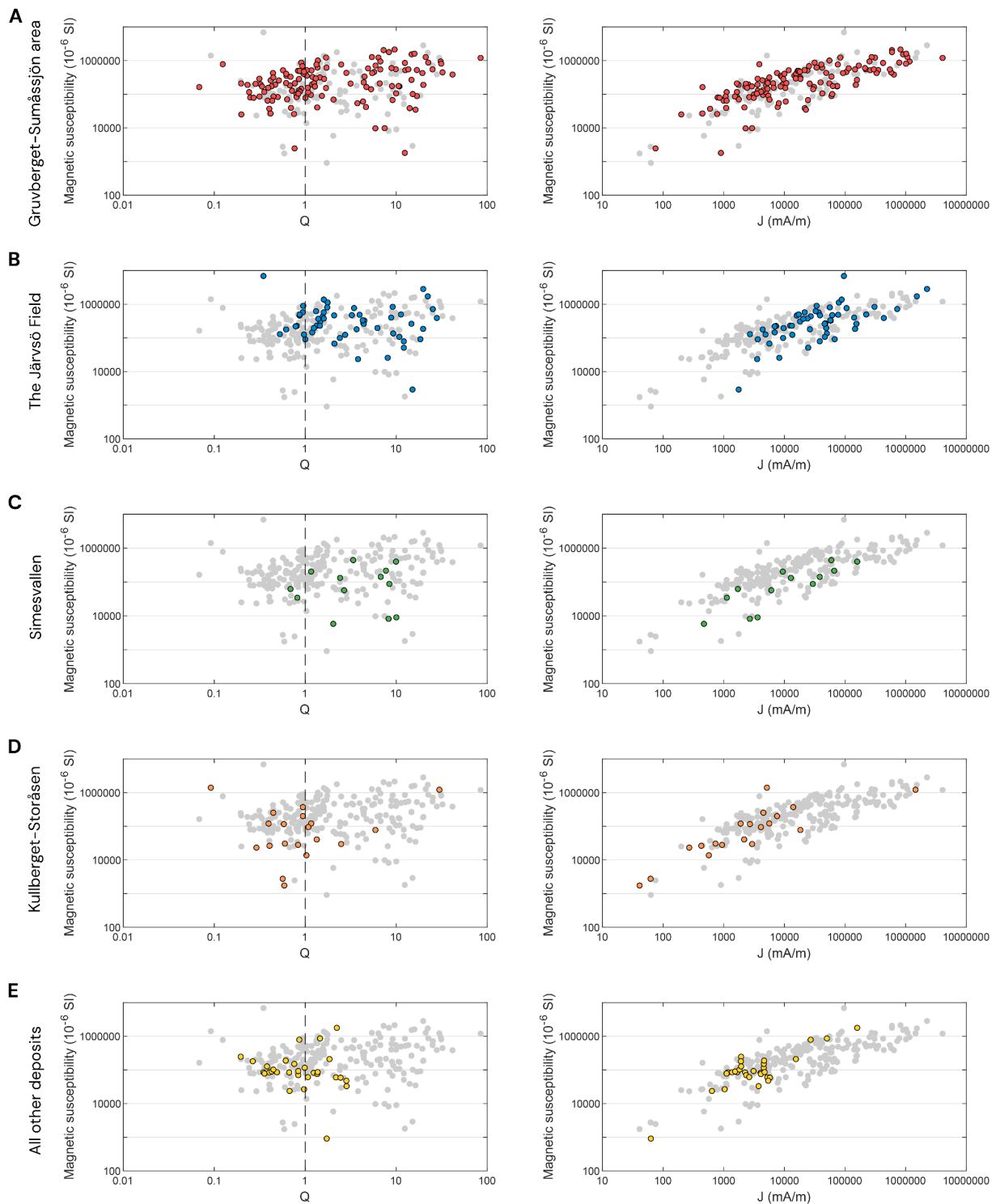


Figure 5. Cross plots of Q and remanent magnetisation (J) against magnetic susceptibility for vanadium-bearing gabbro intrusions, grouped by deposit. The plots on the left-hand side show magnetic susceptibility and Q, while the plots on the right-hand side show magnetic susceptibility and remanent magnetisation (J). On the cross plot the light grey dots show all data, while the coloured dots indicate data from that specific deposit. The different rows show plots for different deposits, where rows A, B, C, D, and E shows data for the Gruvberget–Sumåssjön area, the Järvsö Field, Simesvallen, Kullberget–Storåsen and all other deposits, respectively. See figure 2 for the locations of the different deposits (note that Kramsta lies within the Järvsö Field). Source: SGU's petrophysical database and samples collected in this study.

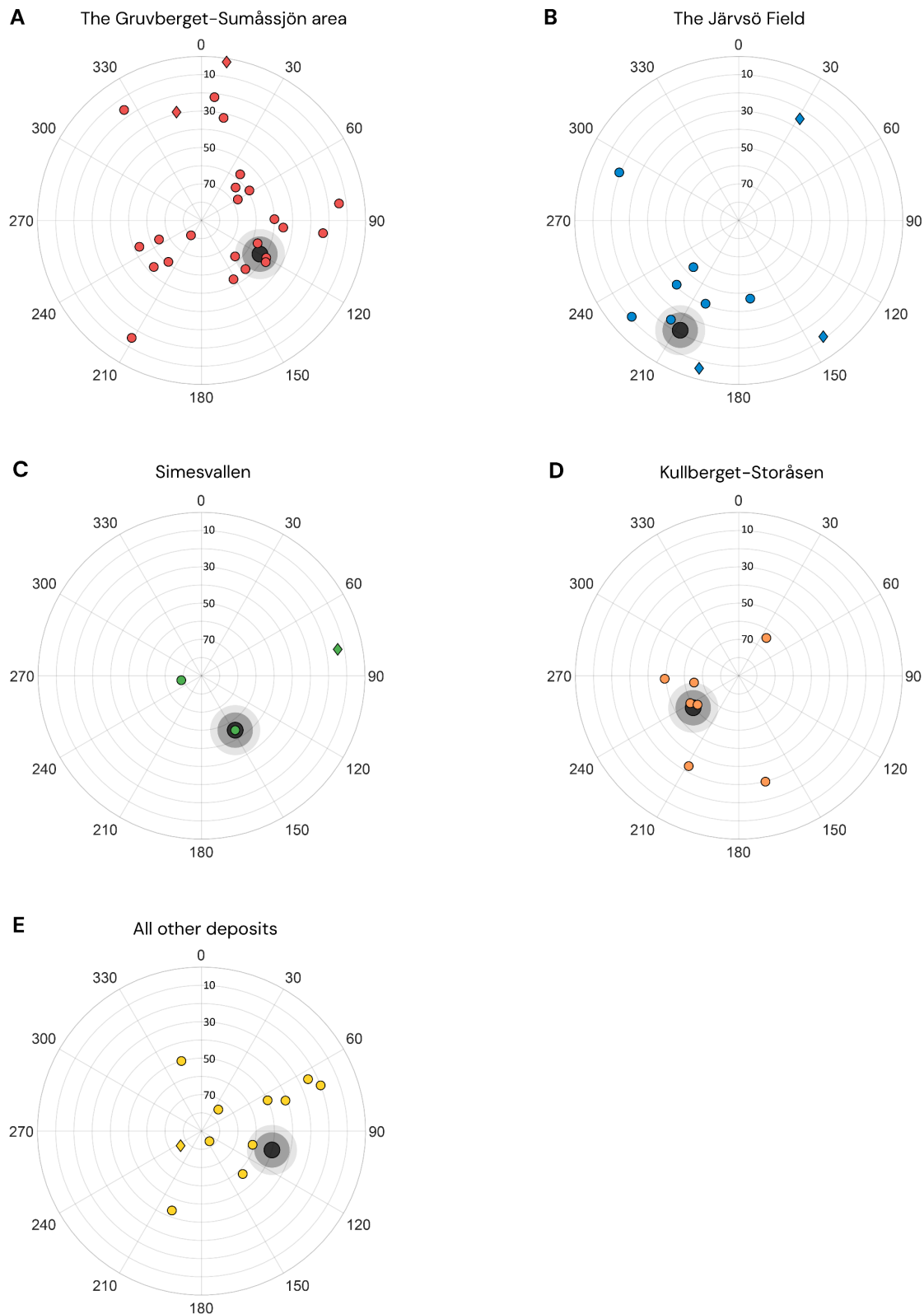


Figure 6. Plots showing the declination and inclination of the remanent magnetisation, measured from orientated petrophysical samples. On each plot the inclination is shown as the radial component (where an inclination of 90° plots in the centre) and the declination as the angular component (where a declination of 0°, or north, plots on the line extending upwards from the centre of the plot). Circles indicate that the inclination is positive, i.e. downwards into the earth, while diamonds indicate an inclination which is negative, i.e. pointing out from the earth. The dark grey circles show the median average inclination and declination of the remanent magnetisation for each plot. The plots in A, B, C, D, and E show data for the Gruvberget–Sumåssjön area, the Järvsö Field, Simesvallen, Kullberget–Storåsen and all other deposits sampled in this study, respectively. See figure 2 for the locations of the different deposits (note that Kramsta lies within the Järvsö Field). Source: SGU's petrophysical database and samples collected in this study.

Comparison of petrophysical and geochemical data

A number of studies have found links between the petrophysical and geochemical properties for mafic intrusions elsewhere in the world. For example, Rosa *et al.* (2020) present geochemical and petrophysical data collected from the Isortoq dyke system, south Greenland, which hosts Fe-Ti-V mineralisation. Here they demonstrate a strong correlation between the magnetic susceptibility and Fe, Ti and V content within the deposit and conclude that magnetic susceptibility is a valid tool for mapping the concentration of these in the field. Another example is presented by Takagi *et al.* (2010), who observe a clear relationship between magnetic susceptibility and magnetite content within gabbroids, southwestern Japan. Furthermore, relationships between the geochemical and petrophysical properties for the vanadium-bearing gabbros from Gävleborg County have also been discussed previously by Persson (1983) and Lagergren (1983).

In this section we investigate the relationship between the petrophysical and geochemical data, available within this study. When collecting new samples from drill cores, efforts were made to first find an interval of several metres which appeared to be relatively homogenous (i.e. similar in appearance and with similar magnetic susceptibilities). The petrophysical and geochemical samples were then collected adjacent to one another within these relatively homogenous intervals. This allows for a direct comparison between the petrophysical and geochemical data. In this study 101 of the petrophysical samples were taken adjacent to geochemical samples, from drill cores which intersect the intrusions in the Gruvberget–Sumåssjön area (Masugnsberget, Gruvberget–Sumåssjön and Bläckmyran), the Järvsö Field (Kramsta), and Simesvallen deposits. Of these samples 94 were taken from gabbros.

Figure 7 shows a plot of the magnetic susceptibility against Fe_2O_3 , TiO_2 , and V content for the corresponding petrophysical and geochemical samples for gabbros. Results are shown for the full dataset and grouped by deposit. There is a clear positive correlation between magnetic susceptibility and Fe_2O_3 , TiO_2 , and V content. A linear trend was fitted to the different groups of data. Furthermore, the standard deviation of the errors between the trend line and the data points was calculated (σ), to provide some measure of the variability of the data away from the trend line. In figure 7 the trend lines are shown on the plots, together with dashed lines, which denote an interval of 2σ above and below the trendline. The gradient, intercept and standard deviation values for the trends can be found in Table 5.

Table 5. Summary of the gradient and intercept values for the best fit linear trend between magnetic susceptibility from petrophysical samples and geochemical data from gabbroic rocks. Results are shown for all data and grouped by deposit. The standard deviation of the misfit between the trend line and the data (σ) is also shown. These values correspond to the trend lines plotted in figure 7.

Geochemical data	Group	Number of samples	Correlation Coefficient	Gradient	Intercept	Standard deviation of misfit between trend and data
Fe_2O_3	All samples	94	0.85	2.288E-05	20.01	6.0
Fe_2O_3	Gruvberget–Sumåssjön area	62	0.86	2.348E-05	19.97	6.2
Fe_2O_3	The Järvsö Field	22	0.81	1.998E-05	21.13	6.1
Fe_2O_3	Simesvallen	8	0.94	3.319E-05	15.95	1.7
TiO_2	All samples	94	0.79	3.630E-06	2.78	1.2
TiO_2	Gruvberget–Sumåssjön area	62	0.83	3.520E-06	2.73	1.1
TiO_2	The Järvsö Field	22	0.68	3.500E-06	3.30	1.6
TiO_2	Simesvallen	8	0.89	8.350E-06	1.48	0.6
V	All samples	94	0.81	2.742E-03	927.90	824.3
V	Gruvberget–Sumåssjön area	62	0.85	2.886E-03	1133.92	782.7
V	The Järvsö Field	22	0.78	1.678E-03	888.31	570.7
V	Simesvallen	8	0.86	3.795E-03	212.38	330.4

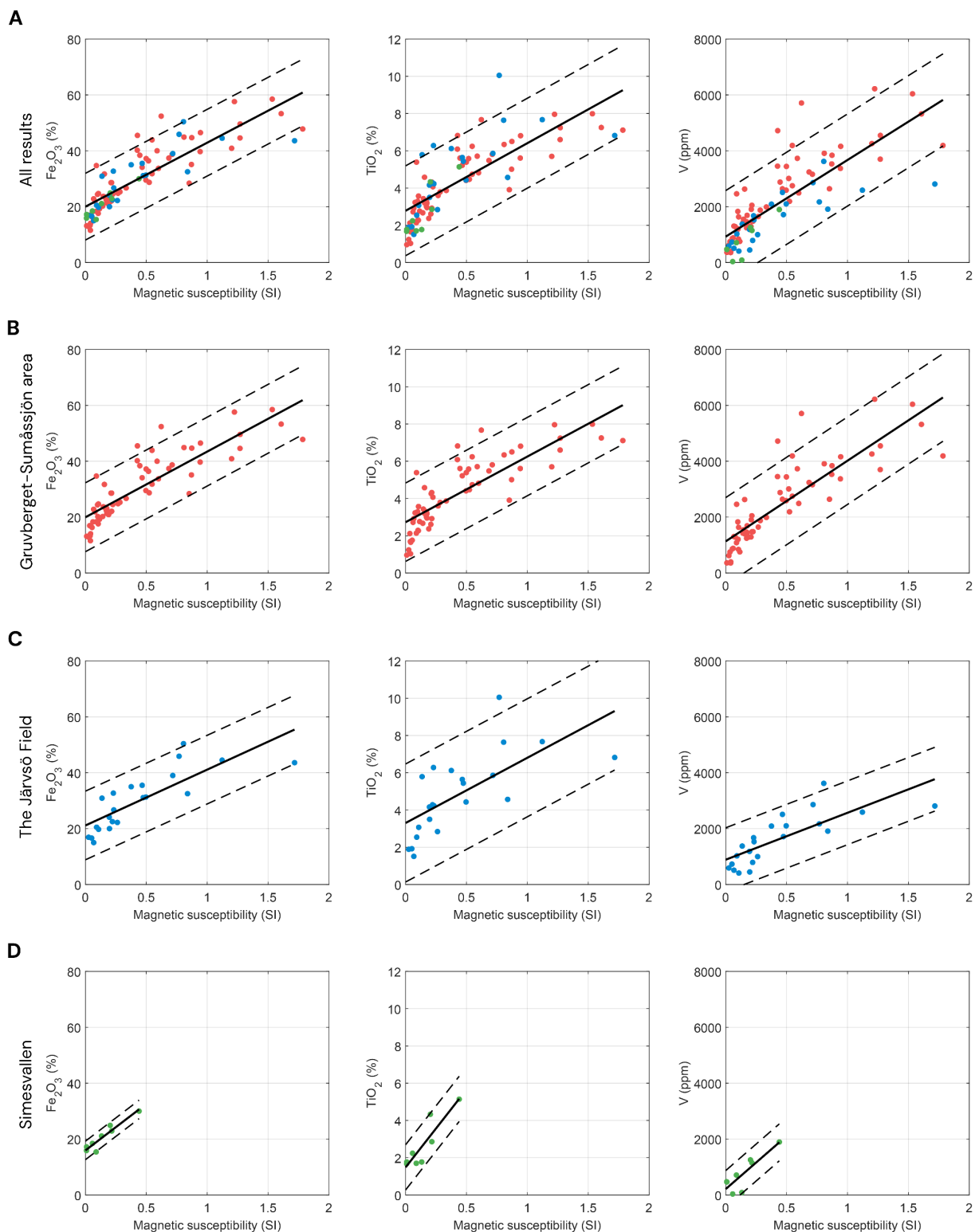


Figure 7. Cross plots of magnetic susceptibility against Fe₂O₃ content (left), TiO₂ content (middle) and V (right) for the petrophysical and geochemical data collected in this study. The different rows show plots for different groups of data, where rows A, B, C, and D show data from all deposits in this study, data from the Gruvberget–Sumåssjön area, data from the Järvsö Field (Kramsta) and data from Simesvallen, respectively. The black line shows the best fit linear trend through the data. The standard deviation of the misfit between the trend line and the data was then calculated (σ). The dashed lines show the trend line $\pm 2\sigma$. Source: SGU's petrophysical database and samples collected in this study.

The data from Simesvallen only comprise 8 samples (fig. 7), and none of these exhibit very high magnetic susceptibilities. This was largely due to the fact that the most mineralised parts of the Simesvallen drill core had already been sampled and for large sections only a quarter of the core remained in the drill core box. Hence, no additional sampling could be performed. As a result, the trends obtained for the Simesvallen deposit are likely not very representative.

For the Järvsö Field and the Gruvberget–Sumåssjön area more data is available. Here relatively similar trends are obtained between magnetic susceptibility, Fe_2O_3 and TiO_2 content. However, the gradient between magnetic susceptibility and vanadium content is notably lower for the Järvsö Field (Kramsta) compared to the deposits from the Gruvberget–Sumåssjön area. As the amount of magnetite is thought to be the main control on the magnetic response, it infers that the gabbro in the Järvsö Field deposits have a lower ratio of vanadium to magnetite than for the deposits in the Gruvberget–Sumåssjön area.

Logging magnetic susceptibility on drill core

In addition to the petrophysical samples collected in this study, logging of magnetic susceptibility was performed on drill core from 19 boreholes. In these cases, the available cores were measured with a hand magnetic susceptibility meter at 0.5 m intervals, in the SGU's drill core archive in Malå using an analogue JH-8 (ABEM) susceptibility meter. This instrument was chosen as the volume of investigation is relatively small, making it the most suitable for measuring drill core. The aim was to provide an indication of the variability of the magnetic susceptibility throughout the deposit and provide constraint for geophysical modelling. Furthermore, since a relationship between magnetic susceptibility and geochemical properties of the gabbro had been inferred from previous work, an additional objective was also to use these measurements to directly deduce geochemical properties.

When measuring the magnetic susceptibility, several practical aspects needed to be considered. Firstly, it became apparent that the metal in the roller tables in the logging room, affected the measurements. Hence, care was taken to raise the box being measured on a stack of empty wooden boxes to avoid unwanted noise. Another aspect to consider was the varying amount of core which remained in the boxes. The vast majority of the core had already been sampled and only half of the core remained, however, in some cases only a quarter of the core was present. Therefore, in the cases when only a quarter of the core was present, pieces of adjacent core were temporarily moved to reconstruct a section of core equivalent to a half core, which was in turn measured. This helped to reduce the geometric effect between different sections of core. However, this means that the measurements are not truly representative of the precise depth.

After logging, the data were compared with the measurements of magnetic susceptibility made in the petrophysics lab from core samples (fig. 8). Some differences are anticipated due to the different methodology employed. Furthermore, it is often the case that the exact part of the core measured by the different methods was not the same, i.e., the logging measurements were made at regular 0.5 m intervals which may not coincide exactly with the position of petrophysical samples. However, it can be observed that as well as some random variation, there is also a systematic difference between the susceptibility values measured in the lab and with that of the hand-held susceptibility meter (fig. 8). The hand-held susceptibility measurements are typically about 60% of the values obtained with the lab measurements.

For the purposes of this study, it is helpful if a direct comparison between the two types of susceptibility measurements can be made. As the lab measurements are considered to be more representative, a correction factor was applied to the logging susceptibility values. Hence, all of the hand-held susceptibility measurements were multiplied by 1.66. When applying this factor to the data the gradient of the best fit linear trend between the lab and hand-held measurements becomes approximately 1.00, facilitating a direct comparison between the two datasets.

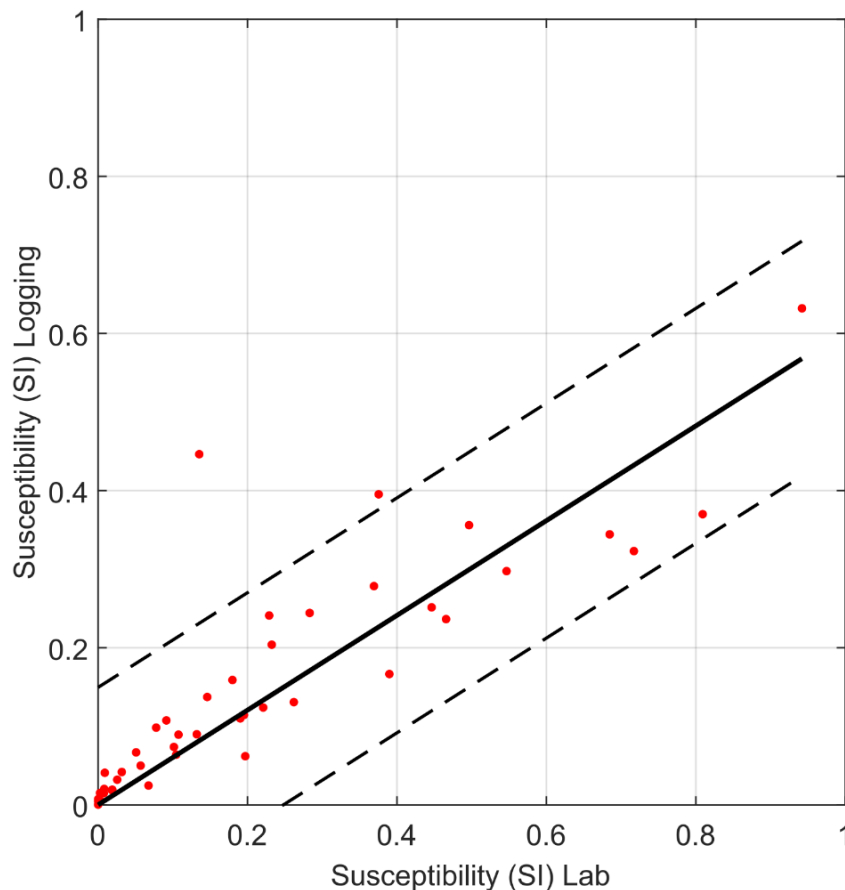


Figure 8. Cross plot of magnetic susceptibility measurements performed on samples in the petrophysics lab and measurements with a hand-held susceptibility meter (JH-8). Data (red dots) are shown before applying a correction factor to the logging measurements. The solid line shows the best fit linear trend to the data, where the line has a gradient of 0.603. The standard deviation of the misfit between the trend line and the data was then calculated (σ). The dashed lines show the trend line $\pm 2\sigma$.

After correcting the hand-held susceptibility log measurements, a comparison was made between these data and the geochemical data, as was done with the petrophysical lab data. However, in the case of the susceptibility log values, a comparison could also be made with pre-existing geochemical data. Often these older geochemical data (described in more detail in the section *Investigated areas*) were collected over relatively large intervals (for example 5 m), in this case the susceptibility log values were averaged over the same interval as the geochemical sample before comparison. Table 6 shows the gradient and intercept values for the best fit linear trend between the susceptibility log values and the available geochemical data. The intercept and gradient values for the best fit trends differ to some degree from the corresponding values for the petrophysical lab data (shown in Table 5). This could be due to differences which remain between the susceptibility log values and the petrophysical susceptibility measurements. It could also be due to the fact that it was possible to include the pre-existing geochemical data as well as the newly acquired data from this study.

Table 6. Summary of the gradient and intercept values for the best fit linear trend between magnetic susceptibility from core logging and different geochemical data taken from gabbro. Results are shown for all data and also grouped by deposit. The standard deviation of the misfit between the trend line and the data (σ) is also shown.

Geochemical data	Group	Number of samples	Correlation Coefficient	Gradient	Intercept	Standard deviation of misfit between trend and data
Fe ₂ O ₃	All samples	159	0.843	3.862E-05	13.64	4.4
Fe ₂ O ₃	Gruvberget–Sumåssjön area	82	0.915	4.394E-05	11.46	3.5
Fe ₂ O ₃	The Järvsö Field	38	0.879	3.129E-05	15.28	3.0
Fe ₂ O ₃	Simesvallen	39	0.716	4.431E-05	14.50	6.0
TiO ₂	All samples	91	0.875	7.060E-06	1.29	0.8
TiO ₂	Gruvberget–Sumåssjön area	14	0.928	7.540E-06	1.00	0.8
TiO ₂	The Järvsö Field	38	0.774	6.180E-06	1.76	0.9
TiO ₂	Simesvallen	39	0.878	7.000E-06	1.19	0.5
V	All samples	159	0.763	3.953E-03	378.20	601.8
V	Gruvberget–Sumåssjön area	82	0.923	4.866E-03	341.62	371.8
V	The Järvsö Field	38	0.769	2.726E-03	405.95	308.5
V	Simesvallen	39	0.518	3.262E-03	478.05	748.8

Figure 9 shows susceptibility log measurements of the drill core BLA82006, from the Bläckmyran deposit. The oxide and element concentrations calculated using the susceptibility log measurements and the trend values in Table 6 are also shown. Petrophysical data from lab measurements and the available geochemical data are also shown on the plots for reference. There is a very good match between the geochemical values calculated from the susceptibility log and the geochemical data as well as a relatively good match between the lab based and hand-based magnetic susceptibility measurements. Both the susceptibility log data and geochemical data indicate that the upper 70 m of the gabbro is more strongly mineralised than the lower 20 m. Intervals with relatively low magnetic susceptibilities appear to correlate well with thin intervals where more felsic granitoid or hybrid rock types are present. Furthermore, the base of the gabbro and transition into foliated granite is clear from the susceptibility measurements.

Maps showing the location of boreholes where magnetic susceptibility logging of drill core was performed are shown in appendix B. Log plots of magnetic susceptibility measurements and geochemical data are shown for each drill core in appendix B.

BLA82006

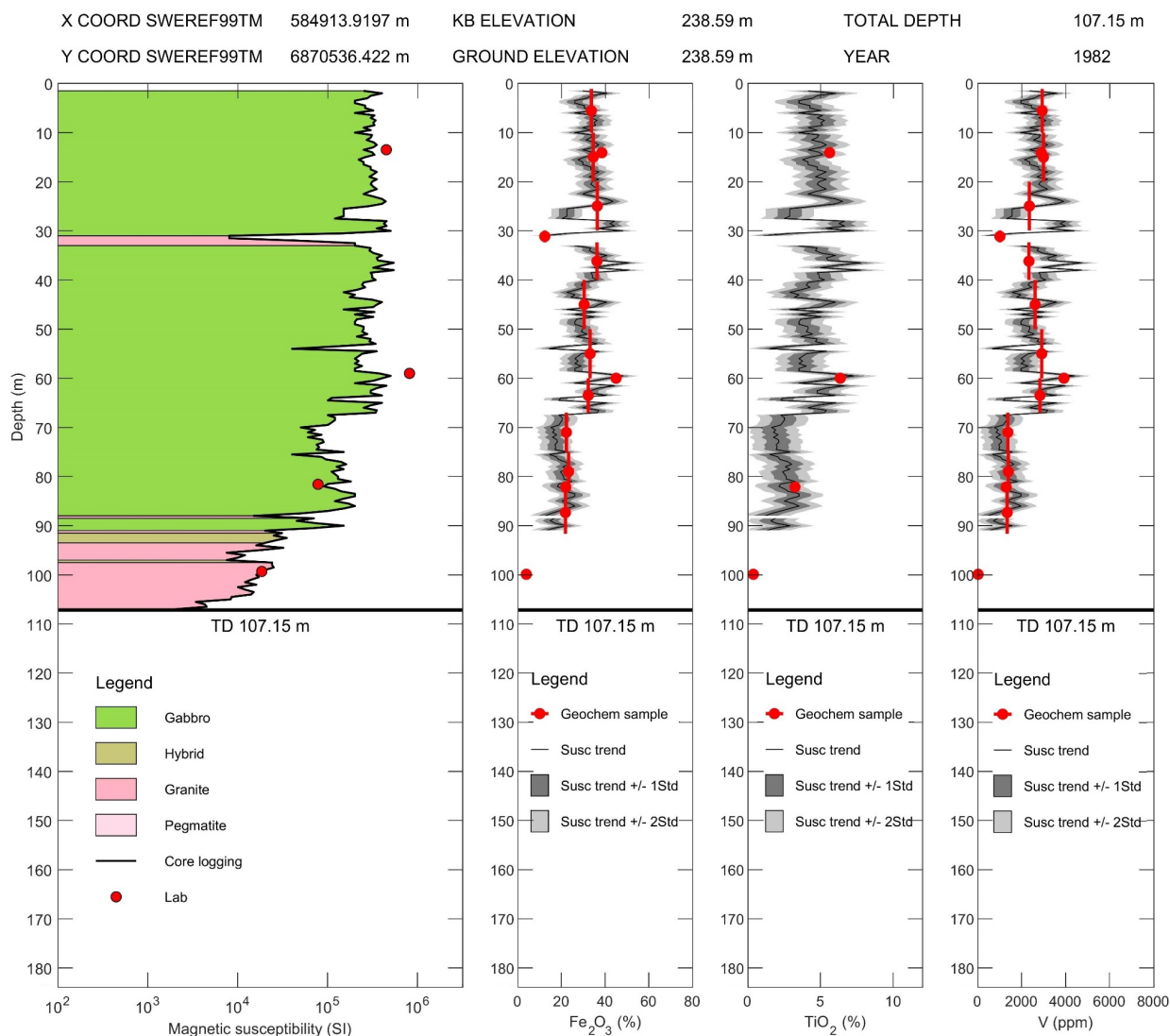


Figure 9. Example of a magnetic susceptibility log measured on drill core from borehole BLA82006, from the Bläckmyran deposit. The magnetic susceptibility log values are shown as the thick black line in the left plot. The magnetic susceptibility from lab samples is shown as red circles. The susceptibility log is shaded with colours to denote a simple lithological interpretation of the core. The three plots to the right of the susceptibility log show the available geochemical data for Fe_2O_3 , TiO_2 , and V. The geochemical data are shown as red points, while the red bars above and below the points show the sampling interval. In the background a black line is shown which denotes the oxide and element concentrations calculated from the magnetic susceptibility data, using the trend values in Table 6. The standard deviation of the error between the trend line and the data is denoted by σ (shown in Table 6). The dark grey and light grey shaded areas show the calculated geochemical values $\pm \sigma$ and 2σ , respectively. See appendix B for the location of the borehole within the intrusion.

Summary of petrophysical data and analysis

In this section we have described the pre-existing and newly collected data from vanadium-bearing gabbros in the Ljusdal lithotectonic unit. Based on analysis of these data the following conclusions can be made:

- Previous mineralogical analysis indicates that the main control on the magnetic response within these deposits appears to be magnetite. Ilmenite is also present but likely contributes in a minor way to the magnetic response.
- The density and magnetic susceptibility of the vanadium-bearing gabbros are typically significantly higher than those from other gabbros in the study area.
- Remanent magnetisation is a significant factor in the magnetic response from the vanadium-bearing gabbros, where Q values above 1 are commonly observed.
- The orientation of the remanent magnetisation within the vanadium-bearing gabbros appears to be quite variable. However, the Järvsö Field and Kullberget–Storåsen appear to typically have a southwest declination, while the remaining deposits typically have a southeast declination.
- There is a good correlation between the magnetic susceptibility and the geochemical data. We utilise this relationship to calculate estimated oxide and elemental concentrations from magnetic susceptibility measurements made on drill core.
- Systematic variations in the magnetic susceptibility values measured with different methods occur. Hence, before using the magnetic susceptibility data to quantitatively estimate the geochemical properties of the gabbros, care should be taken to calibrate the type of measurement being used to the geochemical data. For example, different linear functions were obtained when comparing hand-held and lab-based susceptibility measurements with geochemical data in this study.

Inversion of ground magnetic data

In this study we present ground magnetic data from 22 different intrusions. For each of these datasets we provide a qualitative interpretation of the data, together with the available geological observations and samples. This is presented in the form of an updated bedrock geology map. In addition, an inversion was performed for each of the ground magnetic surveys. This resulted in a 3D model of magnetic susceptibility for each intrusion. In each case, the magnetic field calculated from this 3D model produces a close match to the measured data. To provide a consistent result between surveys the same inversion workflow was applied for each input dataset. We also discuss the assumptions inherent in the inversion process applied here as well as some of the uncertainties and challenges with interpreting the results.

Inversion workflow

The inversion of the ground based magnetic data in this project was performed using the VOXI application in the Seequent Geosoft software. Before performing each inversion, some simple pre-processing was applied to the data. This consisted of three steps described below. Figure 10 shows the ground magnetic data at the different stages of the pre-processing workflow.

1. **Gridding:** The ground magnetic data were first interpolated to a regular X and Y grid using Geosoft (minimum curvature). The grid spacing used varied somewhat between the different input datasets but was typically 5 m.
2. **Upwards continuation:** The gridded data were then upwards continued by 5 metres. This was performed in order to reduce the risk of potential artefacts in the inversion process.

3. **Grid extrapolation:** The upwards continued grid was then extrapolated to cover a larger area. This was performed in order to avoid edge effects and artefacts in the inversion process related to a lack of measurements at the edges of the survey area. For the areas where data was extrapolated (i.e. where no measured data present) a gradual transition from the measured magnetic field values to a constant background value was assumed. The constant background value for each dataset was chosen subjectively based on the measured data. At this stage the data was also re-sampled with a 10 m grid spacing.

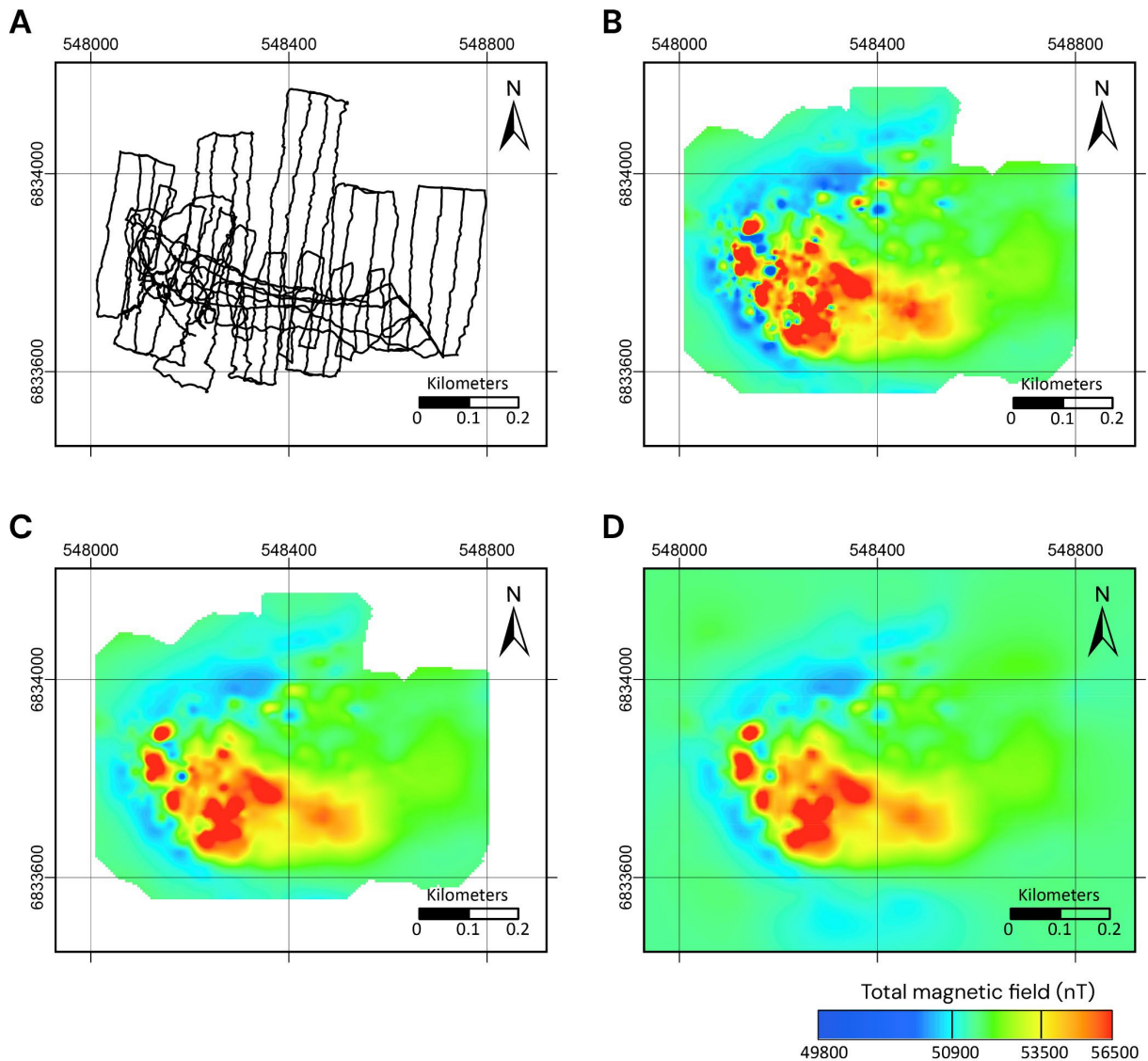


Figure 10. Pre-processing steps for ground magnetic data applied before performing an inversion of the data. The data shown here is from the Skälberget intrusion. **A.** Map showing the location of the survey lines for the ground magnetic data (black lines). **B.** Map showing the ground magnetic data after gridding (5 m grid spacing). **C.** Map showing the ground magnetic data after upwards continuation by 5 m. **D.** Map showing the ground magnetic data after extrapolation and resampling to a 10 m grid spacing. Note that all gridded magnetic field data is shown with the same colour scale, which is shown in the bottom right-hand corner of the figure.

After performing the pre-processing steps, the ground magnetic data for each survey area were inverted. The following parameters were used when inverting each dataset:

- **Unconstrained inversion:** All inversions were largely unconstrained. Hence, no a-priori information or reference models were included. However, the magnetic susceptibility values in the model were constrained to remain between 0 and 10 SI.
- **Constant grid spacing:** All susceptibility models from the inversion had a constant grid spacing of 25 m in the X and Y directions, and constant spacing of 12.5 m in the Z direction.
- **Inversion for magnetic susceptibility:** All inversions were performed to obtain a 3D scalar model of magnetic susceptibility. In this case the measured magnetic field values are assumed to be a product of the primary magnetic field and induced components only, i.e. remanent magnetisation is not considered.
- **Constant background removal:** In each case a constant background value was removed from the input data prior to the inversion.
- **Earth's magnetic field:** The direction and strength of the earth's magnetic field was adjusted according to the coordinates and year in which it was collected.

After performing each inversion, the 3D magnetic susceptibility models were exported from Geosoft and imported into the MATLAB software for further analysis. Here the magnetic susceptibility values from the inversion were compared with the measured data values.

Initially, based on their location, the nearest cell in the model was identified for each magnetic susceptibility measurement (at the surface or from drill cores). The magnetic susceptibility values for each measurement and the nearest cell in the model were then compared quantitatively. A schematic diagram describing this comparison is shown in figure 11A. Here an example is given where the data with red circles would be compared with the cell with a red outline, similarly the cell with a yellow outline would be compared with the data with yellow outlines. Unfortunately, this comparison gave a rather weak or non-existent correlation between the measured data and inverted models. This demonstrates that these models should not be used to make direct quantitative inferences about the mineralisation in the intrusions.

Subsequently, a more general comparison was made between the measured data and inverted models considering only X and Y location and focusing on the uppermost part of the subsurface. In this case, for each cell in the X and Y dimensions, the susceptibility values in the model were averaged for the upper 75 m. These average values were then compared to the average value of all the measured data located in the same model cell, in the X and Y dimensions, up to a depth of 75 m. A schematic diagram describing this comparison is shown in figure 11B. Here the values from the uppermost 6 cells have been averaged and the deeper values disregarded, to give a single average susceptibility per X and Y location in the model. In this example, the average value of the data with red outlines would be compared with the cell with a red outline. Similarly, the average value of the data with yellow outlines would be compared with the cell with a yellow outline. When performing this comparison between the inverted model values and the measured data some degree of correlation was observed. Figure 12 shows a cross plot of average magnetic susceptibility values in the upper 75 m of the model and average measurement values in the upper 75 m, for a given X and Y model cell. The values shown here are for the models and measurements from the Kramsta, Gruvberget–Sumåssjön, Bläckmyran, Masugnsberget and Simesvallen intrusions. These intrusions were chosen for the comparison as drill core data is available from these intrusions which greatly increases the number of measurements available for the comparison. Here a weak correlation exists (correlation coefficient of 0.5) between the average measured susceptibilities and the average model susceptibilities. If a linear trend with an intercept of zero is fitted to the cross plot, we obtain a gradient of 0.61 which describes the relationship between the modelled and measured susceptibilities. In this case a model

susceptibility of 1 SI would correspond to a measured susceptibility of 0.61 SI. It is clear that there is a large degree of uncertainty in this linear trend, where the standard deviation of the error between the data and the trend is some 0.141 SI.

If the above comparison of model and measured values is performed for only one intrusion at a time, then different correlation coefficients are obtained for each comparison. The highest of these was for the Bläckmyran intrusion where a correlation coefficient of 0.61 was obtained between the average model values in the upper 75 m and the measured values.

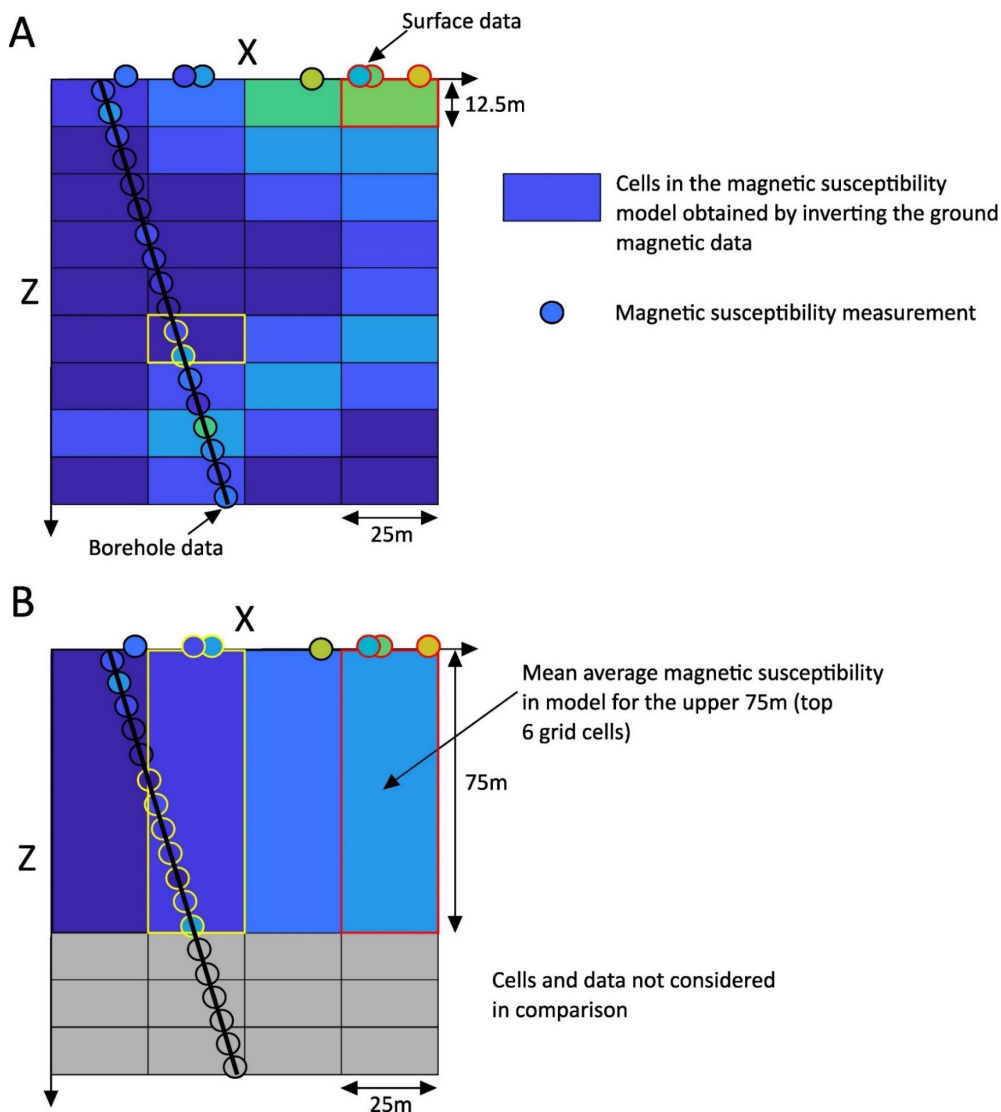


Figure 11. Schematic diagram showing different comparisons made between the magnetic susceptibility model obtained from inversion and the magnetic susceptibility measurements. **A.** Shows the first quantitative comparison made between the model and the measurements. In this case the data and measurements are compared for each cell in the model. Two examples are shown, whereby the measurements and model cell highlighted with red would be compared. Similarly, the measurements and model cell highlighted in yellow would be compared. **B.** Shows the second, more general quantitative comparison made between the model and the measurements. In this case the upper 75 m of the model are averaged and compared with all measurements lying within these larger averaged cells. The data and model values deeper than 75 m are disregarded. Two examples are shown, whereby the measurements and model cell highlighted with red would be compared. Similarly, the measurements and model cell highlighted in yellow would be compared.

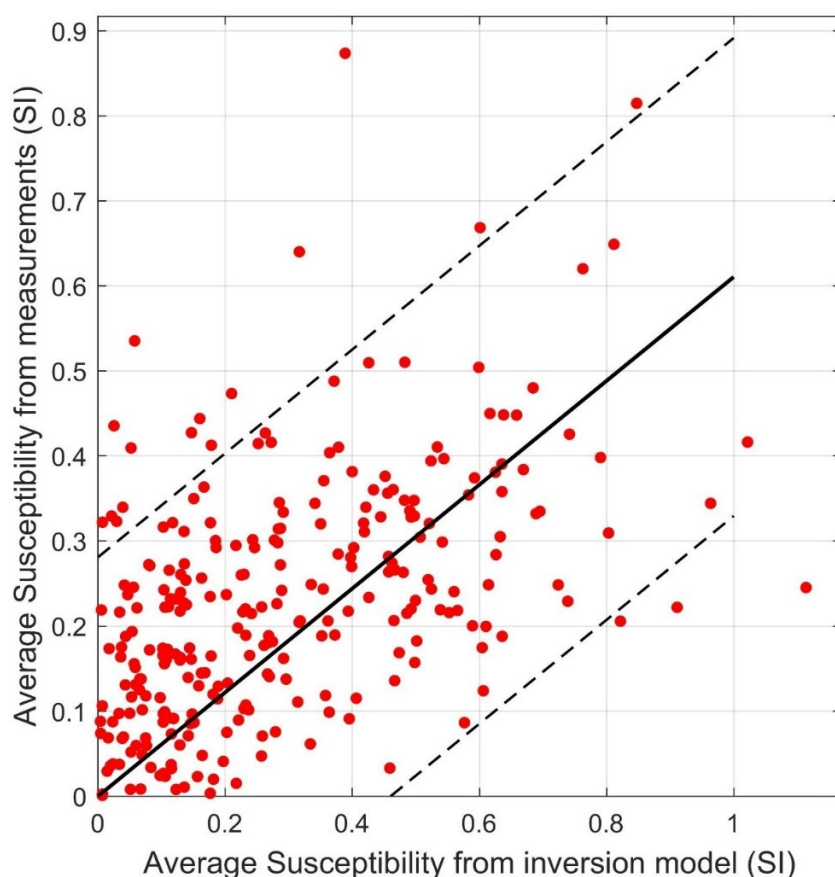


Figure 12. Cross plot of mean average magnetic susceptibility values from the upper 75 m of the inversion model, compared to average values of measurements collected in the upper 75 m, for a given X and Y location in the model. A schematic diagram describing this comparison is shown in figure 11B. The data shown here are from the Kramsta, Gruvberget–Sumåssjön, Bläckmyran, Masugnsberget, and Simesvallen intrusions. The black line shows the best fit linear trend through the data. The standard deviation of the misfit between the trend line and the data was then calculated (σ). The dashed lines show the trend line $\pm 2\sigma$.

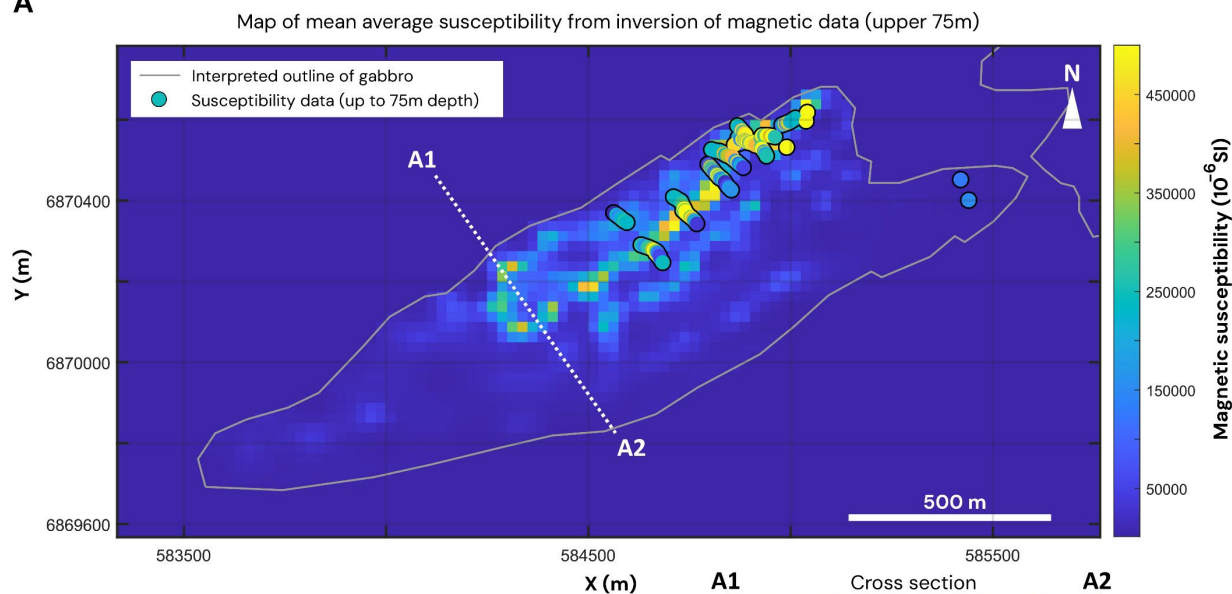
Hence, as there is at least a weak correlation with the measured data, in this report we present a series of maps of average magnetic susceptibility in the upper 75 m of the model obtained by inversion. Before plotting the average values from each model in this report, the average values were multiplied by 0.61 to make them comparable with the measured values. Figure 13A shows an example of one of these maps for the Bläckmyran intrusion. Here the average magnetic susceptibilities from the model in the upper 75 m are shown together with all the measurement values in the upper 75 m. It is apparent that there is a reasonable visual correlation between the measured and inverted susceptibilities in the map.

In addition to the map, a cross section through the inverted model is shown. On inspection of all the inverted models, the dip direction indicated on these cross sections typically agree well with the dips of the intrusions, where it has been confirmed with drill core data (Båk 1984). Hence, we also present one or more representative cross sections through each of the inversion models in this report. These cross sections should be considered to give a more qualitative indication of the dip (or apparent dip in cases when the cross section is not perpendicular to the strike of the intrusion) and geometry of the regions of high magnetic susceptibility at depth.

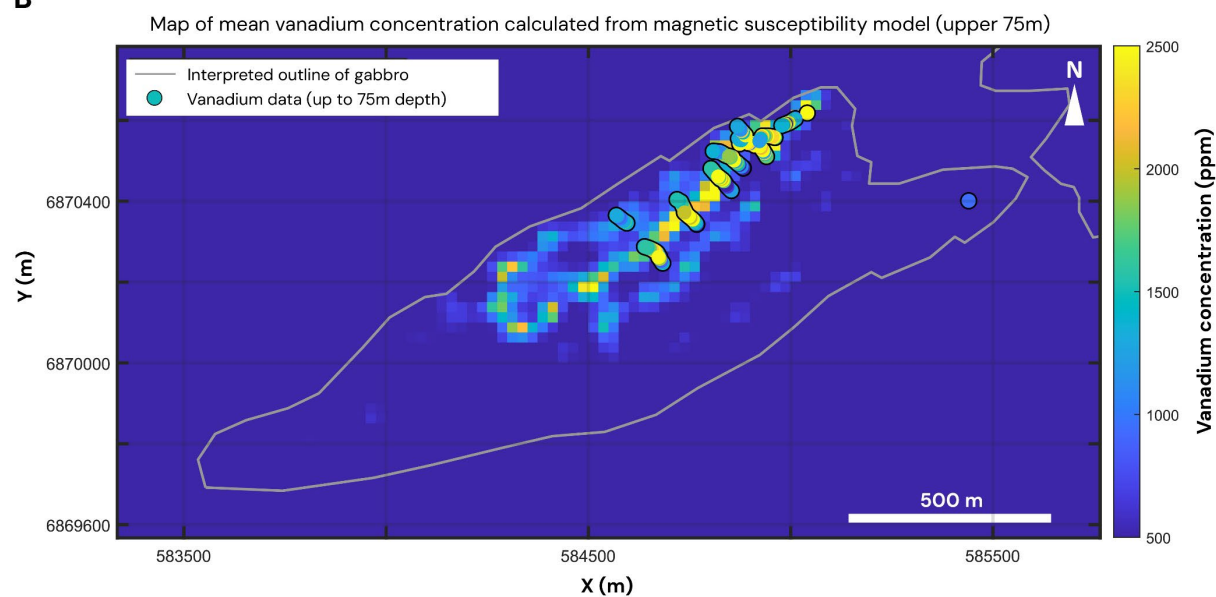
Figure 13 also shows a map of average vanadium concentration within the upper 75 m of the bedrock plotted together with the available geochemical data. This map is calculated directly from the magnetic susceptibility values obtained from the inversion, using the trends discussed in the petrophysics section of the report. It can be observed that there is a good visual correlation between the calculated vanadium concentration and the measured values. It should be noted that these estimates of vanadium concentration are highly uncertain and in no way represent official resource estimates. However, these results are shown here to highlight the potential to utilise the strong relationship between magnetic susceptibility and vanadium concentration during future exploration resource characterisation efforts.

► **Figure 13.** **A.** Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Bläckmyran intrusion. All magnetic susceptibility measurements collected up to a depth of 75 m (measurements on core and at the surface) are shown as dots. In cases where only geochemical data is available from drill cores, magnetic susceptibilities have been calculated using the relationship described in the petrophysics section of the report. These calculated susceptibilities are shown together with the magnetic susceptibility measurements as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown below the map. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale. **B.** Map of the average vanadium concentration in the upper 75 m, calculated directly from the magnetic susceptibility model using the trends detailed in the petrophysics section of the report. The available vanadium concentrations from drill core and surface measurements are plotted on the map as dots. Note that these concentrations are highly uncertain and can in no way be considered official estimates of resource potential.

A



B



Discussion of inversion results, assumptions, uncertainties and potential for future work

In these inversions, the effect of remanent magnetisation was not considered, which has been shown to have a significant effect on the magnetic response of these intrusions (see the petrophysics section of this report). Hence, in this study, where the inversions assume that the entire magnetic field response is related to induced magnetisation only, the resultant magnetic susceptibility values in the model will be overestimated. This may provide some explanation as to why the magnetic susceptibility values in the model are typically about 60% higher than the measured susceptibility values in the comparison described in the previous section (see fig. 12). Therefore, in order to produce a more accurate inverted model of magnetic susceptibility, suitable for quantitative analysis, the effect of remanent magnetisation would need to be included. We have collected additional information of the remanent magnetisation of these intrusions. It is clear from these results that the remanent magnetisation is relatively strong but also that it has a highly variable declination and inclination. Therefore, it could be useful to investigate an inversion process which incorporates and honours the statistical relationship between magnetic susceptibility and remanent magnetisation (fig. 5) as well as the variability in direction of remanent magnetisation (fig. 6).

Furthermore, in this study we have performed largely unconstrained inversions. This means that no a-priori information, start model or reference model was provided. For a number of the intrusions a great deal of a-priori information is available in the form of drill core data which describe the magnetic susceptibility values within the intrusion as well as compositional variations and lithological contacts. The inversions performed here are also constrained to provide a smoothly varying result, where no sharp changes in magnetic susceptibility occur. In reality, the regions of very high magnetic susceptibility in these intrusions are often confined to relatively thin discrete intervals with sharp changes at the boundaries. Similarly, sharp magnetic susceptibility contrasts exist at the contact between the mafic intrusions and the surrounding granitic rocks. Therefore, it is also clear that before these results can be used quantitatively, more effort would be required to incorporate a-priori information and tailor the constraints in the inversion to produce a more representative result.

It is important to note that the inversion results presented in this study should be considered primarily as qualitative. This is due to the assumptions made in the inversion and the relatively weak correlation between the magnetic susceptibility values in the model and from measurements. However, with additional work, if more accurate and better constrained inversions can be performed, there is good potential to extract valuable quantitative information about these deposits from the geophysical data (exemplified in fig. 13B). Bearing this in mind, it is likely that these inversion results can still provide a valuable indication of the general geometry and overall dip direction of these intrusions at depth.

Airborne magnetic data and ground-based gravity data

In this section we present and discuss airborne geophysical data and ground-based gravity data on a regional scale across the study area. Figure 14 shows a map of the total magnetic field over the Ljusdal lithotectonic unit. The map was generated by compiling data from 23 different airborne surveys collected between 1976 and 2021. These surveys were collected at different times and with different altitudes (30–60 m). Hence, before merging, the data from each survey was corrected to the magnetic pole and then, if necessary, upwards continued to an altitude of 60 m. The data from the different surveys was then merged to give a uniform grid across the study area. For areas with overlapping data from different surveys, the most recent data was

utilised. To generate the total magnetic field map, the measurement points were interpolated using a minimum curvature algorithm and a 50 m grid cell size.

A number of large-scale geological features are clearly visible from the airborne magnetic data. For example, the northern boundary of the Ljusdal lithotectonic unit (Hassela shear zone) can be seen clearly in places as a transition from a more variable response with higher magnetic field values in the south to more homogenous response with lower magnetic field values in the north. A number of local deformation zones are also clearly visible within the study area within the magnetic field data. For example, several linear features with a relatively low magnetic field striking northwest–southeast can be observed to the east of Ljusdal and Järvsö (fig. 14). Within the Ljusdal lithotectonic unit, the Fe-Ti-V deposits are clearly associated with high magnetic field values, for example at Kramsta, Gruvberget–Sumåssjön, and Kullberget (figs. 2 and 14). However, high magnetic field values can also be observed with a range of other rock types, for example metasedimentary rocks to the east of Simesvallen, felsic volcanic rocks to the north of Kullberget and rocks within the Dellen impact structure, northeast of Delsbo village.

Figure 15 shows a regional map of the Bouguer anomaly (which includes a correction for terrain) over the Ljusdal lithotectonic unit as well as the location of the measurement points used to generate the map. At the beginning of this project SGU already had a large amount of gravity measurements from across the Ljusdal lithotectonic unit, however, the typical spacing between adjacent points was of the order of 2–3 km. As a result, the gravity anomalies associated with the vanadium-bearing gabbro intrusions were often not well resolved in the data. As part of this project new gravity measurements were collected. The objectives of this new acquisition were (1) to collect relatively dense measurements over the known vanadium-bearing gabbro intrusions and (2) to increase the overall spatial sampling frequency of the gravity data on a regional scale around and between the known intrusions. Within the project, 1 906 new ground gravity measurements were performed which can be seen in figure 15. In addition to the new ground gravity measurements made by SGU, a number of gravity measurements acquired as part of previous exploration activities were digitised and incorporated into the study dataset. This included a series of gravity profiles collected over the Kramsta deposit (Edberg 1981; see fig. 15). As a result, the typical spacing between gravity measurement points has been reduced to as little as 100 to 500 m over the known vanadium-bearing gabbro intrusions. Whilst more regionally over the project area the average spacing has been reduced to about 500 to 1 000 m between measurement points (see fig. 15). To generate the Bouguer anomaly map, the measurement points were interpolated using a minimum curvature algorithm and a 200 m grid cell size.

Within the Ljusdal lithotectonic unit the most striking feature on the regional Bouguer anomaly map (fig. 15) is a prominent positive anomaly, about 80 km wide, centred around Järvsö and the Kramsta and Simesvallen intrusions. The cause of this anomaly is not apparent from the bedrock geology map which is mainly characterised in this area by a large area of fairly homogenous foliated granitic and granodioritic rocks (fig. 2). It could therefore infer the presence of a relatively large amount of more dense rocks (for example mafic rocks) at depth. In the northern part of the Ljusdal lithotectonic unit, south of the Hassela shear zone, there is a zone of relatively low gravity values. The deposits from the Gruvberget–Sumåssjön area (i.e., Bläckmyran, Blistra, Masugnsberget, Gruvberget–Sumåssjön and Gråsjön) are located within this region. A low gravity anomaly can also clearly be observed at the Dellen impact structure. Within the southern part of the Ljusdal lithotectonic unit there is a smaller positive anomaly south of Bollnäs and Söderhamn.

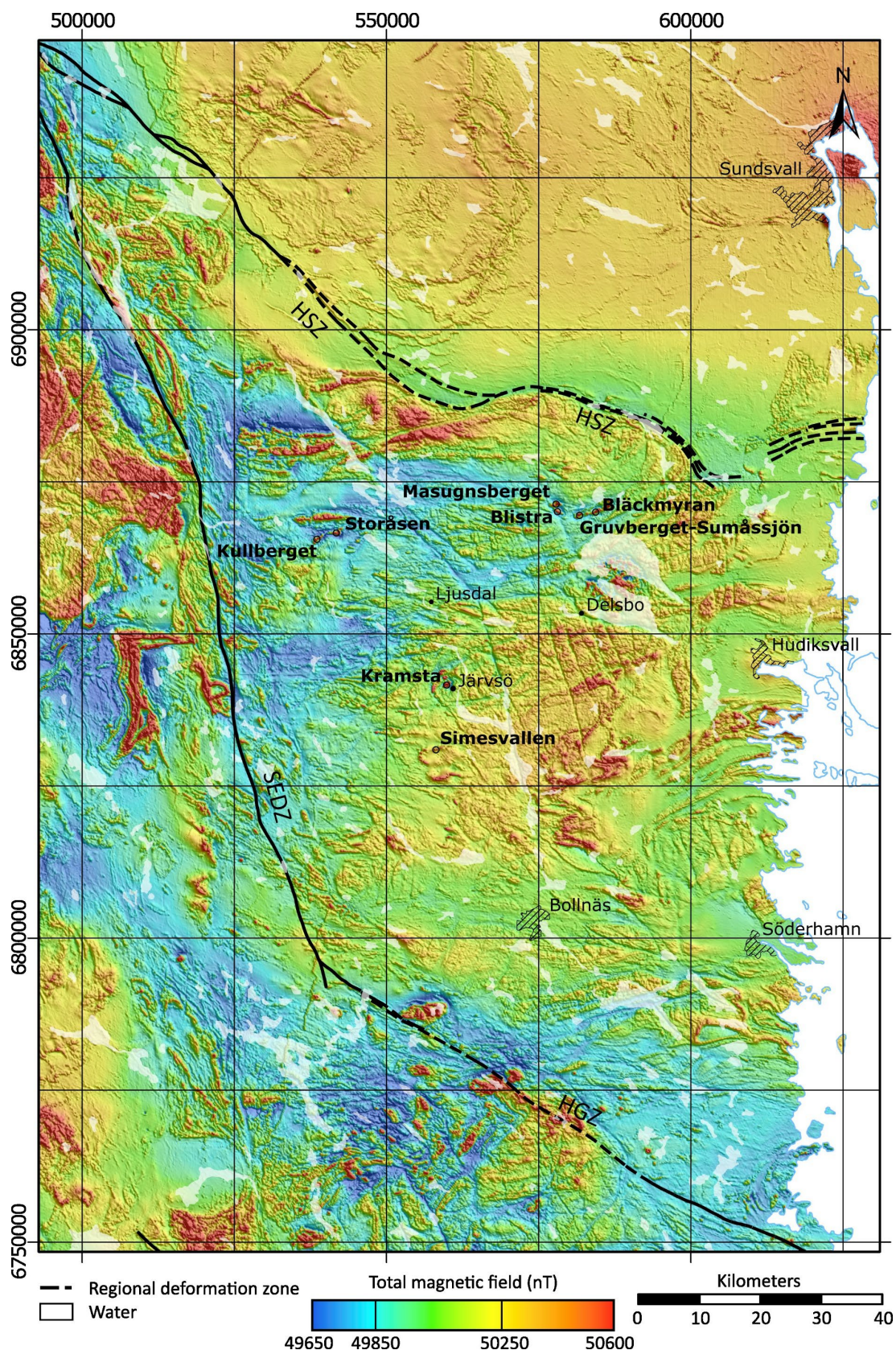


Figure 14. Map of the total magnetic field (reduced-to-pole) generated from airborne measurements performed between 1976 and 2021. HSZ: Hassela shear zone, SEDZ: Storsjön-Edsbyn deformation zone, HGZ: Hagsta gneiss zone. The locations of several Fe-Ti-V deposits are annotated on the map for reference. Note that the so called Järvsö Field, sometimes referred to in the text includes the Kramsta, Storsveden and Järvsö-Gruvberget deposits.

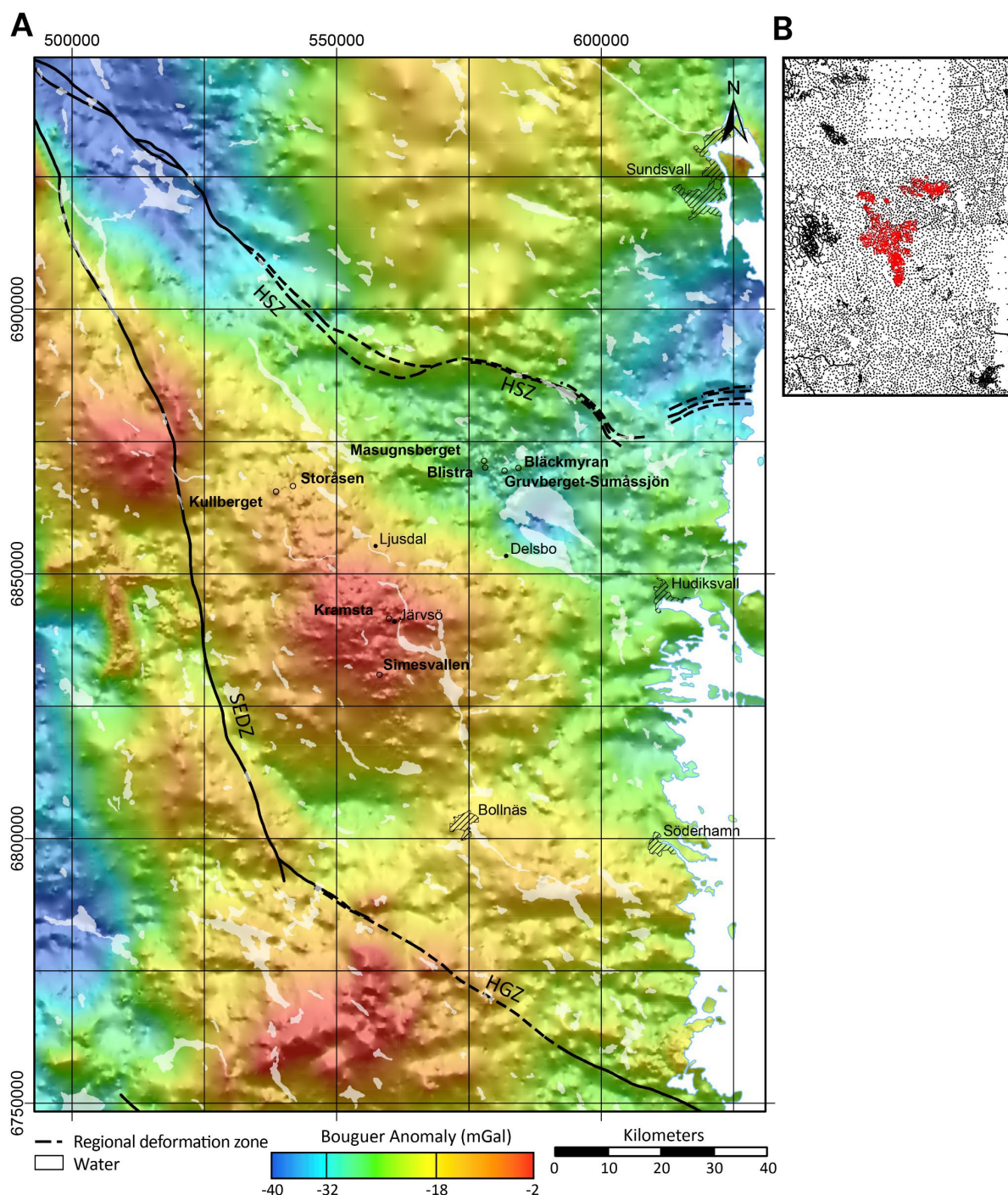


Figure 15. A. Map of the Bouguer anomaly generated from ground gravity measurements taken from SGU's gravity database. HSZ: Hassela shear zone, SEDZ: Storsjön-Edsbyn deformation zone, HGZ: Hagsta gneiss zone. The locations of several Fe-Ti-V deposits are annotated on the map for reference. **B.** Map showing the location of gravity data measurement points. Black dots show locations of all measurements, red dots show the locations of new measurements collected as part of this project. Note that the so called Järvsö Field, sometimes referred to in the text includes the Kramsta, Storsveden and Järvsö-Gruvberget deposits.

Figures 16 and 17 show maps of airborne magnetic and gravity data at a larger scale than in figures 14 and 15, focusing on the northern and southern areas containing vanadium-bearing gabbro intrusions, respectively. The airborne magnetic data shown in these figures are identical to the data shown in figure 14, i.e. the total magnetic field (reduced-to-pole). The gravity data presented in figures 16 and 17 is a residual gravity anomaly map. This was calculated by performing an upwards continuation of the Bouguer anomaly data by 1 000 m. The map that was upwards continued was then subtracted from the Bouguer anomaly map to produce the residual gravity anomaly map. The resulting residual gravity map contains only the higher frequency components of the data, which in this case are assumed to correspond to density variations closer to the surface. The outlines of the vanadium-bearing gabbro intrusions interpreted within this project are annotated on the maps as black lines. These interpretations are based on the airborne magnetic data but also on ground based magnetic measurements and geological observations, which will be discussed later in this report.

Based on the analysis of the petrophysical data (discussed previously) the vanadium-bearing gabbro intrusions often have a significantly higher magnetic susceptibility and density than the other rock types in the study area (fig. 3). On these larger scale maps (figs. 16 and 17) the strong magnetic anomalies associated with these intrusions are more clearly observable, when compared to the smaller scale map in figure 14. Here the intrusions typically give rise to high amplitude positive anomalies with an elongate form. It can be observed that the intrusions often occur in clusters, often along a single lineation. For example, the intrusions at Gruvberget–Sumåssjön, Bläckmyran, and Gråsjön occur close together along a single trend. This infers that the intrusions within these clusters are likely to be related to each other, potentially forming contemporaneously. Similarly, positive gravity anomalies can be observed to be associated with the majority of intrusions in figures 16 and 17. For example, prominent positive anomalies can be observed at the Bläckmyran, Masugnsberget, Kullberget, and Kramsta intrusions. However, it is important to note that due to practical issues, new gravity measurements were not collected over all of the intrusions. For example, in figure 16 no strong gravity anomaly is observed at Storåsen. However, this is most likely due to the fact that the measurements were only performed on the roads around the intrusion and not directly above it.

In figure 17 there appears to be a series of east–west striking positive gravity anomalies which underlie zones where intrusions are observed at the surface. For example, one such zone appears to extend east from the Skalberget intrusion, passing through a number of other intrusions. Similarly, there appears to be another east–west trending anomaly which underlies the Oktjärnen intrusion and several other smaller intrusions. This could be indicative that in these zones the intrusions are part of a larger system along which additional mafic rocks can be found at depth. Furthermore, there are a number of areas with relatively high positive residual gravity anomalies, where gabbro intrusions are not observed at the surface, for example west of the Kramsta and Storsveden intrusions. In these cases, this could infer the presence of gabbro intrusions below the surficial granite and granodiorite rocks.

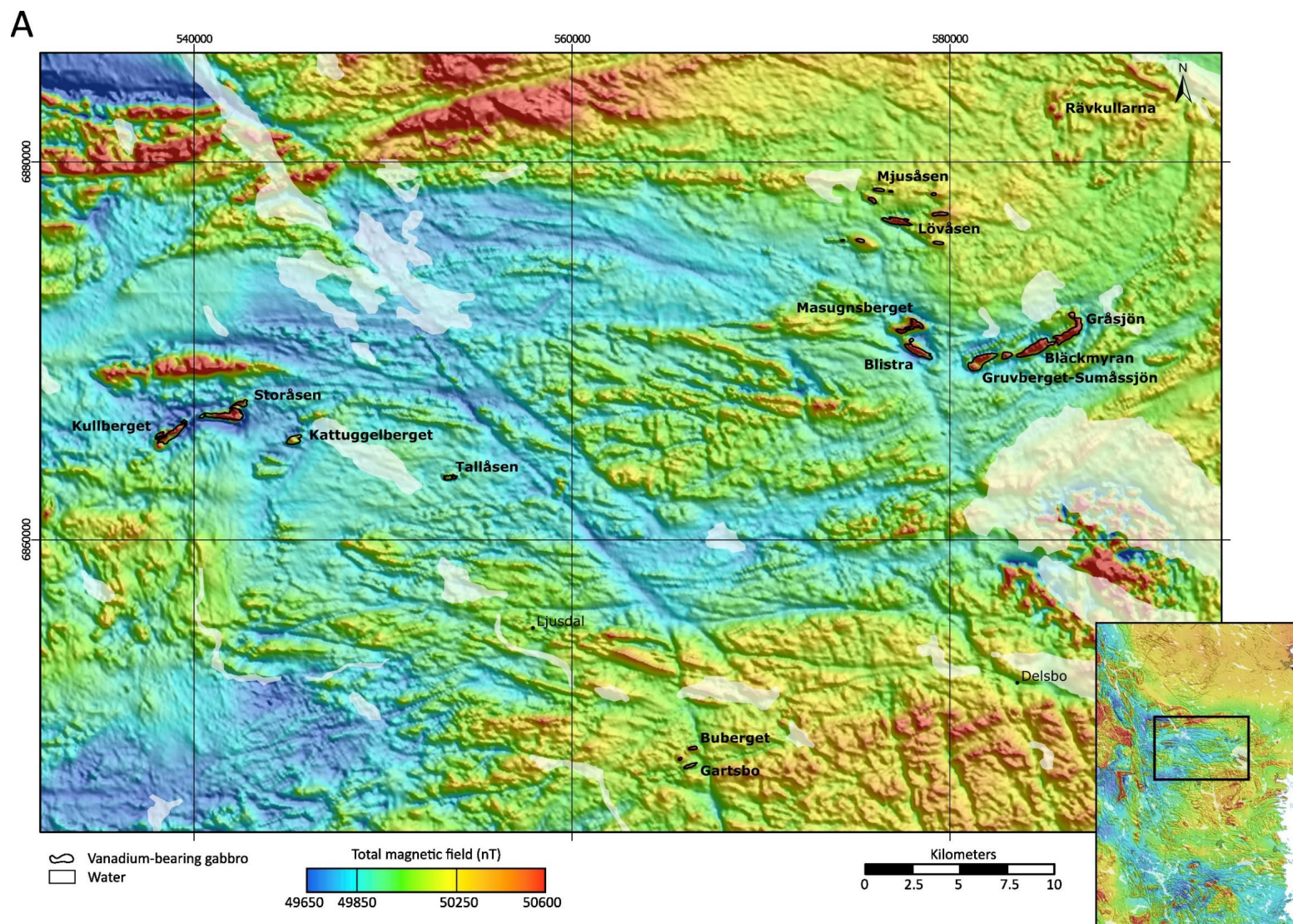


Figure 16. A. A map of the total magnetic field (reduced-to-pole) generated from airborne measurements, which focuses on the northern part of the area containing the vanadium-bearing gabbro intrusions. The locations of the vanadium-bearing gabbro intrusions are highlighted with black polygons. The individual gabbro intrusions referred to in the text in the report have been labelled. The inset map shows the area of the regional airborne magnetic map shown in figure 14 which is covered by this map.

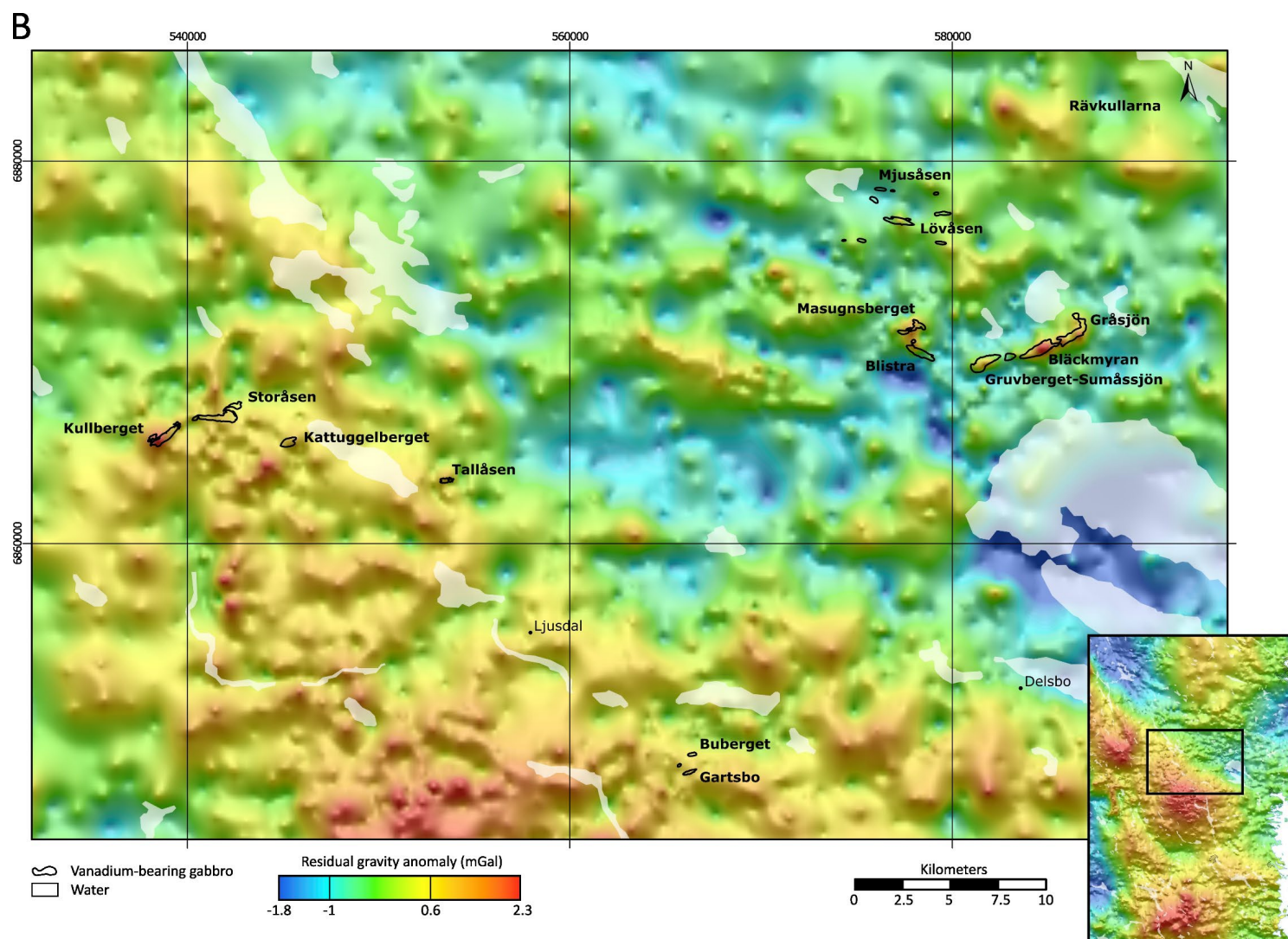


Figure 16 continued. B. A map of the residual gravity anomaly (calculated with 1 000 m upwards continuation), which focuses on the northern part of the area containing the vanadium-bearing gabbro intrusions. The locations of the vanadium-bearing gabbro intrusions are highlighted with black polygons. The individual gabbro intrusions referred to in the text in the report have been labelled. The inset map shows the area of the regional Bouguer anomaly map shown in figure 15 which is covered by this map.

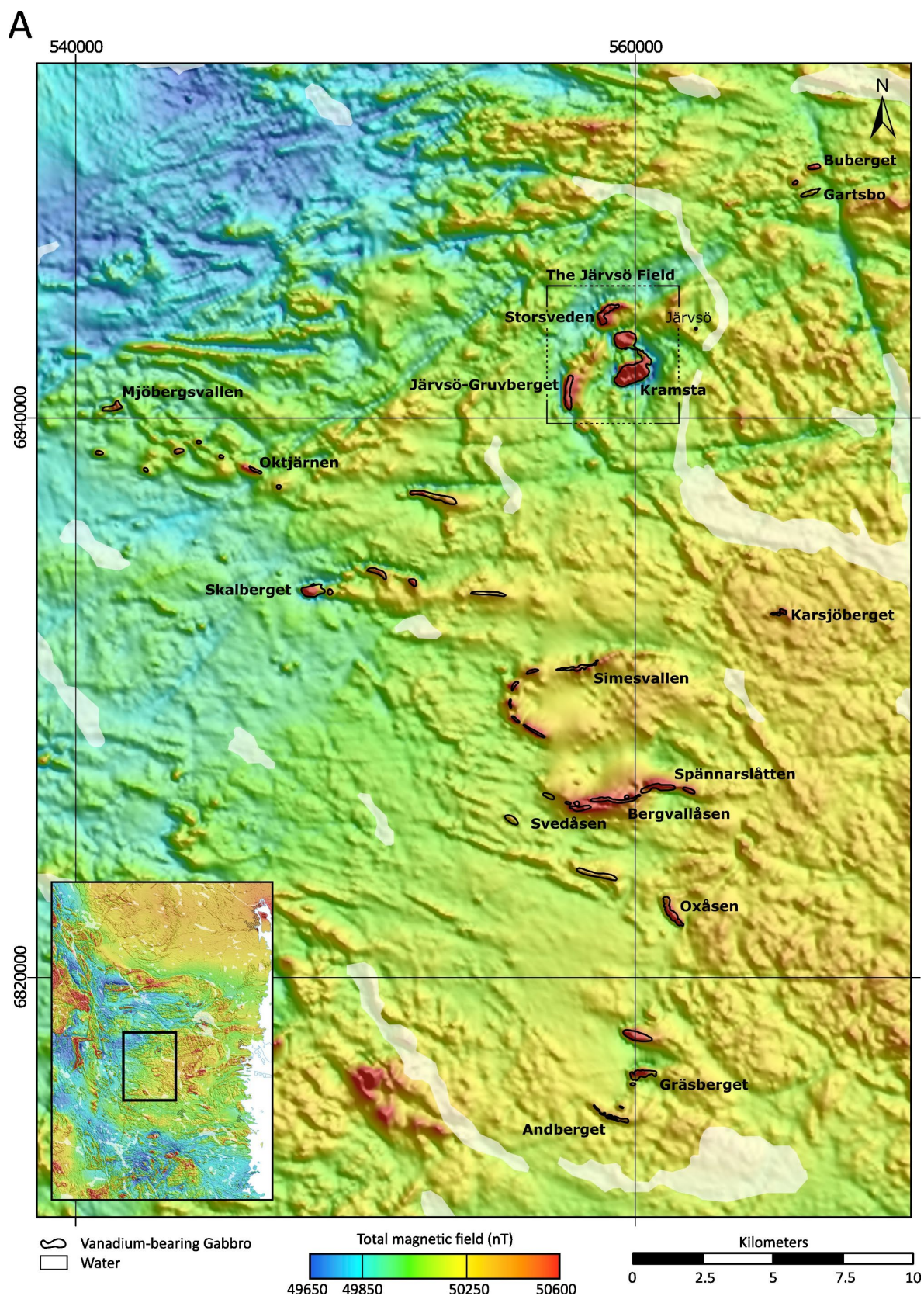


Figure 17. A. Map of the total magnetic field (reduced-to-pole) generated from airborne measurements which focuses on the southern part of the area containing the vanadium-bearing gabbro intrusions. The locations of the vanadium-bearing gabbro intrusions are highlighted with black polygons. The individual gabbro intrusions referred to in the text in the report have been labelled. The inset map shows the area of the regional airborne magnetic map shown in figure 14 which is covered by this map.

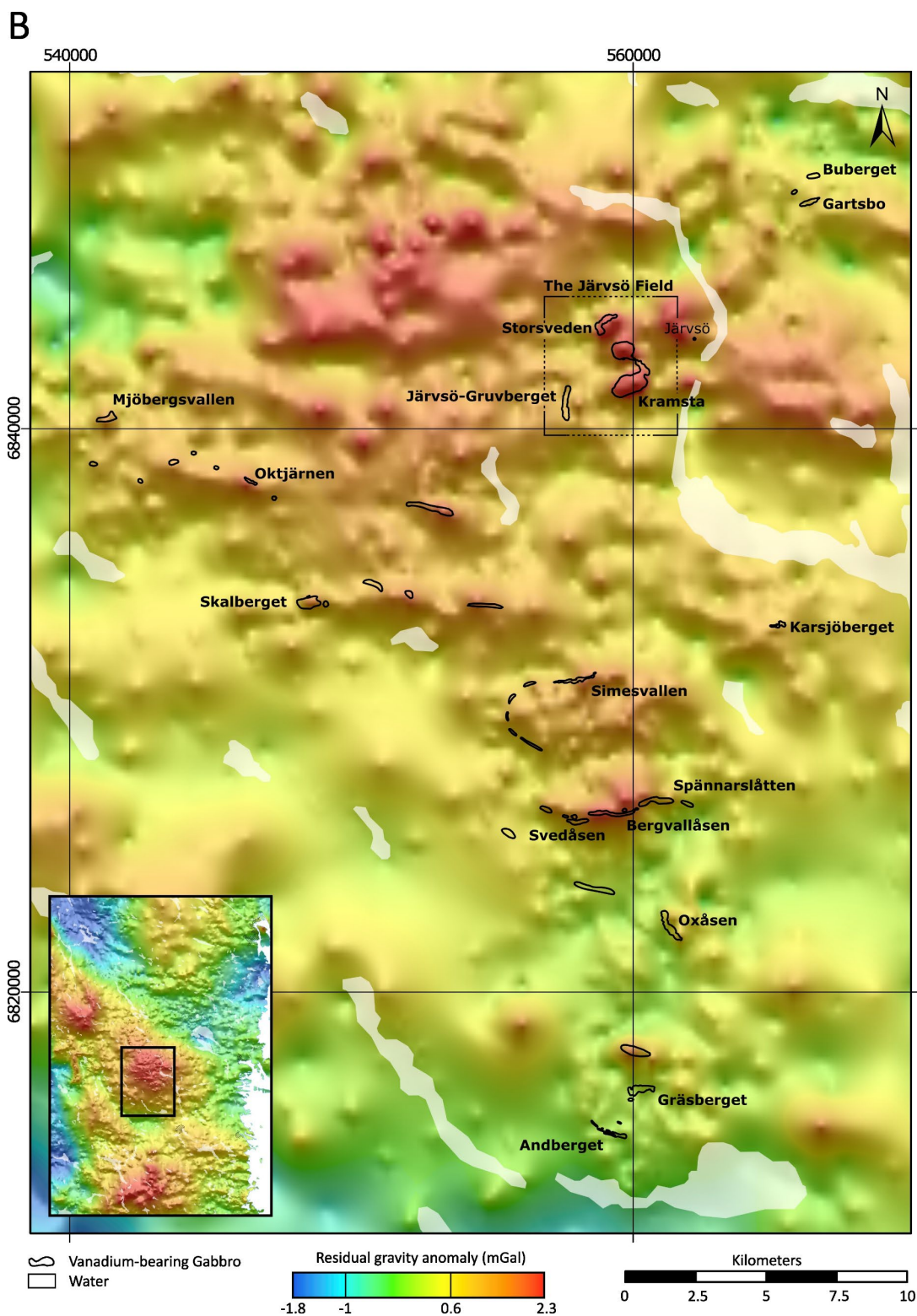


Figure 17 continued. B. Map of the residual gravity anomaly (calculated with 1 000 m upwards continuation), which focuses on the southern part of the area containing the vanadium-bearing gabbro intrusions. The locations of the vanadium-bearing gabbro intrusions are highlighted with black polygons. The individual gabbro intrusions referred to in the text in the report have been labelled. The inset map shows the area of the regional Bouguer anomaly map shown in figure 15 which is covered by this map.

In this section we present some results from a statistical analysis of the interpreted geometries of the vanadium-bearing gabbro intrusions from within the study area (fig. 18). To compile these results the length, width and orientation of the interpreted outlines of the intrusions (figs. 16 and 17) were measured. Here it can be observed that the intrusions typically have lengths between 100 m and 1 000 m, with a median average of about 458 m. The intrusions have widths typically between 50 m and 300 m, with a median average of 150 m. The ratio between length and width of the intrusions is typically between 1 and 5, with a median of 2.89. Finally, the intrusions appear to typically have an east–west orientation. The typical orientation of the intrusions is consistent with the series of striking east–west gravity anomalies which underlie several of the intrusions exposed at the surface (for example below Skjalberget).

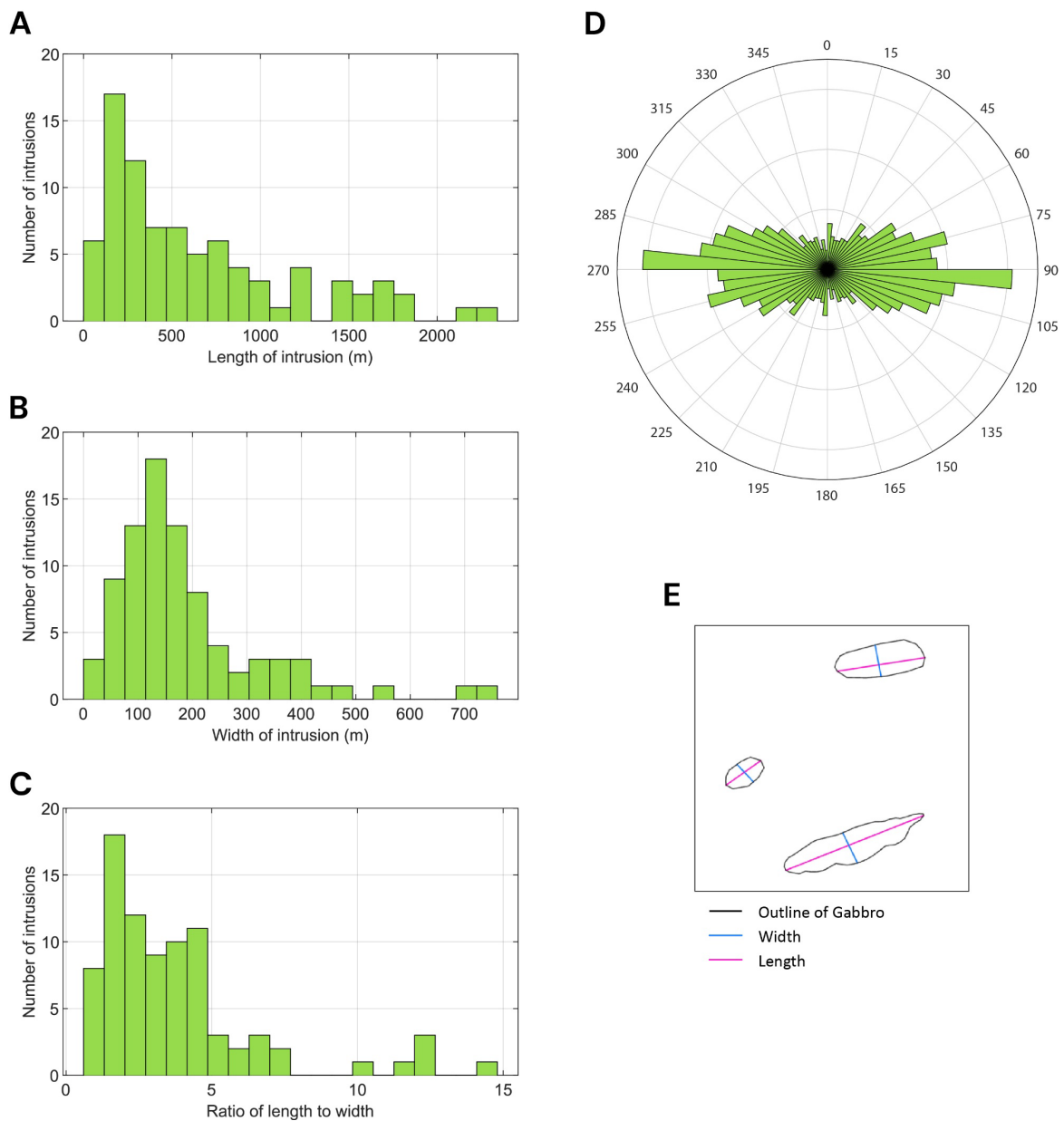


Figure 18. Statistical analysis of the geometry of the vanadium-bearing gabbro intrusions. **A.** Histogram of the lengths of the different intrusions. **B.** Histogram of the widths of the different intrusions. **C.** Histogram of the ratio of length to width for the different intrusions. **D.** Rose diagram showing the typical orientation of the different intrusions. **E.** Schematic showing the interpreted outlines of the mapped intrusions and the corresponding length and width measurements which were made in order to compile the statistics shown in this figure.

Mineral deposits in the Ljusdal lithotectonic unit

In terms of known mineral deposits both in numbers, size, type, and mining activity, the Ljusdal lithotectonic unit differs from the neighbouring Bergslagen and Bothnia–Skellefteå lithotectonic units (Wik *et al.* 2009, NODD2023, SGU 2025). Compared to the latter two, the Ljusdal lithotectonic unit has less documented deposits and much more limited historic mining activity. The total number of entries from the Ljusdal lithotectonic unit in SGU's database of mineral- and bedrock occurrences currently amounts to 320. Excluding aggregates, industrial minerals and other non-metallic commodities reduces the number to 255. Of these, 171 can be classified as iron-oxide (Fe, Fe-Ti, Fe-Ti-V), 61 as sulphide (mainly Cu, Cu-Fe, Zn-Cu), three as precious metal (Au), and 20 as other metals (Li, Sn, Nb, Ta, W, U). In addition, there are a few important deposits of graphite, which is a critical raw material with several uses in modern technologies, not at least in EV batteries.

Recent metal mining activity includes the Enåsen Cu-Au epithermal deposit that was mined during 1984–1991 and produced 1.8 Mt of ore grading 2.8 ppm Au and 0.44% Cu. The Woxna graphite mine which has been on care and maintenance since 2016 has an exploitation concession that includes the four deposits Kringeltjärn, Gropabo, Mattsmyra and Månsberg. Together these comprise a significant graphite resource (Leading Edge Materials 2021). The deposits are stratabound and hosted by regionally metamorphosed volcanosedimentary rocks intruded by granite pegmatites (Isberg 1990).

A characteristic feature of the Ljusdal lithotectonic unit is the presence of several mafic intrusions, mainly gabbroids, containing orthomagmatic iron-titanium-vanadium mineralisation that was coeval with the crystallisation of the host gabbroid. Most of these intrusions occur in the Gruvberget–Sumåssjön–Dellen–Ljusdal area, which constitutes a so-called metallogenic area (Hallberg *et al.* 2012) for this type of mineralisation (fig. 2). More than 50 Fe-Ti-V mineralisations occur within the Ljusdal batholith, and most of these are minor mineralisations and shallow mining pits where small-scale iron mining took place during the 1700s to 1900s (Wik *et al.* 2009).

The intrusion of Fe-Ti-V-bearing gabbroids have previously been interpreted to predate the dominant granitoids in the area (Lundegårdh 1967), although alternative hypotheses that include fractional crystallisation within a basic magma that has intruded both the deformed granitoids and the supracrustal rocks has been proposed (Edberg *et al.* 1978). However, prior to the current project was initiated, no radiometric dating of these mafic intrusions was available.

The deposit at Gruvberget–Sumåssjön was test mined for iron between 1730 and 1790 (Hallberg *et al.* 2012). In 1919, about 575 tonnes of ore were mined in the Kramsta field near Järvsö. It was later discovered that the iron ore contained vanadium and the state authority NSG (“Nämnden för Statens Gruvegendom”) financed an extensive vanadium exploration programme in the Dellen-Ljusdal area during the last part of the 1970s and the beginning of the 1980s. In connection with these efforts, several deposits were identified and investigated in detail. Large datasets were produced at some of the objects, in particular Kullberget–Storåsen, Masugnsberget–Blistra, Gruvberget–Sumåssjön, Bläckmyran, the Järvsö area and Simesvallen (fig. 2). Exploration drilling work was carried out on five of these deposits and many of the historic drill cores are now stored at SGU's office in Malå (Table 7). The results of the geophysical surveys, geological investigations as well as the diamond drilling were reported in several exploration reports (e.g. Edberg *et al.* 1978, Edberg 1980, Lagergren 1983, Lagergren & Lindblom 1983, Persson 1982, Persson & Lindblom 1983, Ros & Lindblom 1983).

Table 7. Available drill cores at SGU's drill core archive in Malå.

Deposit	Number of drill cores	Metres	Logs	Drill year	Previous owner
Masugnsberget	7	705	Yes	1983	NSG
Gruvberget–Sumåssjön	54	5 521	Yes	1981–1982	NSG
Bläckmyran	14	1 949	Yes	1981–1982	NSG
Kramsta–Järvsö	13	n/a	No	1979	AB Statsgruvor
Simesvallen	10	940	Yes	1982–1983	NSG

The vanadiniferous mafic intrusives were classified as norite and/or gabbro-norite, but later studies, including comprehensive microscope studies in the current project, have shown that most of the intrusions lack sufficient primary orthopyroxene for such classification.

Historic (non-compliant) mineral resource estimates (Table 1) indicate that the deposit at Masugnsberget contained 1 million tonnes with 0.19% V (Lagergren 1983), Simesvallen 2.5 million tonnes with 0.19% V (Persson & Lindblom 1983), Gruvberget–Sumåssjön 21 million tonnes with 0.22% V (Andersson 1982). Gruvberget–Sumåssjön was later adjusted to 14.9 million tonnes with an average grade of 0.26% V (Ros & Lindblom 1983). The Bläckmyran deposit was reconnaissance drilled and using this data a rough estimate of approximately 9 million tonnes of “potential ore” with 0.21% V was given (Andersson 1982).

Based on the promising results from exploration, Gruvberget–Sumåssjön was judged to have good potential, and a feasibility study was conducted to determine whether the project was economically viable (AB Statsgruvor 1984). In 2010, SGU designated the deposits at Gruvberget–Sumåssjön and Bläckmyran as being of national interest regarding valuable substances and materials, on the grounds that the area is important from a supply point of view and has good potential for future mining.

Since 2010, the company Svenska Vanadin AB holds an exploitation concession at Brickagruvan that is valid until 2035-12-16. In 2022, the company was given the go-ahead by the Land and Environment Court to mine 1 million tonnes per year of vanadium-containing magnetite ore in an open-pit mining operation (Östersund Tingsrätt 2022). However, this court ruling was appealed to the Supreme Environmental Court, which in November 2024 rejected the decision from 2022 of the Land and Environment Court (Svea Hovrätt 2024).

In November 2023 Svenska Vanadin AB was granted an exploitation concession for the nearby Bläckmyran deposit that is valid until the year 2048.

There are currently exploration permits on several of the Fe-Ti-V occurrences and deposits in the Ljusdal lithotectonic unit and the potential for further discovery of this type may exist at other locations within the unit.

Investigated areas

The initial efforts of the project were to collect and compile existing geophysical ground measurements, airborne geophysics, geological maps, databases, drill core logs, hyperspectral data, and exploration reports from the SGU archives. After an assessment of the historic data, several “candidate objects” were selected as possible Fe-Ti-V targets for follow-up.

As part of the FODD project, Hallberg *et al.* (2012) defined a so-called metallogenic area named S015 Dellen-Ljusdal Fe-Ti-V. This area includes many of the deposits, prospects and occurrences that have been studied in the current project although the area of investigation has been expanded beyond the original metallogenic area to include other possible objects.

Several focus areas were selected and the large deposits in the Järvsö area, Gruvberget–Sumåssjön, Bläckmyran and Simesvallen were chosen as starting points.

The following sections of the report describe a series of different areas which were investigated. Within each area, there are often several individual intrusions which are in turn discussed.

For each intrusion we present (if available) the following data types in the following order:

1. Ground-based geophysical data and an updated interpretation of the bedrock geology.
2. Geological observations and descriptions made at an outcrop scale.
3. Descriptions of thin-sections of both silicate and ore-minerals.
4. Geochemical data and interpretations.

Hence, the aim in this case is to present the available data in order of increasing detail, beginning with the geophysical data which often provides a general characterisation of the intrusion before presenting more detailed outcrop observations. We then transition to observations on a thin section scale, before presenting the geochemical data.

The Järvsö area

Several orthomagmatic Fe-Ti-V mineralisations hosted in mafic rocks occur in the Järvsö area. In addition to the Kramsta gabbroic intrusion, located directly to the west of Järvsö village, vanadiniferous gabbroid rocks are also present at Järvsö-Gruvberget, Storsveden, Gartsbogruvan and Buberget (the latter two are located c. 10 km northeast of Järvsö) (fig. 19). According to SGU's database of mineral- and bedrock occurrences the area contains more than 30 Fe-Ti-V occurrences, small test-pits and abandoned mining pits of which the majority is hosted in the main Kramsta intrusion. Many of the small mines and workings are described in Wik *et al.* (2009).

The mineralisations in the area were discovered at the end of the 19th century, although the deposits were originally mined for their iron content and the vanadium content had not been recognized. During the first half of the 1900s several investigations, including trenching, magnetic measurements, sampling, diamond drilling and test mining of 575 tonnes were undertaken at Kramsta (Kjellberg 1930). Vanadium was subsequently analysed, and ore calculations were performed, e.g. an ore estimate of 25 Mt grading 20% Fe, 5% TiO₂ and 0.15% V by Prof. Magnusson in 1943 (as cited in Edberg *et al.* 1978). The estimate is based on very limited data must be regarded as very uncertain.

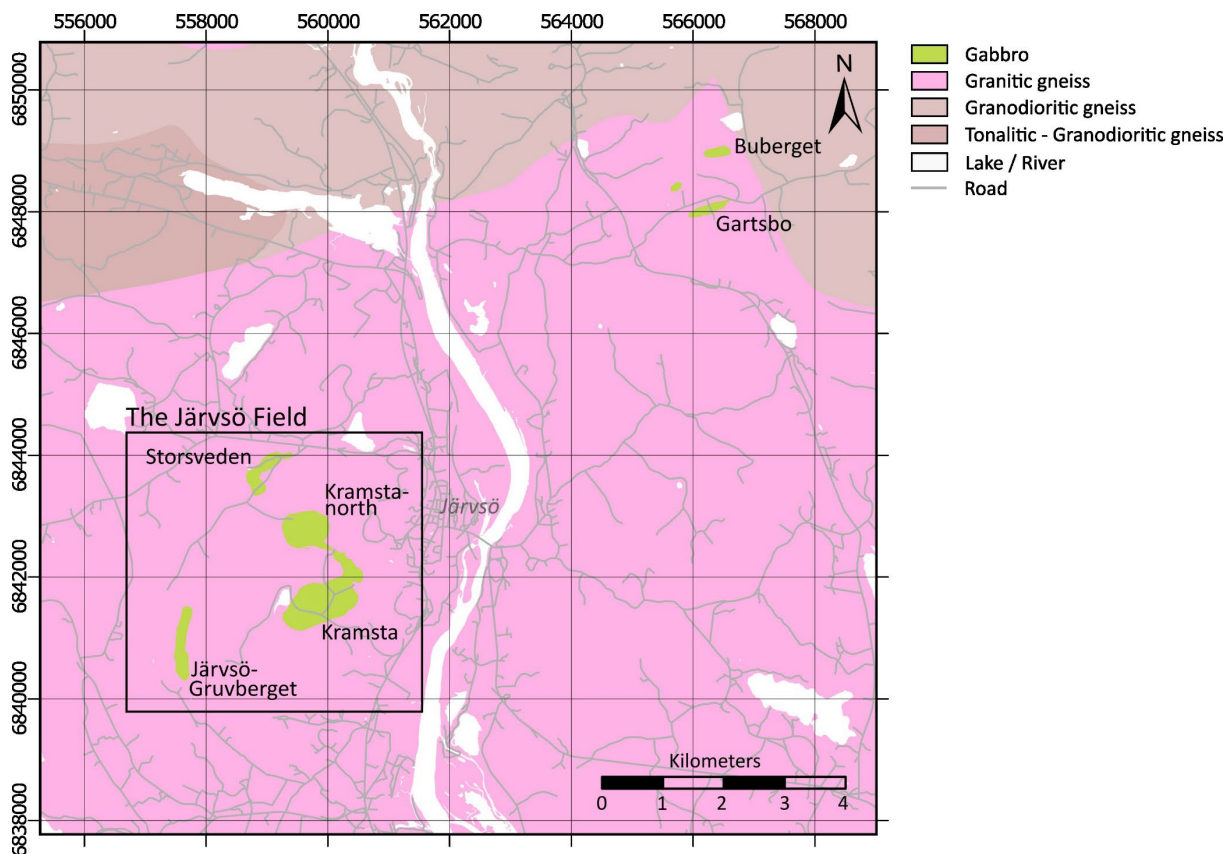


Figure 19. Bedrock geology map showing the area around Järvsö. The names of the mafic intrusions referred to in the report are shown as black text. In this case the Järvsö Field is often used to refer to the sub-area containing the Storsveden, Kramsta, Kramsta-north and Järvsö-Gruvberget intrusions. Location of Järvsö shown as grey italic text.

Renewed interest during the 1970–1980s led to an exploration programme by AB Statsgruvor. This included diamond drilling, sampling, and geophysical campaigns. According to a SGU report (SGU 1984) from 1984, there were plans for mining at Kramsta at that time, but final approval was pending the feasibility of the coeval Gruvberget–Sumåssjön project which was not realised. The SGU report, citing LKAB as a source, listed an ore-estimate for the Kramsta intrusion of 15 Mt grading 18% Fe, 4% Ti and 0.16% V. Since we do not have access to the original data on which this was based, it can only be taken as very crude and uncertain estimate. In any case, the historic ore estimates listed above are non-compliant and not acceptable by modern reporting standards.

Prior to this project, several ground-based geophysical investigations had been conducted over intrusions within the Järvsö Field. During these investigations maps describing the magnetic field over the Kramsta, Järvsö–Gruvberget and Storsveden deposits were generated (fig. 19).

Ground magnetic measurements using a Thalen-Tiberg instrument were conducted over the Järvsö Field as early as 1925 (Kjellberg 1930; Edberg *et al.* 1978). Based on these early measurements, the magnetic anomalies associated with these deposits were clearly visible and correspond well, at least qualitatively to subsequent measurements. In 1978 new ground-based measurements were conducted by LKAB Prospektering over the Kramsta intrusion (Edberg *et al.* 1978). These measurements covered an area of approximately 1 km², with a profile spacing of 40 m and measurement spacing along profiles of 5 m. In 1980 LKAB Prospektering collected additional ground magnetic data over the Järvsö–Gruvberget and Storsveden deposits (Edberg 1980). These

magnetic measurements were performed using similar survey specifications as for the Kramsta survey, covering areas of about 0.5 km² and 0.7 km² for the Storsveden and Järvsö–Gruvberget intrusions, respectively.

As part of this project the data from Järvsö–Gruvberget and Storsveden, collected in 1980, were digitised and georeferenced. The data collected in 1978 over the Kramsta intrusion were available digitally at the start of the project but needed to be georeferenced before they could be used. The measurements for the three surveys were then corrected from magnetic anomaly values to total magnetic field values, using the background magnetic field values quoted on the analogue maps.

As no legacy ground magnetic data were available over the Kramsta-north intrusion (fig. 19), new data were collected as part of this study in 2023. These profiles were collected with a typical line spacing of about 35 m over an area of about 0.5 km². New magnetic field measurements were also performed over the Gartsbo intrusion, located about 7 km northeast of Järvsö (see fig. 19). These measurements covered an area of approximately 0.2 km² with a typical line spacing of about 35 m.

Kramsta and Kramsta-north intrusion

Ground-based geophysical measurements

The magnetic measurements from 1978 over the main Kramsta intrusion (southern intrusion in fig. 20) show a magnetic anomaly with an approximately elliptical form, where the anomaly is strongest towards the edges of the mafic body. The magnetic anomaly appears to be about 1 200 m long and 600 m wide. The highest anomaly values occur on the northern and northwestern sides of the deposit, where the magnetic field can reach values of the order of 15 000 nT above the background level (Edberg *et al.* 1978). Based on the geochemical analysis of drill cores and field samples, the magnetic anomaly from the northern and western sides of the deposit corresponds well to regions with relatively high concentrations of iron and vanadium (Edberg *et al.* 1978). Towards the eastern and southern edge this is somewhat more speculative due to lack of outcrop and drill core information. In the northern and northwestern side of the intrusion the anomaly is somewhat broken up, this is interpreted to be due to topography and small-scale faulting (Edberg *et al.* 1978). Based on 2D modelling of the magnetic data, performed in previous studies, the western edge of the deposit is thought to dip to the east by 65–70°, while the eastern edge is thought to dip to the west or northwest by 55–60°, suggesting a bowl like geometry for the deposit (Edberg *et al.* 1978). These previous modelling efforts suggest that the intrusion continues to depths of at least 500 m below the surface. However, it is important to note that these modelling results are somewhat uncertain as they are 2D and do not account for remanent magnetisation (Edberg *et al.* 1978). As part of LKABs investigations into the Kramsta deposit at least 44 boreholes were collected, mainly targeting the northern and northwestern sides of the deposit where the highest magnetic anomaly values were observed.

Figure 20 also shows an updated geological map, interpreted from the ground magnetic data and geological observations. Here the regions with high magnetic field values have been highlighted and a number of “connections” have been interpreted. These connections trace the axis of continuous positive magnetic anomalies. It is possible that these connections could give an indication of the geometry of the large-scale layering in the structure, highlighting continuous layers with similar magnetic properties.

The results from the unconstrained 3D magnetic susceptibility inversion of the ground magnetic data performed in this study for the Kramsta field are consistent with the previous modelling efforts. The results indicate that the highest magnetic susceptibility values are located along the flanks of the structure, most notably on the northern side. Figure 21 shows a map of the average magnetic susceptibility in the upper 75 m of the inversion model, where the high susceptibility flanks are clearly visible. On inspection of the inversion model in 3D, these high susceptibility flanks dip towards the centre of the intrusion, forming a bowl like geometry (see section in fig. 21).

A series of magnetic susceptibility logs measured on drill core from the boreholes K-D-09, K-D-10, K-D-23, K-D-25, K-D-26, K-D-28, K-D-29, K-D-31, and K-D-34, are found in appendix B. These figures also show the available geochemical data for these drill cores. All of these are located within the northern and northwestern flanks of the Kramsta intrusion (see appendix B for the borehole locations). Many of these are drilled directly into the part of the intrusion with the highest degree of mineralisation, where the magnetic susceptibilities are relatively high. It can be observed that, in general, the magnetic susceptibility values decrease within about 10–20 m of the contact between the gabbro and surrounding granitic rocks. It is often the case that “hybrid” rocks are observed in the contact zone. It is interpreted that in these parts there has been mixing between the mafic intrusion and melts of the surrounding gneissic granitic rocks, which had melted in the contact zone at the time of intrusion. These “hybrid” zones in the Kramsta intrusion are typically less mineralised than the central part of the intrusion. It is important to note that within the area mapped as gabbro, up to 20 m thick sections of granitic and felsic pegmatitic rocks are observed in some of the drill cores. One explanation for these sections is that they are large xenoliths from the surrounding granitic rock. Alternatively, they could be regions where residual melt or more evolved melt has crystallised at a later stage. These are relatively local features and hence are not explicitly mapped on the bedrock geology map. However, on the magnetic susceptibility logs they show up as regions of low magnetic susceptibility.

The new magnetic measurements from the Kramsta-north intrusion collected in this study are shown in figure 20. Here the magnetic data also suggest an approximately elliptical form, where the highest magnetic field values occur on the northeastern and southwestern edges. These areas correlate with documented mineralisation, such as Pojken (numbers 1, 2, and 3) and Gillermyrgruvan (numbers 1 and 2). The magnetic anomaly for Kramsta-north is approximately 700 m by 500 m. In some areas the total magnetic field reaches levels of over 12 000 nT above the background. A map of the average susceptibility in the upper 75 m of the model obtained from inversion, is shown in figure 22. Here the highest magnetic susceptibilities are also observed to lie along the northeastern and southwestern flanks of the structure. From the cross section through the magnetic susceptibility model in figure 22 it appears that the intrusion has a bowl-like geometry, similar to the Kramsta intrusion. However, it is important to note that this bowl-like geometry is a combination of the original geometry of the intrusion and the present-day erosional surface. In other words, before erosion occurred, the intrusion could have been spherical for example. In the case of both the Kramsta and Kramsta-north intrusions, the highest magnetic anomalies appear relatively close to the contact to the surrounding granitic rocks.

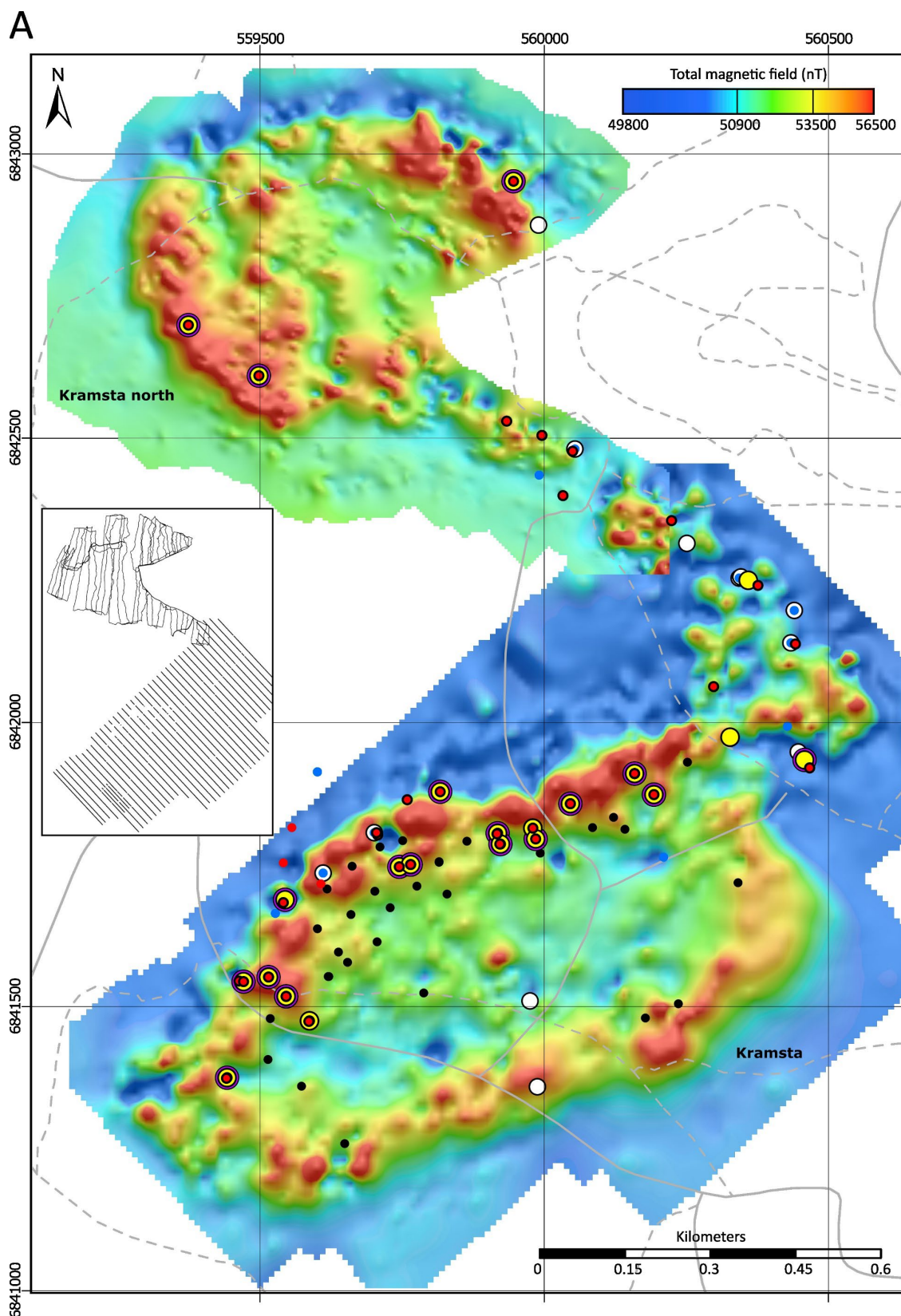


Figure 20. A. Map of the total magnetic field from ground measurements. The data collected over the Kramsta intrusion (south) were collected in 1978 by LKAB. The data over the Kramsta-north intrusion (north) were collected as part of this study in 2023. The inset map shows a smaller version of the map area, where the locations of the measurement profiles for the 2023 and older surveys are shown as black lines. The location of the available geological observations, samples, boreholes, and magnetic susceptibility measurements at outcrop are shown as different coloured dots on the map. See figure 20B for the legend for these symbols.

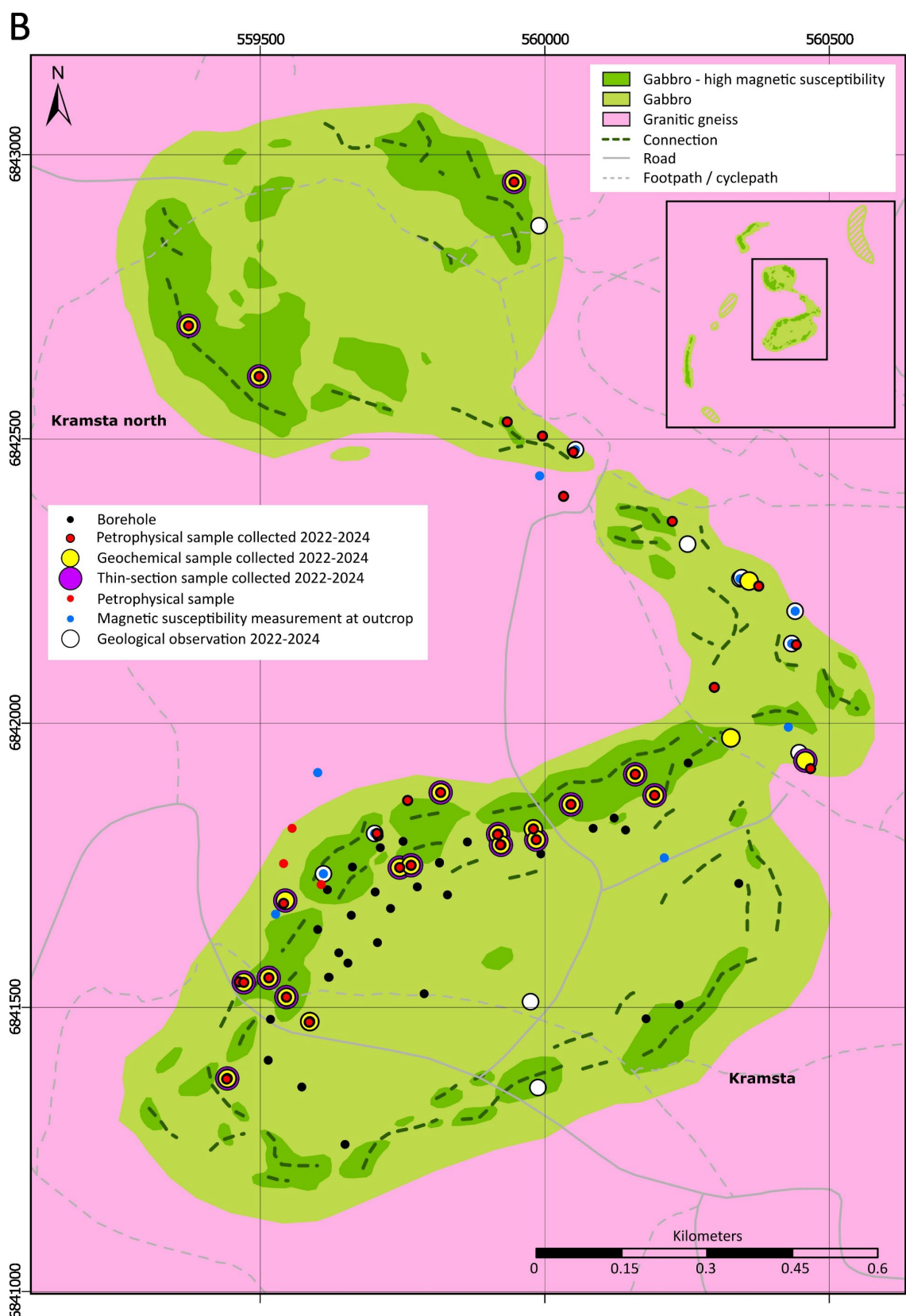


Figure 20 continued. B. Updated map of the bedrock geology around the Kramsta and Kramsta-north intrusions, interpreted from the ground magnetic field data and the available geological observations and samples. The inset map shows the location of the map with regards to the other intrusions in the Järvsö Field. The location of the available geological observations, samples, boreholes, and magnetic susceptibility measurements at outcrop are shown as different coloured dots on the map.

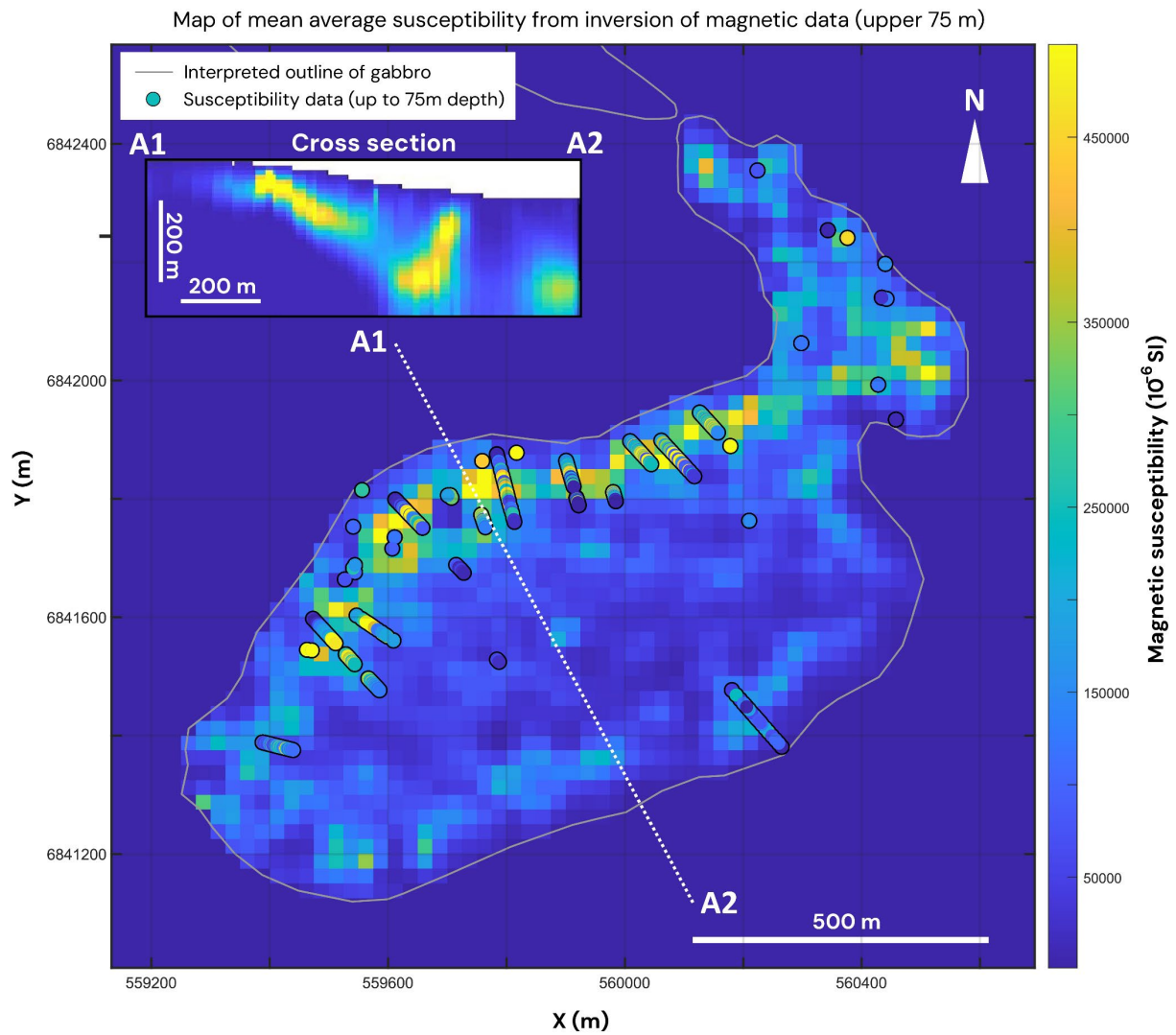


Figure 21. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Kramsta intrusion. All magnetic susceptibility measurements collected up to a depth of 75 m (measurements on drill core and at the surface) are shown as dots. In cases where only geochemical data is available from drill cores, magnetic susceptibilities have been calculated using the relationship described in the petrophysics section. These calculated susceptibilities are shown together with the magnetic susceptibility measurements as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

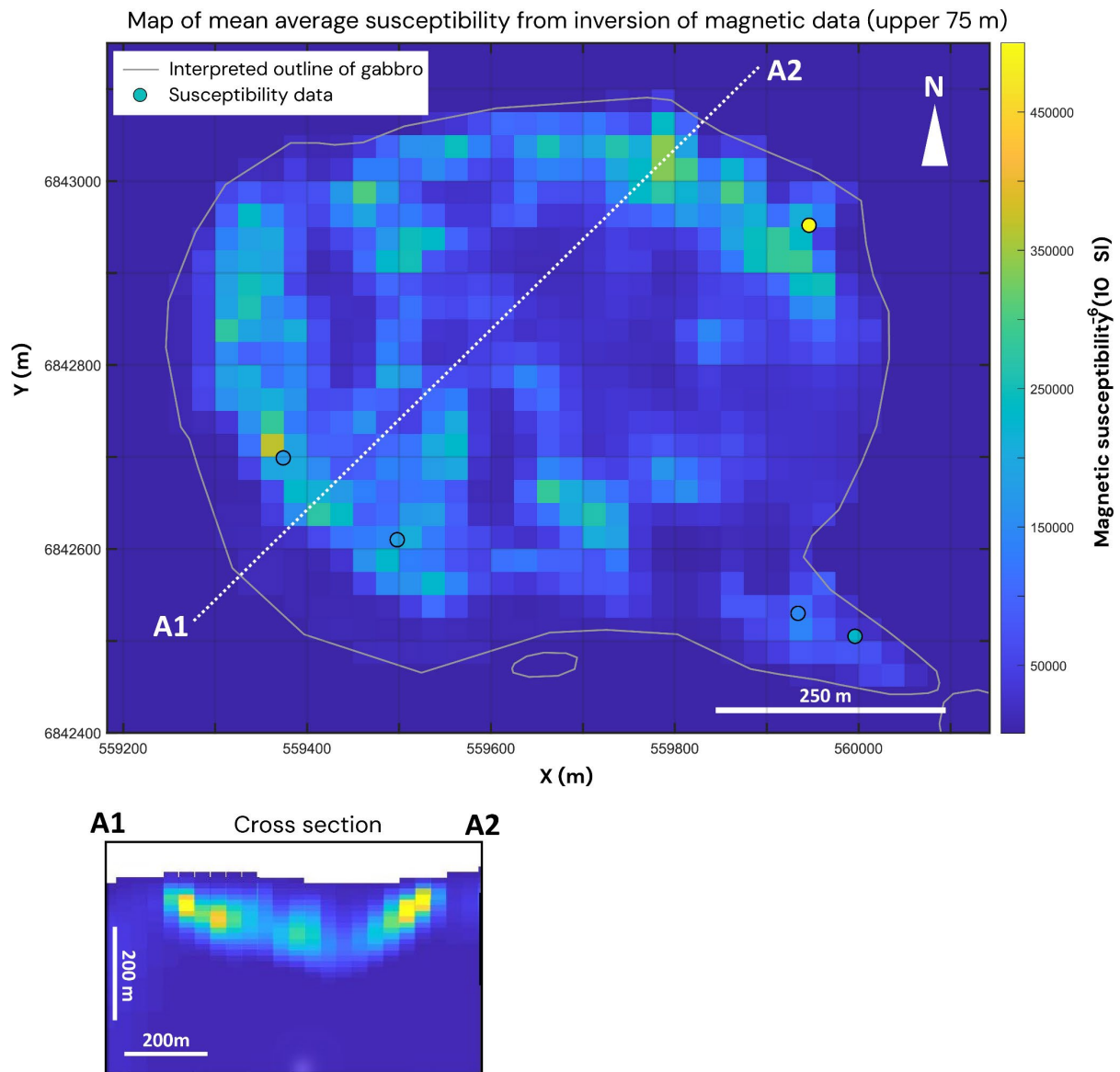


Figure 22. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Kramsta-north intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown below the map. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

Geological observations

The contact between the Kramsta mafic intrusion and surrounding granitic gneiss can be studied in several drill cores, but has not been directly observed in outcrop, although at one location (HRE240014) it is constrained by two outcrops separated by c. 3 m (fig. 23).



Figure 23. Granite (left) and gabbroid (right) outcrops at Kramsta (6841934/560458). The contact is not exposed but is underneath the mountain-bike track. Photo: Helge Reginiussen.

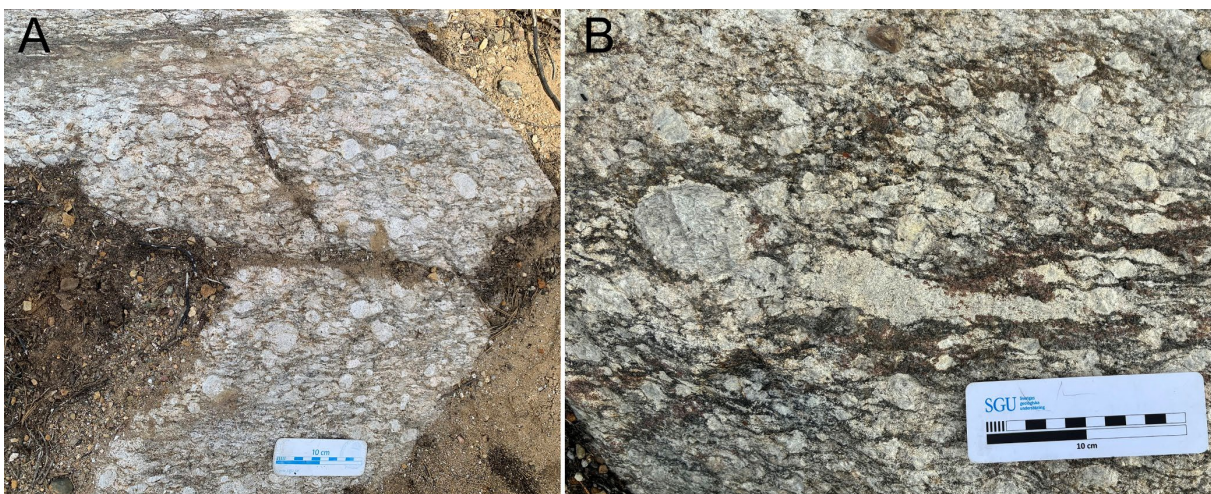


Figure 24. A. and B. Granitic gneiss outcropping close to the contact to the gabbroid at the Kramsta intrusion (6841934/560458). Photo: Helge Reginiussen.

The granite at this locality is an augen-gneiss with a pronounced foliation (possibly S1-foliation) and lens-shaped megacrysts and aggregates of K-feldspar (figs. 24 and 25). In places leucosome is observed suggesting that partial melting took place after formation of the main foliation. Garnet is abundant, often occurring in aggregates (up to cm-thickness) together with other dark minerals in the foliation but is also observed in the leucosome (fig. 24B).

The gabbroid, approximately 3 metres from the granite outcrop, does not have the tectonic foliation that is pronounced in the granite, but appears relatively fresh and undeformed with preserved magmatic textures (fig. 26).



Figure 25. Close-up of the granitic gneiss in figure 24B. Note small garnets in the foliation and in the leucosome (6841934/560458). Photo: Helge Reginiussen.



Figure 26. Gabbroid at Kramsta outcropping close to the contact with the enveloping granitic gneiss (6841934/560458). Photo: Helge Reginiussen.

Several good outcrops of the Kramsta gabbro are accessible in proximity to, and along, the new mountain-bike tracks located approximately in the far northeastern part of the Kramsta intrusion (fig. 20). Examination of several of these shows that the intrusion has typical characteristics of a layered mafic intrusion including modal layering and the formation of cumulates. The layers show considerable variations in terms of grain-size, mineral mode and crystal shape. Modal and textural layering exhibit different thicknesses ranging from centimetre to metre scale, individual layers can both have uniform and irregular contacts and show large variation in lateral continuity (figs. 27 and 28).



Figure 27. Modal layering in the Kramsta intrusion (6842256/560346). Photo: Helge Reginiussen.



Figure 28. Gabbroid at Kramsta showing modal layering (6842256/560346). Photo: Helge Reginiussen.

Evidence for mobilisation and disruption of layers comprising of semi-consolidated crystal-slurry are widespread, suggesting the operation of dynamic processes either during the filling of the magma chamber or during crystallisation. Settling or floating of layers of contrasting modal composition and hence, different density, are frequently observed (fig. 29). Hematite-staining is seen in some outcrops.

In places, magnetite-rich layers with high magnetic susceptibility (0.4 to >0.6 SI units) occur parallel to the overall layering in the intrusion (fig. 30). Analysis of a magnetite-rich sample gave 44.60% Fe_2O_3 , 8.75% TiO_2 and 3 170 ppm V.



Figure 29. Disrupted modal layering in the Kramsta intrusion (6842256/560346). Photo: Helge Reginiussen.

Modal and textural variations can occur over short distance within the same outcrop, suggesting injection or mobilisation of magma into consolidated or semi consolidated material (fig. 31).

Textures and structures consistent with magma mixing and/or mingling are common, and occasionally, resorption between the earlier consolidated and the subsequent intruding magmatic phases can be observed. Evidence for hydrous magma is frequently seen, typically manifested by very coarse-grained to pegmatitic hornblende gabbro.

A notable feature is that minerals with an elongated crystal shape define a fabric with a clear preferred orientation (“shape preferred orientation”), this is particularly evident in plagioclase-rich layers in which plagioclase grains (or aggregates) show a preferred orientation that is parallel or sub-parallel to the magmatic layering (fig. 32). This mineral fabric is interpreted as the result of a process involving crystal settling and accumulation, or alternatively, due to flow differentiation of crystal-laden magma during convection in the magma chamber.



Figure 30. Measuring of magnetic susceptibility (>0.6 SI units) on dull black and rusty, Fe-Ti-V "ore" layer in the Kramsta intrusion (6842250/560359). Photo: Helge Reginiussen.



Figure 31. Variable composition, textures and grain size in the Kramsta intrusion suggesting complex dynamic processes including injection or mobilisation of magma (magma mingling) into consolidated or semi consolidated material (6842250/560359). Photo: Helge Reginiussen.



Figure 32. Primary magmatic layering (cumulates). Note the plagioclase crystals that exhibit shape preferred orientation parallel to the layering (6842254/560337). Photo: Helge Reginiussen.

Studies of drill cores from the Kramsta intrusion confirm the picture of a layered intrusion. Figure 33 shows the drill core K-D-08 which illustrates the modal and textural variations along a continuous c. 90 m long section. The contact between the gabbroid and the enveloping granite which can be studied at the lower end of this drill core is not knife-sharp but is represented by a zone that is c. 2–3 m wide. Intrusion of gabbroid magma has led to partial melting of the granite and thereby formed a zone of hybridisation by magma mixing in the contact zone. A fabric is observed in the hybrid rock (fig. 33, tray 8–9). See figure 69 for the distribution of vanadium with depth in this drill core.

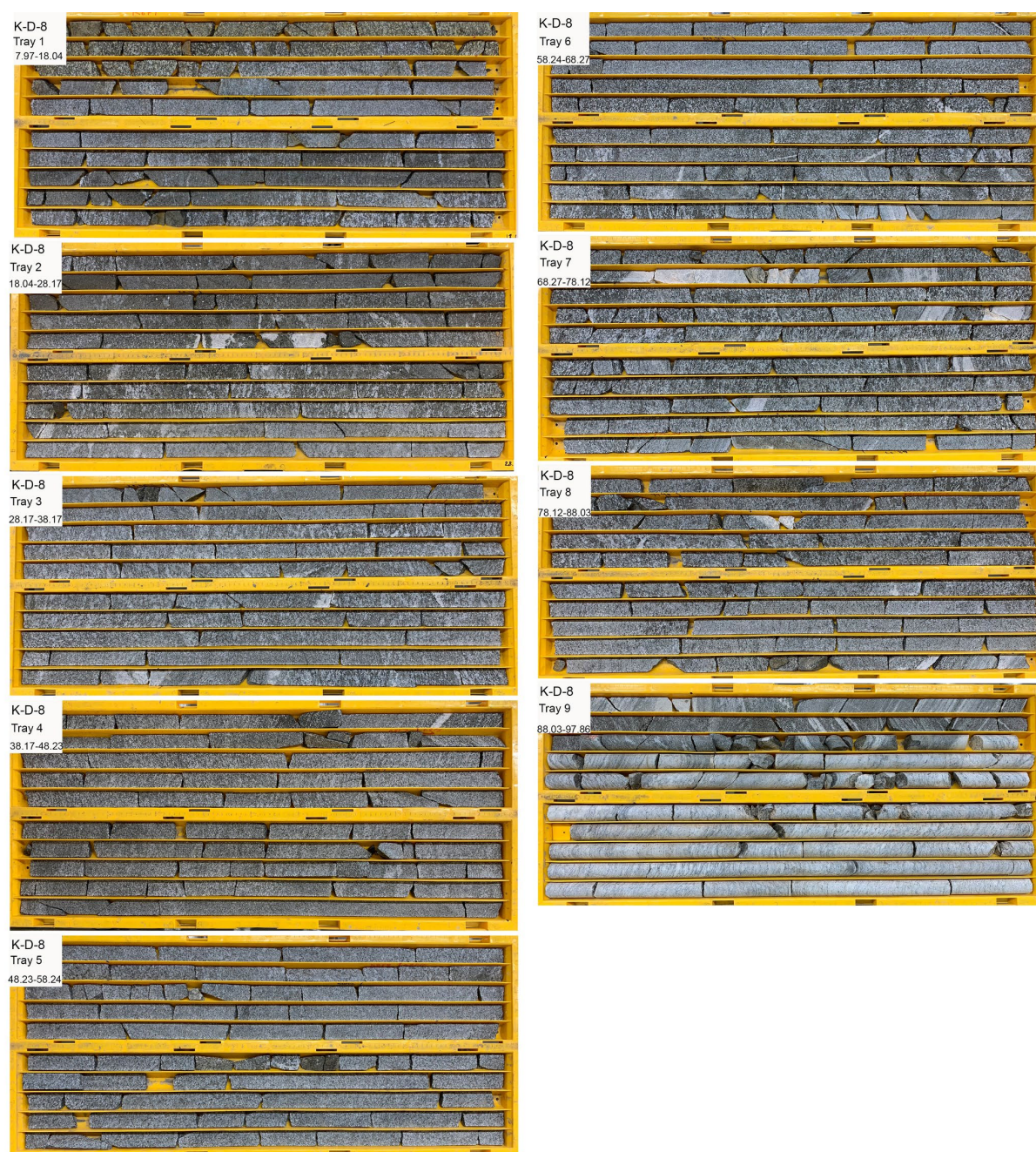


Figure 33. Drill core K-D-08 from Kramsta showing modal and textural variations within the intrusion. Each tray contains approximately 10 metres of drill core and is labelled with section intervals (in metres). The contact zone between gabbroid and granitoid occurs approximately at a depth of 87.80–90.90 metres and is visible in the lowermost part of tray 8 and the upper part of tray 9. Photo: Helge Reginiussen.



Figure 34. The uppermost two trays from drill core K-D-08 from Kramsta (see fig. 33). Red arrows designate 100 cm long sections that have been analysed in the current project and represent the most vanadium-rich layers in this drill core (see also fig. 69). The section in tray 1 is interval 15.04–16.04 m from which analyses gave $\text{Fe}_2\text{O}_3 = 37.20\%$, $\text{TiO}_2 = 5.50\%$ and $\text{V} = 2\,500$ ppm. The section in tray 2 (19.04–20.04 m) gave $\text{Fe}_2\text{O}_3 = 50.40\%$, $\text{TiO}_2 = 7.64\%$ and $\text{V} = 3\,620$ ppm. The mineralised layers have gradational contacts to more barren layers, e.g. at c. 16.50 m in tray 1 the dark grey mineralised layer grades downwards into a light greyish medium to coarse gabbroid with weak magmatic lamination. Photo: Helge Reginiussen.

Typically, the highest concentrations of Fe-Ti-V occur in dark grey fine-medium grained layers (fig. 34) with high magnetic susceptibility. This is also observed in outcrop (fig. 30). Such layers have gradual contacts to less mineralised layers, suggesting that the enrichment of Fe-Ti-V is controlled by primary processes in the crystallising magma where crystallisation of titanomagnetite was instrumental.

Ahlin & Larson (1985) used mineral analyses from drill core samples (one drill core only) to show that the Kramsta intrusion also exhibits cryptic layering, which further strengthens the interpretation as a layered intrusion. According to Ahlin & Larson (1985) the original magma had a tholeiitic character, and the intrusive body has retained its original orientation although the original thickness was probably much greater.

Description of thin sections – ore minerals

There are layers which mostly consist of Fe-Ti oxides at Kramsta, e.g., seen in drill core K-D-29 at 94.31–94.36 m depth, sample DCL223015A from a massive magnetite layer (fig. C3 for panorama).

The ore minerals magnetite, ilmenite, pyrrhotite, pyrite, and chalcopyrite were identified in ultramafic sample DCL223018A, taken from the drill core K-D-08 at 19.00–19.04 m (fig. 35, see fig. C2 for panorama). The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock (figs. 35A–D). There is plenty of exsolved ilmenite as laths and trellis in the magnetite (figs. 35D–F). Ilmenite has exsolved hematite. Other minerals that look like darker exsolution trellis, are feasibly magnetite or ulvöspinel (figs. 35D, G, cf. Haggerty 1991, Tan *et al.* 2016a). It is possible that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolutions in the magnetite (e.g. Haggerty 1991, Tan *et al.* 2016b), but no SEM-work has been done to identify the smallest exsolved minerals and optical microscopy was deemed inadequate for proper identification. The sulphide minerals in ultramafic sample DCL223018A have relatively large grain size compared to the other intrusions in this study but are still only minor components (figs. 35A, G). Most grains are either pure pyrrhotite or pyrite, but some are coprecipitations of pyrrhotite, pyrite, and chalcopyrite (fig. 35G).

The ore minerals magnetite, ilmenite, and pyrrhotite, were identified in mineralised sample DCL228010A from the drill core K-D-32 at 41.84 m (fig. 36, see fig. C1 for panorama). Large grains of both magnetite and ilmenite occur in an interstitial framework of opaque minerals (fig. 36A). There is plenty of exsolved ilmenite as trellis and laths in the magnetite (figs. 36B–C). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are feasibly magnetite or ulvöspinel (fig. 36C). It is possible that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolutions in the magnetite, where pleonaste would appear as the darkest grains but no identification was possible using an optical microscope. A trail of miniscule droplets of pyrrhotite is present within an ilmenite grain, which ends at the boundary between the ilmenite and magnetite crystals (fig. 36B). To determine whether this is the infilling of a hair-thin fissure or a trail of fluid inclusions of sulphide nature in ilmenite, other types of investigations are required (e.g., Pochon *et al.* 2024).

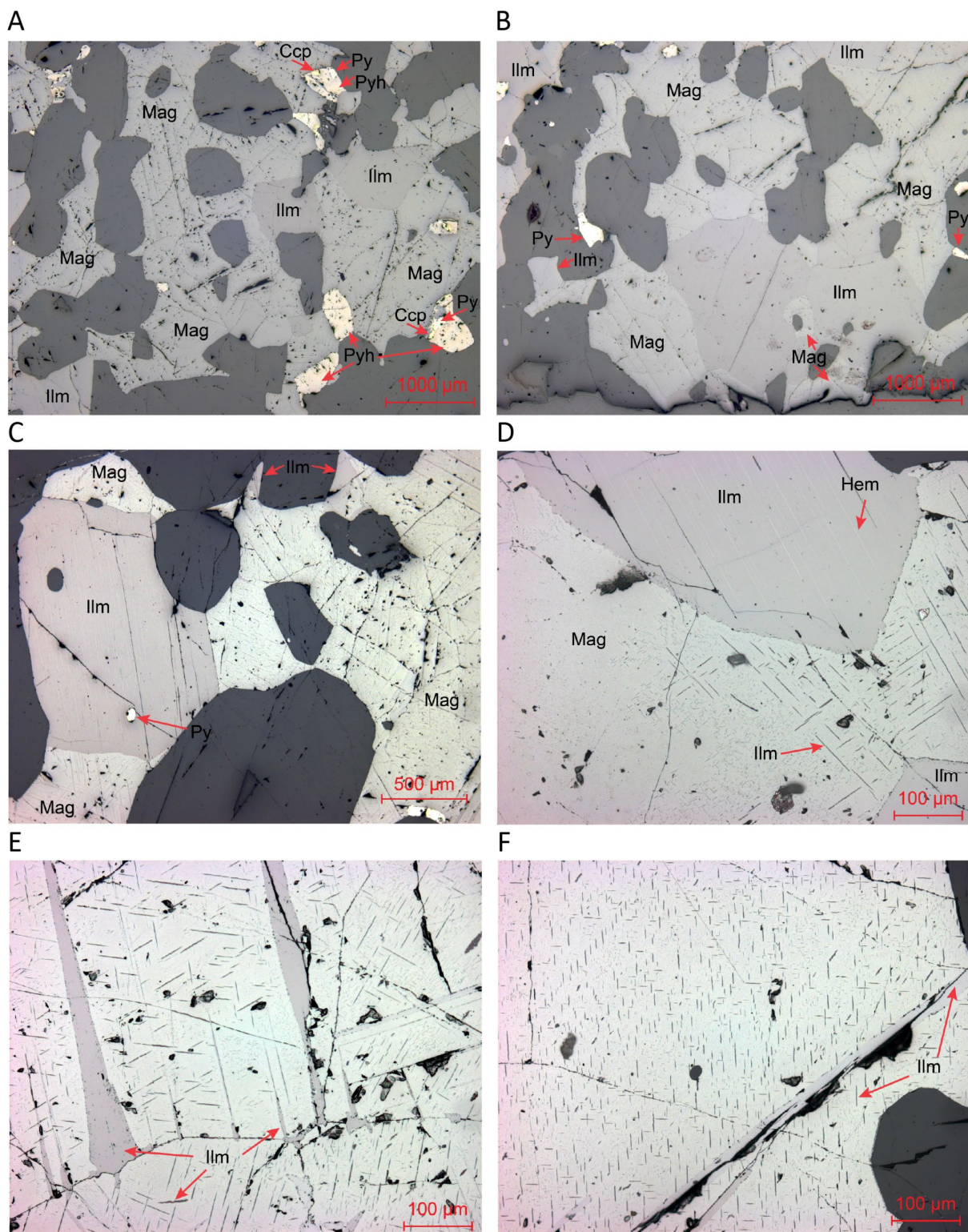


Figure 35. Ore minerals from the Kramsta intrusion, ultramafic sample DCL223018A from drill core K-D-08 at 19.00–19.04 m (see fig. C2 for panorama). **A. to C.** Overviews of relations between magnetite and ilmenite in the opaque framework. **D.** Close-up image of relations between large magnetite and ilmenite (euhedral terminations) grains, note thin exsolution lamellae in both minerals. **E.** Ilmenite as trellis exsolution along crystallographic planes and larger laths within magnetite. **F.** Laths of exsolved ilmenite and abundant trellis-type in predominantly one crystallographic plane. Photo: Dick Claeson.

G

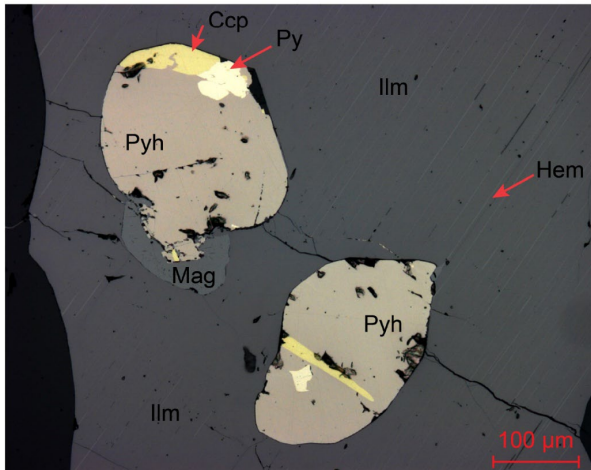
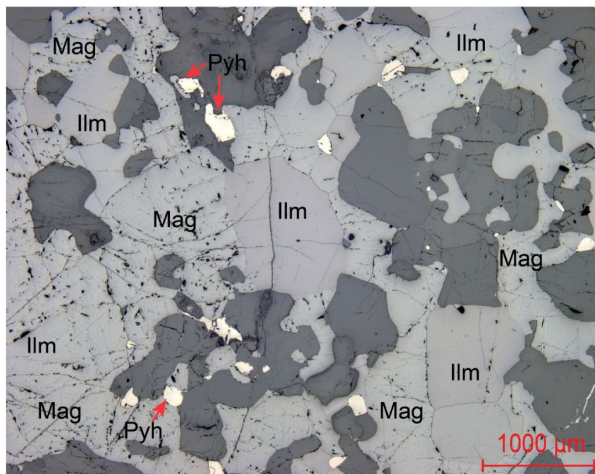
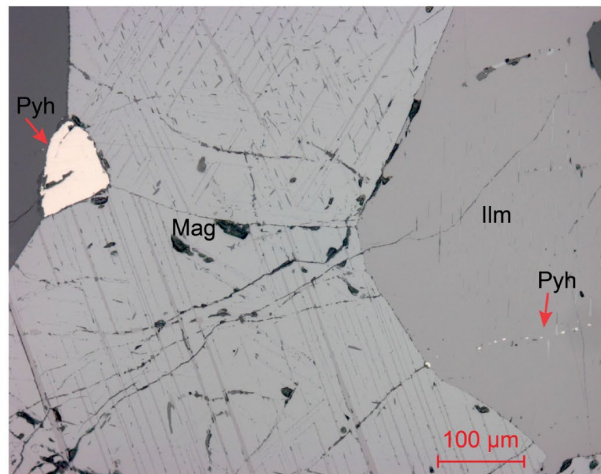


Figure 35 continued. G. Close-up of the sulphide minerals pyrrhotite, pyrite, and chalcopyrite in ilmenite with exsolved hematite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

A



B



C

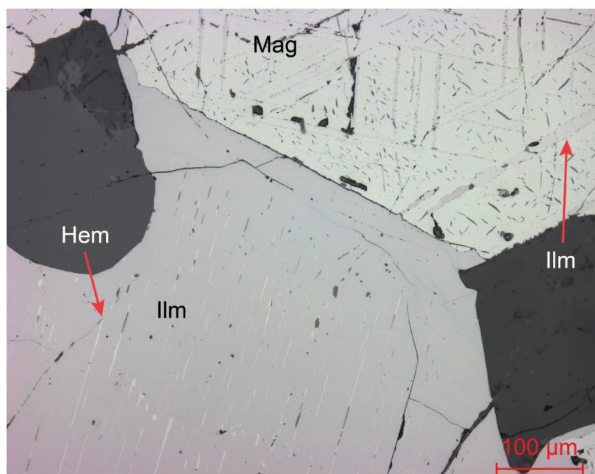


Figure 36. Ore minerals from the Kramsta intrusion, mineralised sample DCL228010A from the drill core K-D-32 (see fig. C1 for panorama). **A.** Overview of relations between magnetite and ilmenite in opaque framework. **B.** Close-up image of relations between large magnetite and ilmenite grains and small pyrrhotite grain, note trail of tiny droplets of pyrrhotite in the ilmenite. **C.** Ilmenite as trellis exsolutions along crystallographic planes and lath-shaped within magnetite, note thin exsolution lamellae in both minerals. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals

Sample DCL228002A from drill core K-D-25 at 105.68–105.72 m has subhedral hornblende grains and anhedral interstitially grown crystals, to a minor extent intergrown with clinopyroxene. Olivine is subhedral to anhedral. Some large grains of subhedral clinopyroxene are present but typically interstitially grown crystals occur, some with lamellae. Subhedral plagioclase is present as large crystals with later formed interfingering outer rims (figs. 37A–B). A few grains of biotite with red to brown pleochroism, and a few euhedral grains of apatite are present.

A rare, large orthopyroxene crystal with low order birefringence, intergrown with clinopyroxene and hornblende is observed in sample DCL228007A from drill core K-D-20 at 48.35–48.40 m (figs. 37C–D). The crystal is probably partly resorbed due to interaction with a more evolved, interstitial liquid that stabilised hornblende. Subhedral to anhedral, large hornblende grains and interstitially grown crystals occur. Subhedral to anhedral clinopyroxene occurs as large grains, in places severe amphibole replacement of clinopyroxene is observed. Plagioclase is subhedral to anhedral. Two generations of biotite are present, one exhibits brownish red pleochroism and a second generation has brownish red to tan. A few euhedral-subhedral apatite grains are present.

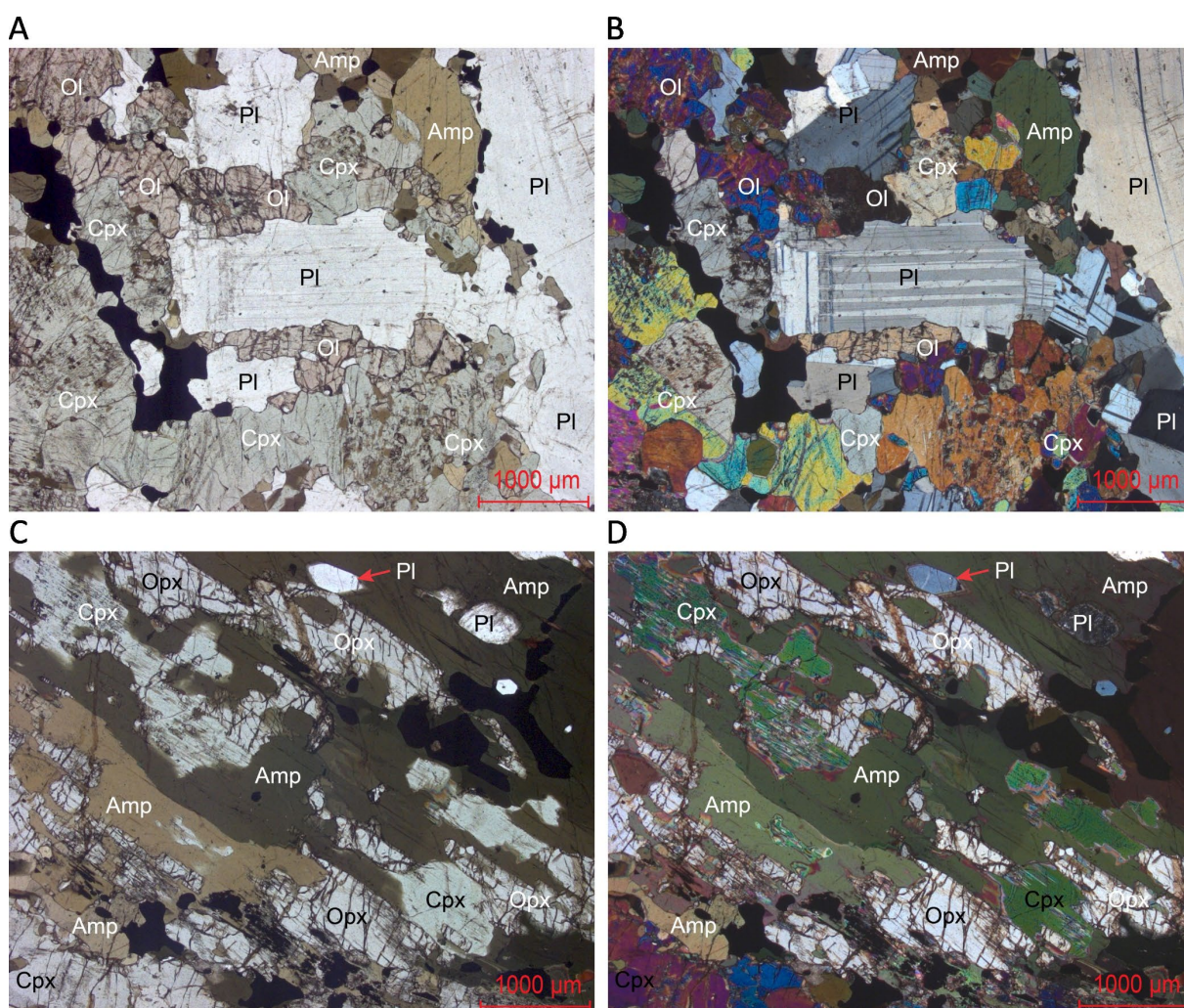


Figure 37. A. and B. Sample DCL228002A from drill core K-D-25 at 105.68–105.72 m, large subhedral plagioclase with late-forming outer parts, in a cumulate with olivine, clinopyroxene, and minor hornblende. C. and D. Sample DCL228007A from drill core K-D-20 at 48.35–48.40 m, large orthopyroxene crystal with low order birefringence intergrown with clinopyroxene and hornblende. Left in ppl and right in xpl. Photo: Dick Claeson.

Subhedral to anhedral, small to large grains of plagioclase with minor sericite-saussurite alteration, subhedral to interstitially grown olivine, subhedral grains to interstitially grown clinopyroxene with minor hornblende alteration in places, interstitially grown hornblende, minor biotite of two generations, first red to brown pleochroism and second green to tan, and rare orthopyroxene occur in the cumulate rock of sample DCL230011A from drill core K-D-09 at 16.95–17.03 m (fig. 38). A rare, large orthopyroxene crystal has pleochroism from greenish to pinkish to tan, low order birefringence, and is intergrown with small clinopyroxene and hornblende crystals.

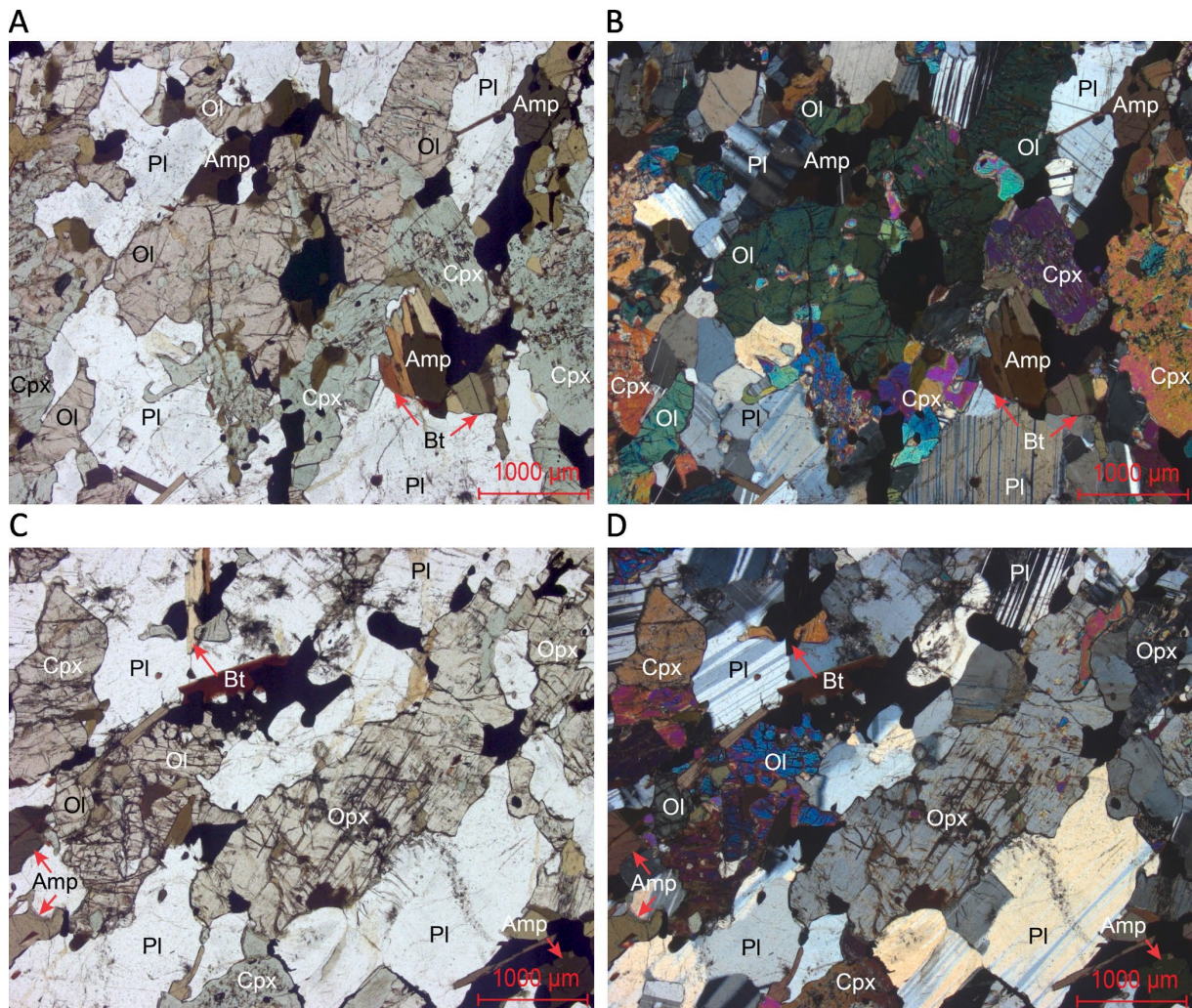


Figure 38. A. and B. Subhedral to anhedral plagioclase, olivine, clinopyroxene, hornblende, and minor biotite in a cumulate rock. C. and D. Large orthopyroxene crystal with low order birefringence, intergrown with small clinopyroxene crystals, in a cumulate with olivine, plagioclase, hornblende, and biotite. All images sample DCL230011A from drill core K-D-09 at 16.95–17.03 m. Left in ppl and right in xpl. Photo: Dick Claeson.

Hornblende occurs as euhedral to subhedral, large grains, often with grain triple junctions at 120 degrees, and smaller crystals are interstitially grown in sample DCL230013A from drill core K-D-09 at 83.80–83.90 m (fig. 39). The granoblastic texture minimises the combined surface energy of the grains. In igneous layered intrusions it signifies the degree of textural equilibrium that cumulate rocks have reached and a textural equilibrium is indeed apparent here (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Subhedral to anhedral plagioclase, olivine mostly as subhedral larger grains and smaller interstitially grown crystals, euhedral to subhedral clinopyroxene, some with lamellae, occurs in the cumulate rock.

Main mafic silicates in the cumulate rock of sample DCL230016A from drill core K-D-23 at 107.99–108.05 m are clinopyroxene, hornblende, olivine, and biotite (fig. 40). Hornblende is mostly interstitial and subhedral to anhedral. Hornblende has grain triple junctions at 120 degrees. Clinopyroxene is subhedral to anhedral, some grains exhibit exsolution lamellae. Olivine occurs as subhedral to anhedral grains and as interstitially grown crystals. Plagioclase has subhedral to anhedral grains and interstitially grown crystals. Two generations of biotite are present, the first has red to brown pleochroism and the second green to tan. Biotite, hornblende, and Fe-Ti oxides form aggregates.

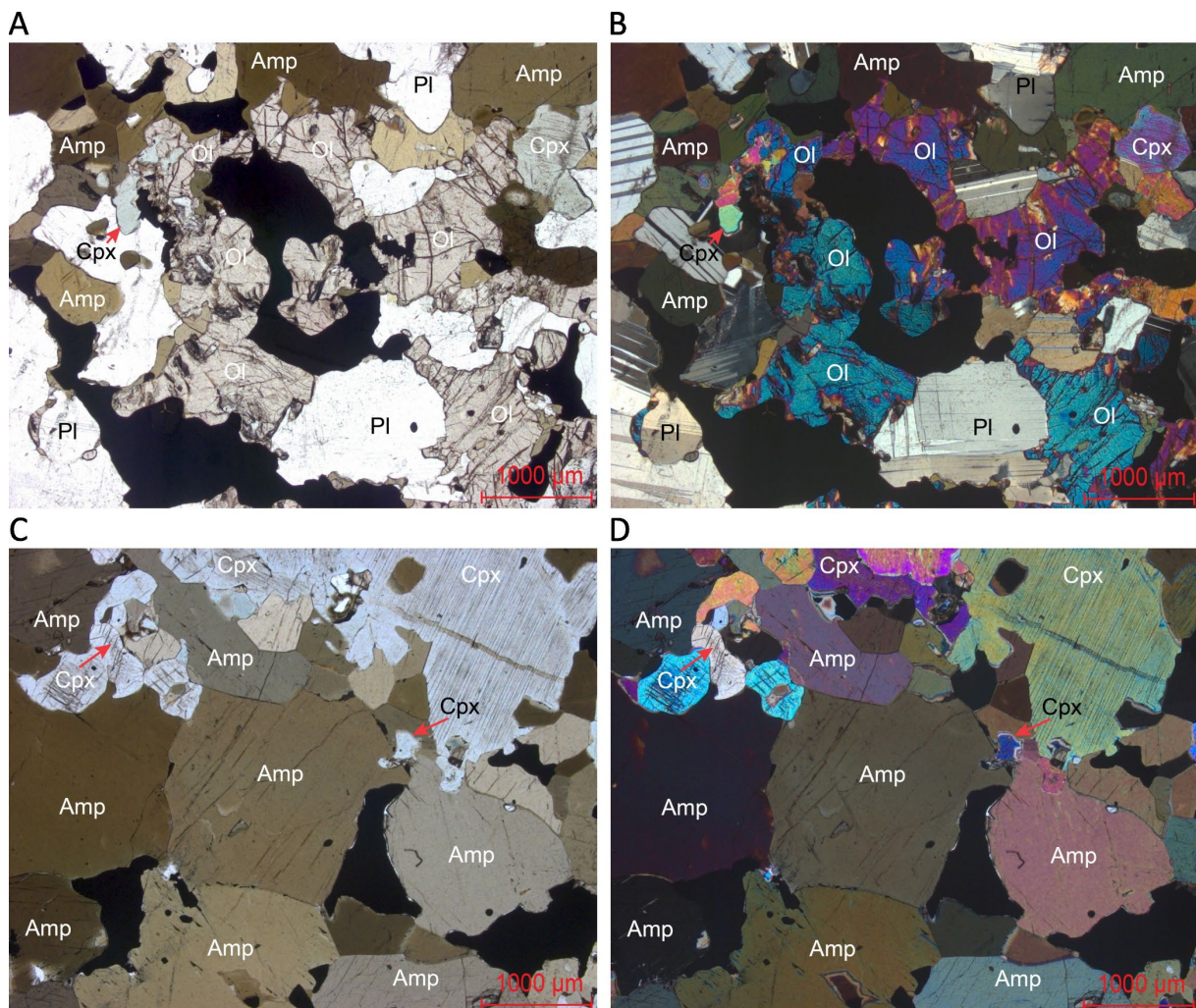


Figure 39. A. and B. Anhedral plagioclase, olivine, hornblende, and clinopyroxene in a cumulate rock. C. and D. Hornblende grain triple junctions at 120 degrees in a cumulate with clinopyroxene with rare olivine and plagioclase. All images sample DCL230013A from drill core K-D-09 at 83.80–83.90 m. Left in ppl and right in xpl. Photo: Dick Claeson.

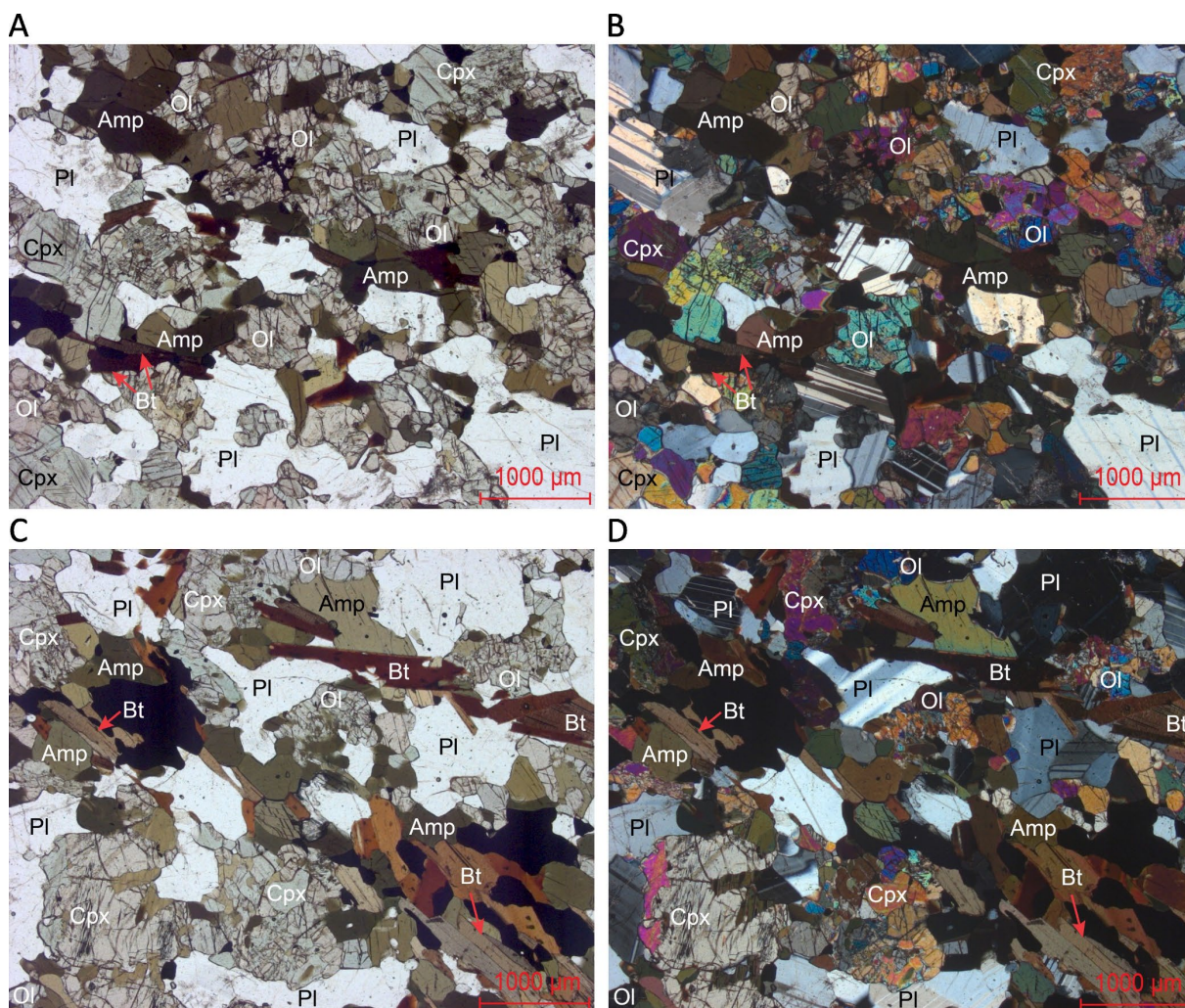


Figure 40. A. and B. Subhedral to anhedral olivine, clinopyroxene, hornblende, and plagioclase, minor biotite in cumulate rock. C. and D. Part where biotite is more abundant. Note aggregates of biotite, hornblende, and Fe-Ti oxides. All images sample DCL230016A from drill core K-D-23 at 107.99–108.05 m. Left in ppl and right in xpl. Photo: Dick Claeson.

Intergrown clinopyroxene and olivine are the main mafic silicate minerals of the well-preserved sample DCL230019A from drill core K-D-31 at 80.77–80.84 m (fig. 41). Subhedral to anhedral clinopyroxene has exsolution lamellae and rare alteration to secondary green amphibole. Olivine is subhedral to anhedral, mostly interstitially grown. Anhedral interstitial hornblende is a minor mineral in the cumulate rock. Large plagioclase crystals have darker grey pigmentation of early-formed central parts, which is lacking in their outermost part, which formed late. Plagioclase crystals that formed entirely within an interstitial position lack pigmentation as well. Some plagioclase grains show bends or kinks due to deformation. Plagioclase bending or kinking while hot in a cumulate rock is considered to result from the process of compaction of the crystal pile or mush, where interstitial liquid is pressed out of the residual porosity of the cumulate rock (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011). Deformation twins and undulose extinction in plagioclase are also features seen in relation to compaction of cumulate rocks (e.g., Holness *et al.* 2017).

For the most part sample HRE220013A from Baxgruvan is well-preserved with minor, interstitial hornblende, subhedral to anhedral, large grains of olivine, subhedral grains and interstitially grown clinopyroxene with some lamellae and exsolution of opaque minerals (fig. 42). Plagioclase is subhedral and some crystals display signs of kinks or bends due to deformation while hot. Grey pigmentation in central portions of large plagioclase crystals is absent in their rims. Two generations of biotite exist, the first has brownish red pleochroism and the second brown-red to tan.

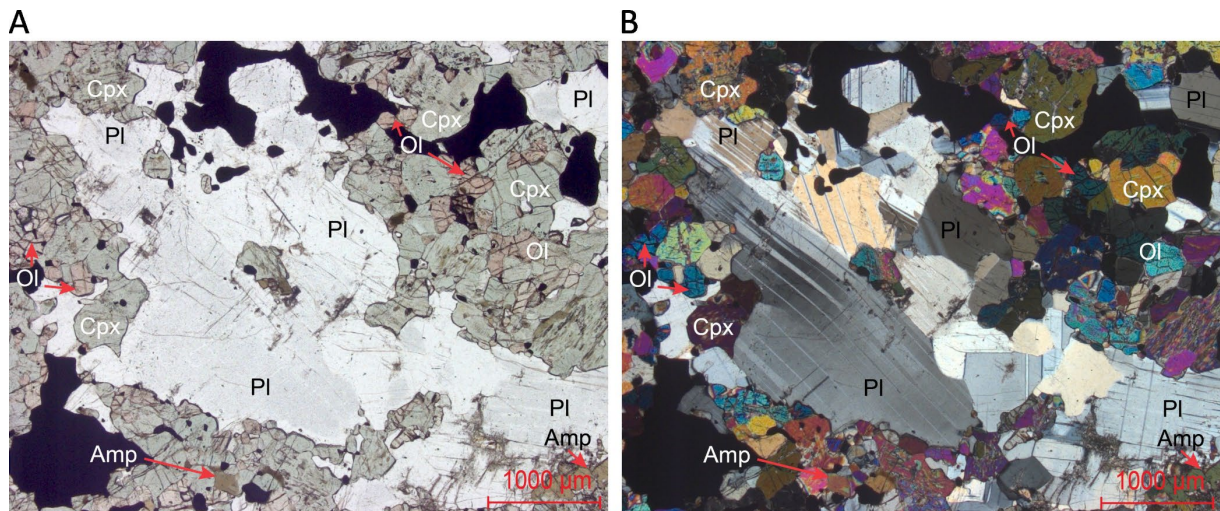


Figure 41. The large plagioclase to the left of the centre of the image has bends or kinks close to the middle of the crystal and continues vertically, as well as deformation twins and undulose extinction. Clinopyroxene and olivine are main mafic minerals, with minor hornblende. Sample DCL230019A from drill core K-D-31 at 80.77–80.84 m. Left in ppl and right in xpl. Photo: Dick Claeson.

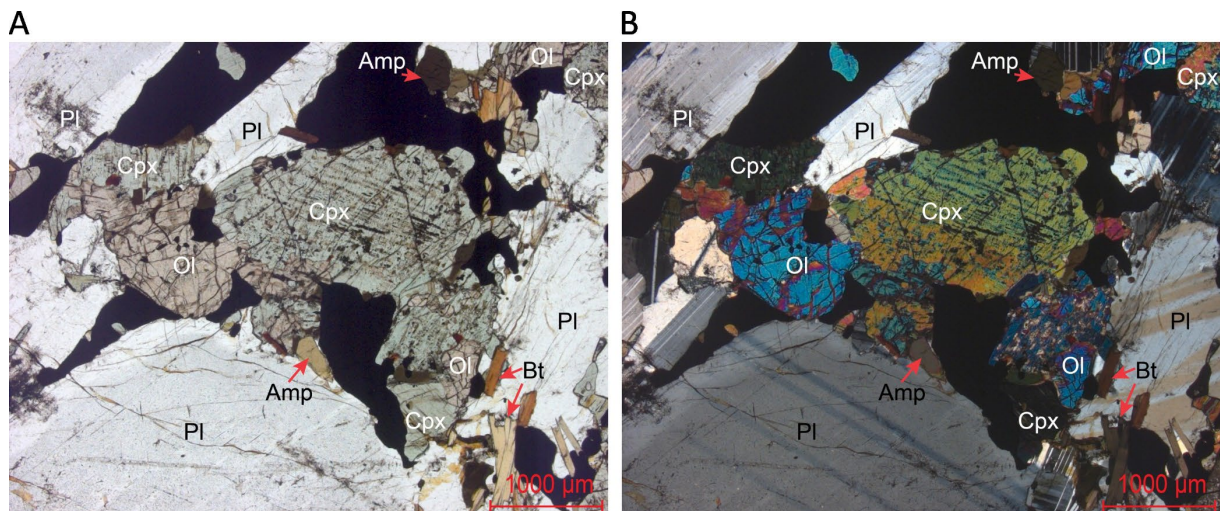


Figure 42. Large subhedral to anhedral plagioclase, clinopyroxene, olivine, minor hornblende and biotite in a cumulate rock. Note that the pigmentation in central portions of large plagioclase crystals is absent in their rims. Sample HRE220013A Baxgruvan (6841688/559544). Left in ppl and right in xpl. Photo: Dick Claeson.

Both clinopyroxene and olivine are rimmed by hornblende in the sample HRE220016A from Fredrikagruvan. Specifically, there is a close relationship between the hornblende rim next to clinopyroxene and olivine and the occurrence of nearby Fe-Ti oxide, even those Fe-Ti oxides included in clinopyroxene have the same pattern of hornblende rim between them (fig. 43). This rim is not related to the reaction between olivine and plagioclase since in contacts of these two minerals there is no hornblende present (figs. 43C-D). Instead, a late-stage interstitial hydrous Fe-Ti-rich liquid is suggested in order to form this particular type of texture (cf. Dong *et al.* 2021). The plagioclase crystals are for the most part anhedral and their rounded and embayed appearance suggests that they were dissolved and replaced by a late-stage interstitial hydrous Fe-Ti-rich liquid, forming Fe-Ti oxide in their place but not hornblende (fig. 43).

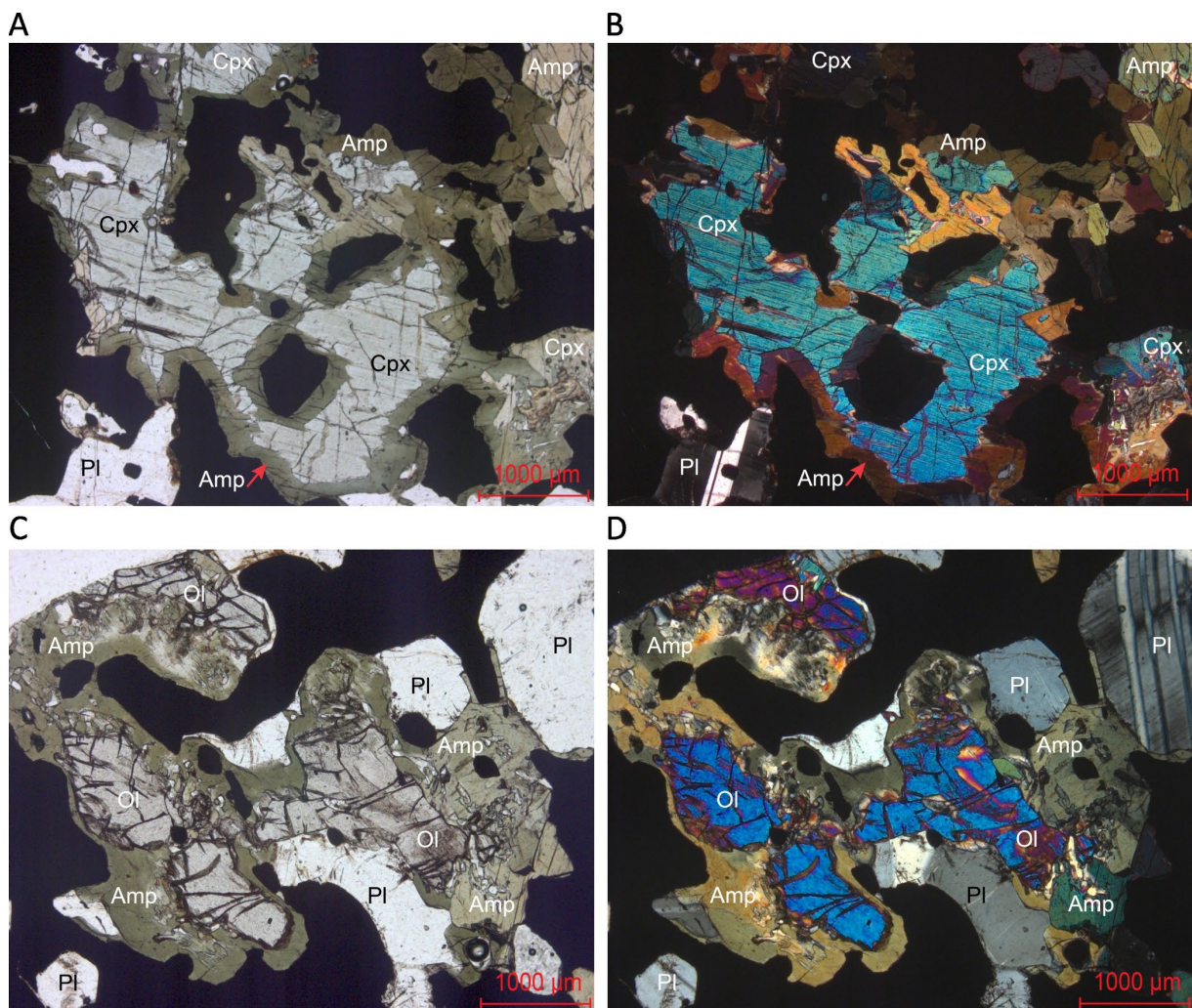


Figure 43. A. and B. Clinopyroxene crystal rimmed by hornblende. Note the close relationship between Fe-Ti oxide and hornblende rim next to clinopyroxene, even those included in the clinopyroxene have the same pattern. C. and D. Olivine rimmed by hornblende in a similar fashion. Sample HRE220016A Fredrikagruvan (6841878/559817). Left in ppl and right in xpl. Photo: Dick Claeson.

The Fe-Ti-mineralised gabbroic cumulate of sample HRE220047A from Axgruvan has hornblende as the main mafic mineral, small interstitially grown clinopyroxene, olivine, and plagioclase, rare larger crystals of plagioclase (figs. 44A–D). Note the hornblende grain triple junction at 120 degrees at several locations of the thin section (figs. 44A–D). This granoblastic texture minimises the combined surface energy of the grains. In igneous layered intrusions it signifies the degree of textural equilibrium that cumulate rocks have reached, which is apparent here (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b).

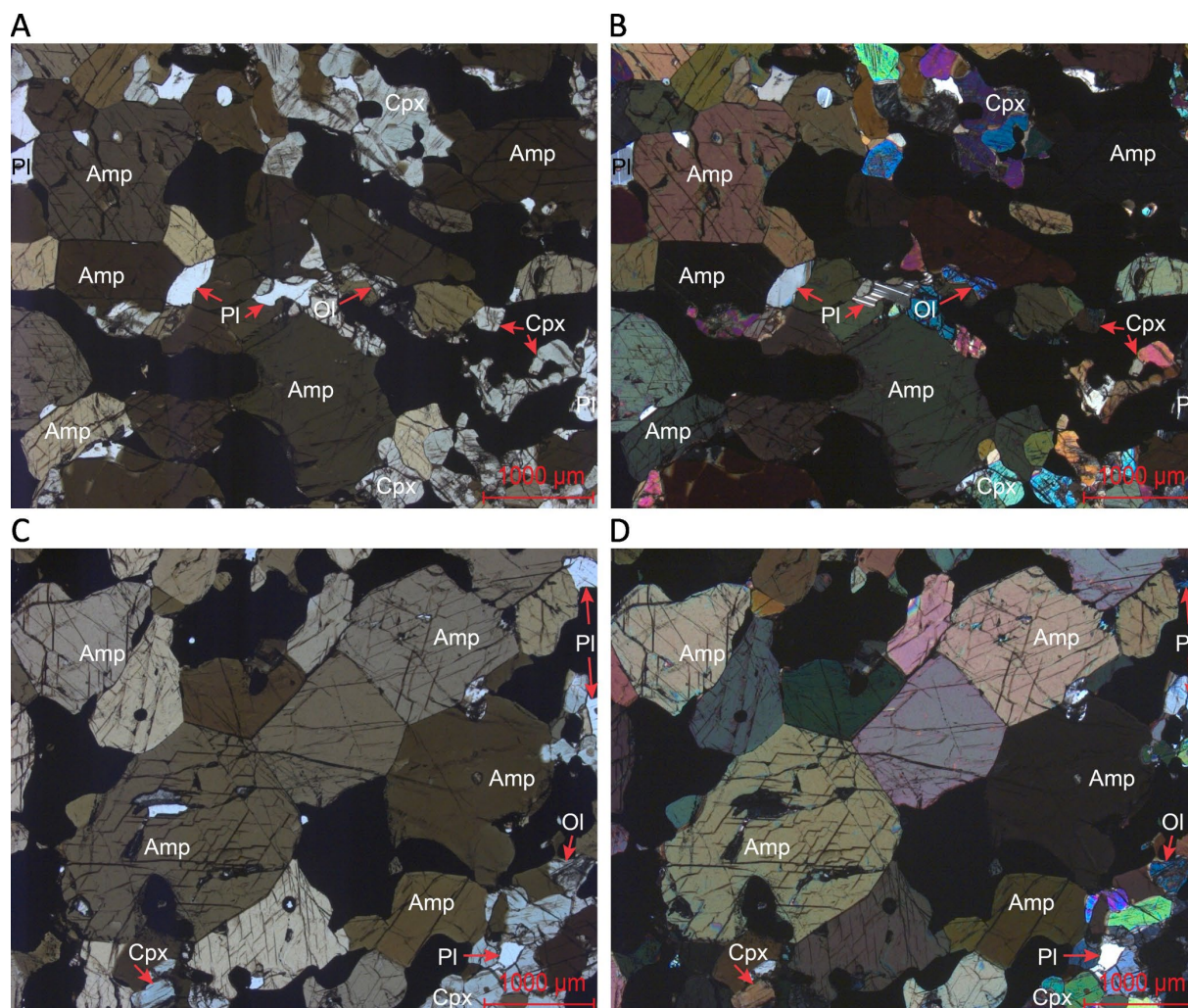


Figure 44. A. and B. Hornblende is main mafic silicate with interstitial clinopyroxene, olivine, and plagioclase. A few well-developed hornblende grain triple junctions at 120 degrees. C. and D. Large subhedral to euhedral hornblende crystals with several well-developed grain triple junctions at 120 degrees. Melagabbro HRE220047A Axgruvan (6841544/559471). Left in ppl and right in xpl. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Gillermyrgruvan (Kramsta-north)

Hornblende is the main silicate mineral with euhedral-subhedral large grains (fig. 45). Olivine and clinopyroxene are anhedral, with mostly small grains and interstitially grown crystals or as inclusions in hornblende. Plagioclase occurs interstitially or as inclusions of small crystals in hornblende.

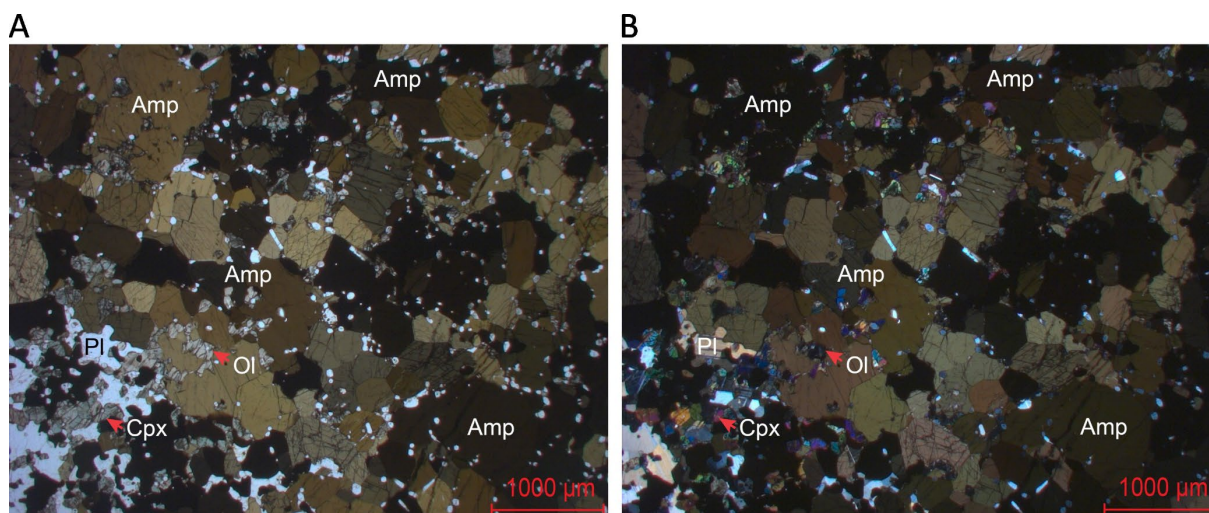


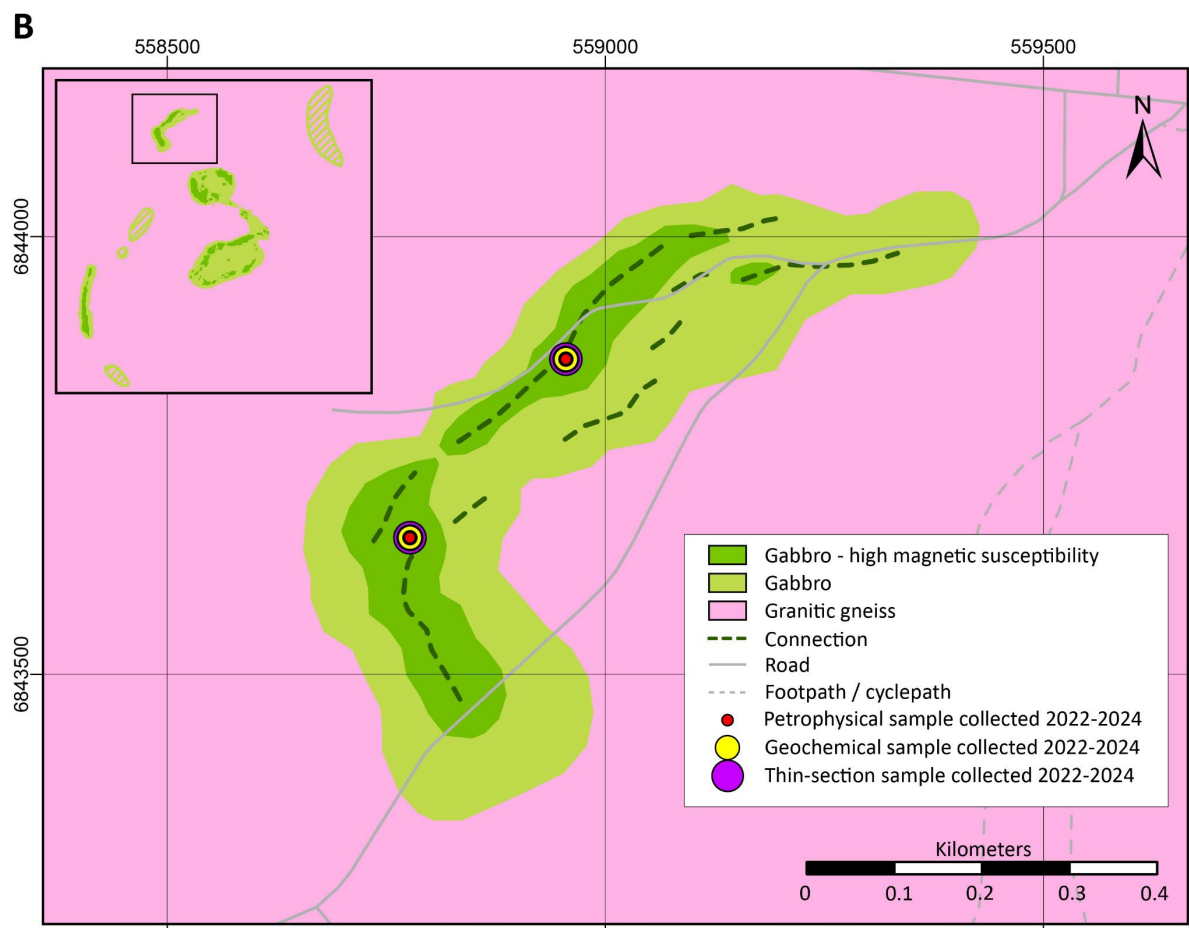
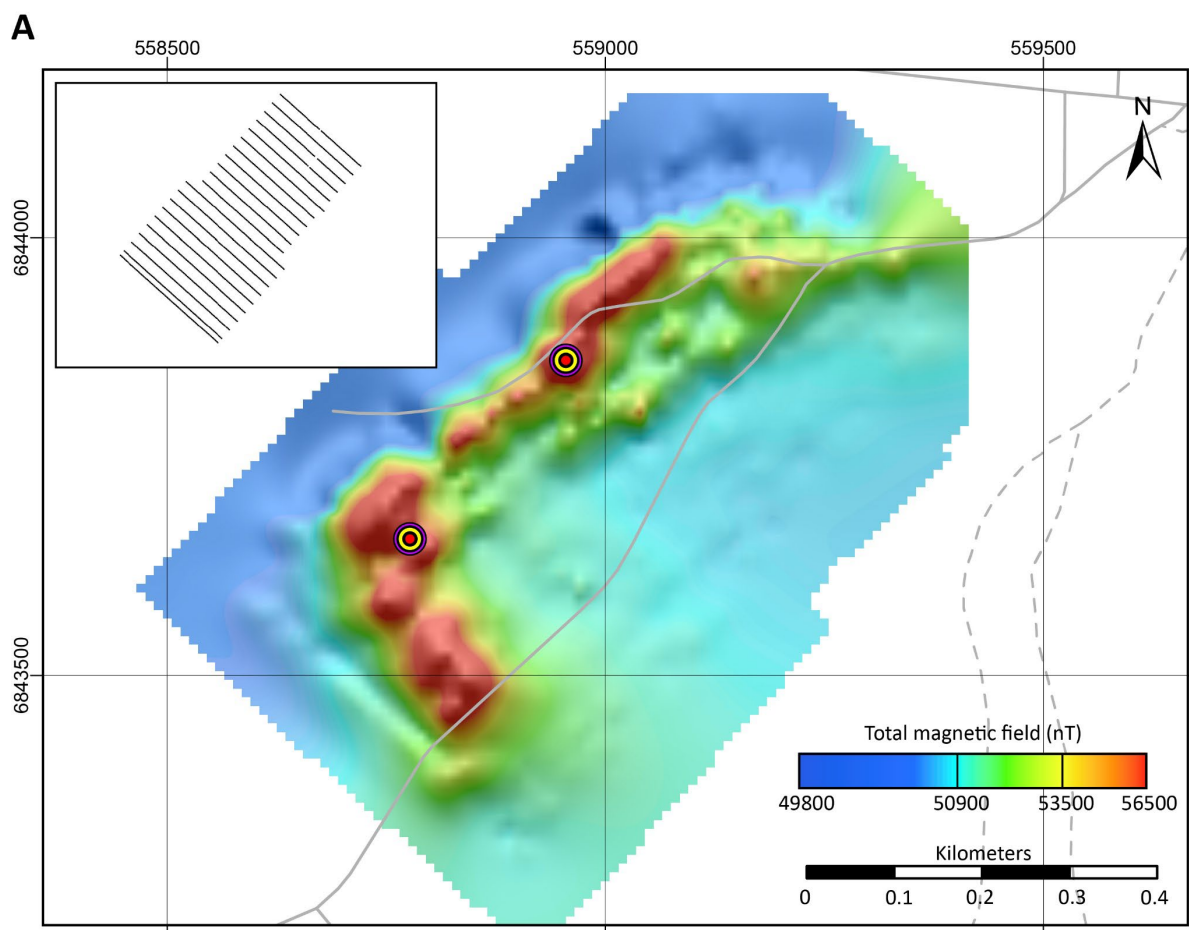
Figure 45. A. and B. Hornblende-rich cumulate with lots of inclusions of plagioclase, olivine, and clinopyroxene. Note the interstitial appearance of plagioclase in the lower left corner of the image. Sample HRE220043A Gillermygruvan 1 (6842610/559498). Left in ppl and right in xpl. Photo: Dick Claeson.

Storsveden

Ground-based geophysical measurements

The Storsveden intrusion is located within the Järvsö Field to the northwest of the Kramsta deposit (fig. 19). The ground-based magnetic data collected in 1980 over the Storsveden intrusion as well as the updated geological map are shown in figure 46. The magnetic anomaly at Storsveden has a curved, elongated form and is about 700 m in length and 200 m wide. The highest magnetic anomalies are observed to lie approximately in the centre of the anomaly, perhaps slightly closer to the western edge of the intrusion. The magnetic field anomaly is relatively strong for the Storsveden intrusion, exceeding 10 000 nT above the background in some places. Several continuous positive anomalies in the magnetic field can be interpreted across the intrusion which could be associated with its internal structure. Breaks or discontinuities in these anomalies are interpreted to be due to small scale faulting and folding (Edberg 1980). The map of the average magnetic susceptibility in the upper 75 m of the model obtained from inversion is shown in figure 47. Here the highest magnetic susceptibilities appear to lie west of the centre of the intrusion. The magnetic susceptibility model from the inversion suggests that the intrusion dips to the southeast, towards the Kramsta and Kramsta-north intrusions (see fig. 47).

► **Figure 46. A.** Map of the total magnetic field over the Storsveden intrusion, made using measurements collected in 1980 by LKAB. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Storsveden intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The inset map shows the location of the map with regards to the other intrusions in the Järvsö Field. The locations of samples are shown as different coloured dots in both A and B.



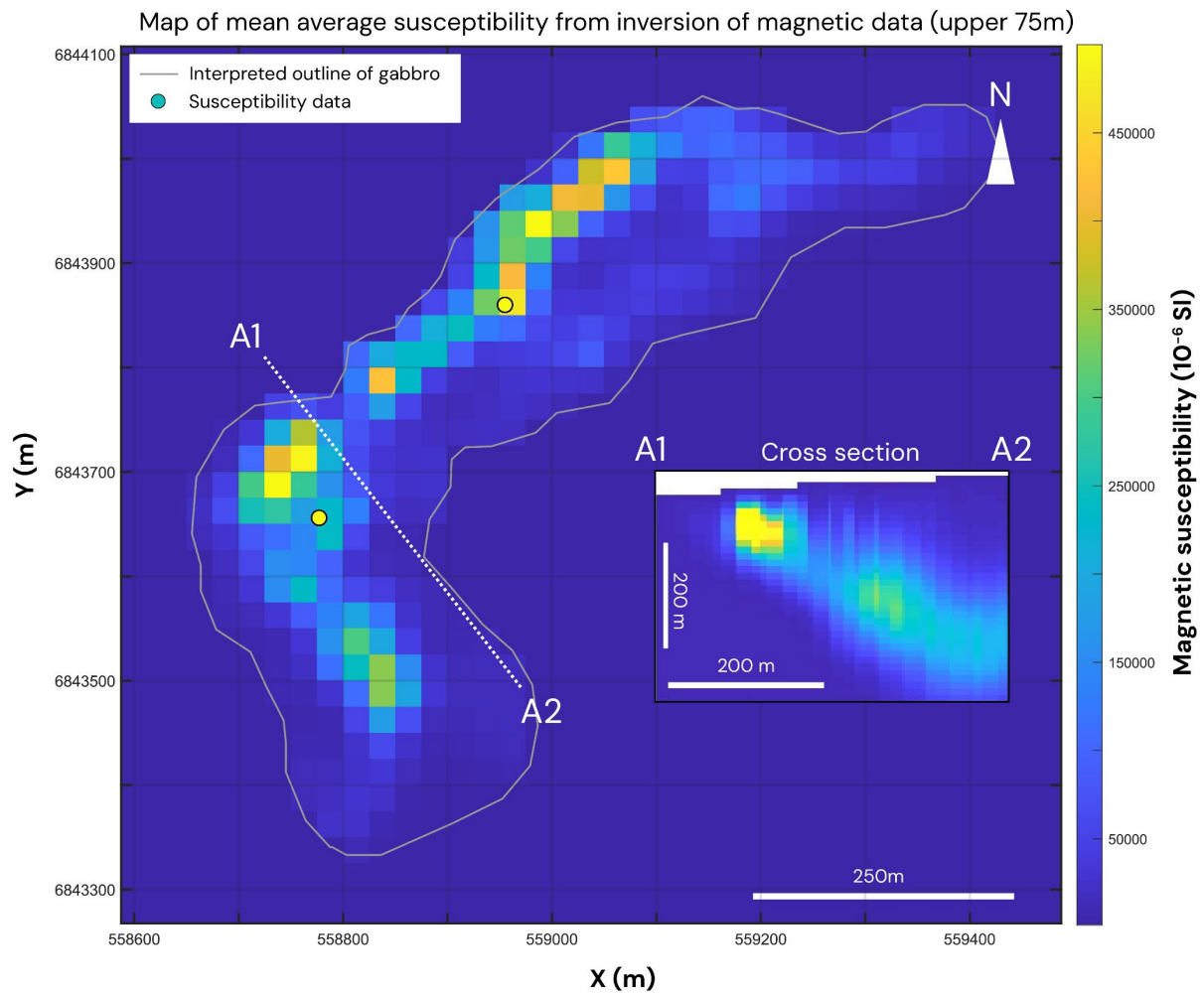


Figure 47. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Storsveden intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

Geological observations

At Storsveden the old mining pits at Skogsgruvan (figs. 48, 49, and 50) and Haggruvan were sampled. The analyses returned the following grades from Haggruvan: 36.40% Fe_2O_3 , 5.38% TiO_2 and 2 460 ppm V. The sample from Skogsgruvan had higher grades at 44.30% Fe_2O_3 , 7.14% TiO_2 and 3 320 ppm V.



Figure 48. Abandoned pit (Skogsgruvan) at Storsveden (6843656/558777). Photo: Helge Reginiussen.



Figure 49. Samples collected from Skogsgruvan at Storsveden (6843656/558777). Photo: Helge Reginiussen.



Figure 50. Close-up of mineralised sample collected from Skogsgruvan at Storsveden (6843656/558777). An analysis returned 44.30% Fe_2O_3 , 7.14% TiO_2 and 3 320 ppm V. Photo: Helge Reginiussen.

Description of thin sections – silicate minerals

Sample HRE220040A displays relations between clinopyroxene and hornblende, where minor parts of the clinopyroxene were probably replaced by hornblende or co-crystallised since some crystals are well within the clinopyroxene. A major part of the hornblende was late-forming outside of clinopyroxene, most often between Fe-Ti oxides and clinopyroxene (figs. 51A–D). Olivine and minor orthopyroxene are other mafic minerals in the sample and plagioclase the only felsic mineral (figs. 51A–B). The non-hydrous mafic minerals possibly outline glomerocrysts (figs. 51A–D). Plagioclase is partly consumed with relatively large embayments and cusps with an overall anhedral appearance (figs. 51C–D). These plagioclase grains also have many inclusions of amphibole and clinopyroxene, not seen to the same extent in the interior of subhedral, larger plagioclase grains (fig. 51). All minerals are well-preserved and show minimal alteration. The large plagioclase crystal in figures 51E–F has a very interesting story to tell, it displays several igneous processes as follows. Firstly, major parts of its outer perimeter have been consumed and now exhibits deep embayments and cusps, some semi-circular. The plagioclase was replaced by a reactive late-stage liquid that was Fe-Ti-rich as well as H_2O -rich, which subsequently formed magnetite, ilmenite and hornblende, the latter mostly along the perimeter of the remaining plagioclase. Secondly, the large plagioclase crystal records bending or kinking in its right part, which is best seen in crossed polars (fig. 51F) Plagioclase bending or kinking while hot in a cumulate rock is considered to result from the process of compaction of the crystal pile or mush, where interstitial liquid is pressed out of the residual porosity of the cumulate rock (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011). Deformation twins and undulose extinction in plagioclase are also features seen in relation to compaction of cumulate rocks (e.g., Holness *et al.* 2017). Thirdly, the inclusion of other minerals or lack thereof in different parts of the large plagioclase crystal records multi-stage growth prior to both the former mentioned processes. Some of the inclusions may have formed during the reactive process, through incipient liquid, possibly in thin cracks seen as linear trails in figure 51F. Bends or kinks are present at two places in a large plagioclase crystal shown with red arrows in figures 51G–H. Both these elongated plagioclase crystals may also have been broken during the movement of reactive liquid during compaction of the crystal pile. This is seen as displacements filled with late-crystallising minerals as Fe-Ti-oxide and hornblende with the single clinopyroxene crystal, shown with white arrows in figures 51E–H.

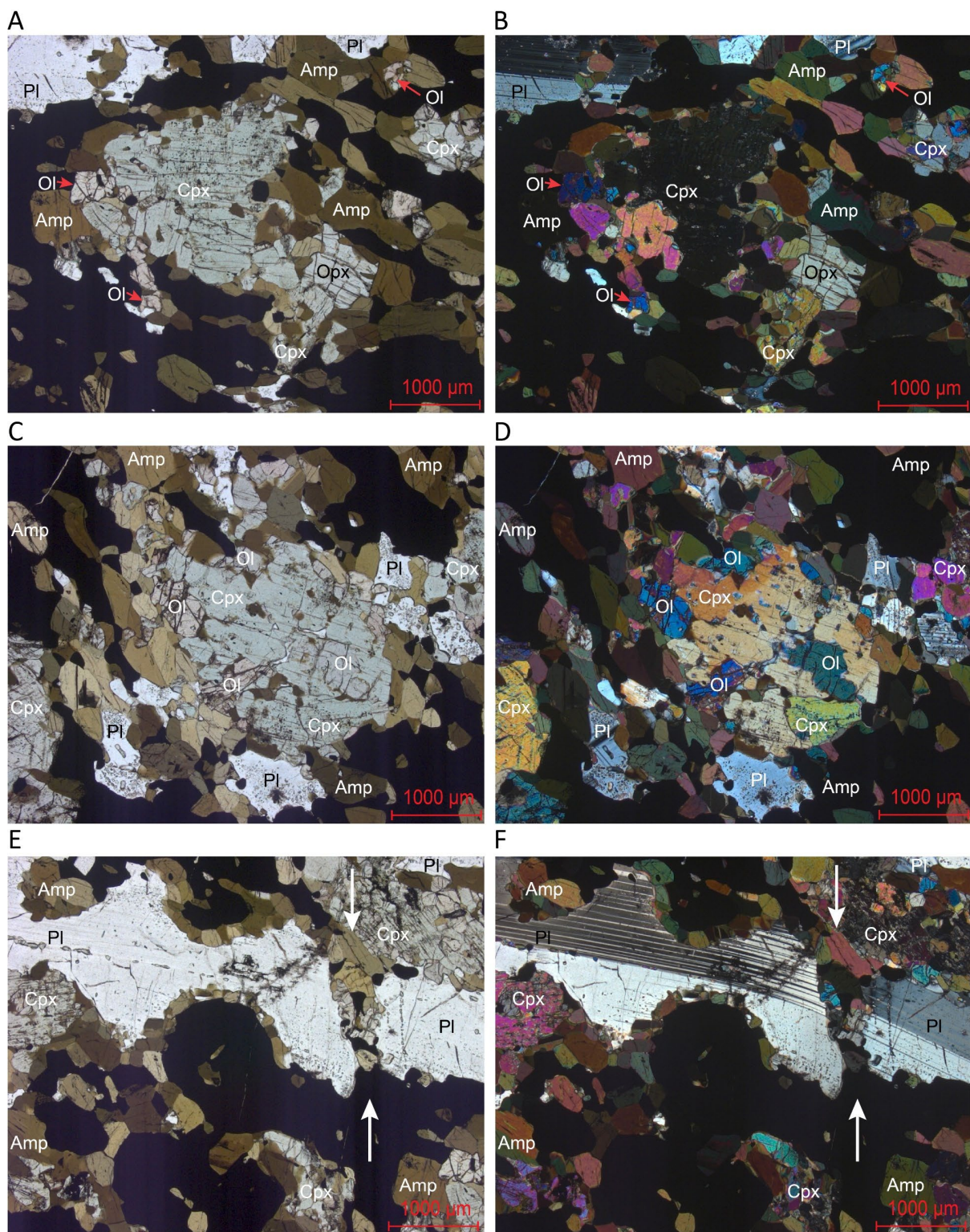


Figure 51. A. to D. Late hornblende outside of clinopyroxene, mostly between Fe-Ti oxides and clinopyroxene along with orthopyroxene and olivine possibly make up glomerocrysts. E. and F. Major parts of the large plagioclase crystals outer perimeter has been consumed and now exhibits deep embayments and cusps and lined with hornblende. At least one bend or kink is present across the large plagioclase in centre of the images, along with deformation twins and undulose extinction. Left in ppl and right in xpl.

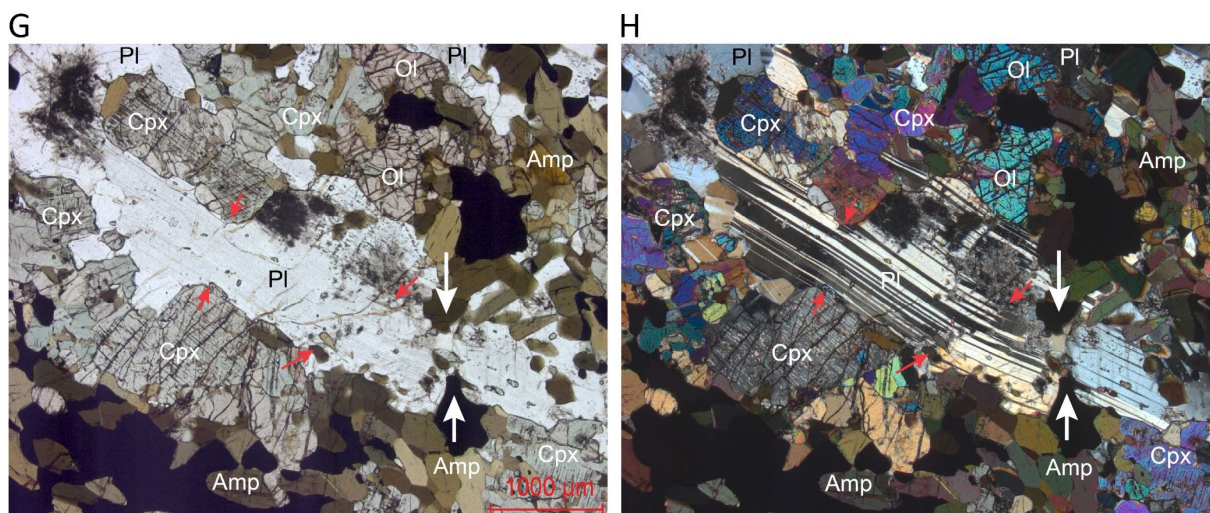


Figure 51 continued. G. and H. At least two bends or kinks are present across the large plagioclase located between the opposing red arrows of respective bend or kink. The crystal also displays deformation twins and undulose extinction. All images from sample HRE220040A (6843656/558777). Left in ppl and right in xpl. Photo: Dick Claeson.

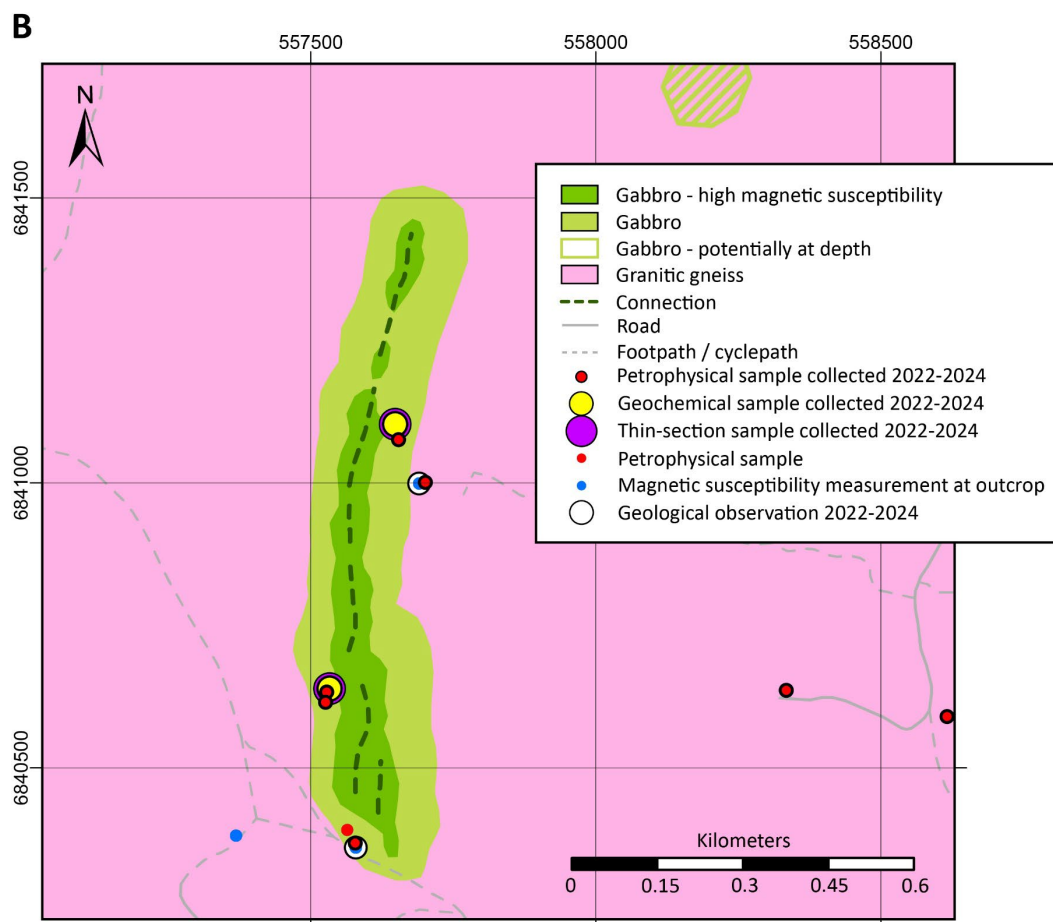
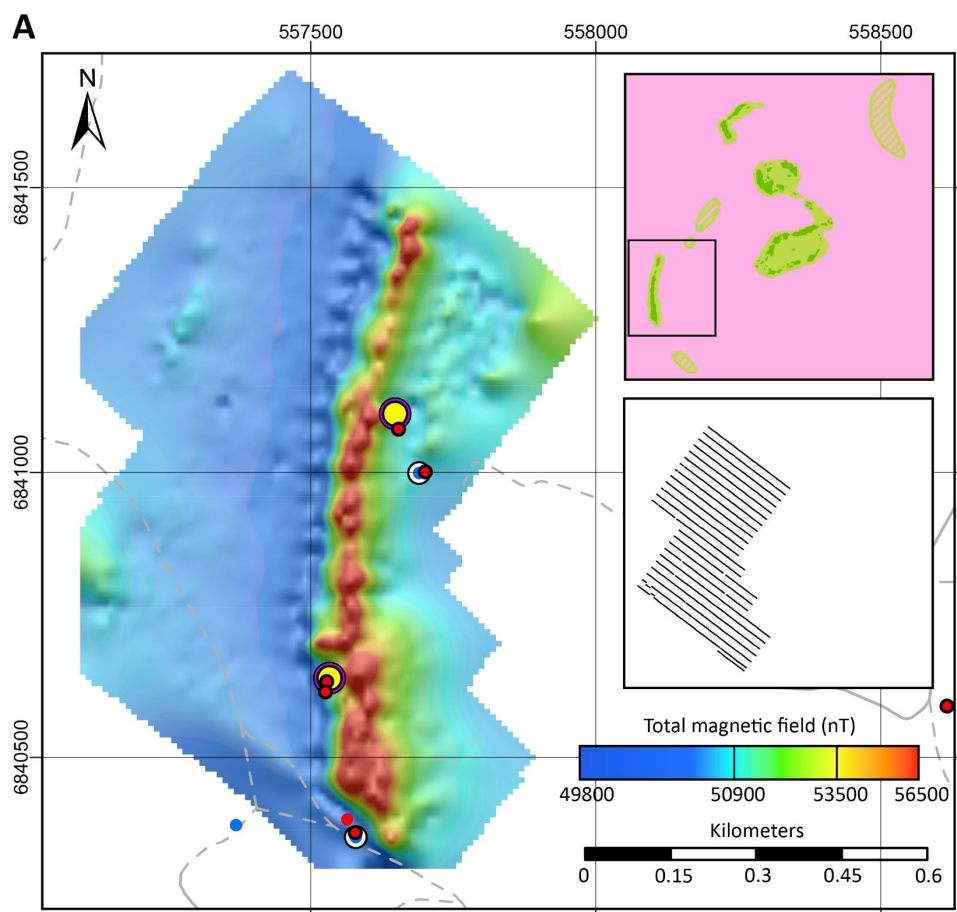
Järvsö–Gruvberget

To avoid semantic confusion with the deposit Gruvberget–Sumåssjön the informal name Järvsö–Gruvberget will be used in the following to describe the area of mining pits that occurs along the southwestern slope of the hill Gruvberget to the west of the Kramsta intrusion.

Ground-based geophysical measurements

The Järvsö–Gruvberget intrusion lies to the southwest of the Kramsta intrusion in the Järvsö Field (fig. 19). The ground magnetic field measurements collected in 1980 over the intrusion as well as an updated geological map are shown in figure 52. Here it can be observed that the Järvsö–Gruvberget intrusion gives rise to an elongate, gently curved anomaly approximately 1 100 m long and 100 m wide. The magnetic anomaly is relatively strong, in places exceeding 10 000 nT above the background level. Unlike the Kramsta and Kramsta-north intrusions which are elliptical in nature, the Järvsö–Gruvberget intrusion has a more planar, dyke-like geometry. In previous work by Edberg (1980), the Järvsö–Gruvberget deposit is interpreted to dip to the east at approximately 50°. Figure 53 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained from inversion. Here the highest magnetic susceptibilities appear to run in a line parallel to the edges of the intrusion, slightly to the west of the centre of the intrusion. On inspection of the susceptibility model from the inversion in 3D, the intrusion appears to dip the east (fig. 53).

► **Figure 52. A.** Map of the total magnetic field over the Järvsö–Gruvberget intrusion, made using measurements collected in 1980 by LKAB. The upper inset map shows the location of the map with regards to the other intrusions in the Järvsö Field. The lower inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines **B.** Updated map of the bedrock geology around the Järvsö–Gruvberget intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of geological observations, samples, and magnetic susceptibility measurements at outcrop are shown as different coloured dots in both A and B.



Map of mean average susceptibility from inversion of magnetic data (upper 75m)

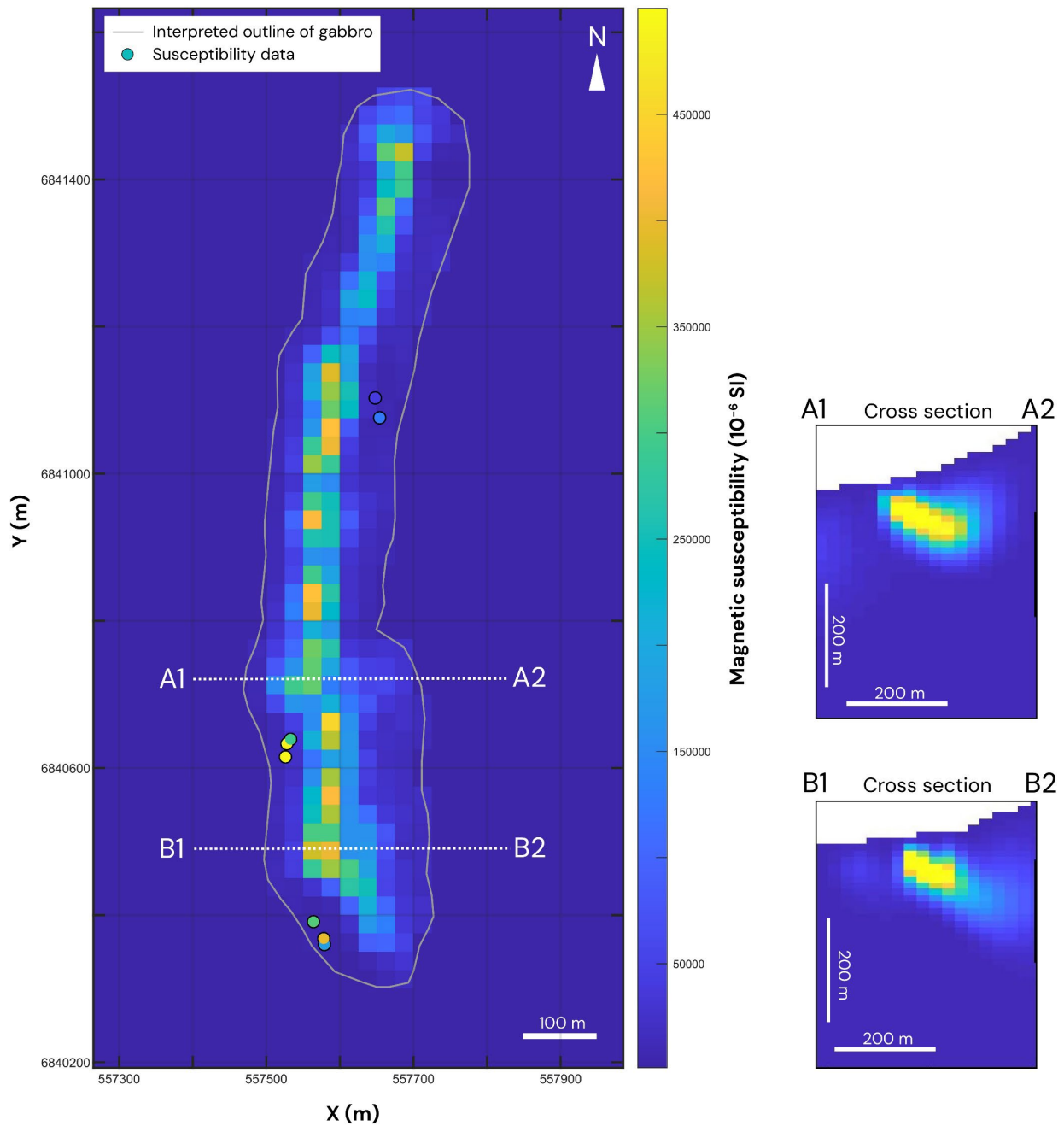


Figure 53. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Järvsö-Gruvberget intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. Cross sections (A1–A2 and B1–B2) through the magnetic susceptibility model obtained from the inversion are shown next to the map. The locations of the cross sections are denoted on the map as dotted white lines. The dots, map and sections are shown with the same magnetic susceptibility colour scale.

Geological observations

At Järvsö–Gruvberget samples were collected at two old mining pits: Björngruvan 2 (figs. 54 and 55) and Venusgruvan. Analysis of the samples returned the following: Björngruvan 2: 34.40% Fe_2O_3 , 5.15% TiO_2 and 2 550 ppm V. Venusgruvan had lower grades with 18.00% Fe_2O_3 , 2.29% TiO_2 and 629 ppm V.



Figure 54. Sampling one of the abandoned pits (Björngruvan 2) at Järvsö–Gruvberget (6840638/557533). Photo: Helge Reginiussen.

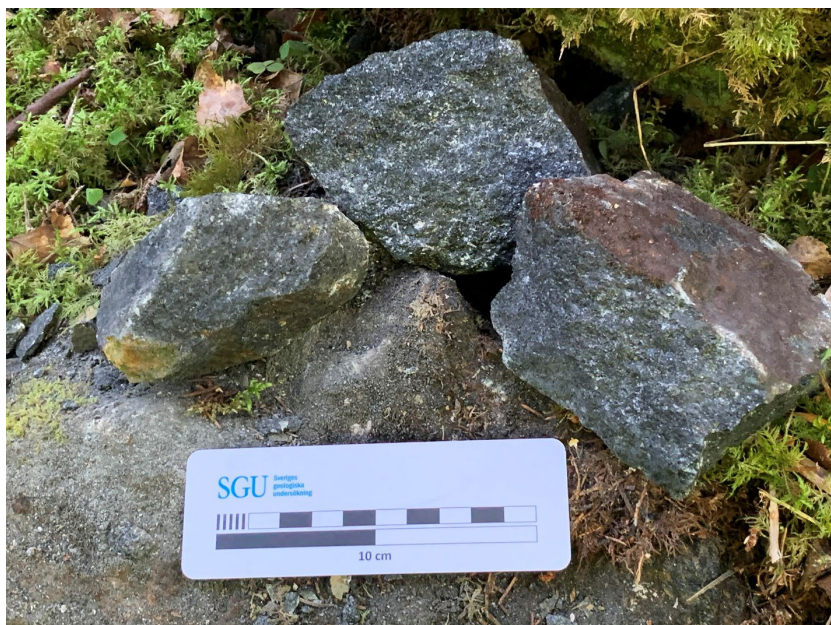


Figure 55. Gabbroic samples collected at Björngruvan 2 at Järvsö–Gruvberget (6840638/557533). Analysis of the samples showed 34.40% Fe_2O_3 , 5.15% TiO_2 and 2 550 ppm V. Photo: Helge Reginiussen.

Description of thin sections – silicate minerals

The gabbroic cumulate of sample HRE220060A has hornblende as the main mafic mineral, clinopyroxene, olivine, and plagioclase, with rare crystals of biotite (figs. 56A–B). Note the hornblende grain triple junction at 120 degree in the centre of figures 56A–B. This granoblastic texture minimises the combined surface energy of the grains. In igneous layered intrusions it signifies the degree of textural equilibrium that cumulate rocks have reached and a textural equilibrium is seen (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). In sample HRE220062A, the cumulate consists of clinopyroxene as main mafic mineral, biotite, plagioclase, and minor olivine (figs. 56C–D). Biotite is relatively abundant in sample HRE220062A and occurs as two igneous generations, the first to form has brownish red pleochroism and the second has brownish red to tan colours (figs. 56C–D). The intensity of colour generally increases with increase in Fe and Ti, where Ti and Fe^{3+} content matters the most (Deer *et al.* 1992). The reddish brown colour is always seen in Ti-rich biotite. The later formed biotite thus had less Ti and Fe^{3+} in the liquid it formed from than the first formed biotite.

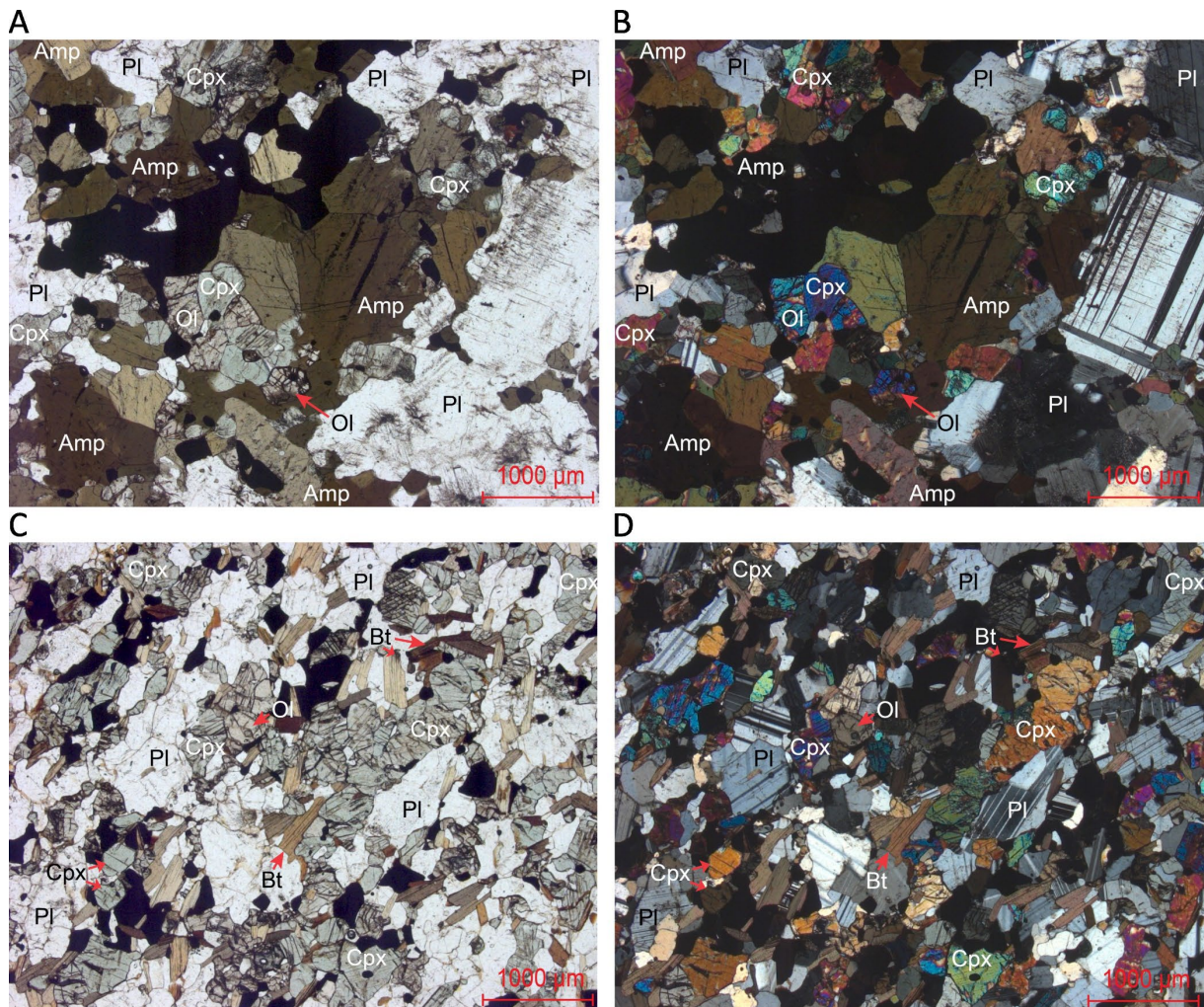


Figure 56. A. and B. Gabbroic cumulate with hornblende as main mafic mineral, clinopyroxene, and minor olivine. Sample HRE220060A (6840639/557533). C. and D. Gabbroic cumulate with clinopyroxene as main mafic mineral, relatively abundant biotite, and minor olivine. Sample HRE220062A (6841103/557648). Left in ppl and right in xpl. Photo: Dick Claeson.

3D geological model of the Järvsö Field

As part of this study a 3D geological model was generated for the Järvsö Field, in order to gain further insight into the geometry, volume, and depth of the different intrusions. Efforts were made to make the model consistent with the airborne and ground-based geophysical data as well as borehole data. Initially, modelling of the gravity response was performed using code written in the Matlab software. A 3D geological model was generated in the Leapfrog software and forward modelling of the gravity response of this model was performed using VOXI in the Geosoft software.

The workflow for generating the model was as follows:

1. **Gravity modelling:** Gravity modelling was first performed for the intrusions in the Järvsö Field using a script written in the Matlab software. As part of the modelling the volume of interest was split into a series of grid cells. A semi-automated routine was then utilised to assign cells in the 3D grid to be gabbro or granite, based on where gabbro was present at the surface and the observed gravity response. This resulted in a 3D grid with both gabbro and granite cells that produced a gravity anomaly, which provided a reasonable match with the observed data.
2. **3D Geological modelling in Leapfrog:** The density model from the gravity modelling was then imported into the Leapfrog software, together with borehole data, a digital elevation model and updated maps of the bedrock geology. 3D volumes corresponding to the different intrusions were then generated using the contacts in the bedrock geology map, borehole data, and density model. A series of additional gabbro intrusions, not present on the bedrock geology map were included in the model, which are inferred from the geophysical data.
3. **Forward Gravity modelling:** In order to validate that the 3D geological model was still consistent with the gravity response, it was imported into VOXI in the Geosoft software, and the gravity response was calculated.

In both the initial and final gravity modelling, the density of gabbro was assumed to be 600 kg/m^3 higher than the surrounding granite, which is consistent with the data presented in the petrophysics section (Table 2). A background correction of -3.36 mGal was applied to the Bouguer anomaly data before modelling the gravity response.

The 3D model generated for the Järvsö Field can be seen in figure 57. Here the intrusions which reach the surface have been included in the model, i.e. Kramsta, Kramsta-north, Storsveden, and Järvsö-Gruvberget. However, three additional intrusions labelled J1, J2, and J3 are also included, which are interpreted to be located at depth. The presence and size of these intrusions is inferred from the ground-based gravity data and airborne magnetic data. The Kramsta intrusion appears to be the largest intrusion in the Järvsö Field, which is modelled to have the largest volume ($96 \times 10^6 \text{ m}^3$). A close-up of the Kramsta intrusion can be seen in figure 57B. Here it can be observed that the northwestern flank is relatively well constrained by borehole data. The intrusion is modelled to be deepest in the centre with a bowl like geometry. The northern part of the Kramsta intrusion appears to be relatively thin compared to the main body of the intrusion. The Storsveden and Kramsta-north intrusions are modelled to have about half the volume of the Kramsta intrusion, with volumes of $46 \times 10^6 \text{ m}^3$ and $42 \times 10^6 \text{ m}^3$, respectively. The Storsveden intrusion is modelled to dip to the southeast. The Kramsta-north intrusion is modelled as being somewhat bowl like, however it increases in thickness towards the northwest. The Järvsö-Gruvberget intrusion is modelled to have the smallest volume of the intrusions mapped at the surface ($27 \times 10^6 \text{ m}^3$) and to dip to the east, into the hillside. Of the intrusions not mapped at the surface the J1 intrusion has the largest volume ($62 \times 10^6 \text{ m}^3$) and is modelled to be somewhat sheet like, dipping to the east. In the model it lies at about 50 m depth below the surface. The J2 and J3 intrusions are modelled to be relatively small intrusions with volumes of about $6 \times 10^6 \text{ m}^3$ and $4 \times 10^6 \text{ m}^3$, respectively. The J2 intrusion is modelled to be relatively deep, at 150 m below the surface, while the J3 intrusion is modelled to be much shallower at about 50 m depth.

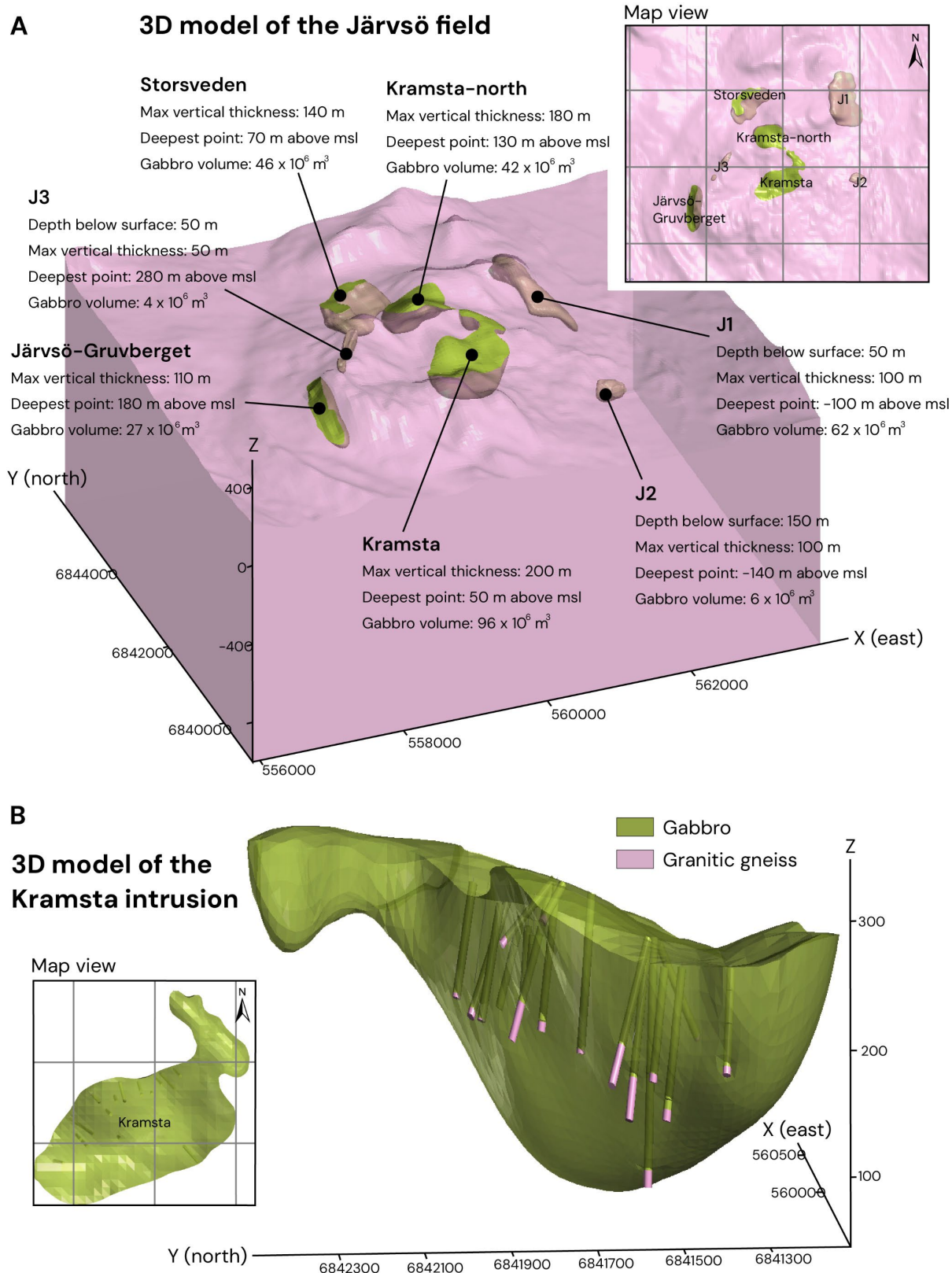


Figure 57. 3D modelling of the Järvsö Field. **A.** Overview of the 3D geological model of the Järvsö Field built as part of this study. Some details about the geometry of the different intrusions are given as text in the figure. **B.** Close-up image of the model of the Kramsta intrusion. Boreholes used in the modelling can be seen as cylinders and are colour coded by lithology (i.e., sections in gabbro and granite are shown as green and pink, respectively).

Figure 58 shows the observed gravity response over the Järvsö Field. Here anomalies associated with the Kramsta, Kramsta-north, and Storsveden intrusions can be observed. There are also clear anomalies which are interpreted to be associated with the deeper intrusions (J1 and J2). No clear anomaly is observed at Järvsö–Gruvberget, but it is important to note that no gravity measurements were collected directly over this intrusion and hence, the anomaly is likely to not be well represented in the data. There appears to be a lower frequency gravity anomaly which sits in the western part of the map shown in figure 58, underlying Järvsö–Gruvberget and J3, and to a lesser extent Kramsta, Kramsta-north, Storsveden, and J1. This is potentially due to the presence of a large mafic intrusion at depth.

Figure 58 also shows the modelled gravity response, using the 3D geological model (assuming that gabbro is 600 kg/m³ denser than granite). Here we can see that the modelled response matches the Kramsta, Kramsta-north, and J1 anomalies relatively well. This infers that in broad terms the geometry and volume of these intrusions are reasonable. The anomalies modelled from the intrusions at Storsveden and J2 appear to match relatively well in terms of their shape, but their amplitudes are notably lower than in the observed data. This infers that they are too small in the 3D geological model and should be increased in volume. The J3 and Järvsö–Gruvberget anomalies are not so clear in the observed data (most likely due to the placement of measurement points and lack thereof) and therefore it is not possible to make a direct comparison between the observed and modelled gravity response.

Figure 59 shows airborne magnetic data collected over the Järvsö Field. Here the magnetic anomalies at the Kramsta, Kramsta-north, Storsveden, and Järvsö–Gruvberget intrusions are clearly visible. However, weaker magnetic anomalies appear to be present above the J1 and J3 intrusions. This supports the interpretation that mafic intrusions are present close to the surface at these locations. No magnetic anomaly is located at the J2 intrusion. However the J2 intrusion is modelled to be located at a greater depth (about 150 m) and hence, it may not give rise to a strong magnetic anomaly at the surface. An updated geological map for the Järvsö Field is also shown in figure 59, here mafic intrusions present at the surface as well as those inferred at depth from the geophysical data are shown.

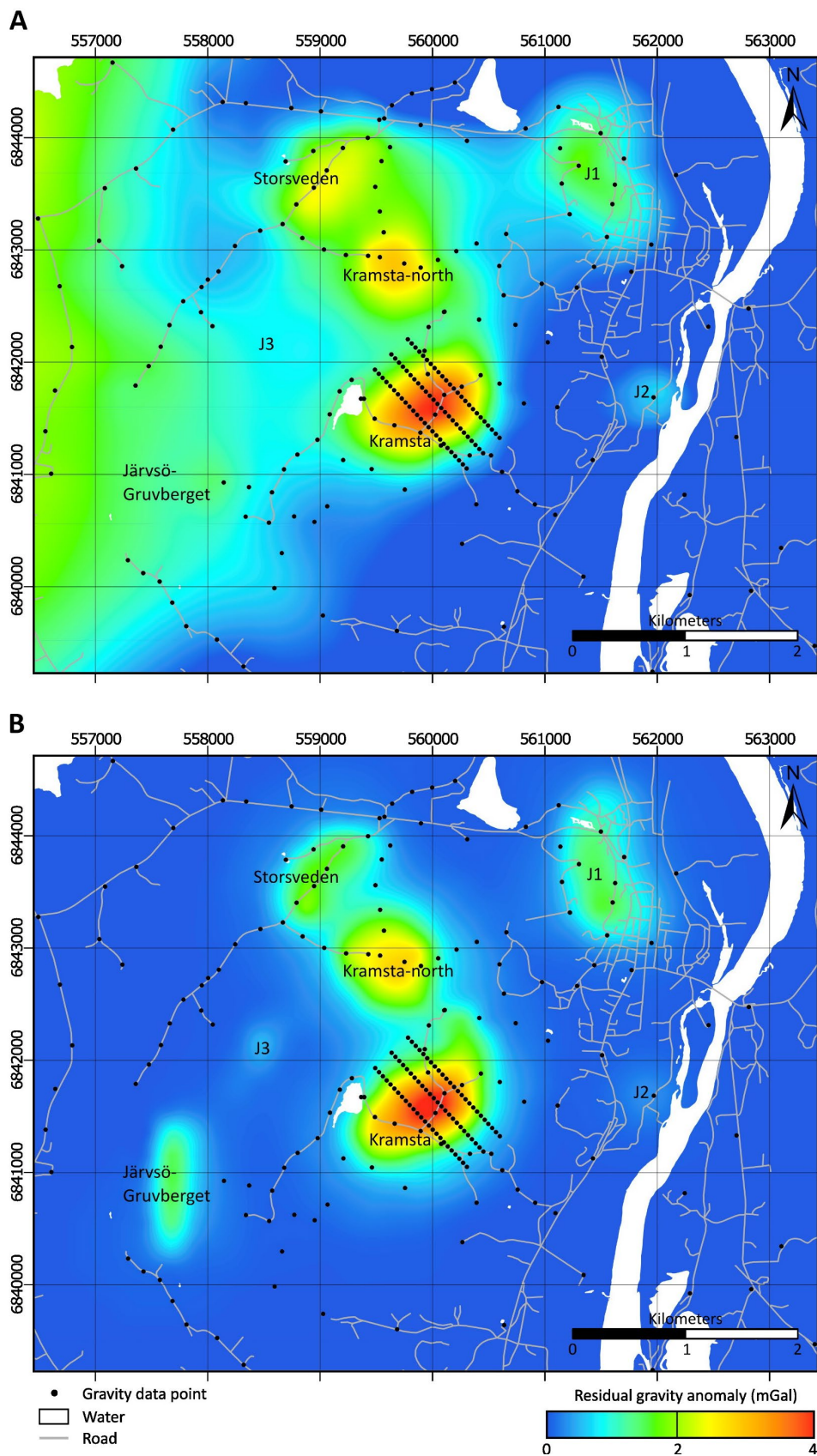


Figure 58. Maps showing the gravity response over the Järvsö Field. **A.** Observed gravity response over the Järvsö Field. The residual anomaly is shown, which is the Bouguer anomaly after subtraction of a background value of -3.36 mGal. **B.** The modelled gravity response for the Järvsö Field, using the 3D model shown in figure 57. The location of ground-based gravity observations are shown as black dots on both maps.

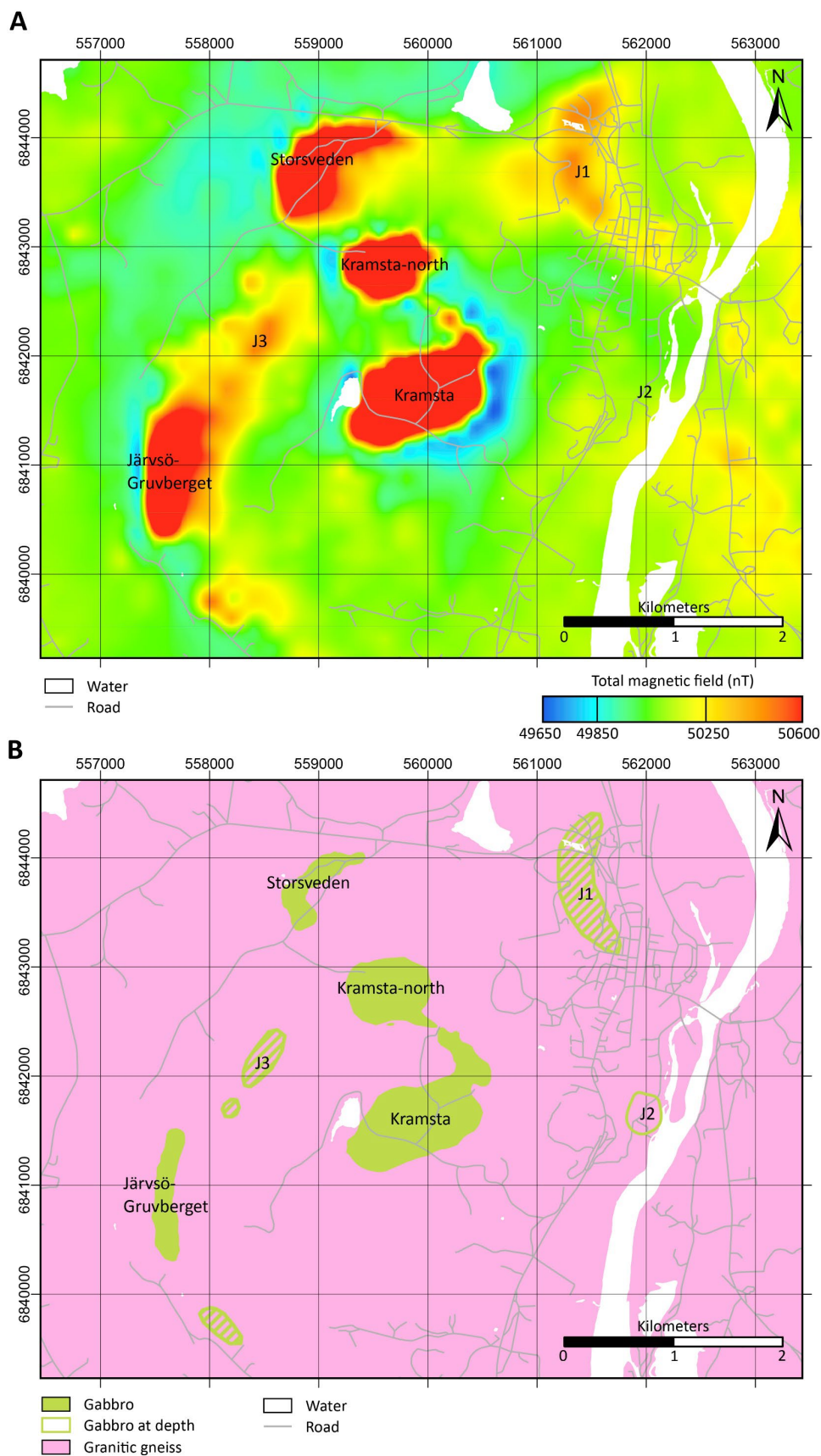


Figure 59. Maps showing airborne magnetic data and bedrock geology for the Järvsö Field. **A.** Map of the total magnetic field (reduced-to-pole) from airborne measurements over the Järvsö Field. **B.** Updated bedrock geology map for the Järvsö Field. Areas where gabbro intrusions are not mapped at the surface but are suspected to be located at depth based on the geophysical data are shown as areas with a green striped pattern.

Gartsbogruvan and Buberget

A small cluster of mafic intrusions is interpreted to be located about 8 km to the northeast of the Järvsö Field (fig. 19). As part of this study, two of these intrusions (Buberget and Gartsbogruvan) were investigated.

Ground-based geophysical measurements

Ground magnetic data were collected over the Gartsbogruvan intrusion. A map of the total magnetic field as well as a small-scale bedrock geology map of the intrusion are shown in figure 60. The magnetic anomaly at Gartsbo is somewhat linear, about 600 m long and 100 m wide. The maximum magnetic field anomaly lies about 5 000 nT above the background level, while the highest anomaly values only cover a relatively small area. Based on the magnetic field data it appears that the highest magnetic field values occur along only one relatively narrow axis within the intrusion, with the highest values occurring in the western part of the intrusion.

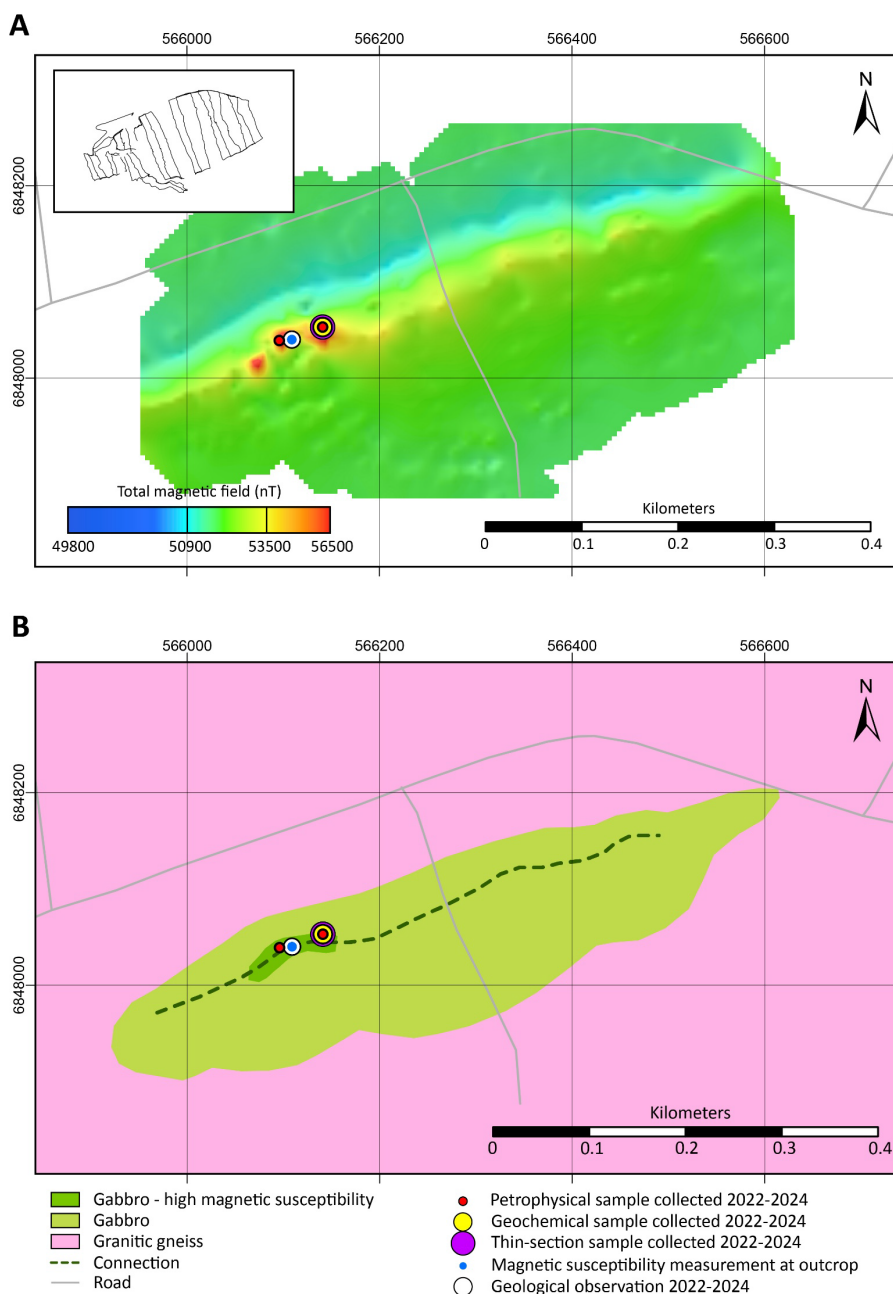


Figure 60. **A.** Map of the total magnetic field over the Gartsbogruvan intrusion, made using measurements collected as part of this study. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Gartsbogruvan intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of geological observations, samples, and magnetic susceptibility measurements at outcrop are shown as different coloured dots in both A and B.

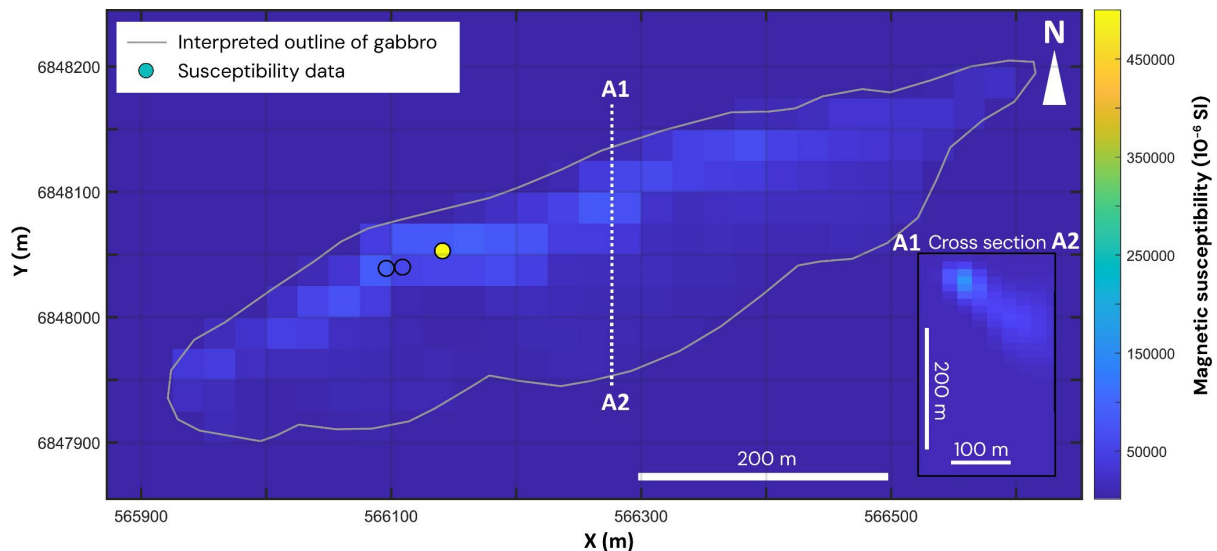


Figure 61. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Gartsbogruvan intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1-A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

Figure 61 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained from inversion. Here the highest magnetic susceptibilities appear to lie within a linear zone within the intrusion, parallel to the magnetic anomaly. On inspection of the unconstrained inversion result, the intrusion appears to dip to the southeast.

Geological observations

The pit at Gartsbogruvan measures approximately 8×10 m and is waterfilled. Waste-rock on-site comprising massive, medium- to coarse-grained gabbroic rocks (fig. 62) and mineralised gabbro containing magnetite and sulphides occur adjacent to the pit. Both mineralised and apparently less mineralised material were sampled and analysed. The assays returned the following: 21.00–35.20% Fe_2O_3 , 3.19–7.61% TiO_2 , and 1 050–1 310 ppm V.

Near the top of Buberget hill a medium- to coarse-grained and massive, in places layered gabbroid displaying magmatic fabric occurs (fig. 63). Segregation and mobilisation of felsic cumulates that truncates the magmatic layering is observed (fig. 64). Analyses of samples show the following concentrations: 17.75–20.40% Fe_2O_3 , 1.86–3.54% TiO_2 , and 554–661 ppm V.



Figure 62. Gabbroic rock from the waste-rock heap adjacent to Gartsbogruvan (6848053/566141). Photo: Helge Reginiussen.



Figure 63. Gabbroid at Buberget (6848955/566299). Photo: Helge Reginiussen.



Figure 64. Gabbroid at Buberget with felsic segregations and remobilisation (6848955/566299). Photo: Helge Reginiussen.

Description of thin sections – ore minerals – Gartsbo

The ore minerals magnetite, ilmenite, and small grains of pyrrhotite were identified in mineralised sample HRE220049B (fig. 65, see fig. C4 for panorama). The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock, note the subhedral ilmenite next to interstitial magnetite (fig. 65). There are very few exsolved ilmenite grains as trellis in the magnetite (figs. 65B–C). Ilmenite has exsolved hematite but other minerals that look like darker exsolution trellis are present, which are most likely magnetite or ulvöspinel (figs. 65B–C, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the few tiny trellis-type exsolution in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but optical microscopy was deemed inadequate for proper identification. In the closeup images, within the euhedral ilmenite crystal's outer part, close to the contact with magnetite, a decrease in abundance of hematite lamellae is seen. This continues up to the contact where they can no longer be observed, when viewing with an optical microscope (figs. 65B–C). An explanation for the lack of exsolution in the contact zones could be that at the point of igneous crystallisation, ilmenite and magnetite are so close to each other that a miniscule amount of interstitial liquid present will lead to the uptake preferred by each mineral. In other words, Fe moves preferably into magnetite and Ti into ilmenite during the competing growth and thus, over time, there will be much less material to exsolve. This also shows the cumulate nature of the rock and that late-stage interstitial liquids were Fe-Ti-rich.

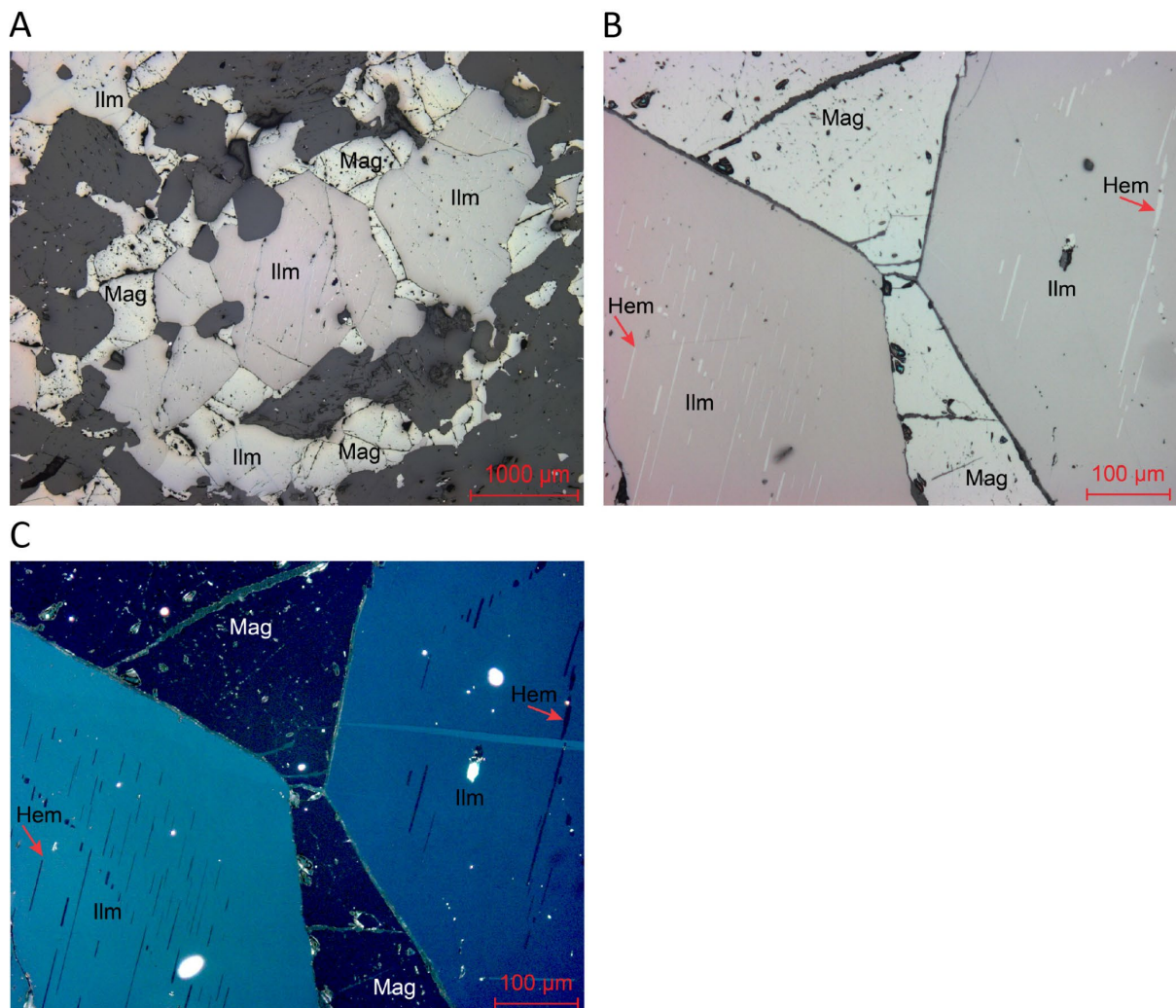


Figure 65. Ore minerals from the Gartsbogravan, mineralised sample HRE220049B (see fig. C4 for panorama). **A.** Overview of textural relations between magnetite and ilmenite in opaque framework, note the subhedral ilmenite next to interstitial magnetite. Close-up images of relations between interstitial magnetite and subhedral ilmenite in **A.**, where scarce ilmenite occurs as trellis exsolutions in magnetite, and hematite as exsolution lamellae in ilmenite, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. Note the decrease and absence of exsolved hematite in ilmenite close to the contact with magnetite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Gartsbo

The cumulate rock of sample HRE220049A is well-preserved with minor alteration along fractures. Hornblende occurs as large grains and interstitial, subhedral to anhedral in shape, and olivine as small to large grains and interstitial, anhedral to subhedral. Clinopyroxene is subhedral to anhedral, occurs as large grains and interstitial, some with exsolution lamellae and some with extensive exsolution of an opaque mineral (fig. 66). Plagioclase occurs as large grains to interstitial, subhedral to anhedral, displaying minor sericite-saussurite alteration mostly as minor spots. Hornblende, clinopyroxene, and plagioclase all have grain triple junction at 120 degrees at several locations of the thin section (fig. 66). This granoblastic texture minimises the combined surface energy of the grains. In igneous layered intrusions it signifies the degree of textural equilibrium that cumulate rocks have reached and a textural equilibrium is apparent here (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b).

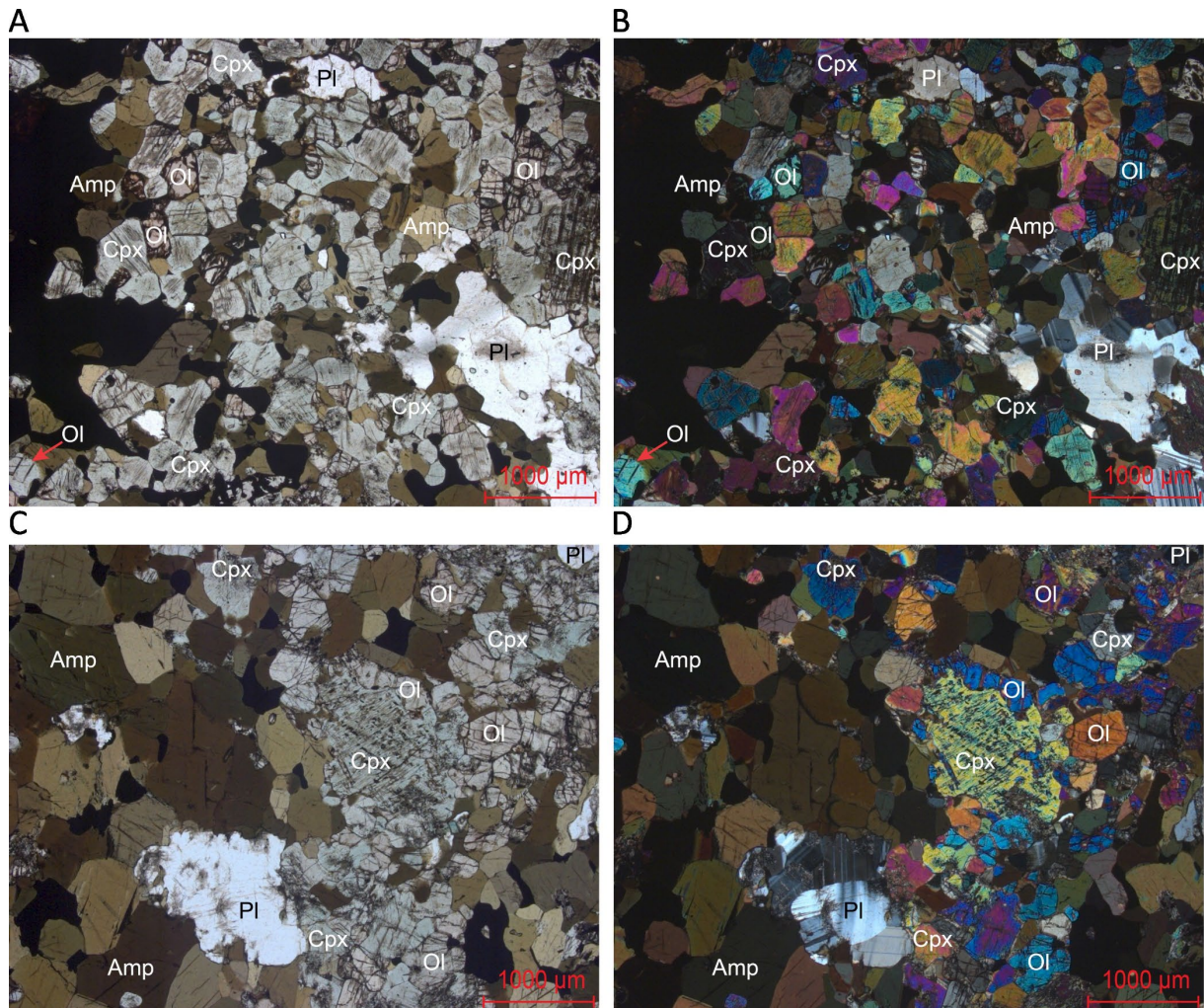


Figure 66. A. and B. Clinopyroxene, olivine, and hornblende mostly occurring as equal-sized crystals, except for one large clinopyroxene crystal with opaque exsolutions to the right. C. and D. Plagioclase is anhedral with several grain triple junctions at 120 degrees in a glomerocryst. Note olivine as interstitial grain next to the upper edge of the large clinopyroxene crystal. Sample HRE220049A (6848053/566141). Left in ppl and right in xpl. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Buberget

The cumulate rock of sample HRE220055A is well-preserved, displays a clearly igneous fabric or layering, and lots of fractures with minor alteration. Clinopyroxene is subhedral to anhedral with large grains and interstitial crystals. Clinopyroxene has grain triple junctions at 120 degrees and large grains display twinning as well as exsolution of opaque minerals (fig. 67). Hornblende occurs as large grains to interstitial, subhedral-anhedral in shape, often associated with Fe-Ti-oxide minerals. Olivine is subhedral to anhedral with small and large grains, some intergrown with clinopyroxene. Plagioclase has grain triple junctions at 120 degrees, both large and small grains are subhedral to anhedral. The minerals in the sample display a granoblastic texture.

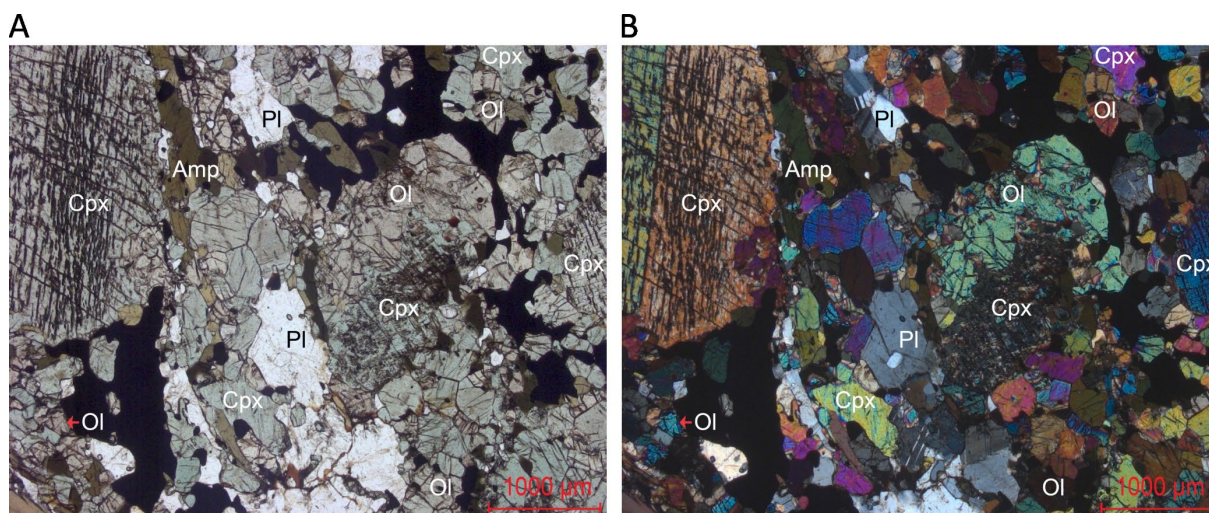


Figure 67. A. and B. Clinopyroxene has granoblastic texture with grain triple junction at 120 degrees just to the left of the centre of the image. The large clinopyroxene to the left displays twinning and exsolution of opaque minerals. Olivine is intergrown with clinopyroxene. Note close relation between amphibole and Fe-Ti-oxides. Sample HRE220055A (6848955/566299). Left in ppl and right in xpl. Photo: Dick Claeson.

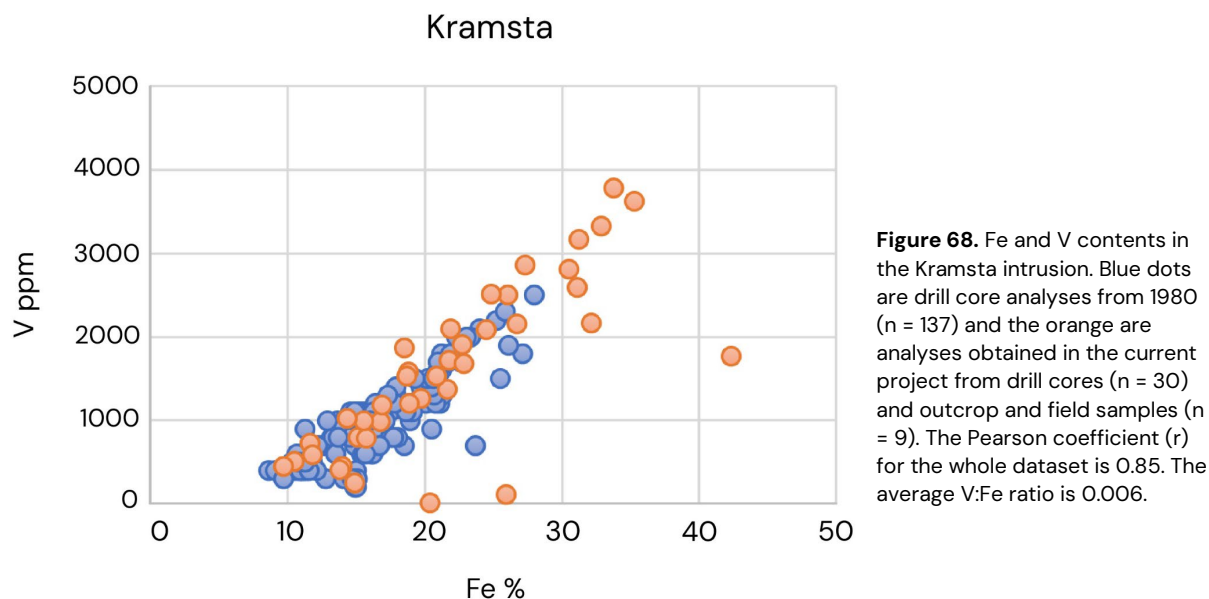
Geochemical data from the Järvsö area

Previous geochemical analyses of drill cores from Kramsta

SGU's database contains information from about 44 drillholes from the Kramsta intrusion that were drilled by AB Statsgruvor and LKAB Prospektering during the late 1970s to early 1980s. Drill cores from a subset of these are physically stored at Malå of which 13 drill cores have been sampled in this project. The sampling included 30 sections for lithogeochemical analysis, 35 for petrophysical analysis and 23 for thin sections. Where possible, the geochemical and petrophysical samples were taken from adjoining core intervals.

Previous geochemical analyses of drill cores from the Kramsta intrusion were performed at LKAB Malmberget in 1980. These analyses only included the elements Fe, Ti and V. Analogue data from eight cores sectioned into 50 cm intervals ($n = 137$) are available in the SGU archive and have been digitised in the current project. The linear relationship between Fe and V in these analyses is very good (fig. 68) with a Pearson coefficient (r) of 0.86. When the new analyses of gabbroids ($n = 39$) obtained in the current project are included, the Pearson coefficient is 0.85 for the whole dataset of 176 samples.

The strong linear correlation between Fe and V indicates that the V:Fe ratio, is relatively constant in most of the samples (average V:Fe ratio for the whole sample suite is 0.006).



New geochemical data

A total of 39 samples (30 drill core samples and nine field samples) from the Kramsta intrusion and two samples each from the nearby Järvsö-Gruvberget, Storsveden, Gartsbogruvan and Buberget deposits were collected and analysed in the current project. Five new analyses of gabbroic rocks have been obtained from the cores K-D-08 and K-D-09. These analyses are compared to the older vanadium analyses from 1980 in figure 69. The older analyses show slightly lower absolute values than the new analyses, which is possibly an effect of the longer section length used in the older analyses. Therefore, we conclude that the general variations downhole most probably are correct and reflects the layered character in terms of V-content with peaks in most of the cores occurring at c. 40-60 metres depth, although shallower in core K-D-08 (fig. 69).

Multielement plots of selected major element oxides and trace elements are shown in figures 70 and 71. The total sample suite ($n = 47$) comprises a broad spectrum of compositional variations from unmineralised gabbro to strongly mineralised ore with ranges of selected oxides (in %) as follows: SiO_2 (20.10–48.70), Al_2O_3 (5.75–15.15), Fe_2O_3 (13.85–60.50, average 30.77), CaO (2.18–11.65), Na_2O (0.70–2.80), MgO (2.07–8.25), K_2O (0.08–1.22), P_2O_5 (0.03–1.44) and TiO_2 (1.18–10.05, average 4.82).

Vanadium varies from 17 to 3 780 ppm with an average of 1 594 ppm. 31 samples have more than 1 000 ppm V. The concentrations of Ni, Co, and Cr are low; (Ni from <1 to 219 ppm, average 63 ppm), (Co from 27 to 222 ppm, average 99 ppm), (Cr from <5 to 273 ppm, average 46 ppm). Cu varies between 7 and 459 ppm with an average of 114 ppm.

Scandium contents are in the range of 18–72 ppm, with average 51 ppm. Yttrium varies between 16 and 67 ppm, with an average of 28 ppm. The ΣREE (total REE contents, not including yttrium and scandium) vary from 33 to 215 ppm. The highest ΣREE value are from a section in drill core K-D-26 containing anorthositic layers, which also contains the lowest V measured (17 ppm).

Among the major element oxides in the Kramsta intrusion dataset, excluding the eight samples from Järvsö-Grubberget, Storsveden, Gartsbogruvan, and Buberget, there are very strong negative linear correlations between SiO_2 and Fe_2O_3 ($r = -0.98$) and TiO_2 ($r = -0.88$). Strong positive correlations exist for Al_2O_3 , ($r = 0.91$), Na_2O ($r = 0.89$), and CaO ($r = 0.84$) (Table 8).

Vanadium shows strong to moderate positive correlations with Fe_2O_3 ($r = 0.78$), TiO_2 ($r = 0.80$), and Co ($r = 0.67$). Strong negative correlations are observed for SiO_2 ($r = -0.85$), Al_2O_3 ($r = -0.73$), and Na_2O ($r = -0.77$).

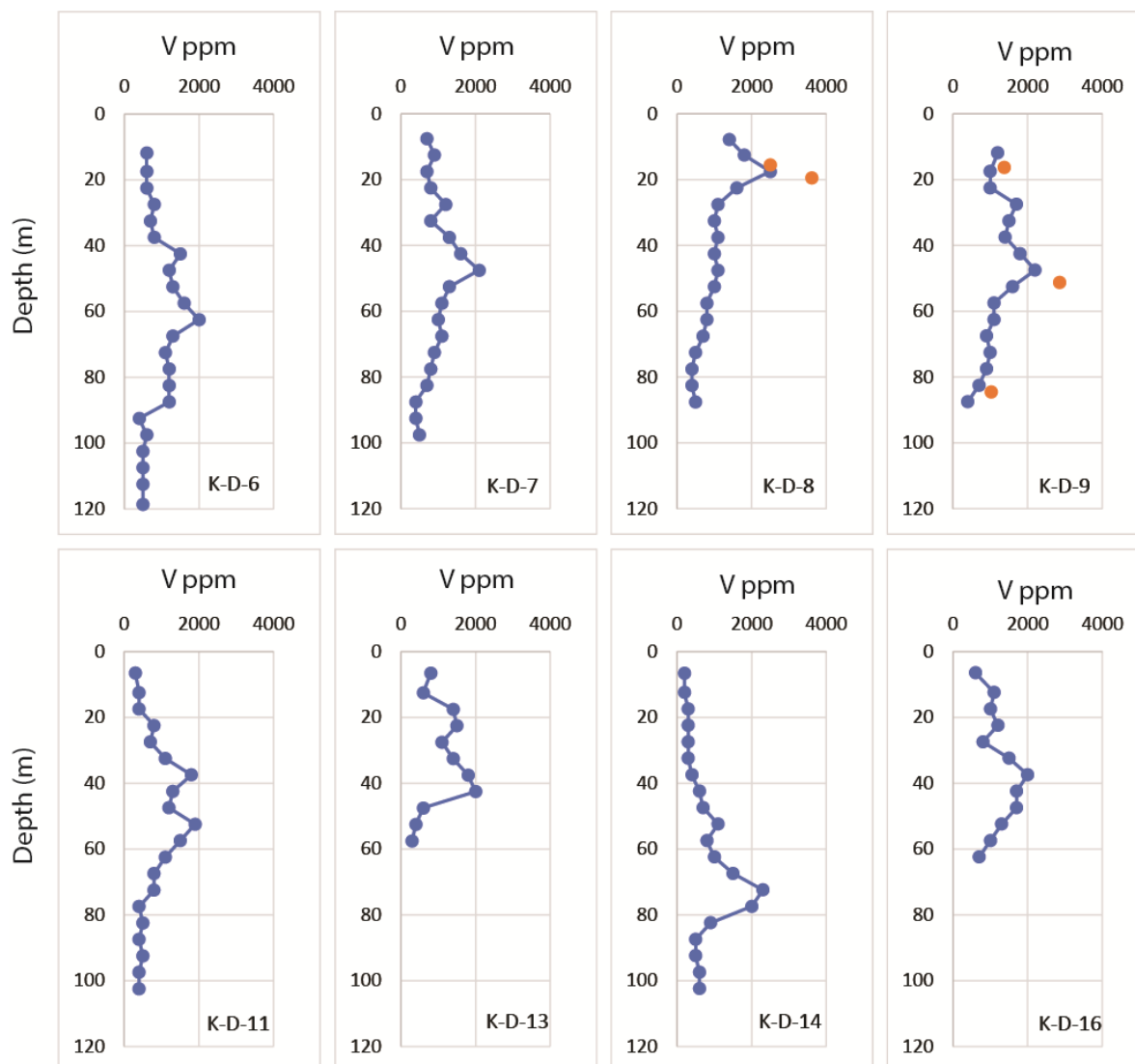


Figure 69. Variations in V contents with depth in Kramsta drill cores. Blue dots are drill core analyses from 1980 and the orange are analyses obtained in the current project. Note that the typical section length for the historic analyses is on average c. 5 m compared to c. 1 m for the current project.

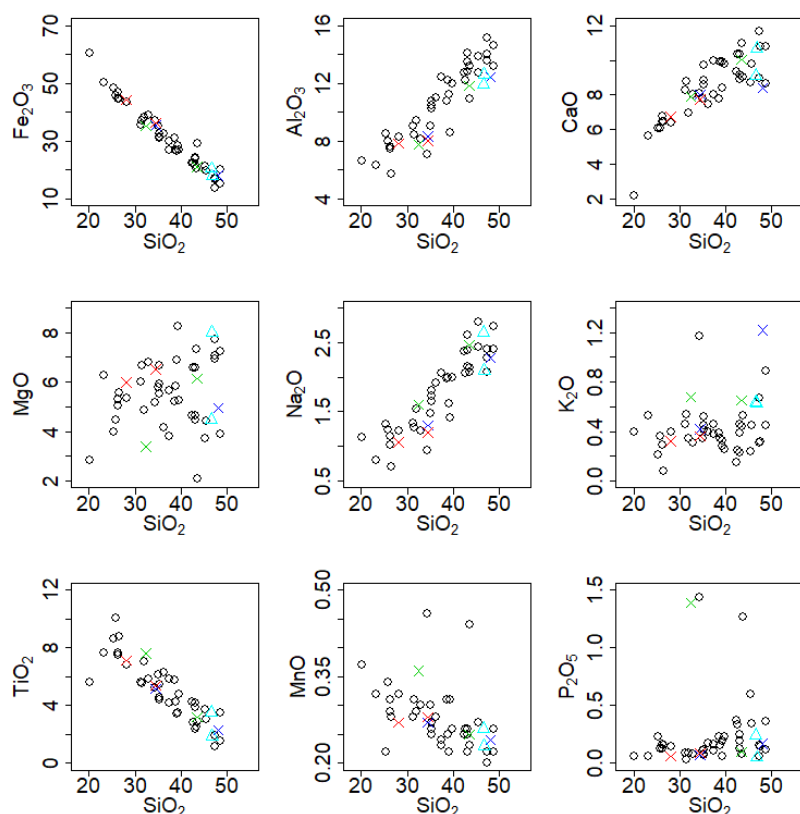


Figure 70. Harker diagrams for major elements vs. SiO_2 in Kramsta drill core and field samples (black circles). Analyses from Järvsö-Gruvberget (blue 'X'), Storsveden (red 'X'), Gartsbogruvan (green 'X'), and Buberget (cyan triangles) are also shown. All concentrations are in %.

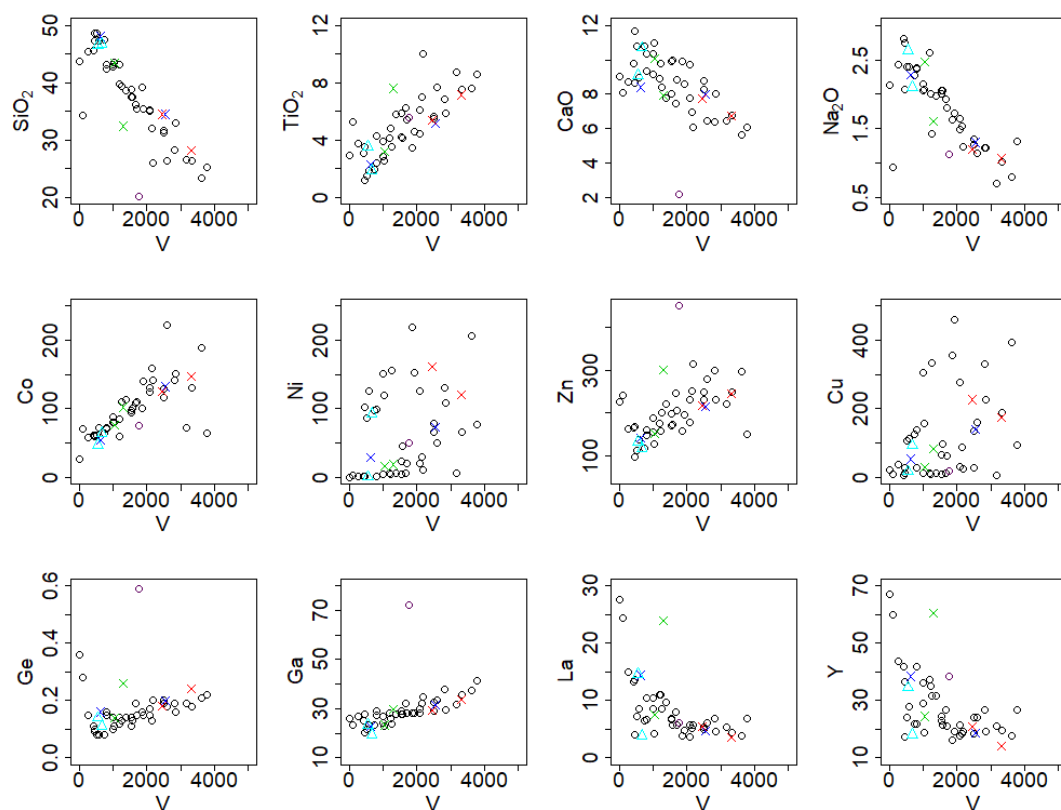


Figure 71. Harker diagrams for vanadium (ppm) vs. selected major and trace elements in Kramsta drill cores and outcrop samples (black circles). Analyses from Järvsö-Gruvberget (blue 'X'), Storsveden (red 'X'), Gartsbogruvan (green 'X') and Buberget (cyan triangles) are also shown. The sample HRE220042A is represented by a purple circle. Major-element-oxide concentrations are in %. Trace elements are reported as ppm.

Table 8. Pearson correlation matrix for selected elements from the Kramsta intrusion (n = 39). The eight samples from Järvsö-Grubberget, Gartsbogravan and Buberget were excluded in the calculations.

	V	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	Ce	Co	Cu	Ga	Ge	In	La	Ni	Y	Zn
V	1																
SiO₂	-0,85	1															
TiO₂	0,80	-0,88	1														
Al₂O₃	-0,73	0,91	-0,81	1													
Fe₂O₃	0,78	-0,98	0,86	-0,92	1												
CaO	-0,60	0,84	-0,78	0,80	-0,91	1											
Na₂O	-0,77	0,89	-0,74	0,95	-0,86	0,67	1										
Ce	-0,59	0,33	-0,23	0,12	-0,19	0,08	0,29	1									
Co	0,67	-0,62	0,59	-0,56	0,54	-0,42	-0,58	-0,51									
Cu	0,37	-0,19	-0,02	-0,23	0,14	0,01	-0,31	-0,39	0,49	1							
Ga	0,49	-0,73	0,52	-0,58	0,79	-0,85	-0,48	-0,20	0,22	-0,01	1						
Ge	0,18	-0,58	0,33	-0,57	0,68	-0,70	-0,47	0,26	-0,02	-0,11	0,80	1					
In	0,36	-0,62	0,51	-0,68	0,69	-0,62	-0,56	0,29	0,35	0,23	0,49	0,59	1				
La	-0,61	0,34	-0,23	0,13	-0,21	0,09	0,28	0,99	-0,52	-0,39	-0,22	0,24	0,28	1			
Ni	0,28	-0,08	-0,20	-0,09	0,02	0,12	-0,24	-0,48	0,31	0,89	-0,02	-0,11	0,03	-0,48	1		
Y	-0,58	0,27	-0,22	0,09	-0,12	-0,03	0,27	0,96	-0,54	-0,42	-0,03	0,38	0,30	0,95	-0,50	1	
Zn	0,47	-0,80	0,66	-0,78	0,86	-0,88	-0,66	-0,03	0,50	0,02	0,80	0,76	0,65	-0,05	-0,10	0,06	1

The samples plot in the tholeiite field in the AFM-diagram with strong Fe-enrichment (fig. 72).

The Kramsta samples show irregular trace-element patterns in a primitive mantle normalised diagram (fig. 73). Notable features are the strong negative Th and Nb anomalies (except one sample that shows a positive Nb anomaly) and positive Pb and Ti anomalies (except one sample that has a negative Ti anomaly).

Chondrite normalised REE patterns from Kramsta are generally sub-parallel, flat to slightly LREE enriched (fig. 74) with $(La/Yb)_N$ in the range 0.63–3.01. They have $(La/Sm)_N$ values between 1.03 and 1.75 indicating slight to moderate fractionation between the LREEs. $(Gd/Yb)_N$ is in the interval (0.55–1.86) and $(Dy/Yb)_N$ ranges between (0.57–1.42) indicating some degree of fractionation between the HREEs.

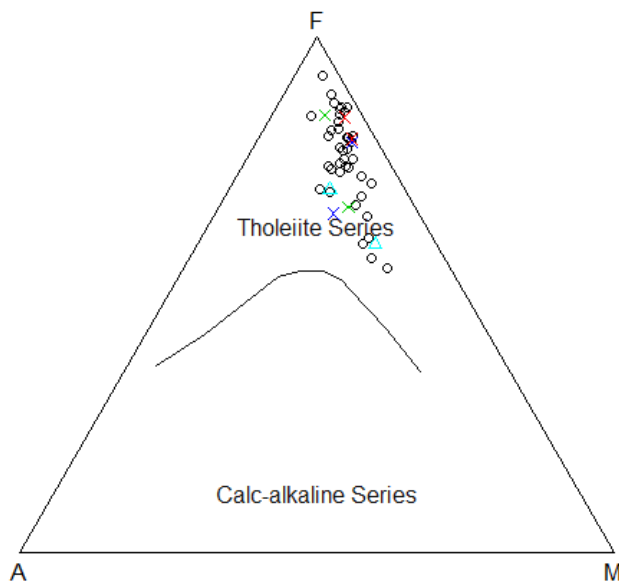


Figure 72. AFM-diagram (Irvine & Baragar 1971) with samples from Kramsta (black circles), Järvsö–Gruvberget (blue 'X'), Storsveden (red 'X'), Gartsbogravan (green 'X'), and Buberget (cyan triangles).

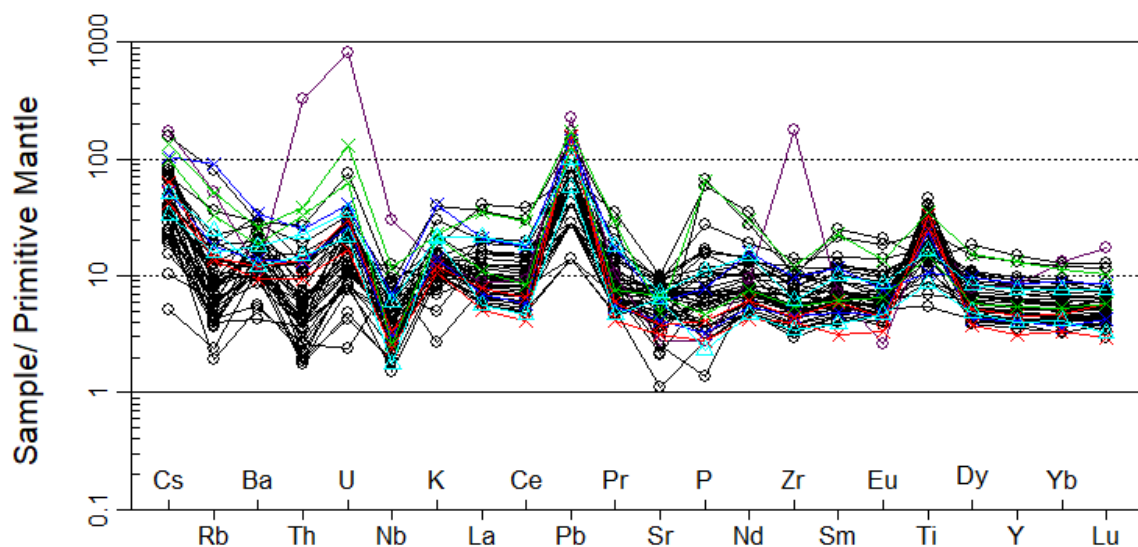


Figure 73. Primitive mantle normalised diagram for samples from Kramsta (black circles), Järvsö–Gruvberget (blue 'X'), Storsveden (red 'X'), Gartsbogravan (green 'X'), and Buberget (cyan triangles). Note the extreme enrichment of Th, U, and Zr for sample HRE220042A (purple circle). Normalising values from Sun & McDonough (1989).

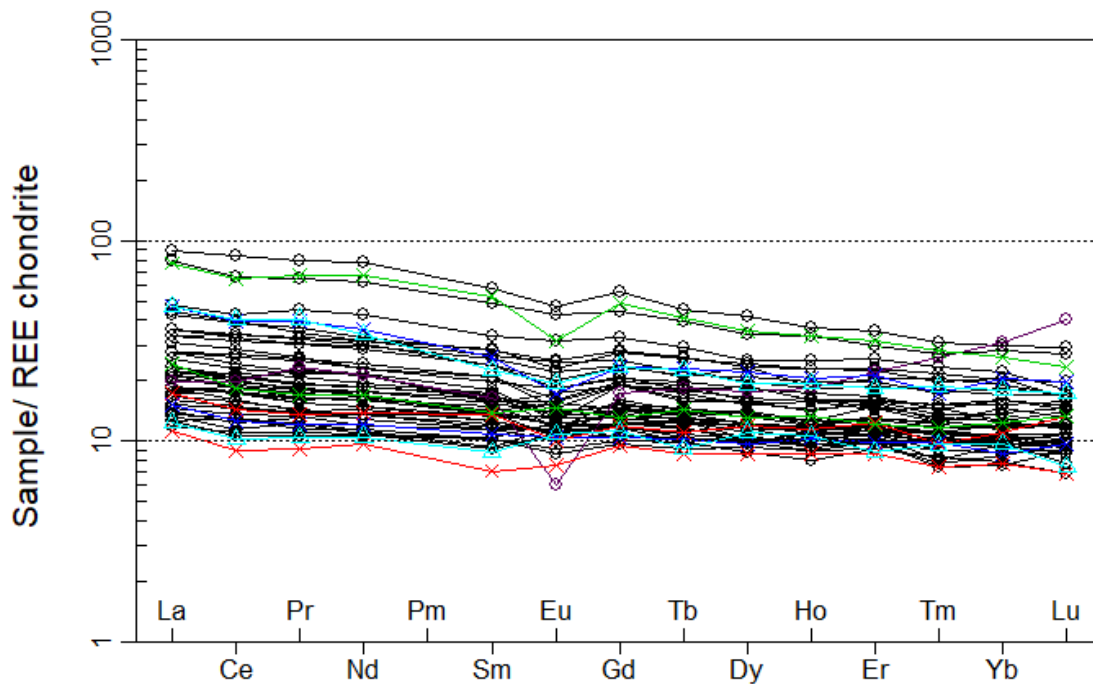


Figure 74. Chondrite normalised REE diagram for samples from Kramsta (black circles), Järvsö-Grubberget (blue 'X'), Storsveden (red 'X'), Gartsbogruvan (green 'X'), and Buberget (cyan triangles). The sample suite is characterised by flat patterns with low to moderate $(La/Yb)_N$ ratios. Note the “anomalous” pattern with $(La/Yb)_N = 0.63$ displayed by sample HRE220042A (purple circles). Chondrite values are from Boynton (1984).

Overall, the Kramsta samples have negative Eu anomalies ($Eu/Eu^* = (Eu)_N / [(Sm)_N \times (Gd)_N]^{0.5}$) with 33 samples in the range 0.36–0.97, suggesting plagioclase fractionation. Six samples have positive Eu/Eu^* in the interval 1.01–1.21.

The 8 samples from Järvsö-Grubberget, Storsveden, Gartsbogruvan, and Buberget have overall similar primitive mantle normalised patterns as the main Kramsta intrusion (fig. 73), although the negative Th anomalies that characterises the Kramsta dataset are not observed in these. The chondrite normalised REE patterns are rather flat with $(La/Yb)_N$ in the range 1.27–2.92, broadly similar to those of the Kramsta samples (fig. 74).

Most samples plot in the field of destructive plate-margin volcanic basalts (CAB and IAT) in the triangular Th-Hf-Nb diagram, although some samples plot close to the border with, and even within, the N-MORB and E-MORB-WPT fields (fig. 75). The same general picture of a volcanic arc signature, possibly with a slight MORB component is evident in the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb and diagrams (fig. 76A and 76B).

We emphasise that caution must be taken when interpreting these diagrams, because wall rock interaction may be important in mafic intrusive rocks, and contamination at some stage in the magma evolution cannot be ruled out. Furthermore, since the analysed rocks are cumulate rocks, their compositions do not represent the composition of the primary magma. However, the overall geochemical characteristics, with the ubiquitous negative Nb and positive Pb anomalies (fig. 73) and the key incompatible trace-element ratios which will not change significantly during fractionation, show rather consistent patterns, suggest formation in a subduction zone environment i.e., in a magmatic arc setting along an active continental margin.

Negative Nb anomalies of subduction-zone magmas (Pearce 1982) are generally attributed to relative mobility of trace elements in the presence of aqueous fluids released from the subducted slab. A characteristic feature of primary arc-magmas is the low Ti-content. The ubiquitous positive Ti-anomaly that is observed in the Kramsta sample suite, including the samples from Järvsö–Gruvberget, Storsveden, Gartsbogruvan and Buberget, is most probably related to the accumulation of titanomagnetite.

The relatively flat chondrite-normalised REE-patterns indicate relatively low degree of fractionation between the light and heavy REEs and suggest relatively high-degree of partial melting. However, the sub-parallel REE patterns reflects that the intrusion has undergone fractional crystallisation at one or multiple stages in the magmatic evolution.

Sample HRE220042A, which is extremely enriched in certain incompatible elements compared to the rest of the sample suite, is discussed in more detail in section *Immiscibility of Fe-rich melt in the mafic intrusions of the Ljusdal batholith, an example from the Kramsta intrusion*.

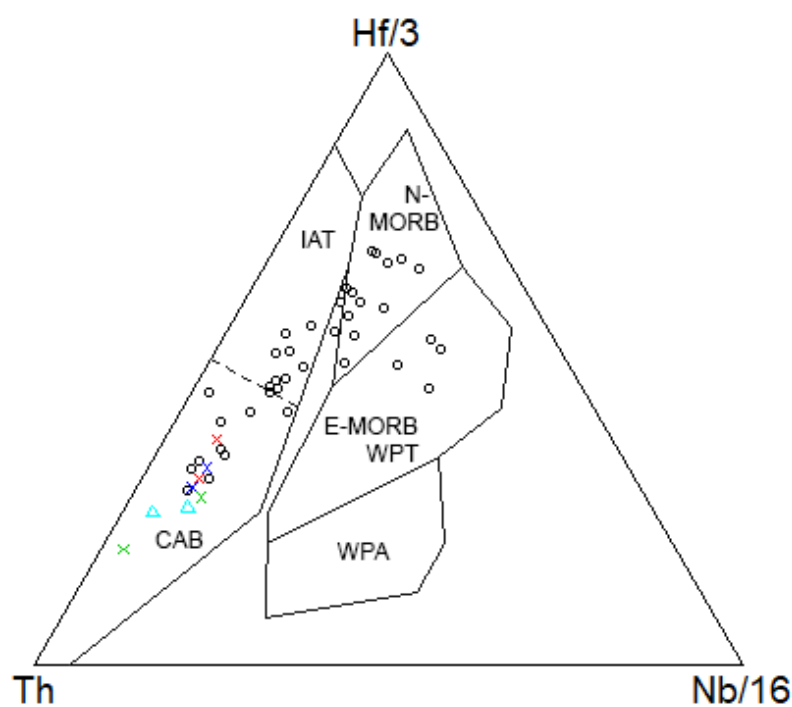


Figure 75. Plotting of samples from Kramsta (black circles), Järvsö–Gruvberget (blue 'X'), Storsveden (red 'X'), Gartsbogruvan (green 'X'), and Buberget (cyan triangles) in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

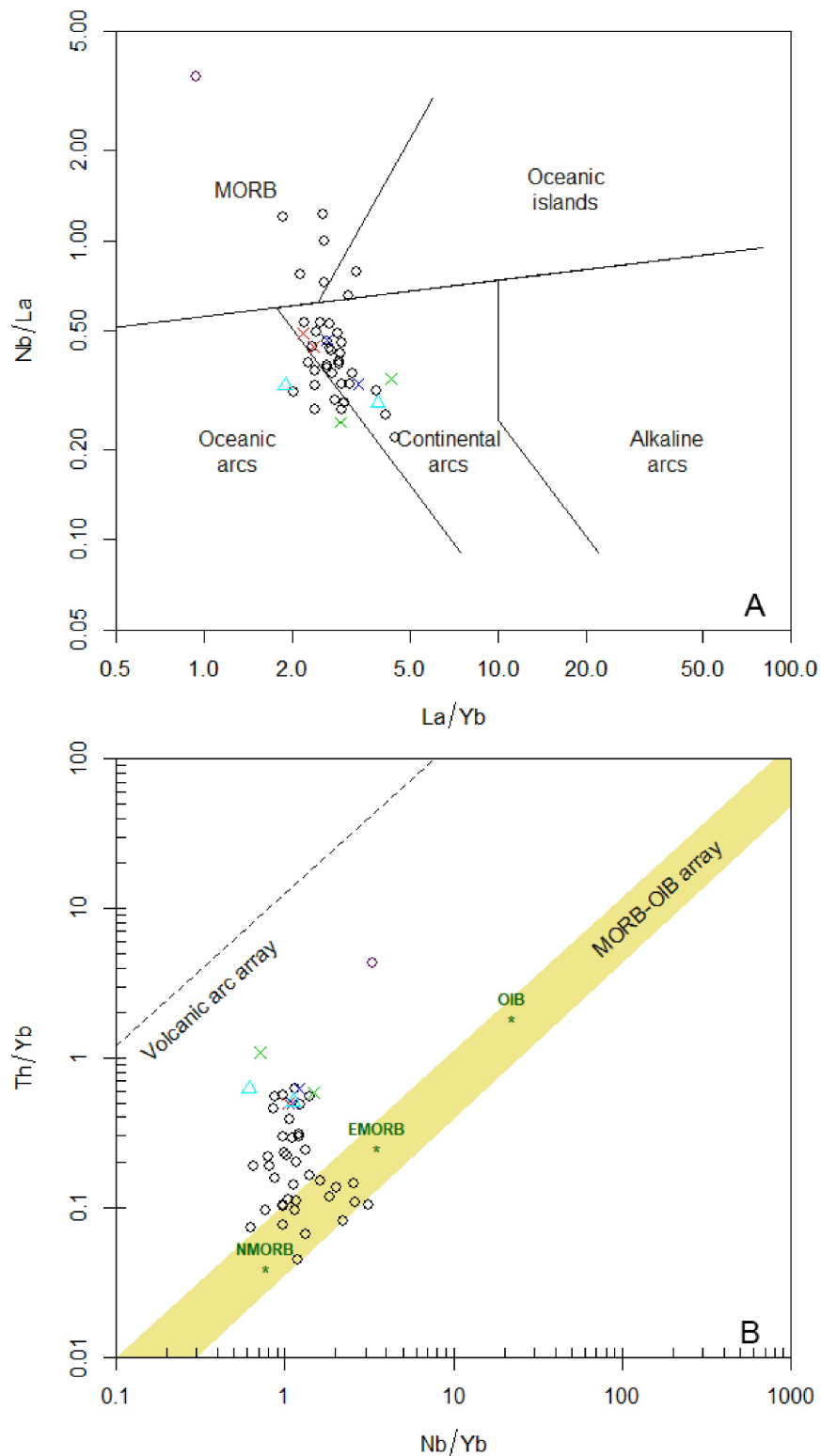


Figure 76. Plotting of samples from Kramsta (black circles), Järvsö-Gruvberget (blue 'X'), Storsveden (red 'X'), Gartsbogravan (green 'X'), and Buberget (cyan triangles) in diagrams for geotectonic discrimination. The purple circle is sample HRE220042A. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

The area southwest of the Järvsö area

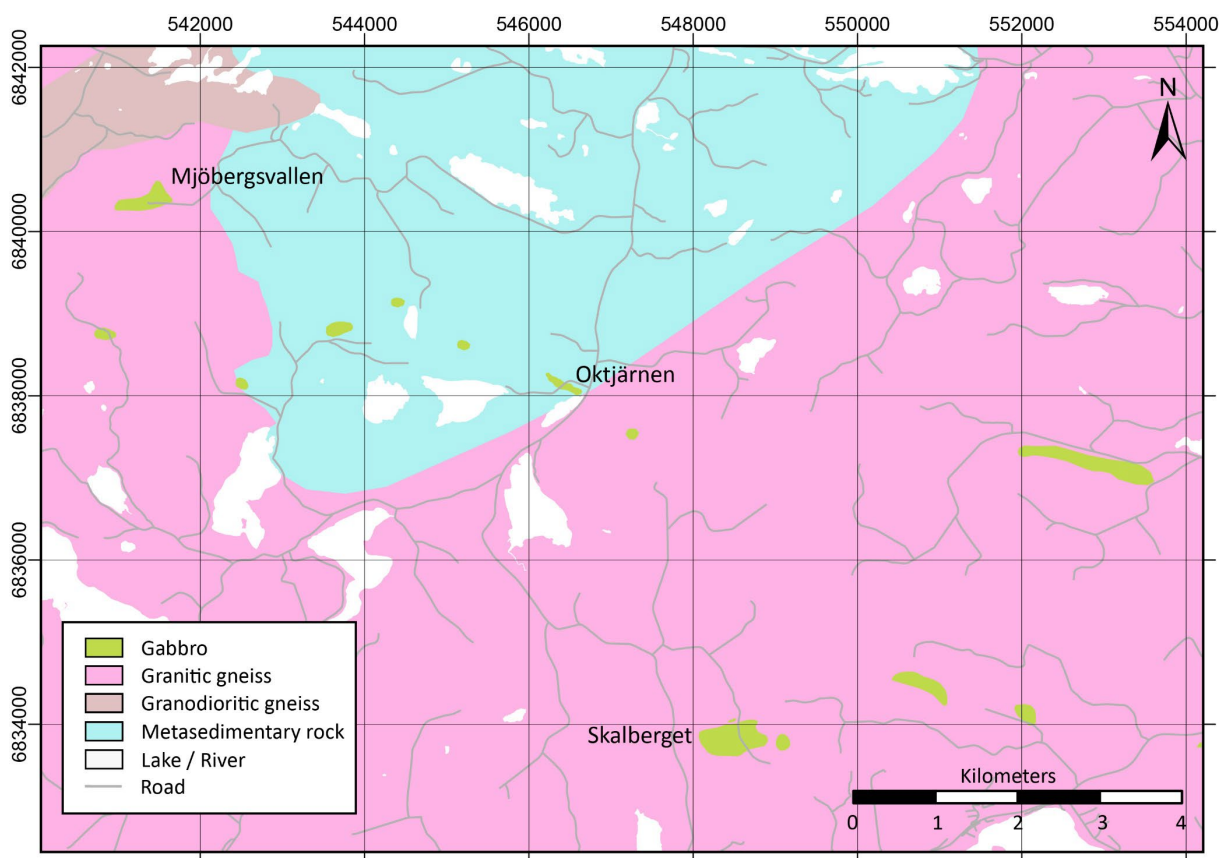


Figure 77. Bedrock geology map showing the area southwest of the Järvsö area. The names of the mafic intrusions referred to in the report are shown as black text.

In this section we discuss three intrusions which are located approximately 10–15 km to the west of Järvsö, namely the Skälberget, Oktjärnen, and Mjöbergsvallen intrusions (fig. 77). Efforts were made to collect additional geological, geochemical, and geophysical data from these intrusions, however, due to low levels of exposure, it was only possible to collect one sample from both Oktjärnen and Mjöbergsvallen.

Prior to this project, no ground-based geophysical data were available above the intrusions in the area southwest of Järvsö. Hence, during 2023 ground based magnetic measurements were performed over the Skälberget and Oktjärnen intrusions. These intrusions were prioritised due to the relative size and amplitude of the associated anomalies in the airborne magnetic data. Both surveys were performed with a nominal line spacing of about 40 m and covered areas of about 0.4 km² and 0.3 km² for the Skälberget and Oktjärnen intrusions, respectively.

Skalberget

Ground-based geophysical measurements

Figure 78 shows a map of the ground-based magnetic field measurements collected over the Skalberget intrusion as well as an updated map of the bedrock geology. Based on these data the intrusion appears to be some 700 m long and 400 m wide, slightly elongated in an approximately east–west direction. The strength of the magnetic field is notably higher in the western part of the intrusion, close to the interpreted contact between the intrusion and the surrounding granitic rocks. In some places the total magnetic field reaches a maximum of about 23 000 nT above the background value. Furthermore, the magnetic field exceeds 10 000 nT above the background value over an area of more than 1 000 m². Hence, the anomaly from the Skalberget intrusion is one of the stronger anomalies of those investigated in this study. In some places it is possible to interpret a weak trend in the magnetic anomalies, which lie approximately parallel to the edges of the intrusion. However, in general, the magnetic anomalies in the western part of the intrusion appear to be somewhat chaotic and do not have a clear lineation.

The frequency of the magnetic anomalies appears to be higher in the western part, when compared to the eastern part. One possible explanation for this could be that while the western part of the intrusion lies at the surface, the eastern part may lie at a greater depth, below the surrounding granitic rocks. This is consistent with the model from the unconstrained inversion, where the high magnetic susceptibilities observed in the western part of the intrusion appear to dip gently towards the east (see fig. 79). However, another possible explanation could be that the eastern part has a lower concentration of magnetic minerals.

Figure 79 shows the average magnetic susceptibility in the upper 75 m of the model from the unconstrained inversion of the ground-based magnetic data. Here the highest magnetic susceptibilities are located in the western part of the intrusion, beneath the strong magnetic anomalies.

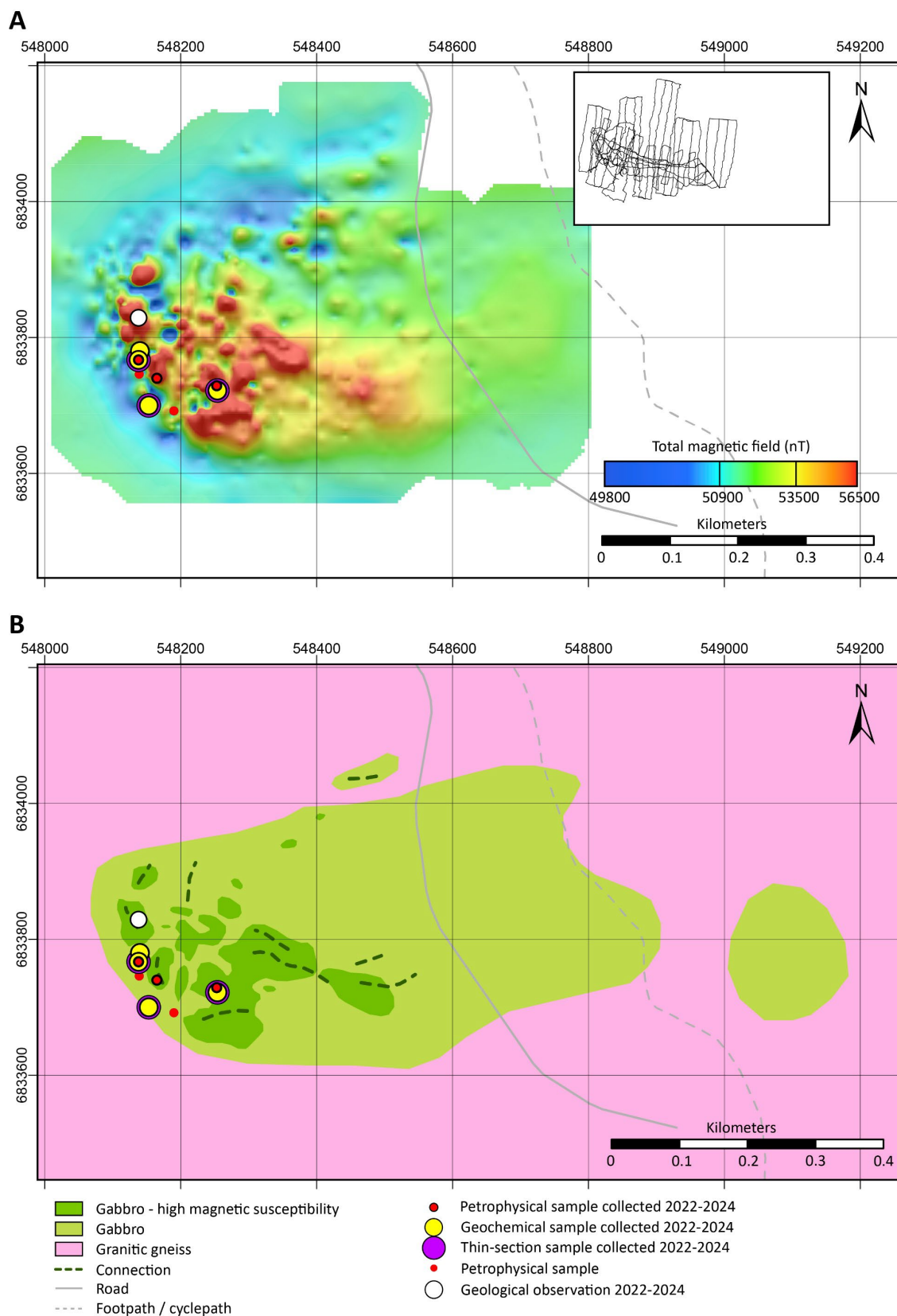


Figure 78. A. Map of the total magnetic field over the Skalberget intrusion, made using measurements collected as part of this study. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Skalberget intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of the available geological observations and samples are shown as different coloured dots in both A and B.

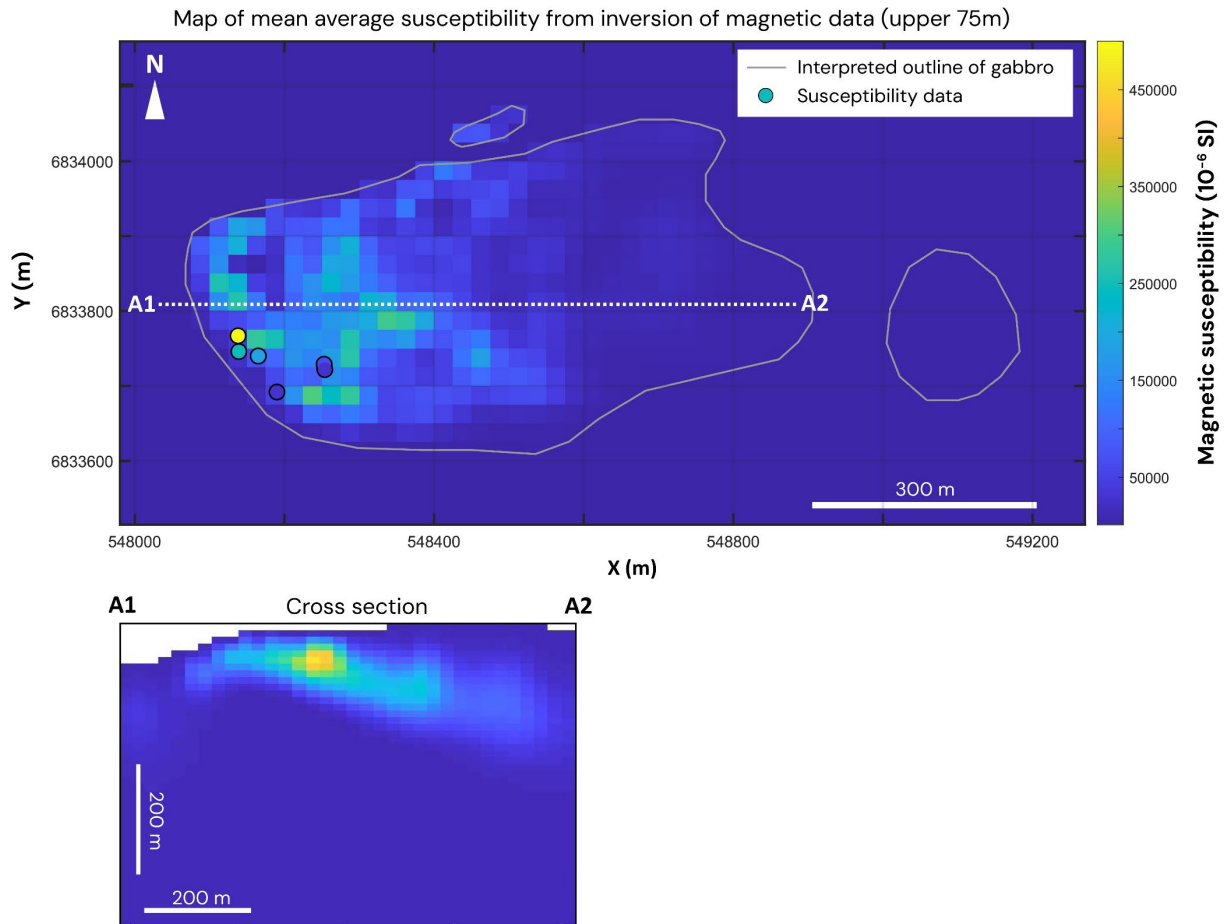


Figure 79. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Skalberget intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

Geological observations

Outcrops at Skalberget are generally rare, except at the western slope of Skalberget where a gabbroid was observed in several outcrops. Generally, medium- to coarse-grained gabbro (fig. 80), locally displaying modal layering, is most common. Occasional dm-sized magnetite aggregates can be found (fig. 81) and in places very rich vanadiniferous magnetite mineralisation occurs (fig. 82). Five outcrops comprising gabbroic rocks, including strongly mineralised material, have been sampled.



Figure 80. Coarse-grained gabbroid at Skalberget (6833700/548153). Photo Helge Reginiussen.



Figure 81. Magnetite-rich aggregate in medium- to coarse-grained gabbroid at Skalberget (6833722/548254). Photo: Helge Reginiussen.



Figure 82. Sample of Fe-Ti-V mineralisation at the western slope of Skalberget (6833767/548138). Analysis returned Fe_2O_3 48.20%, TiO_2 5.69%, and V 3 630 ppm. Photo: Helge Reginiussen.

Description of thin sections – ore minerals

The ore minerals magnetite and ilmenite, with some large interstitial grains of rutile but no sulphide crystals, were identified in sample HRE230039A (fig. 83, see fig. C21 for panorama). The hornblende-rich ultramafic rock has a framework rich in opaque minerals. The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage (fig. 83). Plenty of exsolved ilmenite occur as laths and trellis in magnetite (fig. 83B). Around these laths, trellis are scarce, suggesting that the laths exhausted the adjacent area while exsolving and thus formed prior to the trellis. Ilmenite has exsolved hematite but also contains other minerals that look like darker exsolution trellis, which are feasibly magnetite or ulvöspinel (figs. 83B–C, cf. Haggerty 1991, Tan *et al.* 2016a). Ulvöspinel and pleonaste are probably present among the tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but no proper identification was done.

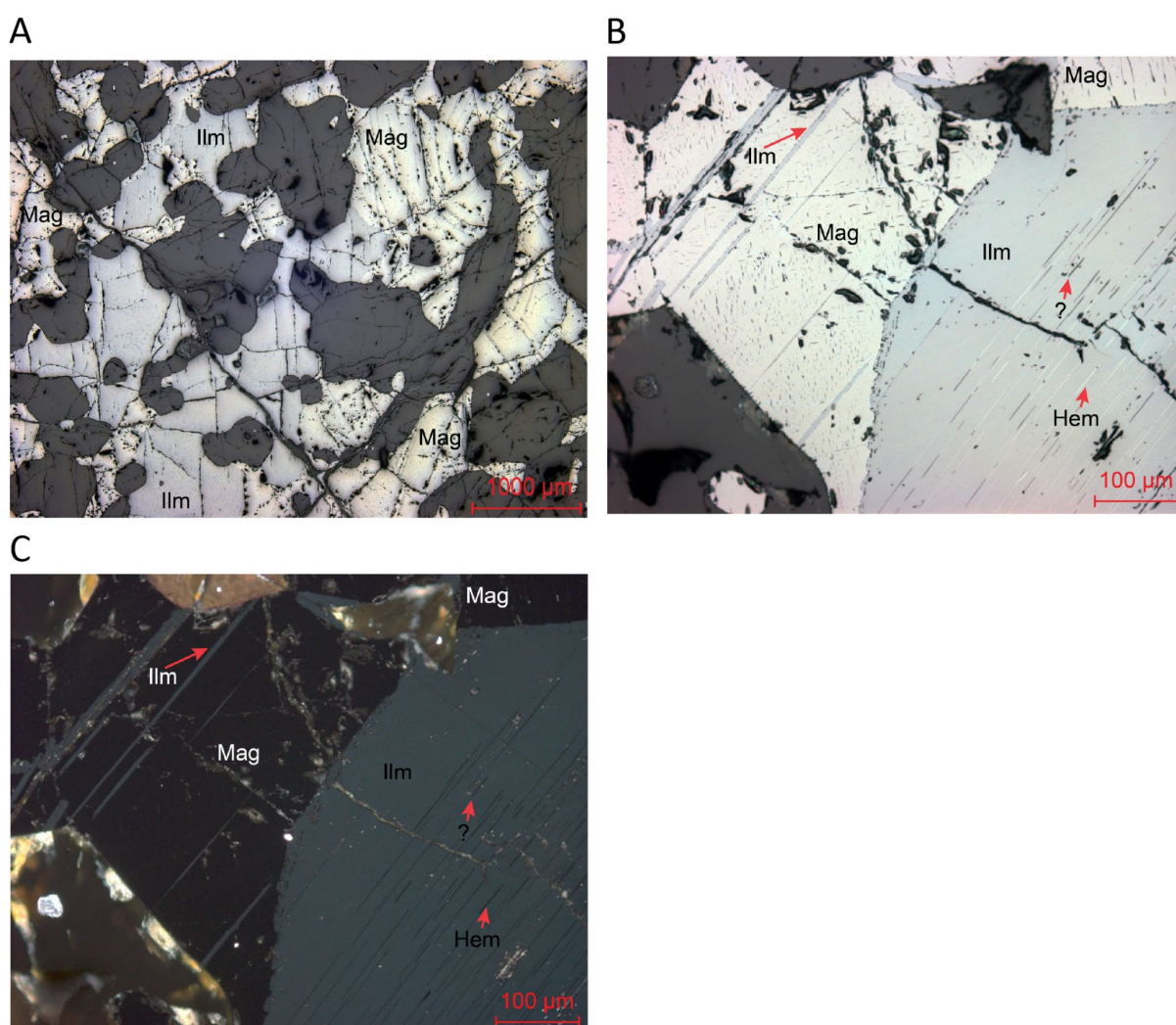


Figure 83. Ore minerals from the Skälberget intrusion, ultramafic mineralised sample HRE230039A (see fig. C21 for panorama). **A.** Overview of relations between magnetite and ilmenite in interstitial opaque framework. Close-up images of **B.** relations between large magnetite and ilmenite grains, note ilmenite as trellis exsolutions along crystallographic planes and laths within magnetite and thin exsolution lamellae in both minerals, **C.** same area as in B. using differential interference contrast (DIC) objective to record exsolved minerals in ilmenite and magnetite. The trellis are not clearly visible due to the orientation of the thin section that is optimised for showing those in the ilmenite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals

Igneous myrmekite, intergrowth between plagioclase and quartz, is developed in a part of the thin section HRE220058A from Skälberget where plagioclase dominates and clinopyroxene is interstitial, biotite occurs mostly as thin lath-shaped crystals, and quartz occurs as grains (fig. 84). Clinopyroxene occurs as large crystals and interstitially, with irregular thin rims of hornblende in contact with plagioclase. Olivine has no reaction relation towards plagioclase or clinopyroxene. Biotite is late-forming, lath-shaped in the cumulate rock and is mostly located between larger grains of plagioclase and clinopyroxene.

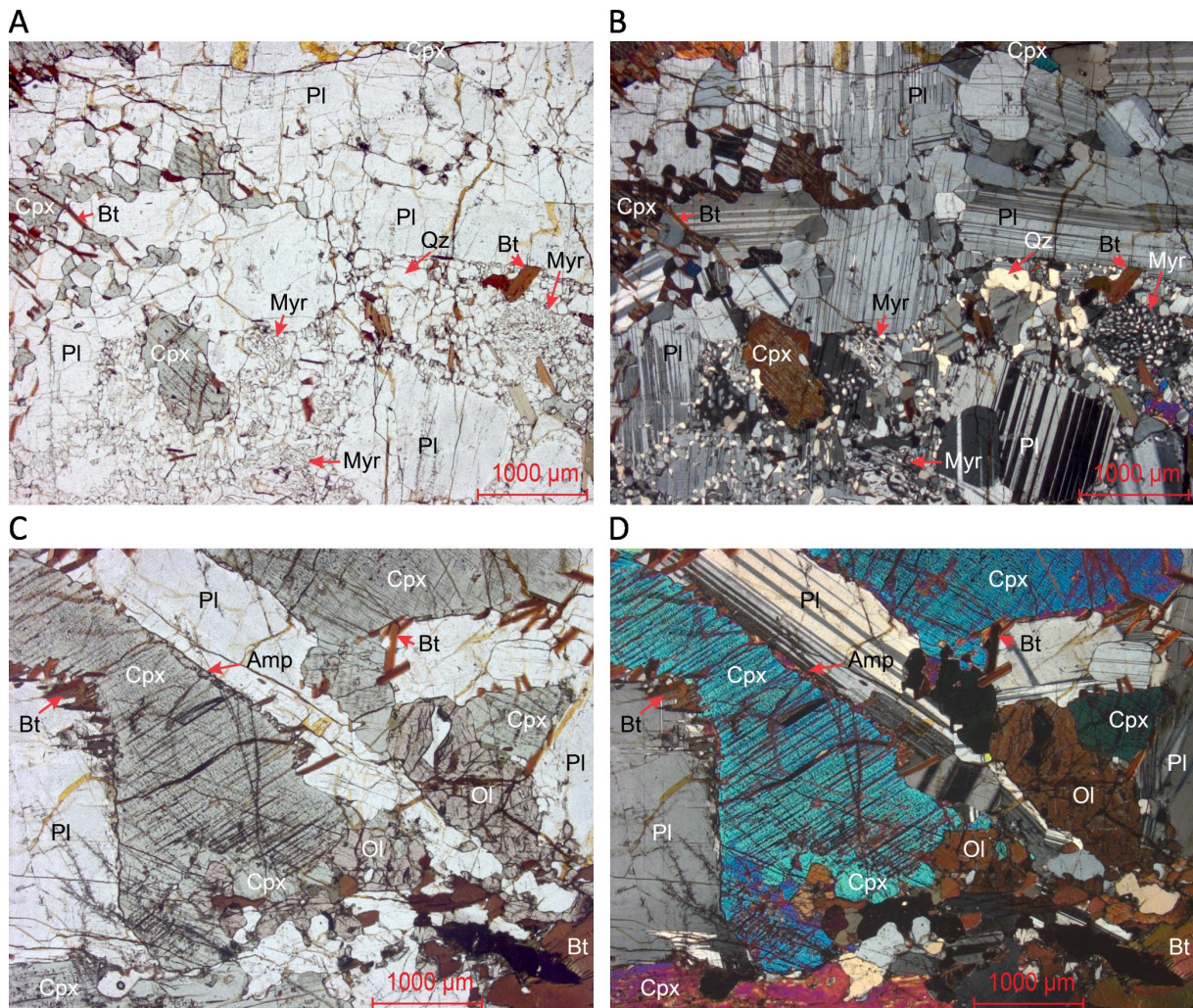


Figure 84. A. and B. Igneous myrmekite (Myr) of intergrown plagioclase and quartz as mm-sized areas at the outer edges of large plagioclase crystals. C. and D. Clinopyroxene occurs as large crystals and interstitially, with irregular thin rims of hornblende in contact with plagioclase. Note small laths of biotite mostly along contacts of clinopyroxene and plagioclase. Sample HRE220058A (6833722/548254). Left in ppl and right in xpl. Photo: Dick Claeson.

Oktjärnen

Ground-based geophysical measurements

A magnetic anomaly at Oktjärnen was identified based on airborne magnetic data. Given the size and shape of the anomaly together with the understanding of geology in the area there is a strong possibility that the anomaly is related to a mafic intrusion. Therefore, ground-based measurements were performed over the anomaly. Samples were taken from a loose boulder in the western part of the survey area consisting of gabbroid rock with relatively low magnetic susceptibility. However, it should be noted that due to the lack of outcrops in the area it was not possible to confirm that the anomaly is related to a mafic intrusion.

Figure 85 shows a map of the ground magnetic measurements collected over the Oktjärnen intrusion as well as an updated interpretation of the bedrock geology. The new magnetic measurements appear to show a 300 m long anomaly with relatively high frequency, striking approximately northwest–southeast. This anomaly is located in the eastern part of the survey area and has a maximum anomaly of some 3 500 nT above the background level. In the central and western part of the survey area there appears to be a secondary anomaly with a lower frequency and lower amplitude, also striking approximately northwest–southeast.

A potential interpretation of these data is shown in the updated bedrock geology map. Here the high frequency anomaly in the eastern part of the survey area is interpreted to be an area where gabbro rocks with a relatively high magnetic susceptibility are present at, or close to the top of the bedrock surface. However, it should be noted that these rocks are not exposed as an outcrop and are interpreted to lie beneath the soil layer. The lower frequency anomaly in the central and western parts of the survey area is in turn interpreted to be due to the presence of gabbro rocks with high magnetic susceptibility at depth. This would infer that the gabbro, interpreted to be close to the surface, potentially continues at depth, dipping to the southwest. Figure 86 shows a map of the average magnetic susceptibility in the upper part of the model, obtained by inverting these data. Note that only the area around where the gabbro is interpreted to be present at the top of the bedrock surface is shown on the map. Here a linear band of higher magnetic susceptibility values can be observed to be associated with anomalous magnetic field values. The 3D susceptibility model obtained from the inversion is consistent with the interpretation. The model includes a high susceptibility feature that dips to the southwest. This feature is shallowest in the eastern part of the survey area, where the gabbro is interpreted to be at or close to the top bedrock surface (fig. 86).

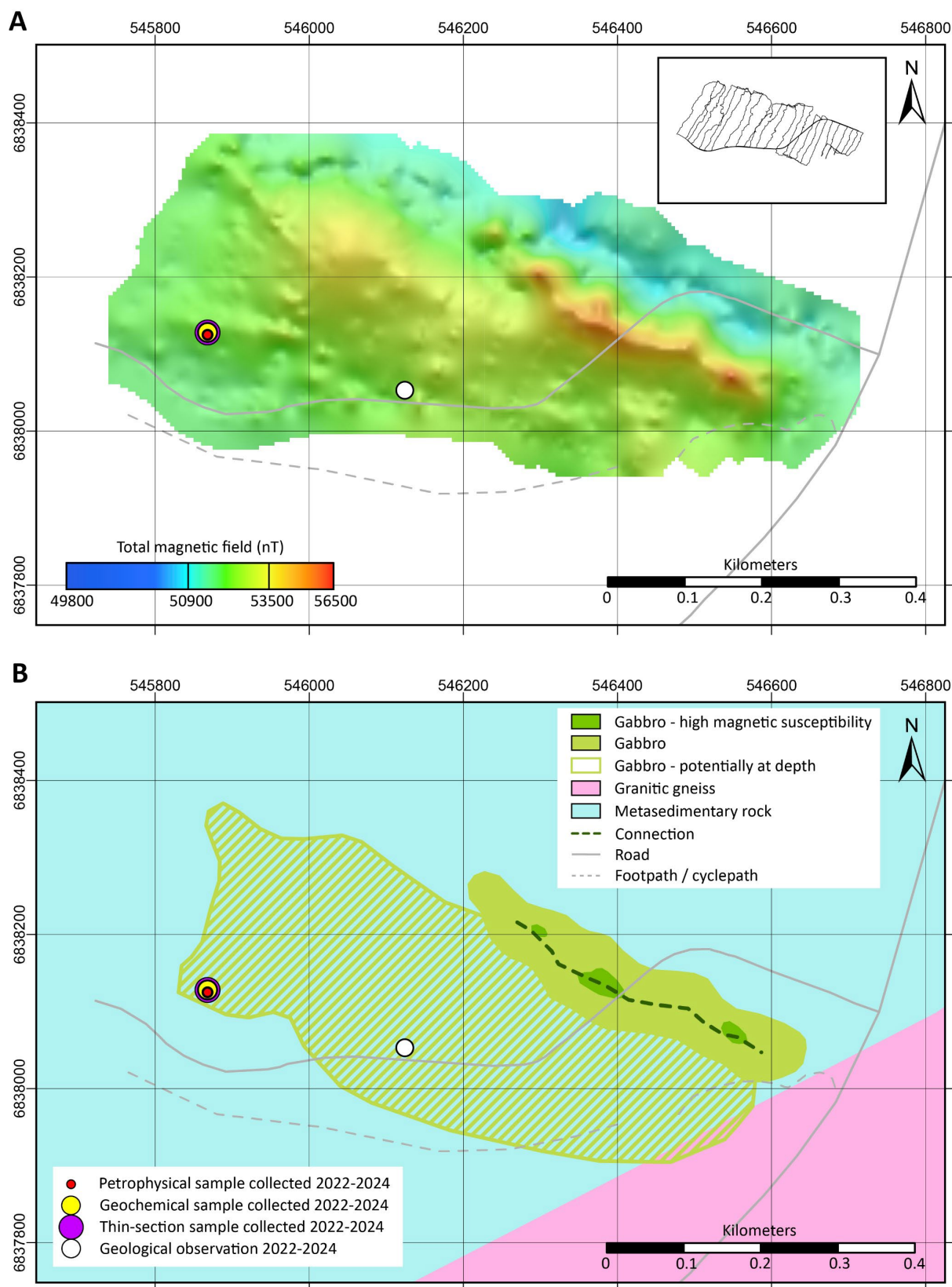


Figure 85. A. Map of the total magnetic field at Oktjärnen, made using measurements collected as part of this study. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology at Oktjärnen, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of geological observations and samples are shown as different coloured dots in both A and B.

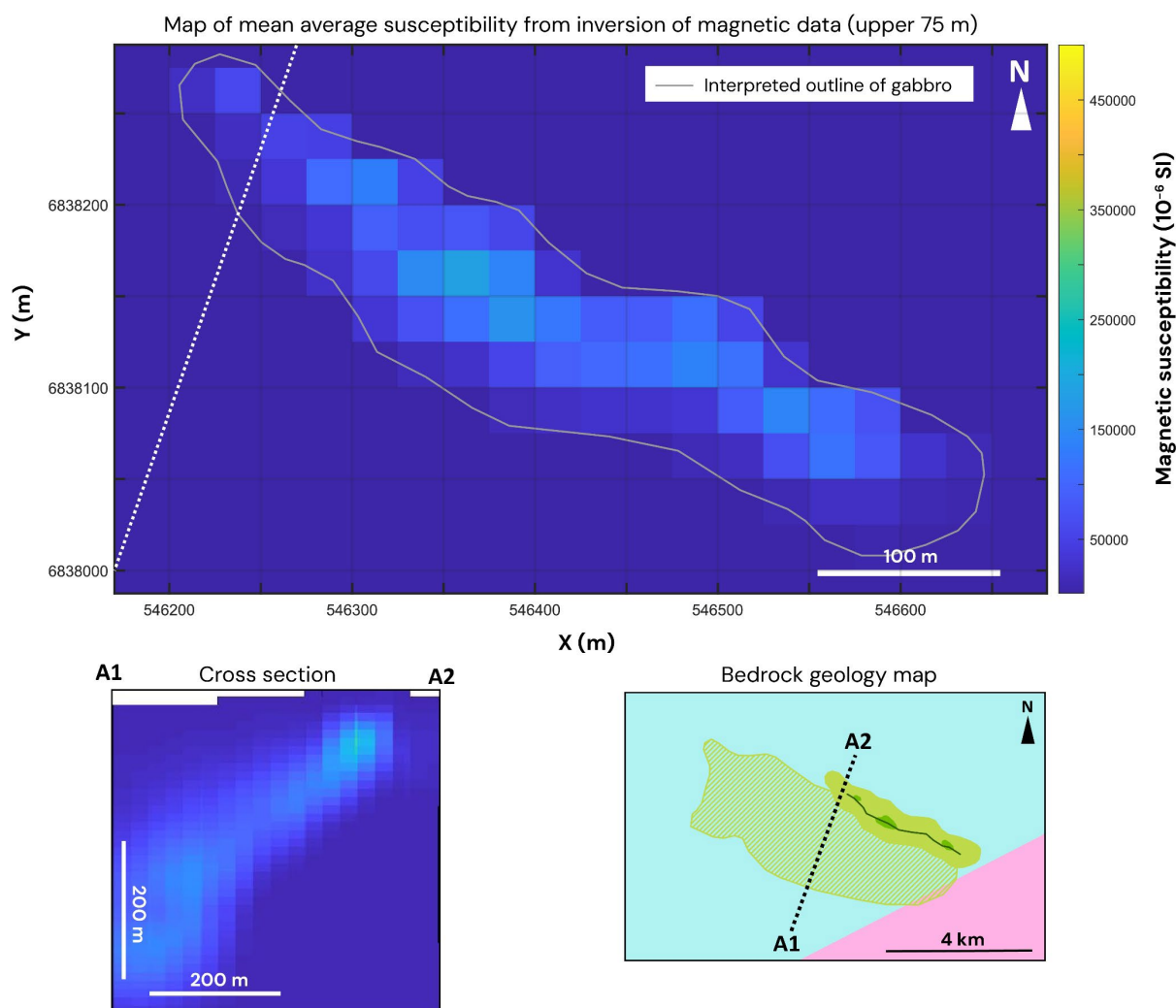


Figure 86. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Oktjärnen intrusion. Note that this map is constrained to the area where an intrusion is interpreted to be present at the top bedrock surface. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown in the bottom left part of the figure. The location of the cross section is denoted on the main map as a dotted white line and on a larger-scale bedrock geological map in the bottom right as a black dotted line. See figure 85 for the legend for the geological map. The map and section are shown with the same magnetic susceptibility colour scale.

Description of thin sections – silicate minerals

Euhedral to anhedral hornblende is the main mafic silicate mineral and occurs as interstitially grown grains. There are several grain triple junctions at 120 degrees among the hornblende displaying a granoblastic texture. Severe sericite-saussurite alteration is present as patches in plagioclase whereas other parts are well-preserved. Two generations of biotite are found, the first has brownish red to light brown pleochroism and the second brownish red to light tan. Chlorite alteration of biotite is present with an anomalous blue interference colour in chlorite, typical of an iron-rich composition (fig. 87). Prehnite occurs as thin, lath-shaped alterations within biotite crystals and has high interference colours. The presence of prehnite together with chlorite indicates that alteration occurred after formation of the igneous minerals. The metamorphic condition is estimated to correspond to the lower end of the prehnite-pumpellyite facies since no epidote is present and are hence typical of low-grade metamorphic conditions between the zeolite facies and the greenschist facies in mafic rocks (Spear 1993).

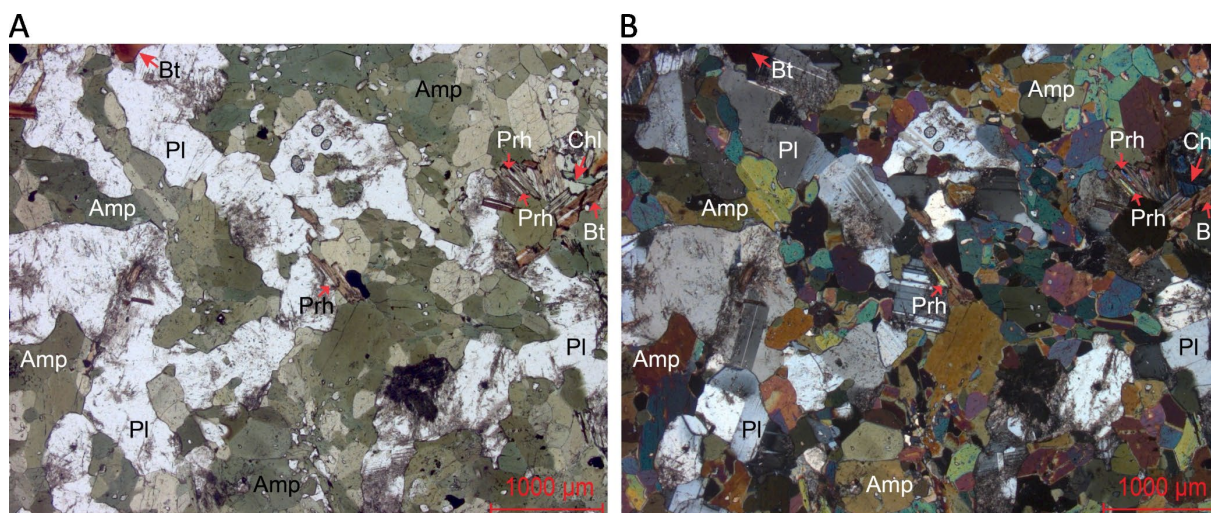


Figure 87. A. and B. Euhedral to anhedral, interstitial hornblende with a granoblastic texture. In places, plagioclase exhibits severe sericite-saussurite alteration. Biotite occurs with prehnite and minor chlorite alteration with anomalous blue interference colour in chlorite. Sample HRE230051A (6838128/545868). Left in ppl and right in xpl. Photo: Dick Claeson.

Mjöbergsvallen

Geological investigations were performed at Mjöbergsvallen (see fig. 77). However, despite a relatively large number of boulders which consisted of gabbro, it was challenging to locate outcrops. A sample was taken from a potential outcrop exposed at the margin of a forest road. However, there remains uncertainty as to whether this was a genuine outcrop or a very large boulder beneath the road surface.

Description of thin sections – silicate minerals

The sample HRE230015A from Mjöbergsvallen is a gabbroid rock. The main mafic mineral clinopyroxene occurs as subhedral to anhedral small to large grains, with lamellae and opaque exsolutions (fig. 88). Subhedral to anhedral, small to large grains of hornblende and olivine are observed. Biotite occurs as two generations, the first has brownish red pleochroism and second brownish red to light tan and is relatively abundant. Subhedral to anhedral plagioclase grains are well-preserved. Quartz occurs interstitially as small to large grains and has weak undulose extinction.

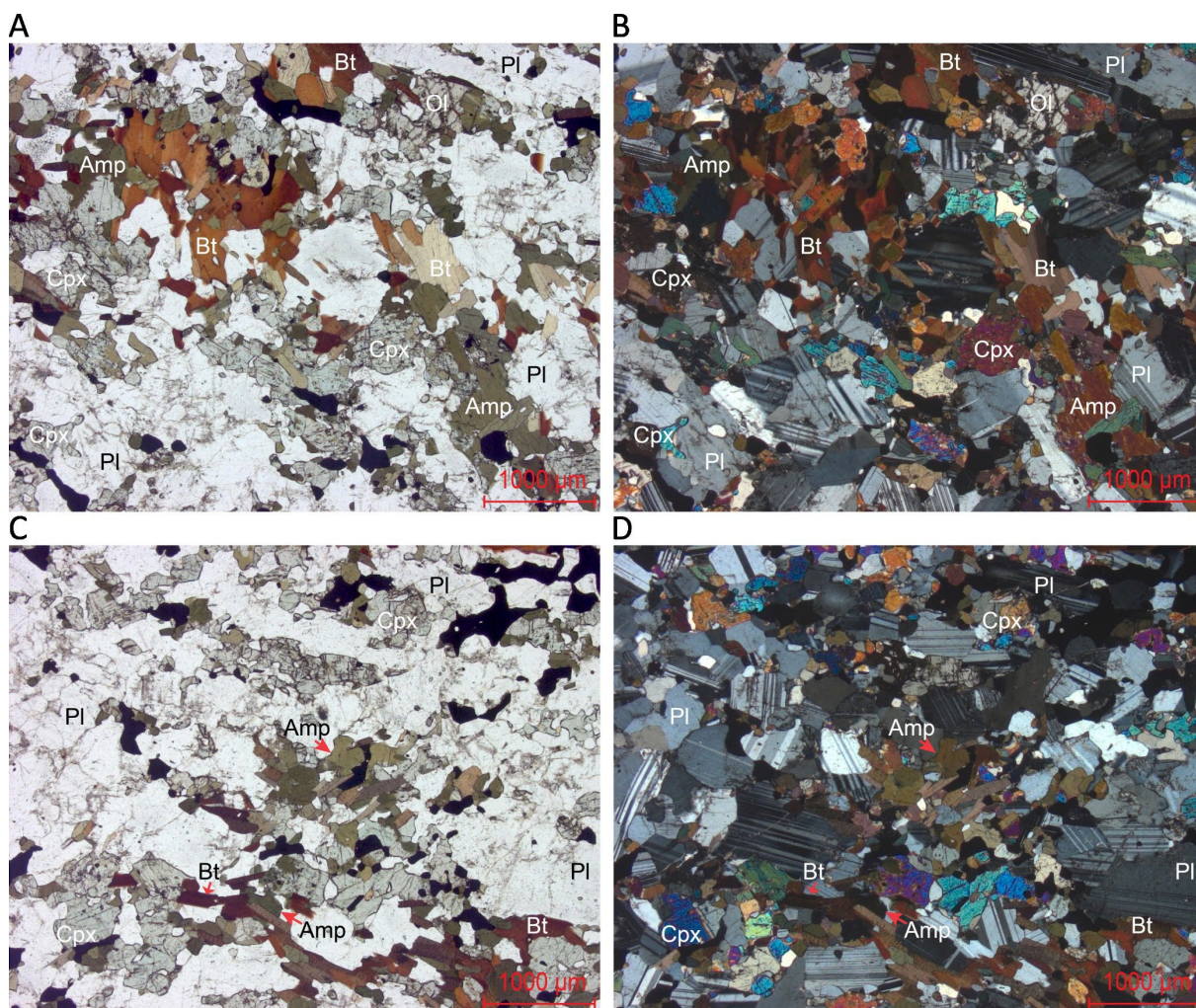


Figure 88. A. and B. Cumulate with relatively abundant biotite and plagioclase, clinopyroxene, hornblende, and olivine. C. and D. Biotite is orientated in several directions in a massive cumulate of clinopyroxene, hornblende, and plagioclase. Sample HRE230015A (6840350/541488). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data for the area southwest of the Järvsö area

Harker plots of major-element oxides are shown in figure 89. Ranges of selected oxides (in %) are as follows: SiO_2 (28.10–48.10), Al_2O_3 (7.74–12.60), Fe_2O_3 (17.75–44.30, average 27.58), CaO (6.73–10.70), Na_2O (1.06–2.64), MgO (3.39–7.99), K_2O (0.32–1.22), MnO (0.23–0.36), P_2O_5 (0.05–1.39), and TiO_2 (1.86–7.61, average 4.43).

Vanadium varies from 554 to 3 320 ppm with an average of 1 426 ppm. The concentrations of Ni, Co, Cu, and Cr are low; (Ni from 1 to 161 ppm, average 62 ppm), (Co from 47 to 147 ppm, average 88 ppm), (Cr from <5 to 192 ppm, average 47 ppm), (Cu from 18 to 226 ppm with an average of 97 ppm).

The samples plot in the tholeiite field in the AFM-diagram (fig. 90).

The samples show irregular trace-element patterns in a primitive mantle normalised diagram (fig. 91). Notable features are the strong negative Nb anomalies and positive Pb and Ti anomalies (except one sample that has a weak negative Ti anomaly).

The chondrite normalised REE patterns (fig. 92) have low to moderate $(\text{La}/\text{Yb})_N$ in the range 1.35–3.76. Four samples have negative Eu anomalies (Eu/Eu^*) in the range 0.58–0.92. Three samples have positive Eu/Eu^* in the interval 1.11–1.33. The subparallel REE patterns probably reflect different stages of fractional crystallisation.

All but one sample plot in the field of destructive plate-margin volcanic basalts (CAB and IAT) in the triangular Th-Hf-Nb diagram (fig. 93). The same general picture of a volcanic arc signature is seen, in the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 94A–B).

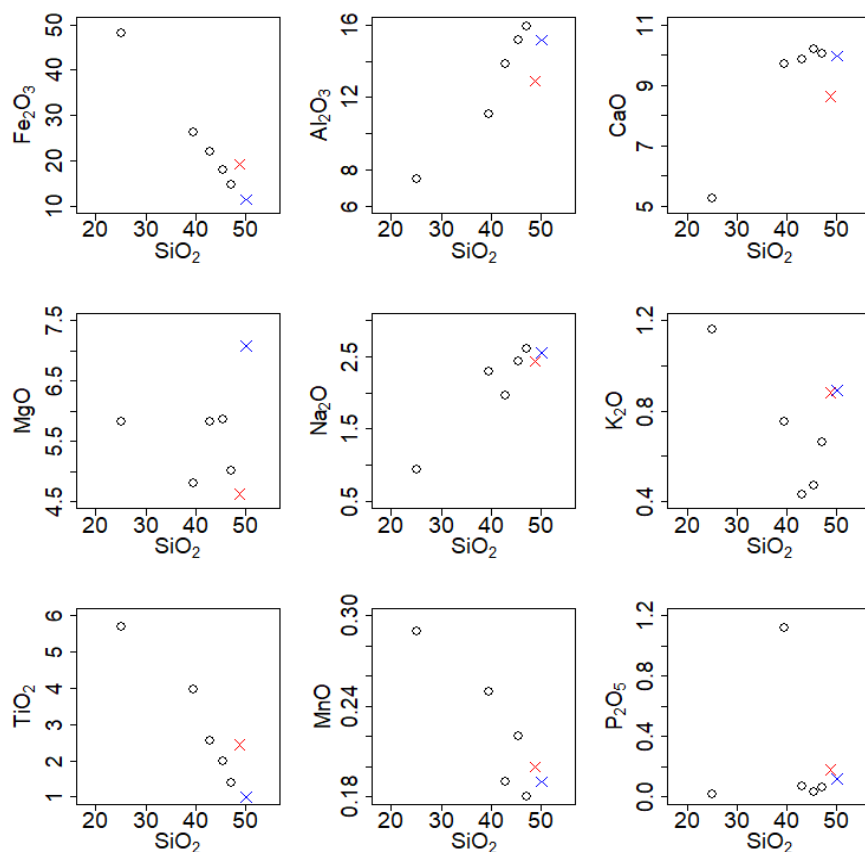


Figure 89. Harker diagrams for major elements vs. SiO_2 in Skalberget (black circles), Mjöbergsvallen (red 'X'), and Oktjärnen (blue 'X'). All concentrations are in %.

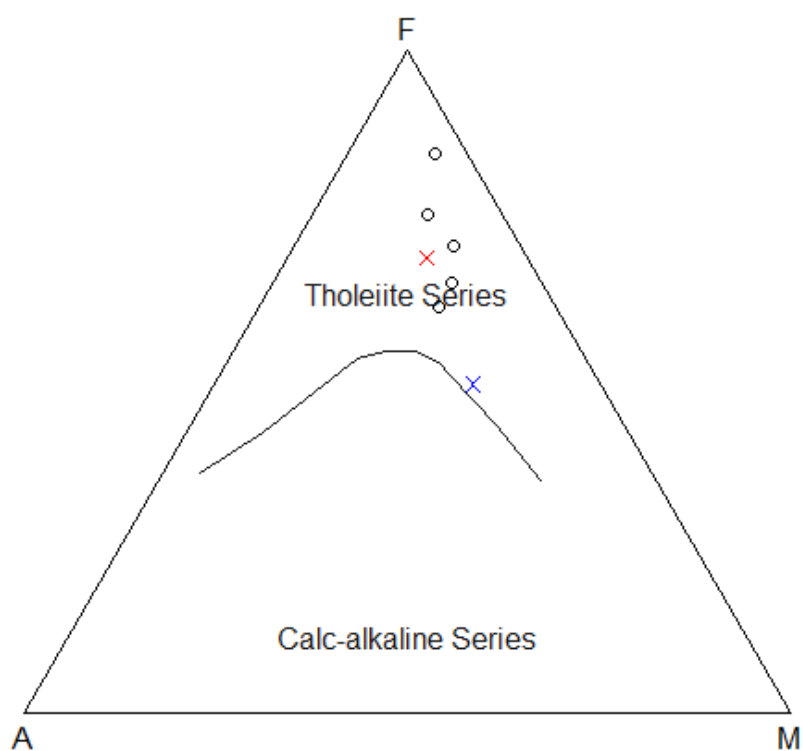


Figure 90. AFM-diagram (Irvine & Baragar 1971). Skalberget (black circles), Mjöbergsvallen (red 'X'), and Oktjärnen (blue 'X').

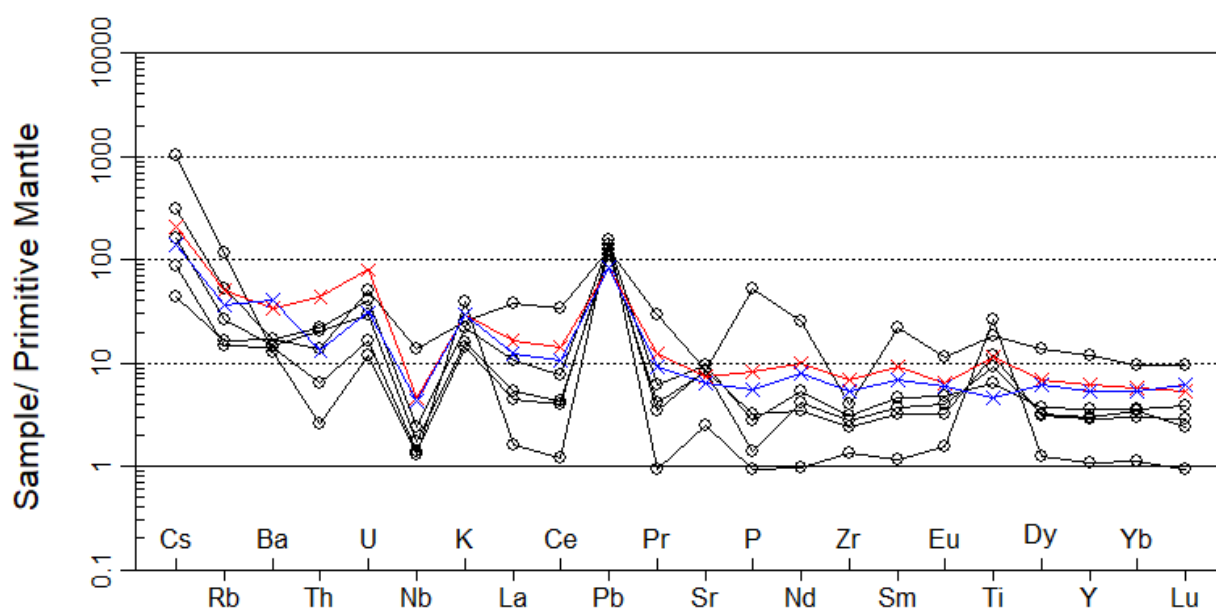


Figure 91. Primitive mantle normalised trace element diagram for Skalberget (black circles), Mjöbergsvallen (red 'X'), and Oktjärnen (blue 'X') samples. Normalising values from Sun & McDonough (1989).

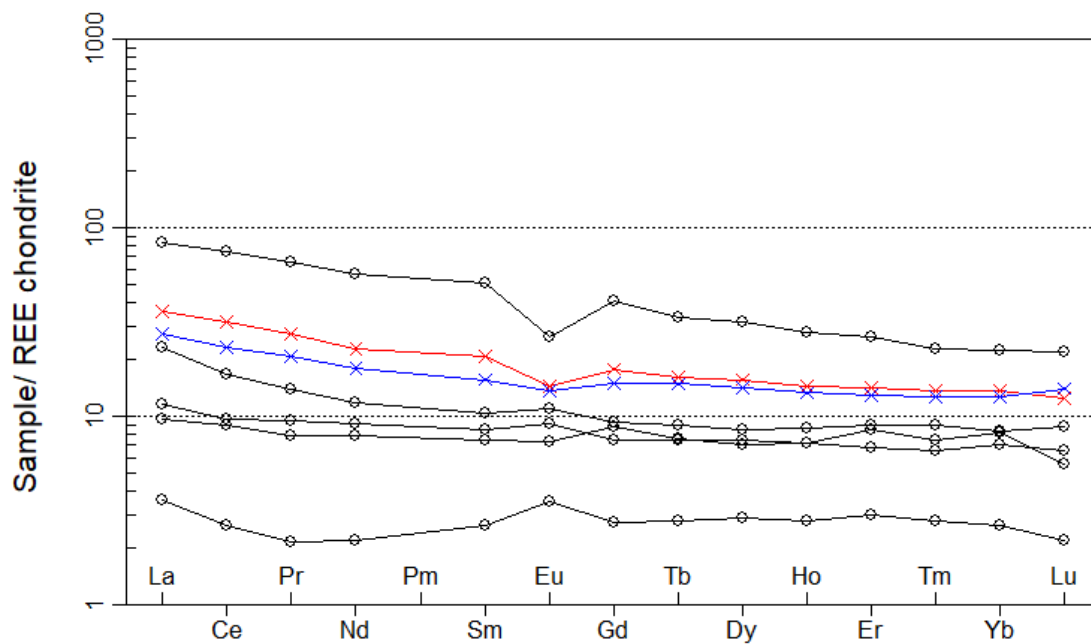


Figure 92. Chondrite normalised REE spider diagram for Skalberget (black circles), Mjöbergsvallen (red 'X'), and Oktjärnen (blue 'X'). Chondrite values are from Boynton (1984).

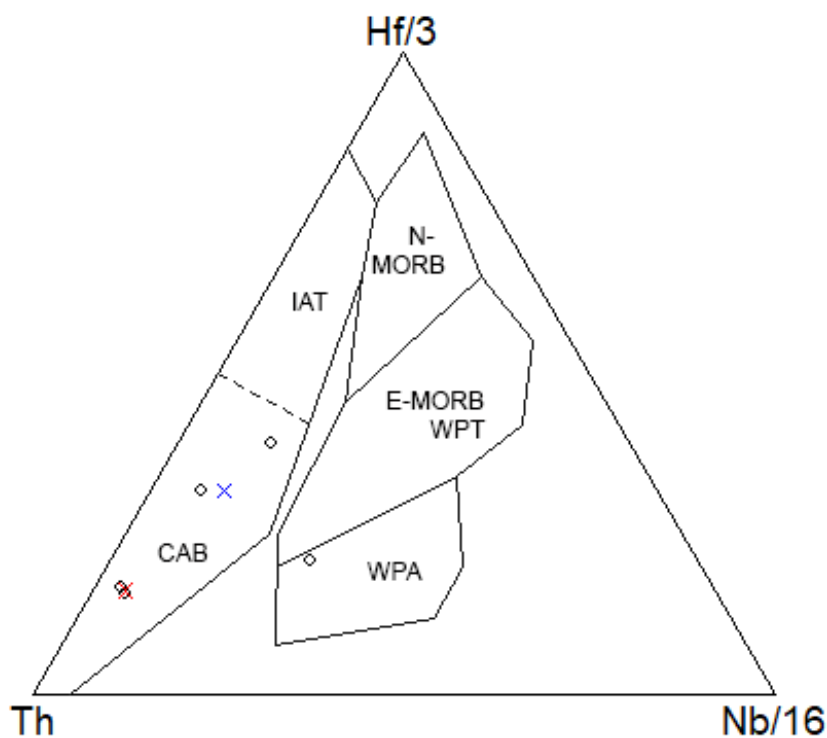


Figure 93. Skalberget (black circles), Mjöbergsvallen (red 'X'), and Oktjärnen (blue 'X') plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

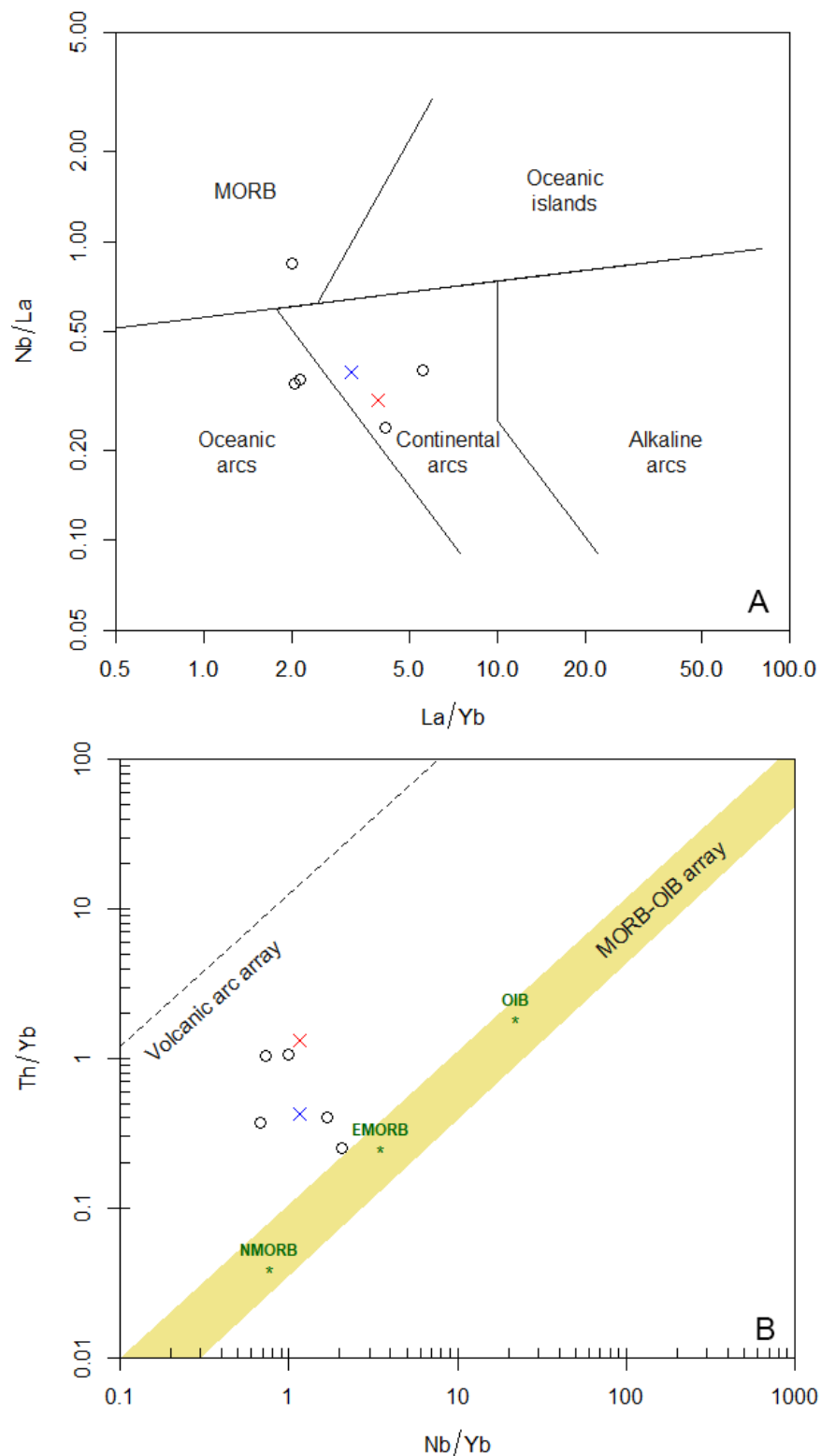


Figure 94. Skalberget (black circles), Mjöbergsvallen (red 'X'), and Oktjärnen (blue 'X') plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Gruvberget–Sumåssjön, Bläckmyran, Gråsjön, Masugnsberget and Blistra

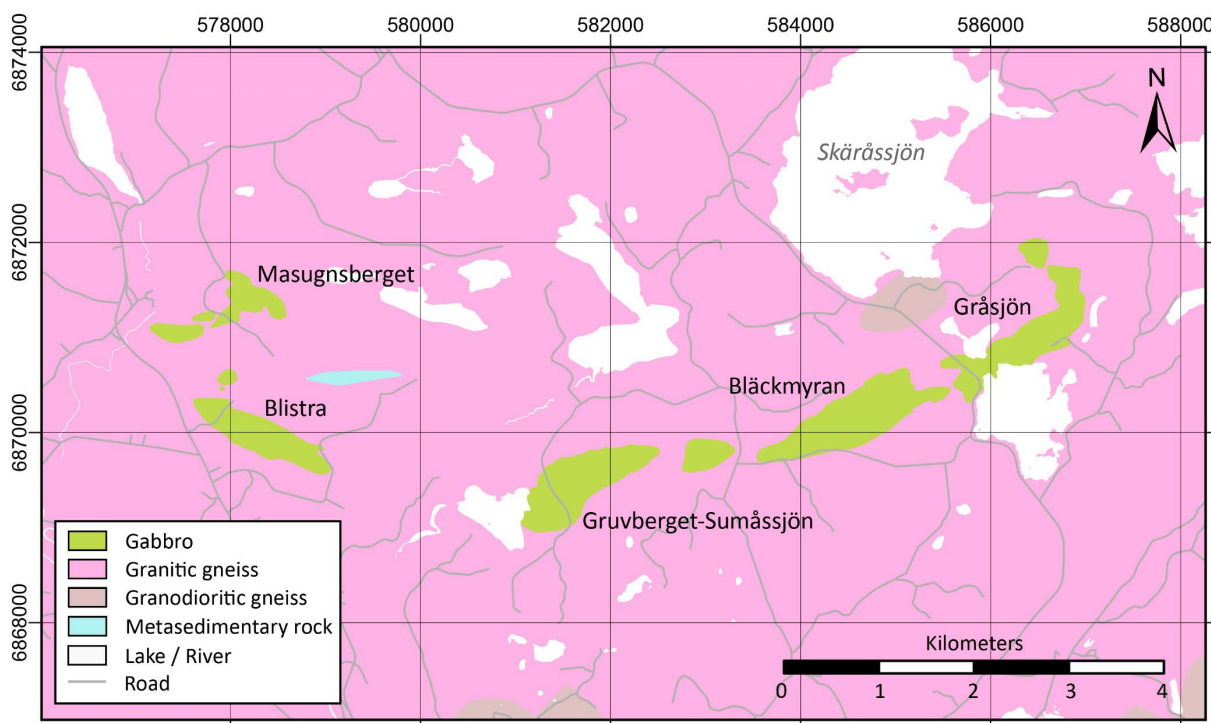


Figure 95. Bedrock geology map showing the Gruvberget–Sumåssjön area. The names of the mafic intrusions referred to in the report are shown as black text. Names of some lakes are shown as grey italic text. Note that when referring to deposits in the “Gruvberget–Sumåssjön area” we are referring to all of the deposits shown on this map.

Several mineralised gabbroic intrusions outcrop approximately 15–20 km north of Delsbo in an east–west trending area stretching from Masugnsberget to Gråsjön (fig. 95). The main ore-mineral in these rocks is magnetite and some of the deposits and occurrences have been mined earlier on a small scale for iron (Hallberg *et al.* 2012). Although the gabbroids had been known to contain both titanium and vanadium in addition to iron (Lundegårdh 1957), the full vanadium potential in the area was first discovered in the late 1970s early 1980s in connection with a campaign of known mineral occurrences and old mining pits.

Between 1979 and 1983 a significant number of geophysical investigations were performed by SGU in the area around Gruvberget–Sumåssjön as part of an investigation into the vanadium mineralisation potential in Gävleborg County. As part of these investigations, SGU acquired airborne magnetic data over the county in 1979 (Holdar 1980, Ros & Persson 1981). Based on these measurements a series of magnetic anomalies were identified and subsequently investigated. Several anomalies in the Gruvberget–Sumåssjön area correspond to the mafic rocks which had previously been documented to the northwest of Delsbo (Lundegårdh 1957). Due to the strength of these anomalies, SGU collected ground magnetic profiles over the Bläckmyran and Gruvberget–Sumåssjön deposits in 1980 (Ros & Persson 1981). The results from these initial investigations motivated SGU to acquire grids of ground magnetic measurements over the Bläckmyran and Gruvberget–Sumåssjön deposits as well as profile magnetic measurements over the Masugnsberget, Blistra, and Gråsjön deposits in 1981 (Holdar 1981, Lagergren 1983). Grids of ground magnetic measurements was subsequently performed over the Masugnsberget, Blistra,

and Gråsjön deposits in 1982 (Lagergren 1983). In addition, a total of six gravity profiles were measured over the Bläckmyran and Gruvberget–Sumåssjön deposits in 1982 (Ros & Lagergren 1982).

The dense grids of magnetic measurements performed over the Gruvberget–Sumåssjön and Bläckmyran deposits were collected along a series of parallel profiles with a typical line spacing of 40 m. The typical spacing between measurement points along these profiles was 10–20 m. An exception to this was the western 800 m of the Bläckmyran survey area, which was measured with a line spacing of 160 m. The surveys at Masugnsberget, Blistra, and Gråsjön were performed with a profile spacing of about 80 m and typically with 10–20 m between measurement points along profiles. The total combined area covered by these different surveys was about 8 km².

Due to the availability and coverage of these previous ground magnetic measurements in this area, no new measurements were performed as part of this study. Instead, we present and discuss these pre-existing data which have now been converted from analogue format to digital format.

Gruvberget–Sumåssjön

Ground-based geophysical measurements

Figure 96 shows a map of the magnetic field from ground measurements over the Gruvberget–Sumåssjön intrusion. The figure also shows an updated bedrock geology map based on the magnetic field data and geological observations. The magnetic field data show a series of strong magnetic anomalies above the intrusion. These anomalies cover an area which is approximately 1 000 m long and 300 m wide, with a strike of approximately 74°. The magnetic field values at Gruvberget–Sumåssjön are relatively strong, reaching as high as 30 000 nT above the background in places. It also covers a relatively large area, where the field values lie more than 10 000 nT above the background over an area of about 3 000 m². The intrusion appears to include a number of discrete, approximately linear positive anomalies, which lie parallel to one another. These have been highlighted as connections (continuous positive magnetic anomalies) in figure 96. The strongest of these anomalies appears at the northwestern edge of the intrusion. It is possible that these anomalies can be interpreted as lenses within the intrusion with greater iron and vanadium concentrations. Lateral displacement of these positive anomalies can be observed in places, which is interpreted as due to faulting (fig. 96B).

► **Figure 96. A.** Map of the total magnetic field at Gruvberget–Sumåssjön, made from ground measurements collected by SGU in 1981. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Gruvberget–Sumåssjön intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The inset map shows the location of the map with regards to the other intrusions in the area. The locations of available geological observations, samples, boreholes, and magnetic susceptibility measurements at outcrop are shown as different coloured dots in both A and B.

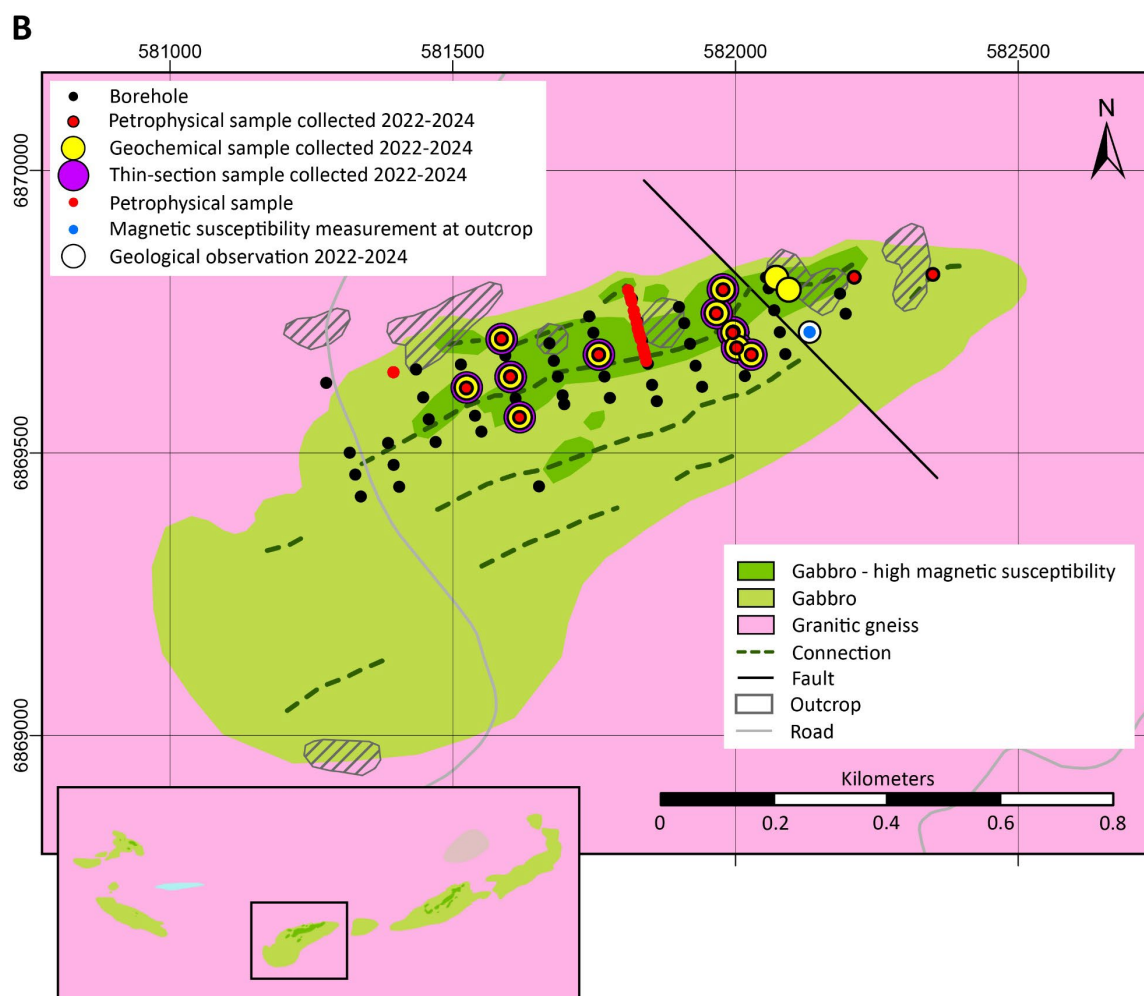
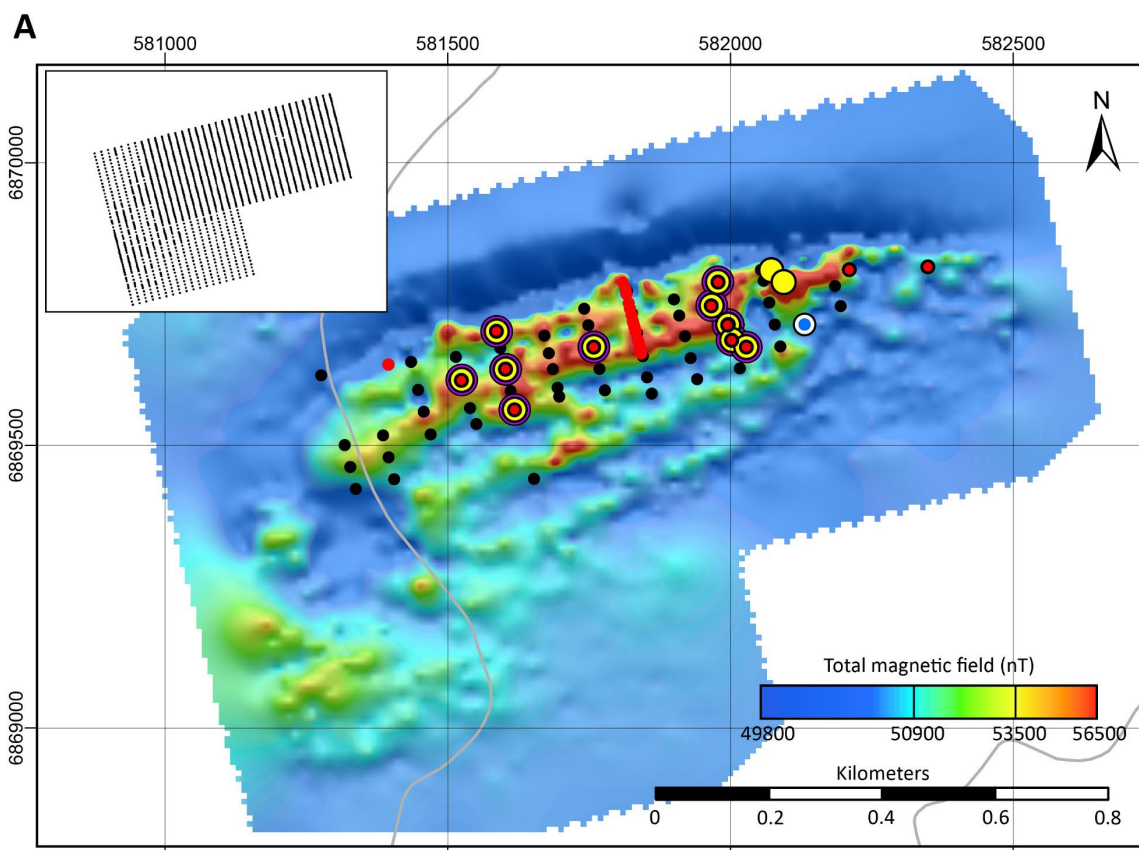


Figure 97 shows the average magnetic susceptibilities in the upper 75 m of the model, obtained by performing an unconstrained inversion of the ground magnetic data. Here it can be observed that the highest magnetic susceptibilities lie within a zone on the northwestern edge of the intrusion. Zones of higher susceptibility, striking parallel to the main zone also exist in the southeastern part of the intrusion. There appears to be a relatively good visual correlation between the magnetic susceptibility measurements from drill cores and at the surface (shown as dots in fig. 97). However, it is important to note that the magnetic susceptibility data shown here also includes magnetic susceptibilities calculated from geochemical data using the trend described in the petrophysics section of the report. The 3D susceptibility model obtained from the inversion shows that the intrusion dips to the south (fig. 97). This is consistent with the available drill core data and previous investigations by SGU which show that the intrusion dips at about 20°-50° to the south (AB Statsgruvor 1984).

Magnetic susceptibility logs of the drill cores SUM81001, SUM81017, and SUM81022 can be found in appendix B. A map showing the location of these is shown in appendix B. In the case of these three drill cores, there appears to be more variability in the magnetic susceptibilities closer to the contact with the surrounding granitic rock, inferring a higher degree of heterogeneity. In this interval some of the highest magnetic susceptibilities can be observed occurring in layers of gabbro some 5–15 m thick. However, these layers with high magnetic susceptibility are interbedded with layers of gabbro and hybrid rock with relatively low magnetic susceptibilities. Further from the contact, the magnetic susceptibilities within the intrusion appear to vary more gradually.

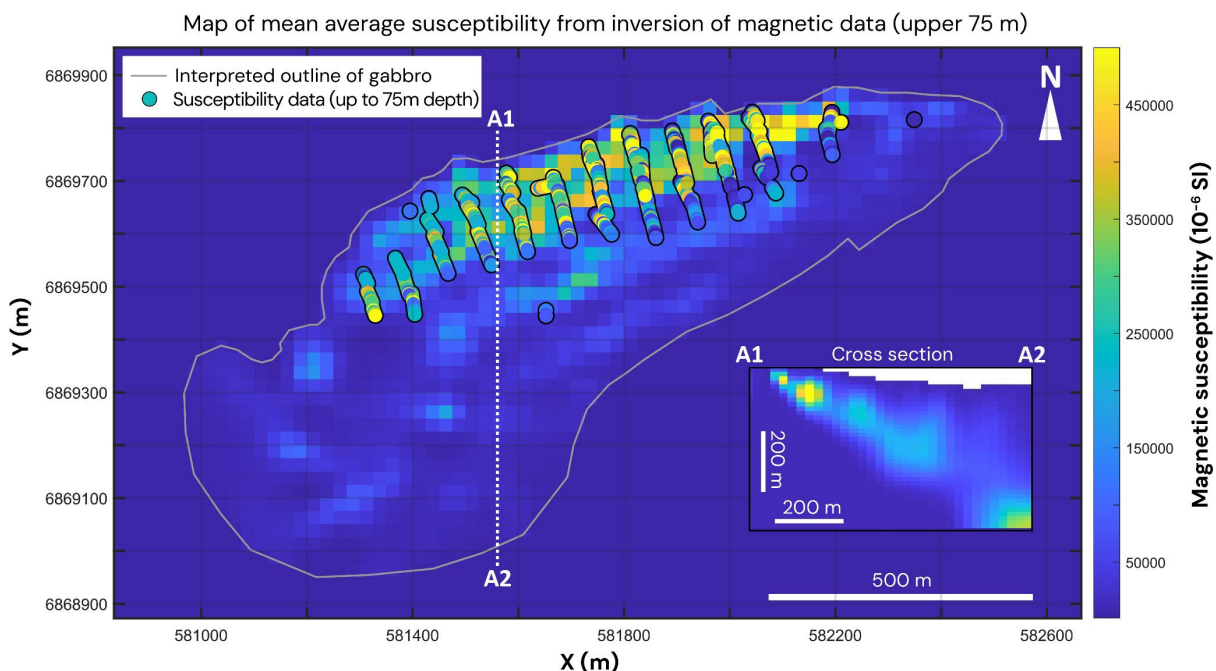


Figure 97. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Gruvberget–Sumåssjön intrusion. All magnetic susceptibility measurements collected up to a depth of 75 m (measurements on drill cores and at the surface) are shown as dots. In cases where only geochemical data is available in drill cores, magnetic susceptibilities have been calculated using the relationship described in the petrophysics section of the report. These calculated susceptibilities are shown together with the magnetic susceptibility measurements as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

Geological observations

Gruvberget (fig. 98) is a small mountain or hill located south of lake Sumåssjön, about 15 km north of Delsbo. Two old mining pits occur near the top of Gruvberget hill at the eastern slope. According to Wik *et al.* (2009) test-mining for iron occurred here between 1730 and 1790. The last mining attempt was in the late 1870s, but the produced iron was of poor quality.

At Gruvberget–Sumåssjön a detailed drilling program was undertaken during 1981–1982 that yielded 54 drillholes distributed in 12 profiles with an internal separation of 80 metres. Three exploration trenches were sampled in 1982 from which approximately 300 tonnes of mineralised gabbroid rocks was extracted and analysed (Andersson 1983). In the current project nine of the drill cores were sampled and analysed for major and trace elements including a total of 25 sections, each comprising c. 1 m of core. In addition, two field samples were collected from outcrop (fig. 99) and one sample from waste-rock at a shallow test-mining pit at the top of Gruvberget (figs. 100 and 101).

Six drill cores from Gruvberget–Sumåssjön were included in SGU's drill core scanning project. The scanning project, which ran from 2014 to 2015, produced hyperspectral imagery of 233 000 metres of selected drill cores from the Malå archive (Söderberg *et al.* 2020). The hyperspectral data include reflectance spectra in the visible-near infrared and shortwave infrared (VNIR-SWIR) and the longwave infrared (LWIR) regions.



Figure 98. View towards west from the top of Gruvberget (6869775/581936). Photo: Helge Reginiussen.



Figure 99. Gabbroid outcrop at Gruvberget (6869719/582128). Photo: Helge Reginiussen.



Figure 100. Sampling of mineralised waste-rocks at a small, shallow test-pit at the top of Gruvberget (6869789/582094). Photo: Helge Reginiussen.



Figure 101. Fine- to medium-grained Fe-Ti-V mineralised gabbroid from the abandoned pit in figure 100 at the top of Gruvberget (6869789/582094). Assays returned 38.20 % Fe_2O_3 , 5.74 % TiO_2 , and 3 680 ppm V. Photo: Helge Reginiussen.

Mineralised sections were quickly defined using hyperspectral data (fig. 102). Unfortunately, such data is only available for six drill cores.

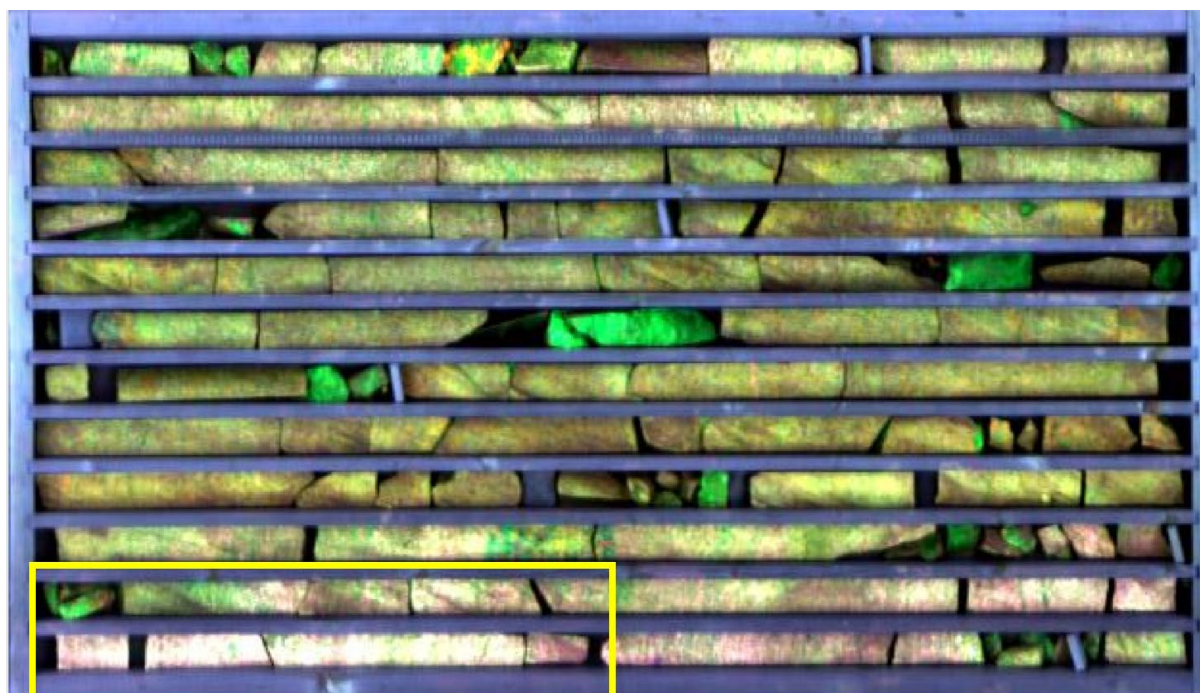


Figure 102. False Colour Composite image of drill core box 9 from the Gruvberget–Sumåssjön drill core SUM82014 that uses data from the longwave infrared (LWIR) part of the infrared spectrum. The LWIR camera covers the wavelength interval 7 500–12 000 nanometres (nm) and three infrared bands are rendered in RGB using red = 8 611 nm, green = 10 022 nm, blue = 11 810 nm. Magnetite-rich portions render bright yellowish white in this image. The yellow rectangle shows the outline of figure 103A. Photo: SGU.



Figure 103. A. Close-up of drill core SUM82014 showing the best Fe-Ti-V mineralised section (88.11–88.73 m) that has been analysed in the current project. **B.** Enlargement showing very rich Fe-Ti-V mineralisation (57.60% Fe_2O_3 , 7.96% TiO_2 , and 6 220 ppm V). The black mineral clearly visible in the lower image is mainly magnetite which is the main vanadium host. Photo: Helge Reginiussen.

Description of thin sections – ore minerals

The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage (figs. 104, 105A–B, 106A, 107, 108A, 109A–B). There is exsolved ilmenite as lamellae, laths and trellis, which follow crystallographic planes, and also as blobs in the magnetite, discernible in ordinary reflected light but using differential interference contrast (DIC) highlights them (figs. 104B–C, 105B–C, 106B, 107B–C, 108B–C, 109C). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are feasibly magnetite or ulvöspinel (figs. 104B–C, 105B–C, 106C, 107B, 108C, 109C, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the almost orthogonal tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), easily seen in ordinary reflected light and less obvious in DIC where they are beige, but no proper identification was done (figs. 104B–C, 107B–C). In the closeup images an additional observation is evident (figs. 104B–C, 107B–C), where there is a decrease in the abundance of lamellae in the outer part of the ilmenite crystals. This decrease continues to the contact of the mineral where they are no longer visible with a microscope. This is best viewed in the differential interference contrast image but can also be clearly seen in the plain reflected light image.

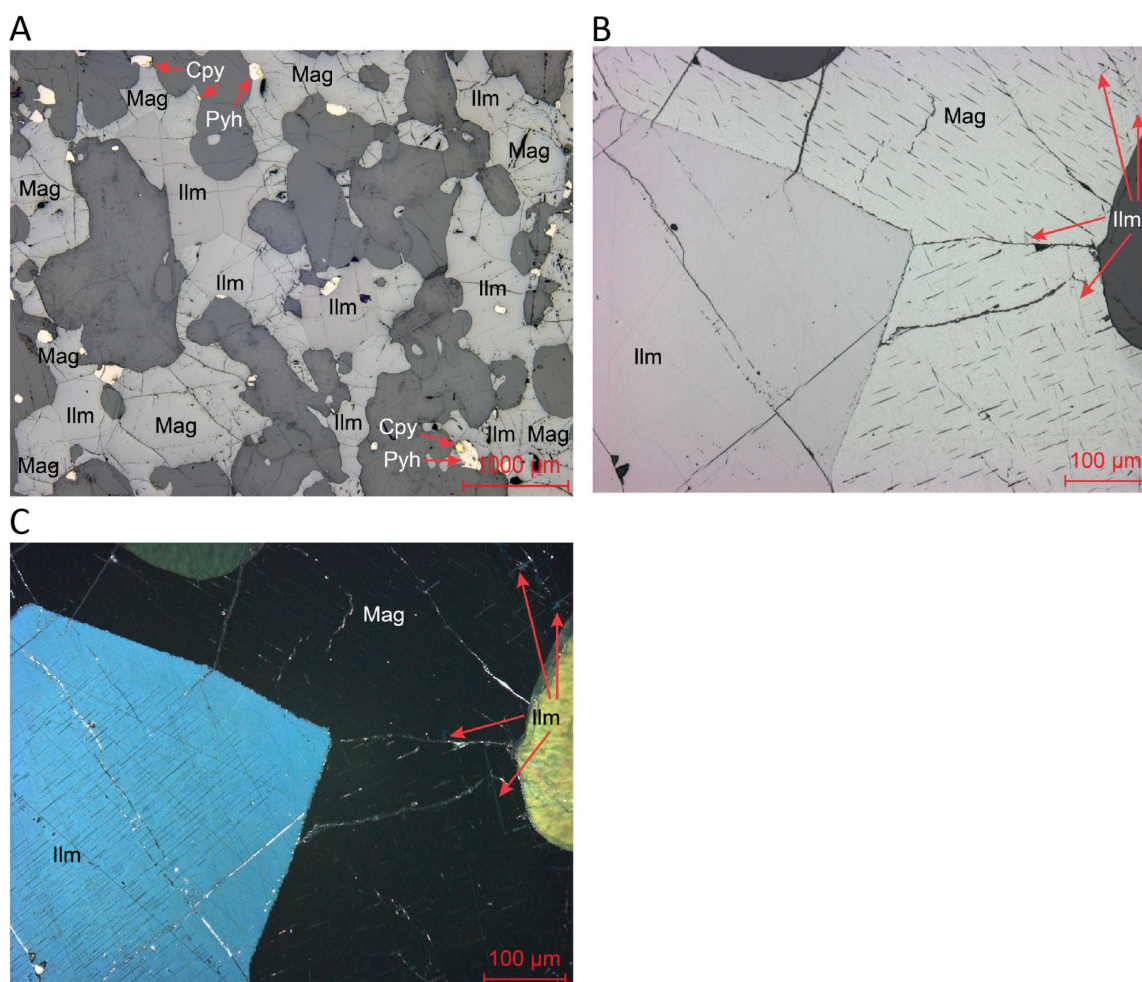


Figure 104. Ore minerals from the Gruvberget–Sumåssjön intrusion, mineralised sample DCL222022B from drill core SUM82004 at 6.12–6.17 m (see fig. C25 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework with small crystals of pyrrhotite and chalcopyrite. Note the subhedral ilmenite and 120 degrees triple junction to the left of the centre. Close-up images of **B.** magnetite with a few thin ilmenite exsolution lamellae and blobs, and lots of trellis-type occurring as dark exsolutions almost at right angle to each other in the lower crystal. The ilmenite crystal has thin exsolution lamellae of hematite and unknown darker minerals, **C.** same area as in B. using differential interference contrast (DIC) objective that highlights the very faint ilmenite lamellae in magnetite and exsolved minerals in ilmenite. Note euhedral ilmenite and absence of most exsolution minerals in the contact zone with magnetite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

The ore minerals magnetite, ilmenite, pyrrhotite, and chalcopyrite were identified in mineralised sample DCL222022B from drill core SUM82004 at 6.12–6.17 m (fig. 104, see fig. C25 for panorama). Sulphides occur mostly as small grains. Some ilmenite crystals are subhedral and to the left of the centre in figure 104A a grain triple junction of approximately 120 degrees is present. Note also the euhedral shape of ilmenite (figs. 104B–C). There is also a set of fractures that to the lower right part of the ilmenite seems to have inhibited or dissolved magnetite lamella (fig. 104C). This contact phenomenon is possibly also observed in the magnetite, but in reverse, where there is an outer zone containing no trellis or laths (figs. 104B–C). This zone in the magnetite, however, is thinner than in the ilmenite.

The ore minerals magnetite, ilmenite, pyrrhotite, chalcopyrite, and pentlandite were identified in mineralised sample DCL222023B from drill core SUM82004 at 37.85–37.89 m (fig. 105, see fig. C26 for panorama). Some grains of sulphide minerals consisting of pyrrhotite, chalcopyrite, and pentlandite surrounded by magnetite, ilmenite, and silicate minerals appears to be relatively unaltered (figs. 105B–C). Chalcopyrite is present in thin fractures in both magnetite and ilmenite (figs. 105B–C).

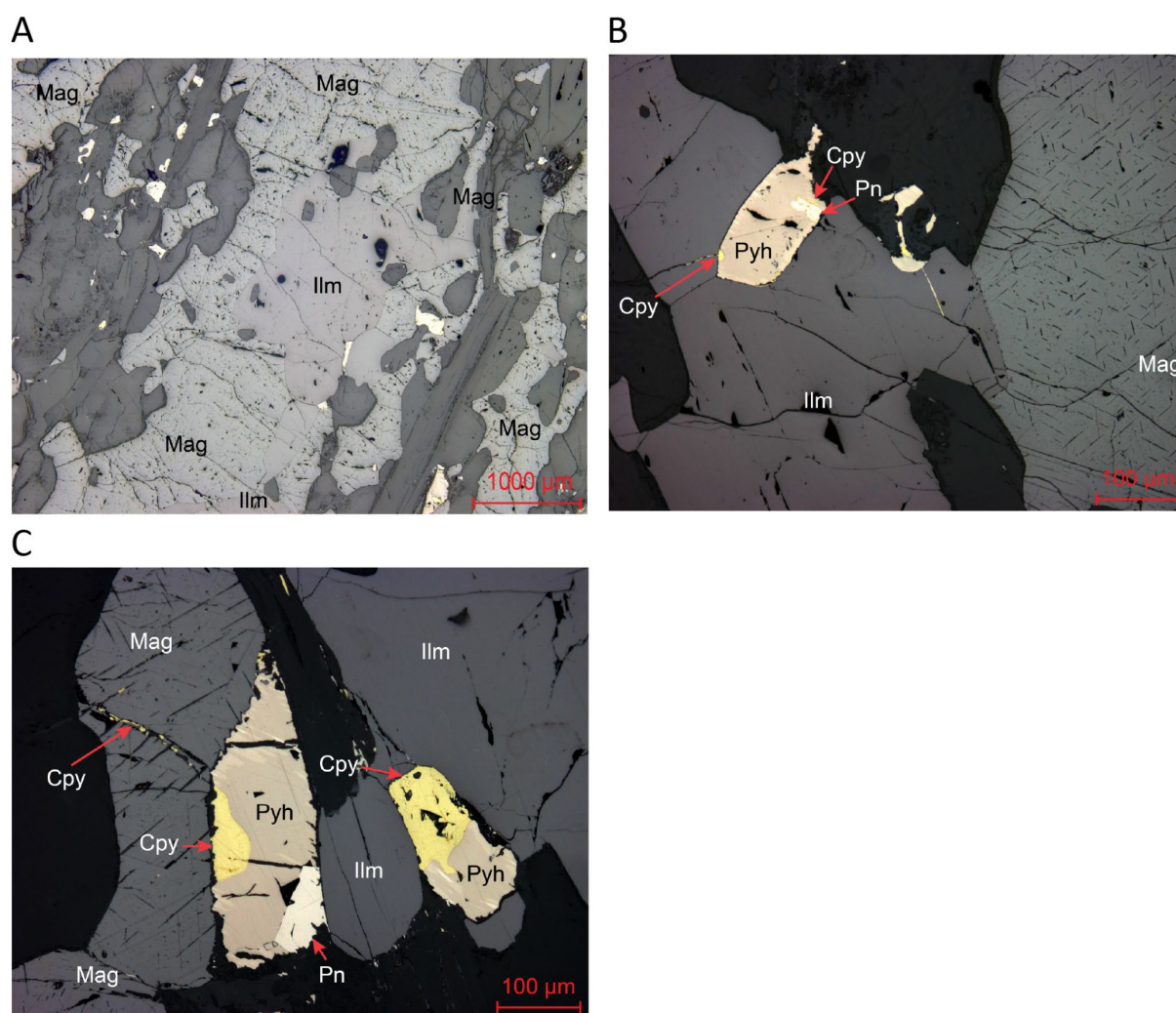


Figure 105. Ore minerals from the Gruvberget– Sumåssjön intrusion, mineralised sample DCL222023B from drill core SUM82004 at 37.85–37.89 m (see fig. C26 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework with crystals of pyrrhotite (light yellow). **B.** and **C.** Close-up images of grains of sulphide minerals consisting of pyrrhotite, chalcopyrite, and pentlandite surrounded by magnetite, ilmenite, and silicate minerals. Note chalcopyrite in thin fractures in both ilmenite and magnetite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

The ore minerals magnetite, ilmenite, pyrrhotite, and chalcopyrite were identified in mineralised sample DCL222024B from drill core SUM82014 at 87.97–88.03 m (fig. 106, see fig. C27 for panorama). A grain of sulphide minerals consisting of pyrrhotite and chalcopyrite surrounded by magnetite and ilmenite appears to be relatively unaltered (figs. 106B–C). Both pyrrhotite and chalcopyrite occur along a contact between magnetite and ilmenite, and chalcopyrite is seen in thin fractures (figs. 106B–C).

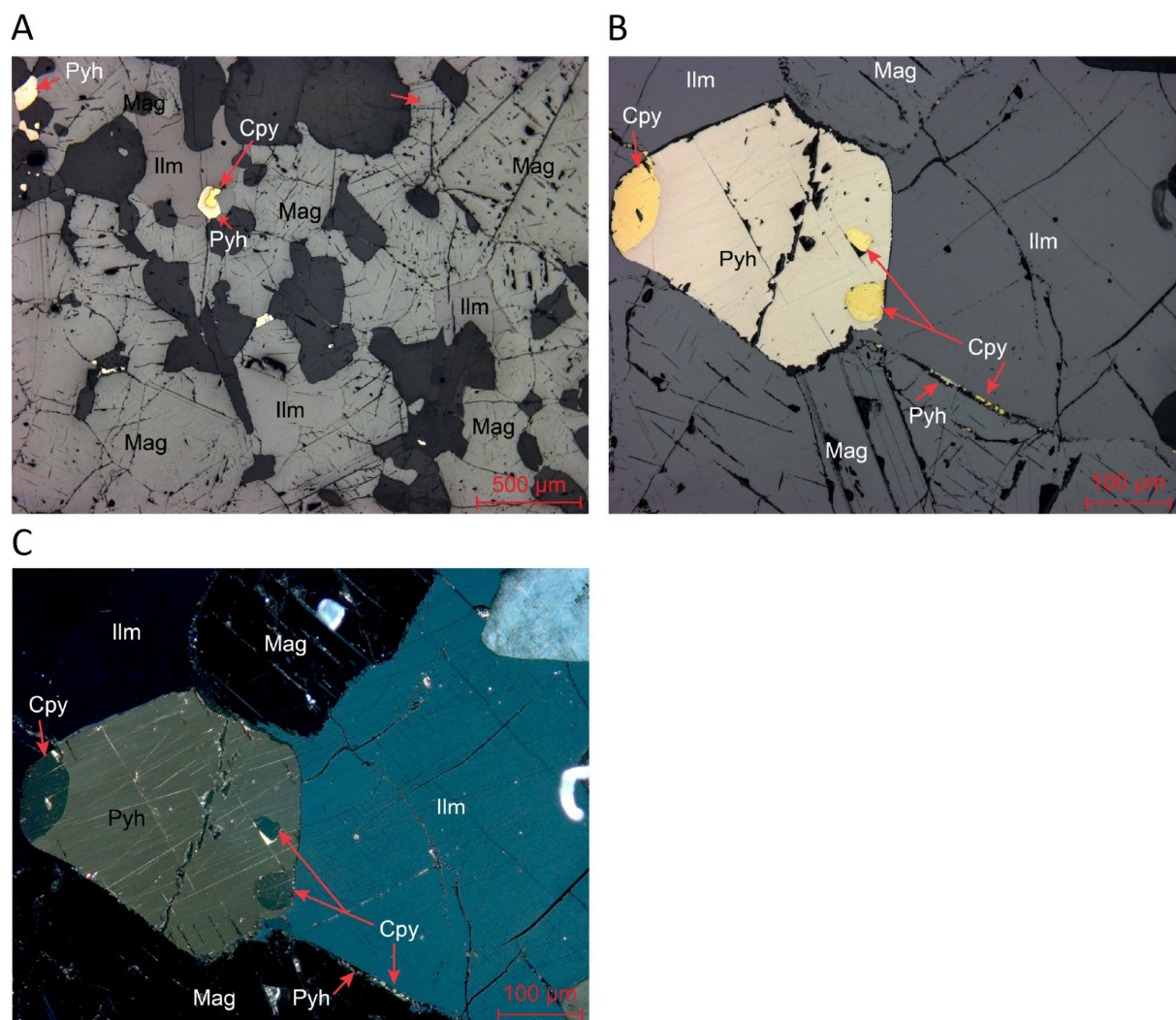


Figure 106. Ore minerals from the Gruvberget– Sumåssjön intrusion, mineralised sample DCL222024B from drill core SUM82014 at 87.97–88.03 m (see fig. C27 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework with crystals of pyrrhotite and chalcopyrite. Small grains of sulphide minerals consisting of pyrrhotite and chalcopyrite surrounded by magnetite and ilmenite, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. Note both sulphide minerals occur along contact between ilmenite and magnetite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

The ore minerals in a large aggregate of opaque minerals consist of mostly magnetite with minor ilmenite, and no sulphide minerals were detected in this part of the thin section of mineralised sample DCL230023A from drill core SUM81005 at 105.94–106.00 m (fig. 107, see fig. C28 for panorama).

The ore minerals magnetite, ilmenite, pyrrhotite, and chalcopyrite were identified in mineralised sample DCL230026A from drill core SUM81014 at 91.45–91.52 m (fig. 108, see fig. C29 for panorama). A grain of sulphide minerals consisting of pyrrhotite and chalcopyrite is surrounded by magnetite and silicate minerals, with a partial rim of ilmenite towards the magnetite. There are also two laths of ilmenite that continue into magnetite at the pointy corners of the sulphide grain. The relations suggest that the rim of ilmenite crystallised simultaneously with the well-developed sulphide minerals. The assemblage is relatively unaltered (figs. 108B–C).

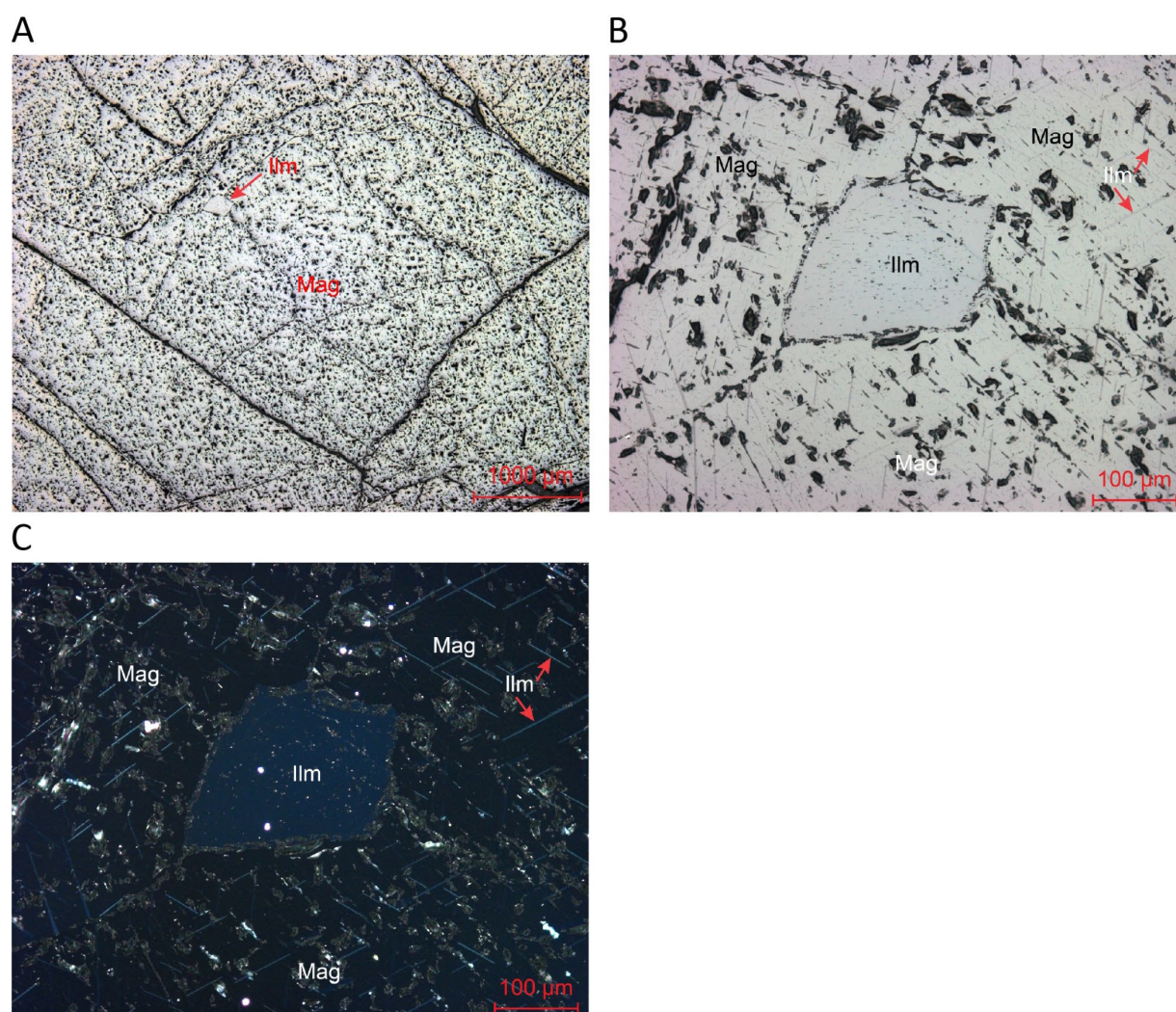


Figure 107. Ore minerals from the Gruvberget–Sumåssjön intrusion, mineralised sample DCL230023A from drill core SUM81005 at 105.94–106.00 m (see fig. C28 for panorama). **A.** Overview of relations between magnetite and a single ilmenite crystal in an opaque framework. Close-up images of an ilmenite crystal surrounded by magnetite (seen in A. red arrow), **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. Note the near absence of exsolved minerals along the ilmenite’s contact with magnetite. All images in reflected light. Photo: Dick Claeson.

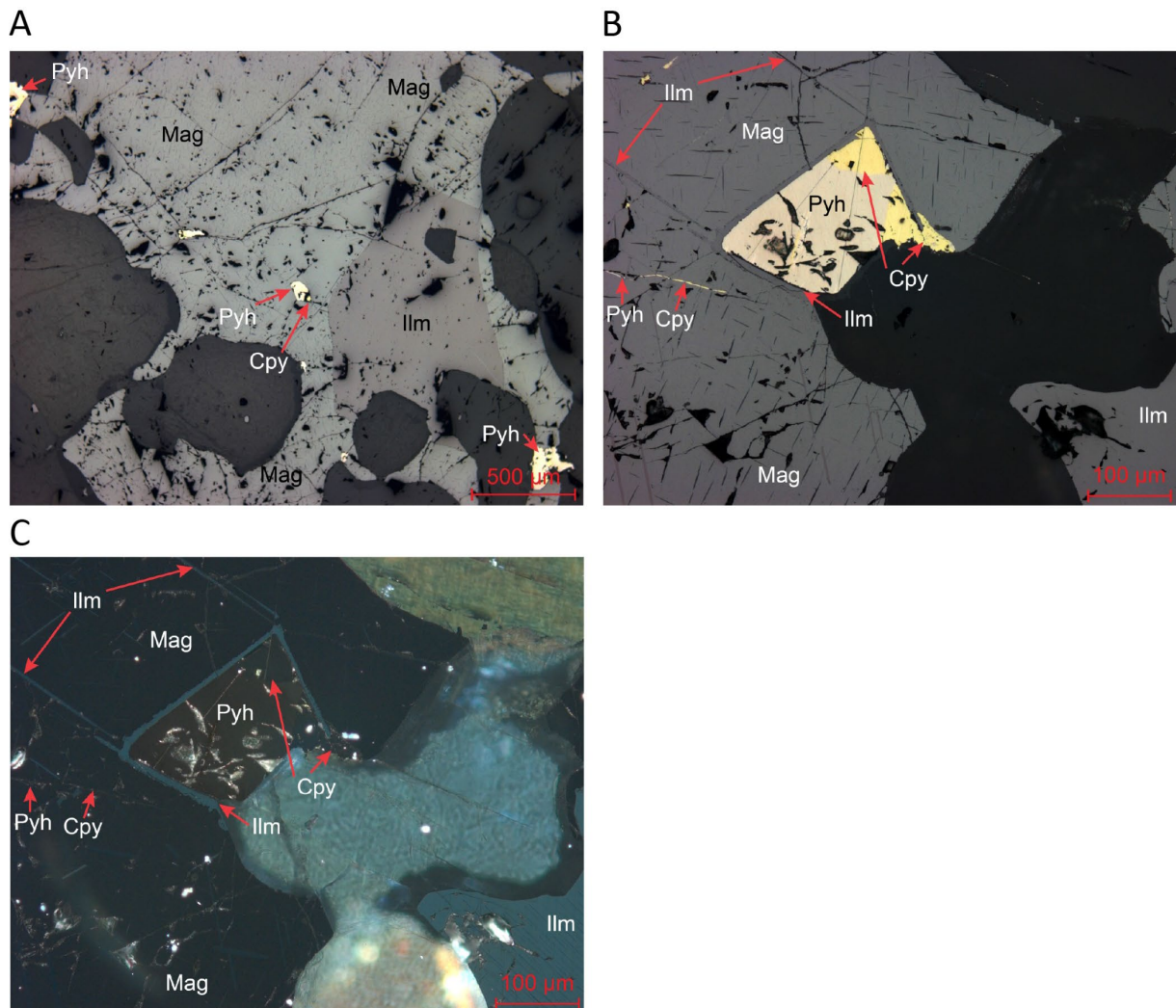


Figure 108. Ore minerals from the Gruvberget–Sumåssjön intrusion, mineralised sample DCL230026A from drill core SUM81014 at 91.45–91.52 m (see fig. C29 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework. A grain of sulphide minerals consisting of pyrrhotite and chalcopyrite is surrounded by magnetite and silicate minerals, and has a partial rim of ilmenite towards the magnetite. There are two laths of ilmenite continuing into magnetite at the pointy corners of the sulphide grain, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. Note both sulphide minerals occur in thin fracture. All images in reflected light. Photo: Dick Claeson.

The ore minerals magnetite, ilmenite, pyrrhotite, chalcopyrite, cubanite, pyrite, and marcasite were identified in mineralised sample DCL234011A from drill core SUM81017 at 76.62–76.68 m (fig. 109, see fig. C30 for panorama). Several grains of sulphide minerals consisting of chalcopyrite, cubanite, pyrite, and marcasite surrounded by magnetite and silicate minerals, display relatively low temperature hydrothermal alteration (maximum of around 200 °C, e.g., Qian *et al.* 2011, Holwell *et al.* 2017). Chalcopyrite became partly replaced by cubanite and possible pyrrhotite (none left in the assemblage in image but present in thin section in A) replaced by pyrite and marcasite (fig. 109C).

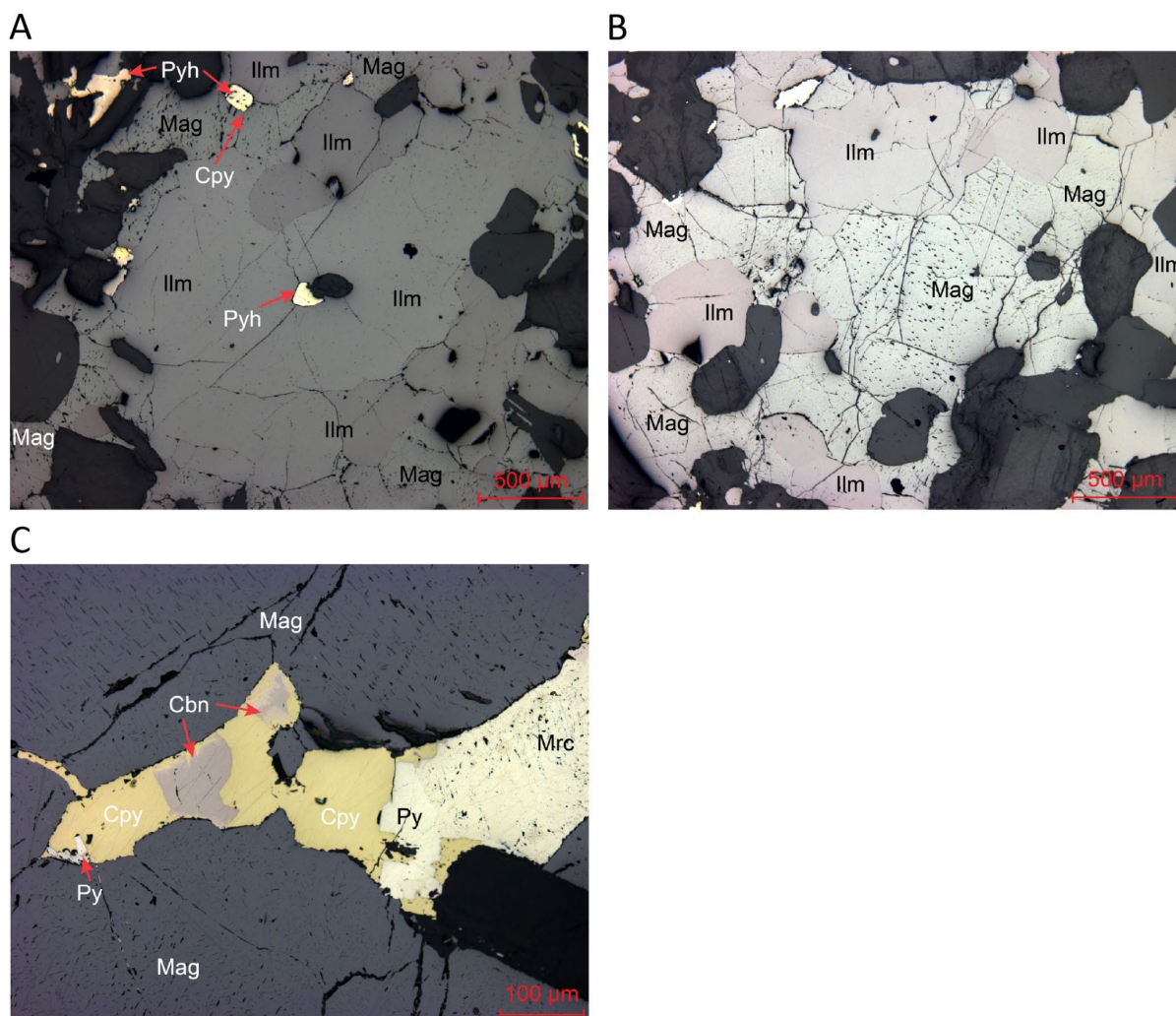


Figure 109. Ore minerals from the Gruvberget–Sumåssjön intrusion, mineralised sample DCL234011A from drill core SUM81017 at 76.62–76.68 m (see fig. C30 for panorama). **A.** Overview of relations between magnetite, ilmenite, and sulphide minerals in an opaque framework. **B.** Overview of relations between magnetite and ilmenite in another part of the same thin section as A, still lots of ilmenite. **C.** Grains of sulphide minerals consisting of chalcopyrite with cubanite alteration and possible pyrrhotite with pyrite and marcasite alteration, surrounded by magnetite and silicate minerals. All images in reflected light. Photo: Dick Claeson.

Description of thin sections – silicate minerals

Euhedral to anhedral grains, interstitially grown crystals, and aggregates of hornblende with biotite and opaque minerals occur in sample DCL222011B from drill core SUM81005 at 2.36–2.42 m (figs. 110A–B). Hornblende has several grain triple junctions at 120 degrees, an igneous granoblastic texture that signifies textural equilibrium in cumulate rocks (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Clinopyroxene occurs as subhedral to anhedral grains and interstitially grown crystals, with lamellae and opaque exsolutions. Olivine is subhedral to anhedral occurring as interstitially grown crystals. Subhedral to anhedral plagioclase is present, in parts with patchy sericite-saussurite alteration. A few brownish red biotite crystals and rare quartz grains with slightly undulose extinction are observed.

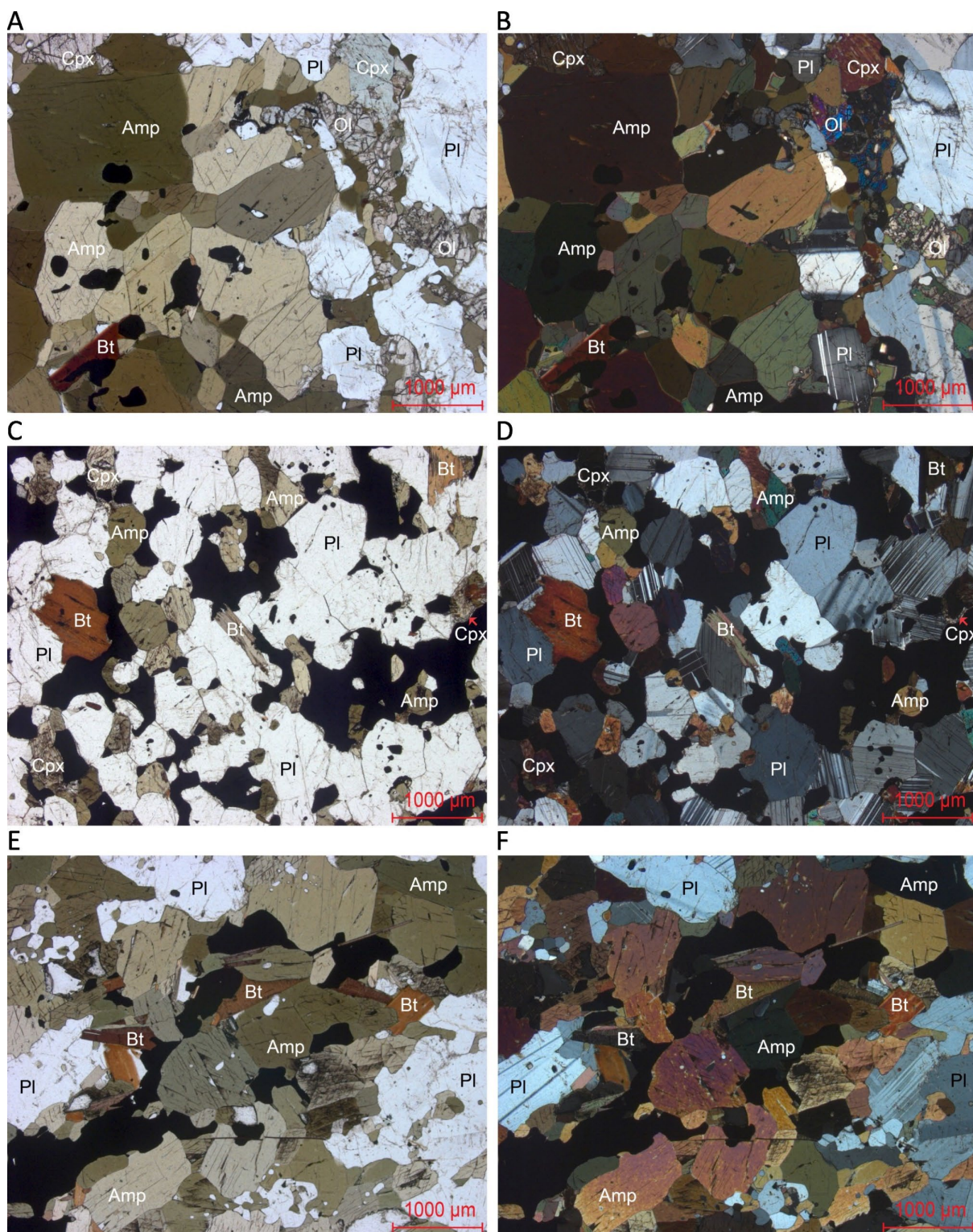


Figure 110. A. and B. Sample DCL222011B from drill core SUM81005 at 2.36–2.42 m, with several hornblende grain triple junctions at 120 degrees, and plagioclase, clinopyroxene, olivine, and minor biotite. C. and D. Sample DCL222012B from drill core SUM81005 at 32.40–32.47 m. Hornblende is the main mafic silicate mineral occurring together with biotite and rare clinopyroxene. E. and F. Sample DCL222013B from drill core SUM81005 at 82.91–82.96 m. Aggregate dominated by hornblende together with Fe-Ti oxides and biotite. Left in ppl and right in xpl. Photo: Dick Claeson.

The mineralised cumulate rock of sample DCL222012B from drill core SUM81005 at 32.40–32.47 m (panorama fig. C22), is well-preserved with hornblende as the main mafic silicate mineral (figs. 110C–D). Rare, small clinopyroxene crystals occur. Plagioclase is subhedral to anhedral and two generations of biotite are observed, one generation shows brownish red to brown pleochroism and the second generation are brownish red to light tan. A few fine-grained crystals of apatite are present.

The cumulate rock of sample DCL222013B from drill core SUM81005 at 82.91–82.96 m has hornblende, clinopyroxene, olivine, biotite, plagioclase, and quartz as silicate minerals. Euhedral to anhedral hornblende occurs as grains, interstitially grown crystals, and aggregates with Fe-Ti oxides and biotite (figs. 110E–F). Hornblende has several grain triple junctions at 120 degrees. Subhedral to anhedral olivine and clinopyroxene are found as grains and interstitially grown crystals, the latter with lamellae and opaque exsolutions (figs. 111A–B). Subhedral to anhedral plagioclase occur, with patchy sericite-saussurite alteration. Two generations of biotite are present, the first generation has brownish red to brown pleochroism and the second brownish red to tan, often occurring in aggregates with hornblende. Rare quartz grains with slightly undulose extinction are observed.

The mineralised cumulate rock in sample DCL222017B from drill core SUM82010 at 31.00–31.05 m (panorama fig. C23), is well-preserved with clinopyroxene and olivine as main mafic silicate minerals (figs. 111C–D). Subhedral to anhedral clinopyroxene is present as grains and interstitially grown crystals with lamellae and opaque exsolution. Anhedral small to large grains and interstitially grown olivine occurs. Relatively few small grains and interstitially grown hornblende crystals are observed. Subhedral to anhedral plagioclase is present and also two generations of biotite, the first showing brownish red pleochroism and the second brownish red to tan.

A mostly coarse-grained cumulate rock, sample DCL222018B from drill core SUM82010 at 57.99–58.10 m, is well-preserved and the silicate minerals consists mainly of clinopyroxene, hornblende, and plagioclase (figs. 111E–F). Clinopyroxene has lamellae and opaque exsolution. Hornblende is anhedral to euhedral and occurs in aggregates with Fe-Ti oxides. Plagioclase is subhedral to anhedral. Olivine is a minor mineral. Orthopyroxene is absent except for rare cases where it occurs in intergrowth with clinopyroxene. Two generations of biotite are present, the first displaying brownish red to light brown pleochroism and the second brownish red to tan. A few grains of quartz with slightly undulose extinction and possibly alkali feldspar occurs together with quartz.

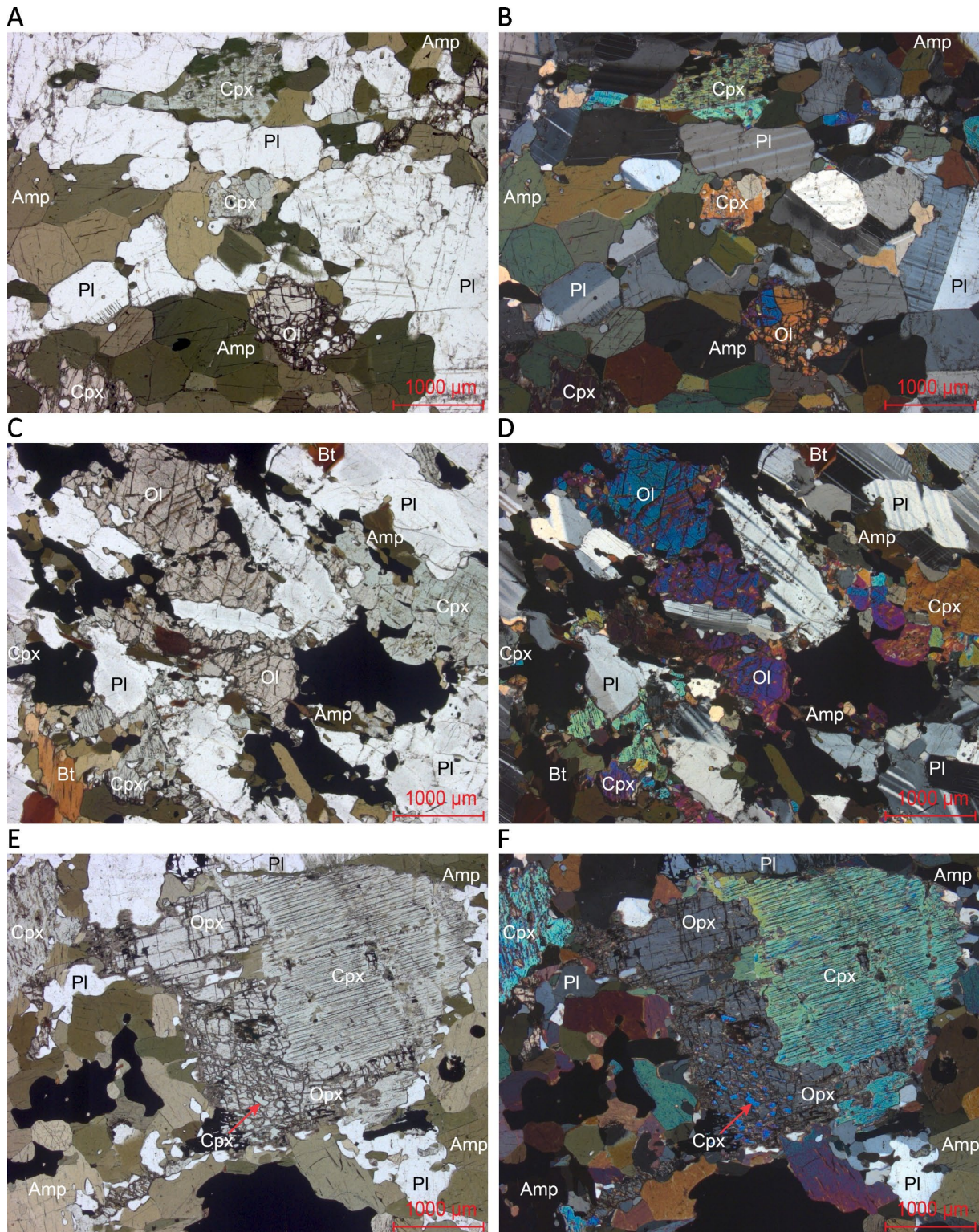


Figure 111. A. and B. Sample DCL222013B from drill core SUM81005 at 82.91–82.96 m, with grains of hornblende, olivine, clinopyroxene, and plagioclase in a cumulate rock. C. and D. Sample DCL222017B from drill core SUM82010 at 31.00–31.05 m, with clinopyroxene and olivine main mafic silicate minerals in a mineralised sample. E. and F. Sample DCL222018B from drill core SUM82010 at 57.99–58.10 m, where rare intergrowth of orthopyroxene and clinopyroxene is observed. Left in ppl and right in xpl. Photo: Dick Claeson.

The mineralised sample DCL222020B from drill core SUM82007 at 21.66–21.73 m (panorama fig. C24), is well-preserved with a strong preferred orientation of minerals. Hornblende is the main mafic silicate mineral (figs. 112A–B). Subhedral to anhedral hornblende and plagioclase occur both as grains and interstitially grown crystals. Plagioclase has minor sericite-saussurite alteration. A few grains of biotite with brownish red to light brown pleochroism are present.

Hornblende is the main mafic silicate mineral of sample DCL222021B from drill core SUM82007 at 23.45–23.52 m (figs. 112C–D) and occurs as euhedral to anhedral grains and interstitially grown crystals. Hornblende has several grain triple junctions at 120 degrees, leading to an igneous granoblastic texture that signifies textural equilibrium in cumulate rocks (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Plagioclase crystals are subhedral to anhedral and most have patchy sericite-saussurite alteration. Very few, small, altered grains of biotite are present and quartz grains with weak undulose extinction occur.

Anhedral to subhedral hornblende is the main mafic silicate mineral of sample DCL222022B from drill core SUM82004 at 6.12–6.17 m (panorama fig. C25), a well-preserved mineralised cumulate rock (figs. 112E–F). Plagioclase is anhedral to subhedral. The subhedral shapes of hornblende and plagioclase are mostly found where these minerals are not in contact with Fe-Ti oxides. Two generations of biotite are found, the first generation has brownish red to light brown pleochroism and the second brownish red to tan. A few grains of quartz with weak undulose extinction are present.

The well-preserved mineralised sample DCL222023B from drill core SUM82004 at 37.85–37.89 m (panorama fig. C26), has a distinct fabric of parallel-oriented minerals. Anhedral to subhedral hornblende, clinopyroxene, and olivine occur as grains and interstitially grown crystals (figs. 113A–B). Anhedral to subhedral plagioclase has minor patches of sericite-saussurite alteration. In contact with Fe-Ti oxides plagioclase has embayments and cusps related to dissolution from a hydrous Fe-Ti-rich liquid. Some plagioclase crystals have bends or kinks, deformation twins and undulose extinction formed during compaction of a crystal pile or mush while they were still hot (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). Two generations of biotite are found, the first has brownish red pleochroism and the second brownish red to tan.

Mineralised sample DCL222024B from drill core SUM82014 at 87.97–88.03 m (panorama fig. C27), is mostly fine-grained and well-preserved. Anhedral to subhedral hornblende, clinopyroxene, olivine, and plagioclase occur as small grains (figs. 113C–D). The subhedral shapes are mostly where these minerals are not in mutual contact with Fe-Ti oxides. Hornblende has grain triple junctions at 120 degrees, an igneous granoblastic texture that signifies textural equilibrium in cumulate rocks (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Biotite has brownish red to tan pleochroism.

Hornblende is the main mafic silicate mineral of sample DCL230024A from drill core SUM81006 at 92.5–92.55 m (figs. 113E–F), a well-preserved cumulate rock, except for patchy sericite-saussurite alteration of plagioclase. Euhedral to anhedral hornblende occurs as grains and interstitially grown crystals. Rare, small grains of brownish red biotite and quartz grains with slightly undulose extinction are observed. Hornblende has grain triple junctions at 120 degrees.

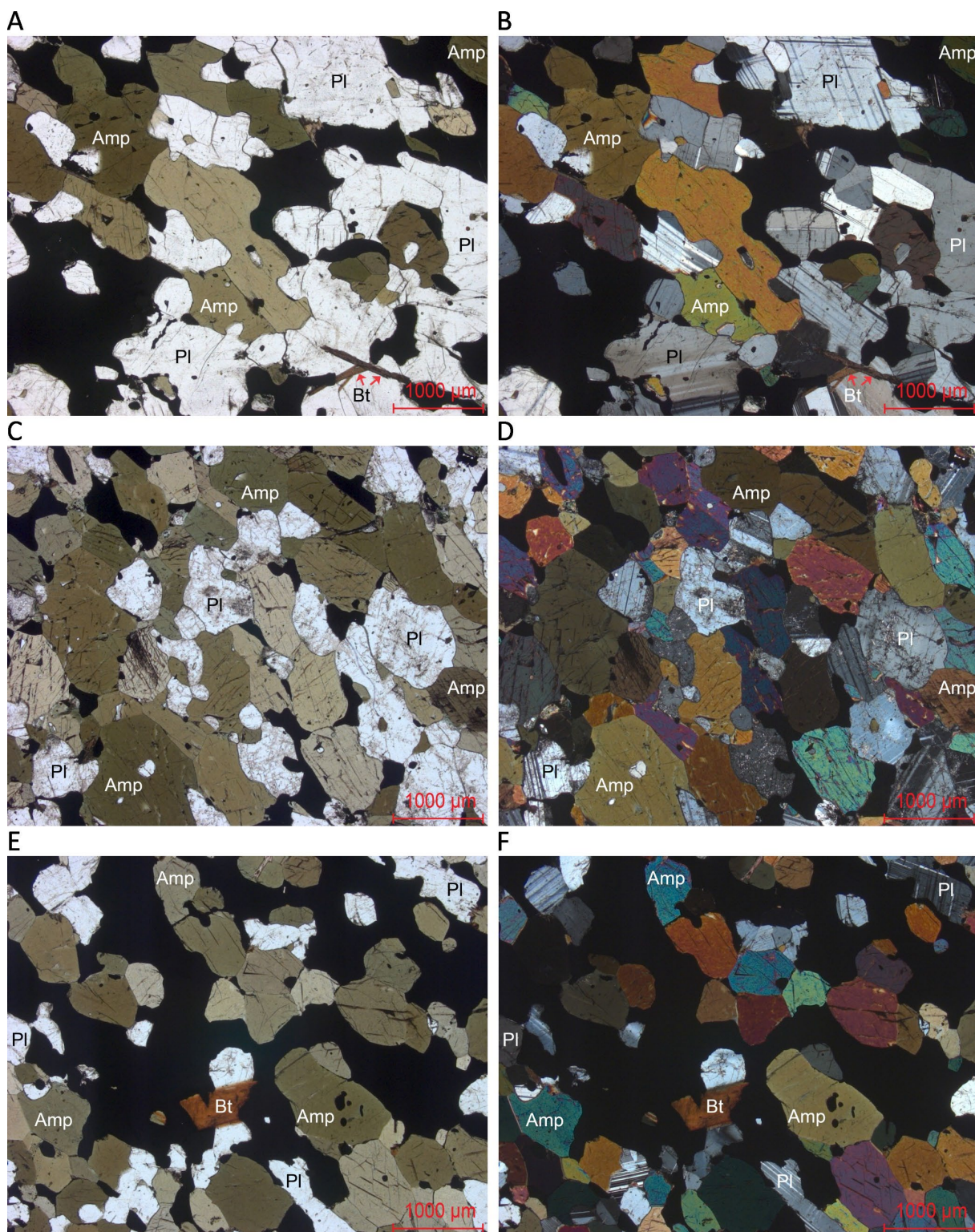


Figure 112. A. and B. Mineralised sample DCL222020B from drill core SUM82007 at 21.66–21.73 m, with hornblende as main mafic silicate mineral. Note mostly anhedral silicate crystals. C. and D. Sample DCL222021B from drill core SUM82007 at 23.45–23.52 m, where euhedral to anhedral hornblende is the main mafic silicate mineral with several grain triple junctions at 120 degrees. E. and F. Sample DCL222022B from drill core SUM82004 at 6.12–6.17 m, a mineralised sample with hornblende as main mafic silicate mineral. Note mostly anhedral silicate crystals when in contact with Fe-Ti oxides. Left in ppl and right in xpl. Photo: Dick Claeson.

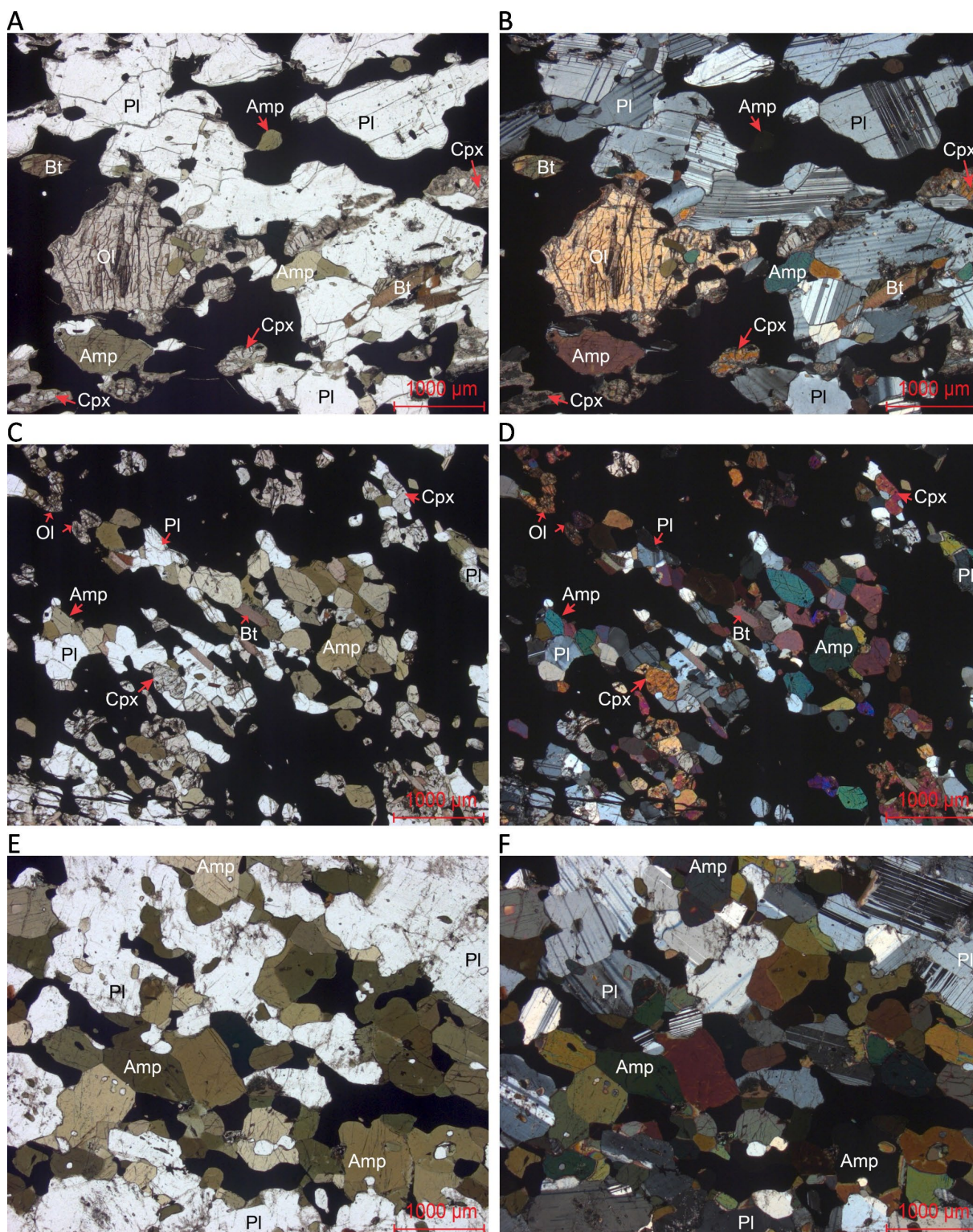


Figure 113. **A.** and **B.** Mineralised sample DCL222023B from drill core SUM82004 at 37.85–37.89 m where plagioclase has dissolution features as embayments and cusps. Note bend or kink in plagioclase in centre of image, also with deformation twins and undulose extinction. **C.** and **D.** Sample DCL222024B from drill core SUM82014 at 87.97–88.03 m, mostly anhedral grains but for areas without contact to Fe–Ti oxides. Hornblende grain triple junctions at 120 degrees. **E.** and **F.** Sample DCL230024A from drill core SUM81006 at 92.50–92.55 m, hornblende and plagioclase dominated cumulate rock. Hornblende grain triple junctions at 120 degrees. Left in ppl and right in xpl. Photo: Dick Claeson.

The well-preserved sample DCL230025A from drill core SUM81006 at 5.14–5.22 m has euhedral to anhedral hornblende as the main mafic silicate mineral, which occurs as grains and interstitially grown crystals (figs. 114A–B). Subhedral to anhedral clinopyroxene has lamellae and opaque exsolutions. Subhedral to anhedral plagioclase has patchy sericite-saussurite alteration. Apatite occurs as rare small anhedral crystals. Interstitially grown quartz grains have slightly undulose extinction.

Sample DCL230026A from drill core SUM81014 at 91.45–91.52 m displays mineral compositional layering (panorama fig. C29). The cumulate rock is well-preserved and euhedral to anhedral hornblende is the main mafic silicate mineral occurring as grains and interstitially grown crystals (figs. 114C–D). Plagioclase grains are subhedral to anhedral where some plagioclase crystals look consumed, dissolved in contact with opaque minerals. Two generations of biotite are present, the first generation has brownish red to brown pleochroism and the second brownish red to tan. A few subhedral apatite crystals are observed.

Hornblende is the main mafic silicate mineral of sample DCL230027A from drill core SUM81014 at 27.78–27.84 m, occurring as euhedral to anhedral grains and interstitially grown crystals (figs. 114E–F). It has triple junctions at 120 degrees, and an igneous granoblastic texture. A few subhedral to anhedral clinopyroxene grains, with lamellae and opaque exsolutions, in some cases altered to secondary green amphibole are present. Subhedral to anhedral plagioclase has patchy to severe sericite-saussurite alteration. Some plagioclase crystals have bends or kinks, deformation twins, and undulose extinction formed while they were hot and results from the process of compaction of a crystal pile or mush (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). A few, small grains of biotite with brownish red to brown pleochroism are observed. Rare apatite crystals and a few quartz grains with slightly undulose extinction are present.

The well-preserved sample DCL230028A from drill core SUM81022 at 44.18–44.25 m has clinopyroxene and olivine as the main mafic silicate minerals along with biotite, hornblende, and plagioclase (fig. 115). Subhedral to anhedral clinopyroxene occur as grains and interstitially grown crystals, often intergrown with olivine. Olivine is subhedral to anhedral, occurring as small to large grains and is interstitially grown. Subhedral to anhedral plagioclase has patches of sericite-saussurite alteration. Some plagioclase crystals have bends or kinks, deformation twins, and undulose extinction formed while they were hot, which results from the process of compaction of a crystal pile or mush (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). Dark grey pigmentation is observed in the central portion of early-formed plagioclase crystals. This is lacking in plagioclase rims that formed interstitially at a late stage. Relatively few subhedral to anhedral hornblende grains have grown interstitially. Two generations of biotite are present, the first generation has brownish red to brown pleochroism and the second brownish red to tan.

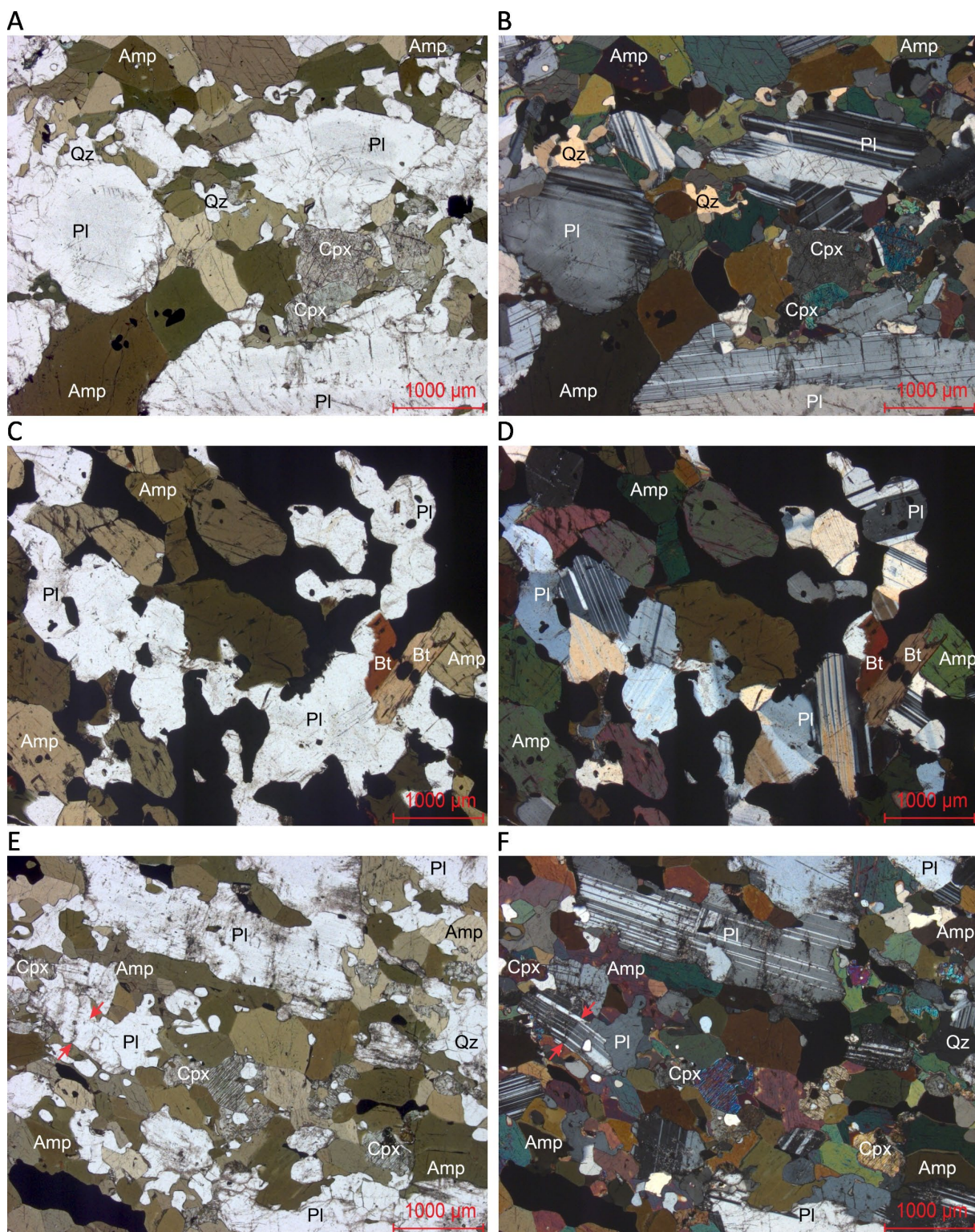


Figure 114. A. and B. Sample DCL230025A from drill core SUM81006 at 5.14–5.22 m, containing hornblende, clinopyroxene, plagioclase, and interstitial quartz in a cumulate rock. C. and D. Sample DCL230026A is from drill core SUM81014 at 91.45–91.52 m, having hornblende as main mafic silicate mineral. Some plagioclase crystals are partially dissolved in contact with opaque minerals. E. and F. Sample DCL230027A from drill core SUM81014 at 27.78–27.84 m. Note plagioclase crystal that has bend or kink between the two red arrows. Hornblende grain triple junctions at 120 degrees. Left in ppl and right in xpl. Photo: Dick Claeson.

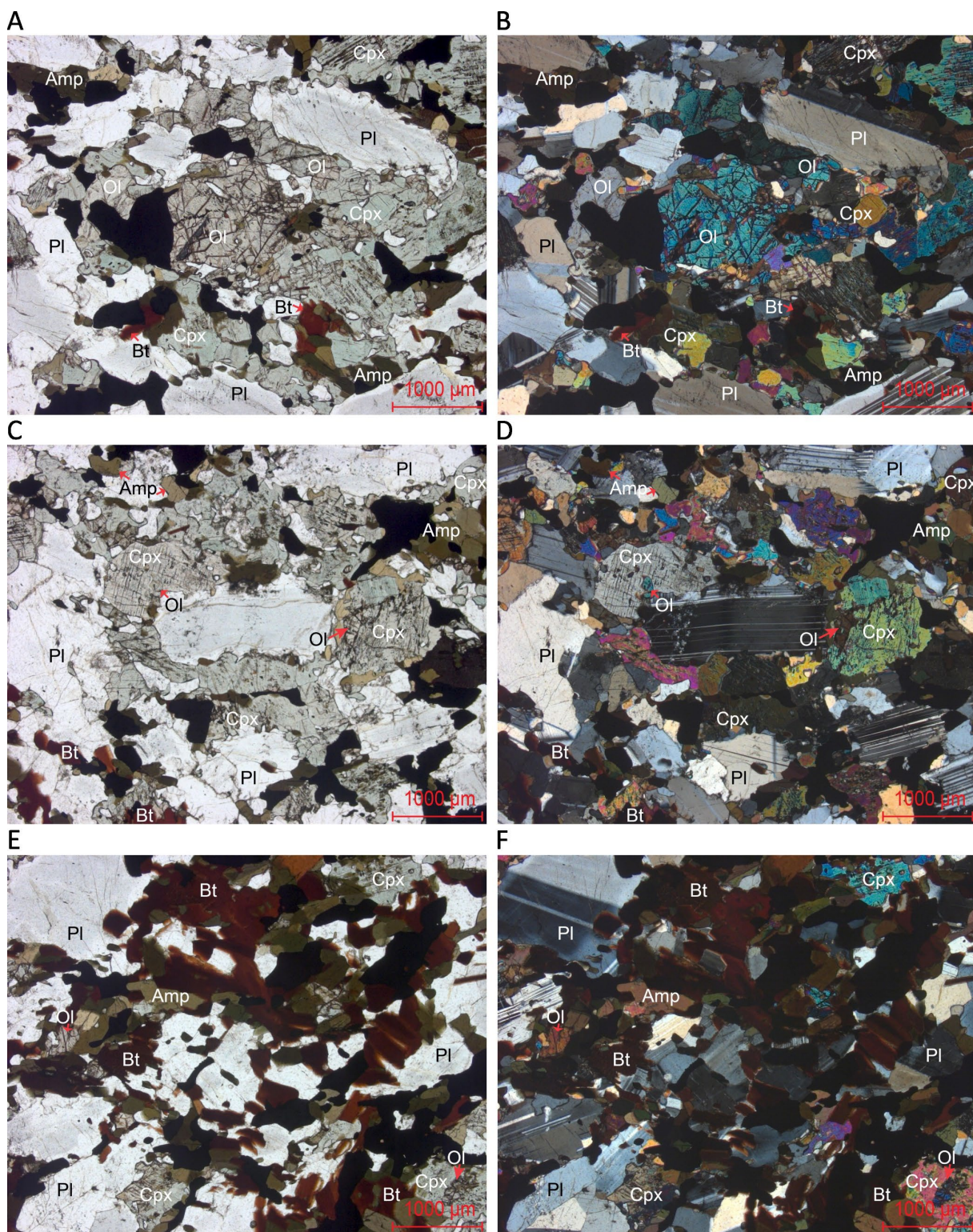


Figure 115. A. and B. Intergrown clinopyroxene and olivine. Note strong pigmentation in central parts of large plagioclase crystals and less in the perimeter. C. and D. Bend or kink in centre of plagioclase in centre of image, along with deformation twins and undulose extinction. Note strong pigmentation in central parts of large plagioclase crystals and less in the perimeter. E. and F. Late-forming aggregate of interstitial biotite, hornblende, and Fe-Ti oxides between plagioclase crystals. All images are from sample DCL230028A from drill core SUM81022 at 44.18–44.25 m. Left in ppl and right in xpl. Photo: Dick Claeson.

The mineralised cumulate rock of sample DCL234011A from drill core SUM81017 at 76.62–76.68 m (panorama fig. C30), is well-preserved with insignificant alteration of clinopyroxene to green amphibole and plagioclase to sericite-saussurite. Hornblende is the main mafic silicate mineral, having subhedral to anhedral grains, mostly isolated within the framework of Fe-Ti oxides (figs. 116A–D). Subhedral to anhedral plagioclase as mostly isolated grains occur within opaque framework, with some crystals displaying bends or kinks, deformation twins, and undulose extinction formed while they were hot and results from the process of compaction of a crystal pile or mush (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). Abundant biotite occurs as two generations, the first have brownish red to red pleochroism and the second brownish red to tan.

Sample HRE220006A is well-preserved with grains, interstitially grown, and aggregates of euhedral to anhedral hornblende (figs. 116E–F). Olivine is often intergrown with clinopyroxene, both with subhedral to anhedral grains and interstitially grown crystals. Clinopyroxene has lamellae and opaque exsolutions. Plagioclase is subhedral to anhedral. Few biotite crystals with brownish red to tan pleochroism, are found in aggregates with hornblende and Fe-Ti oxides. Quartz occurs as small to large grains with slightly undulose extinction.

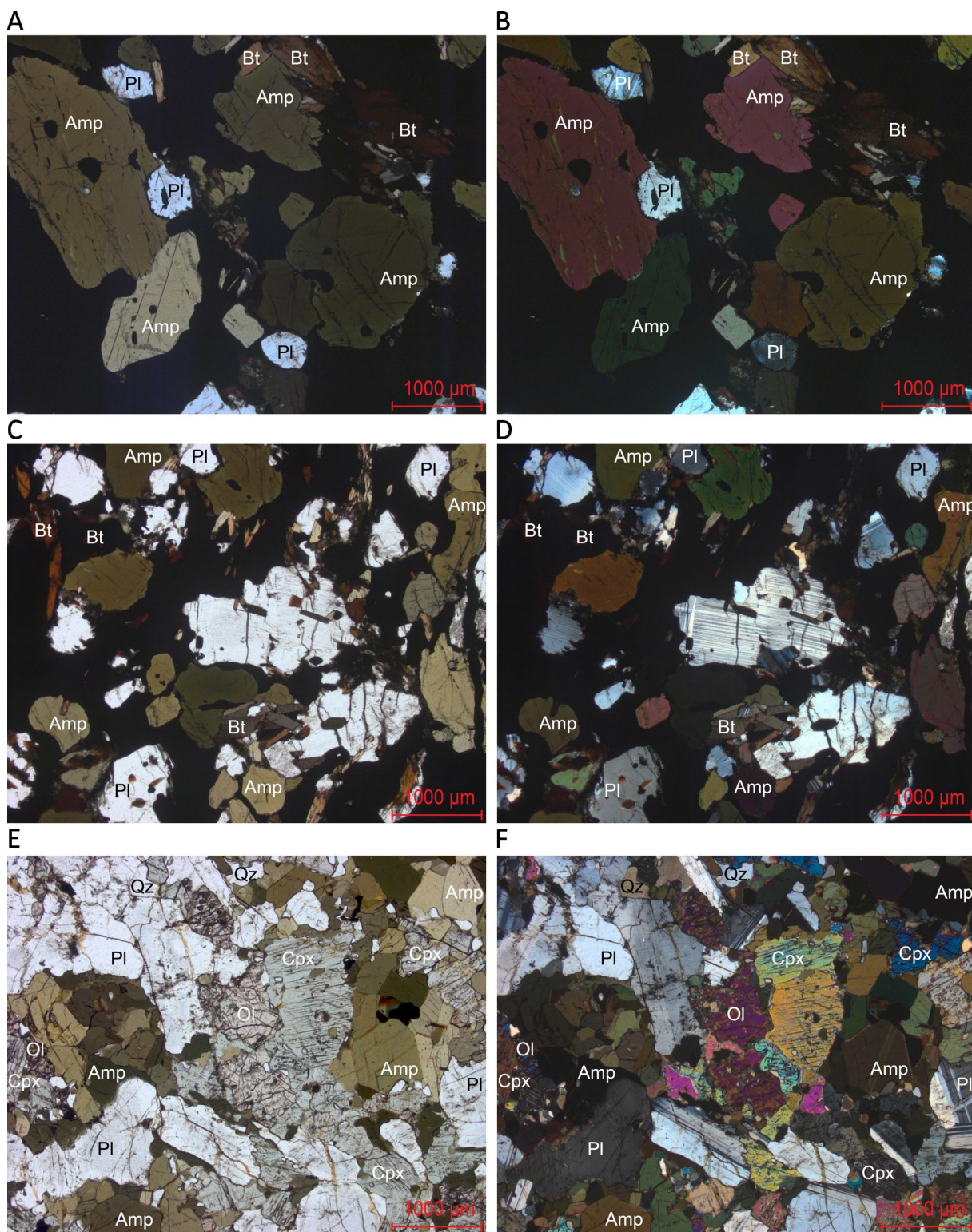


Figure 116. **A.** and **B.** Hornblende, plagioclase, and biotite as mostly isolated grains within opaque framework. **C.** and **D.** Large plagioclase in centre of image has bends or kinks, deformation twins, and undulose extinction due to compaction of crystals while hot. Images from sample DCL234011A from drill core SUM81017 at 76.62–76.68 m. **E.** and **F.** Intergrown olivine and clinopyroxene and aggregates of hornblende, biotite, and Fe-Ti oxides. Sample HRE220006A (6869674/582028). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data from Gruvberget–Sumåssjön

Previous geochemical analyses of the 54 drill cores from Gruvberget–Sumåssjön were performed at Swedish Mineralprocesses AB (Minpro AB) during 1981–1982 which included the elements Fe and V. Analogue data from these cores ($n = 547$) was digitised during this project. The linear relationship between Fe and V in these analyses is excellent (fig. 117) with a Pearson coefficient (r) of 0.97. When the new geochemical data from gabbroids ($n = 28$) obtained in this project are included the Pearson coefficient is 0.98.

Variations in vanadium contents with depth in the drill cores are shown in figures 118, 119, and 120. The section intervals used in the older analyses are much longer (c. 3–10 m) than those used in this project (c. 1 m), but overall, the results from the old and new analyses are very consistent.

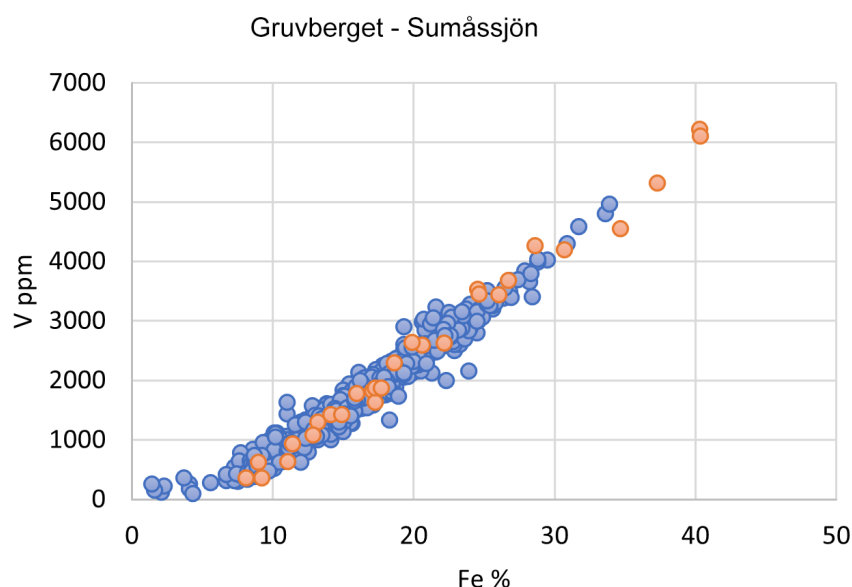


Figure 117. Fe and V contents in gabbroids at Gruvberget–Sumåssjön. Blue dots are drill core analyses from 1981–1982 ($n = 547$) digitised in the current project and the orange are new analyses obtained in the current project from drill cores ($n = 25$) and outcrops ($n = 3$). The positive correlation is very good with a Pearson coefficient (r) for the whole dataset of 0.98. The average V:Fe ratio is 0.01.

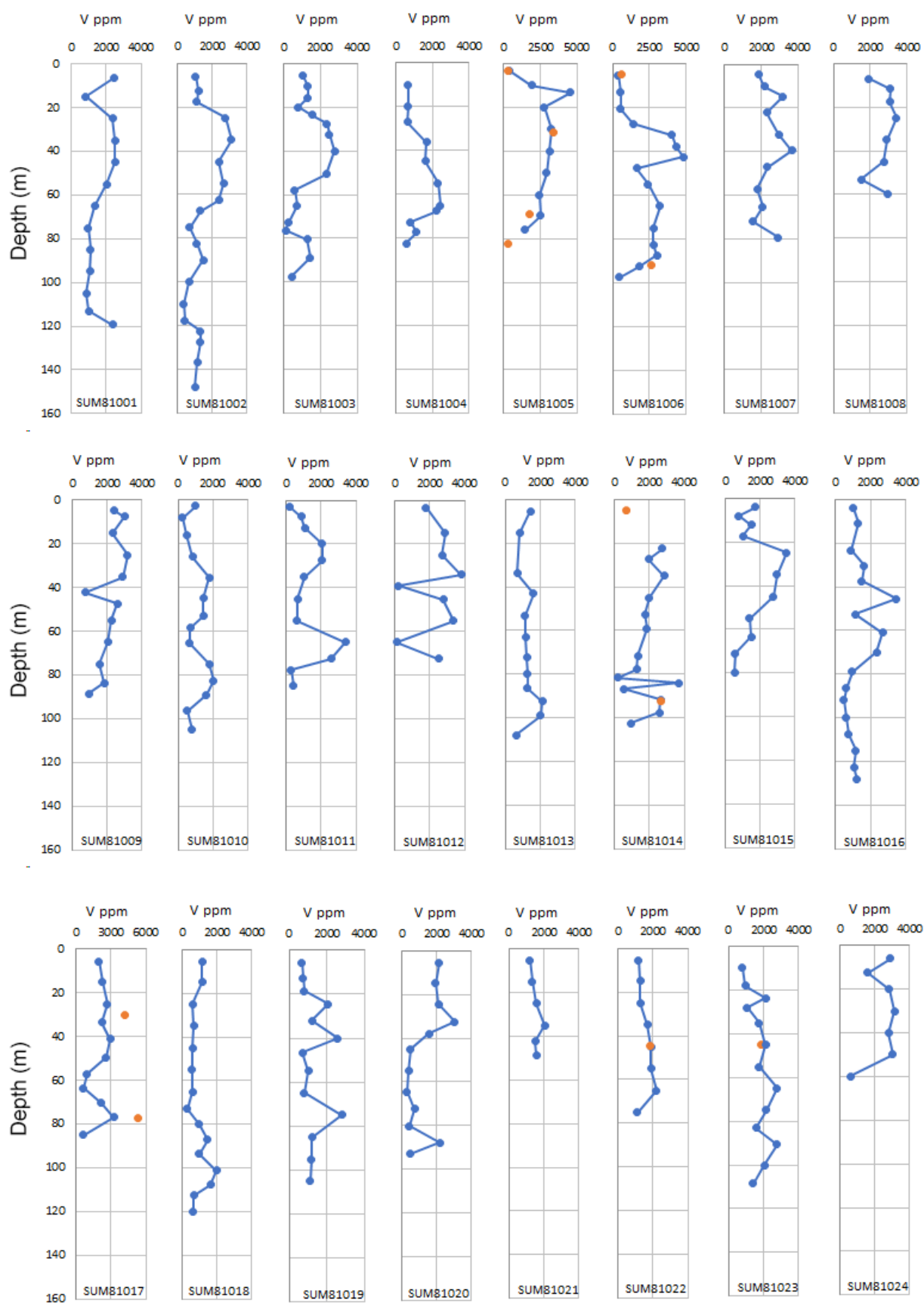


Figure 118. Variations in vanadium contents with depth in Gruvberget–Sumåssjön drill cores. Blue dots are drill core analyses from 1981 and the orange are analyses obtained in the current project. Note that the scale on the X-axis (V ppm) is not the same for all samples.

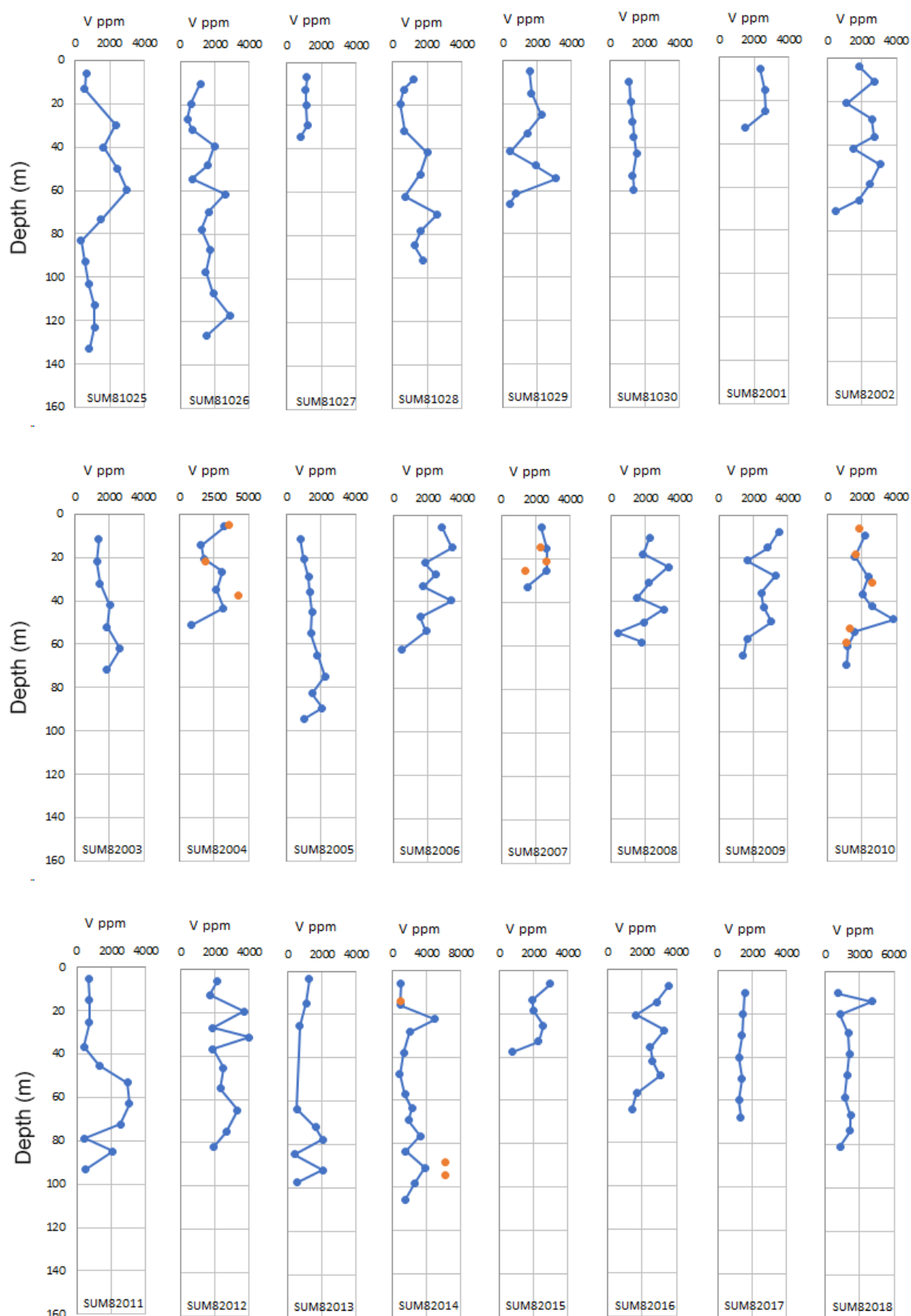


Figure 119. Variations in vanadium contents with depth in Gruvberget–Sumåssjön drill cores. Blue dots are drill core analyses from 1981–1982 and the orange are analyses obtained in the current project. Note that the scale on the X-axis (V ppm) is not the same for all samples.

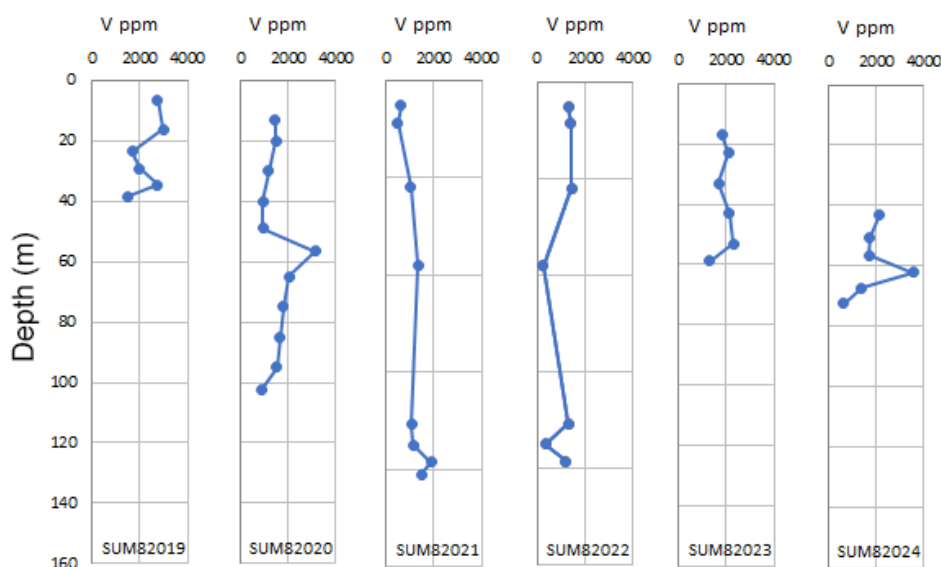


Figure 120. Variations in vanadium contents with depth in Gruvberget–Sumåssjön drill cores. Blue dots are drill core analyses from 1982.

The compositional variations in the Gruvberget–Sumåssjön samples collected and analysed in the current project ($n = 28$) span a large range from barren gabbro to strongly Fe-Ti-V mineralised ore-samples. SiO_2 varies from 17.05 to 50.80%, Al_2O_3 (8.72–17.65%), Fe_2O_3 (11.55–57.70%, average 30.35%), CaO (3.33–10.40%), MgO (2.16–6.76%), Na_2O (1.01–3.12%), K_2O (0.21–0.98%), MnO (0.15–0.26%), P_2O_5 (0.01–0.14%) and TiO_2 (0.96–8.09%, average 4.17%). Vanadium varies from 358 to 6 220 ppm with an average of 2 645 ppm, and 23 samples have more than 1 000 ppm V.

Harker diagrams of selected major element oxides and trace elements are shown in figures 121 and 122. Fe_2O_3 ($r = -0.99$) and TiO_2 ($r = -0.99$) show excellent negative correlations against SiO_2 , while CaO ($r = 0.99$) has positive correlations.

For SiO_2 contents below 30–35% there is positive correlation for Al_2O_3 and Na_2O with SiO_2 . With higher SiO_2 contents the pattern is more scattered.

Binary plots of vanadium against selected oxides and trace elements are shown in figure 122. Vanadium shows positive correlations with TiO_2 ($r = 0.99$), Fe_2O_3 ($r = 0.99$), Zn ($r = 0.96$), In ($r = 0.94$), Co ($r = 0.90$), Ga ($r = 0.90$), Cu ($r = 0.89$), Ce ($r = -0.90$), Ni ($r = 0.88$) and Ge ($r = 0.85$) (Table 9). Negative correlations are observed for SiO_2 ($r = -0.99$), CaO ($r = -0.98$), Na_2O ($r = -0.88$), Y ($r = -0.92$), La ($r = -0.90$) (Table 9). Negative correlations (not shown in Table 9) also exist for Sm ($r = -0.87$) and Yb ($r = -0.90$).

The content of nickel lies within the range of 31 to 319 ppm with an average of 116 ppm. Copper concentrations are 51–528 ppm (average 226 ppm). Zinc contents vary from 90 to 326 ppm (average 180 ppm). Cobalt and chromium contents are low; Co ranges from 48 to 222 ppm (average 109 ppm) and Cr contents are in the range of <5 to 336 ppm with an average of 40 ppm.

Gallium concentrations are in the range of 15–48 ppm (average 31 ppm) and show positive correlation with Fe_2O_3 ($r = 0.90$), TiO_2 ($r = 0.90$), V ($r = 0.90$), Zn ($r = 0.87$), and In ($r = 0.85$).

Scandium contents are in the range of 13–51 ppm, with an average of 33 ppm. Yttrium varies from 5 to 29 ppm, average 15 ppm.

The ΣREE (not including scandium or yttrium) contents vary from 13 to 64 ppm (average 44 ppm).

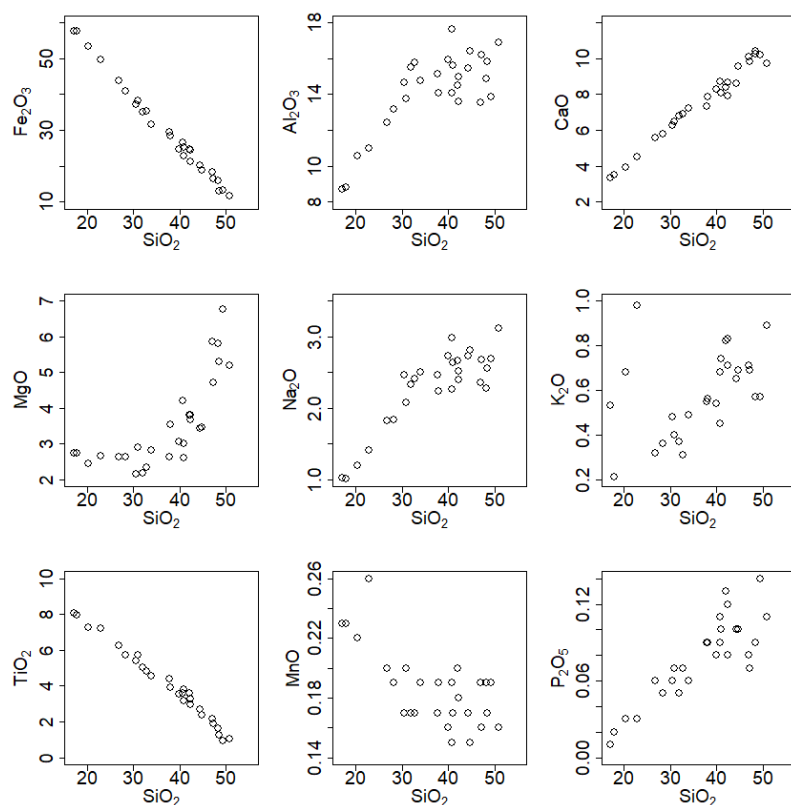


Figure 121. Harker diagrams for major elements vs. SiO_2 in Gruvberget–Sumåssjön samples. All concentrations are in %.

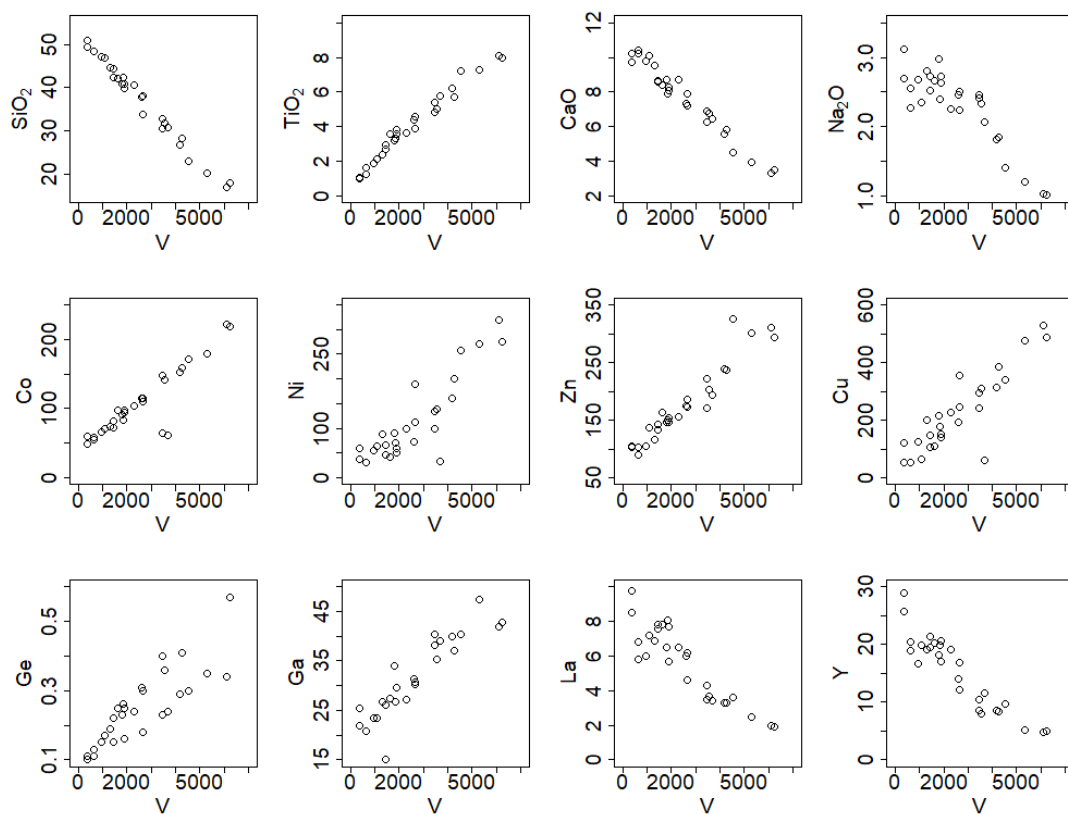


Figure 122. Harker diagrams for vanadium (ppm) vs. selected major and trace elements in Gruvberget–Sumåssjön samples. Major element oxide concentrations are in %. Trace elements are reported as ppm.

Table 9. Pearson correlation matrix for selected elements from Gruvberget–Sumåssjön samples (n = 28).

	V	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	Ce	Co	Cu	Ga	Ge	In	La	Ni	Y	Zn
V	1,00																
SiO₂	-0.99	1.00															
TiO₂	0.99	-0.99	1.00														
Al₂O₃	-0.79	0.78	-0.77	1.00													
Fe₂O₃	0.99	-1.00	0.99	-0.82	1.00												
CaO	-0.98	0.99	-0.99	0.78	-0.99	1.00											
Na₂O	-0.88	0.87	-0.85	0.95	-0.89	0.85	1.00										
Ce	-0.90	0.90	-0.87	0.66	-0.89	0.84	0.82	1.00									
Co	0.90	-0.91	0.89	-0.80	0.91	-0.90	-0.84	-0.79	1.00								
Cu	0.89	-0.89	0.85	-0.71	0.88	-0.88	-0.77	-0.80	0.93	1.00							
Ga	0.90	-0.91	0.90	-0.59	0.90	-0.90	-0.70	-0.84	0.77	0.79	1.00						
Ge	0.85	-0.82	0.82	-0.63	0.82	-0.82	-0.69	-0.75	0.85	0.78	0.78	1.00					
In	0.94	-0.91	0.91	-0.81	0.93	-0.91	-0.86	-0.83	0.85	0.78	0.85	0.85	1.00				
La	-0.90	0.91	-0.88	0.65	-0.89	0.85	0.81	0.99	-0.78	-0.79	-0.84	-0.74	-0.82	1.00			
Ni	0.88	-0.89	0.85	-0.81	0.89	-0.88	-0.85	-0.80	0.93	0.96	0.77	0.72	0.77	-0.79	1.00		
Y	-0.92	0.93	-0.91	0.62	-0.91	0.89	0.78	0.96	-0.82	-0.83	-0.87	-0.81	-0.82	0.96	-0.80	1.00	
Zn	0.96	-0.97	0.97	-0.83	0.97	-0.97	-0.88	-0.83	0.93	0.87	0.87	0.79	0.87	-0.83	0.91	-0.86	1.00

In the AFM diagram all the samples show strong Fe-enrichment and plot in the tholeiite field (fig. 123).

Primitive mantle normalised trace-element compositions are shown in figure 124. A characteristic feature is the negative Nb anomaly, and positive Pb and Ti anomalies.

Chondrite normalised REE patterns from drill core and outcrops show weakly enriched LREE patterns (fig. 125) with $(La/Yb)_N$ in the range 1.85–3.28. The $(La/Sm)_N$ values are between 1.41 and 2.33 indicating moderate fractionation between the LREEs. Slight degree of fractionation among the HREEs is shown by the $(Gd/Yb)_N$ ratios (1.10–1.53) and by $(Dy/Yb)_N$ ratios in the range 0.85–1.37.

The REE patterns are generally subparallel except for the Eu anomalies where 16 samples show negative (Eu/Eu^*) , spanning the interval 0.71–0.99. Twelve samples have positive Eu/Eu^* (in the range 1.01–1.21).

The REE patterns reflect different degrees of fractional crystallisation. The Eu anomalies can be attributed to fractionation and accumulation of plagioclase.

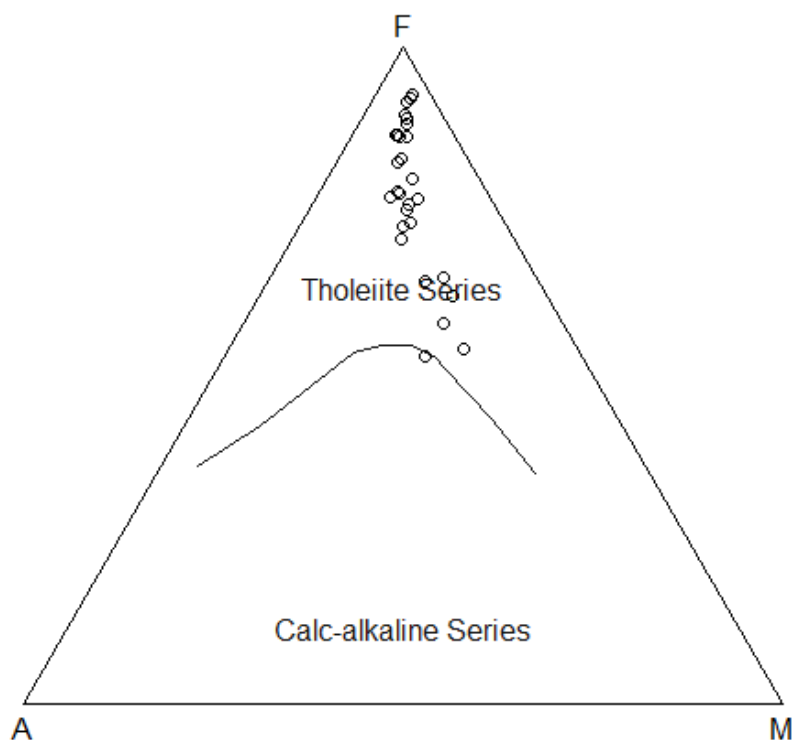


Figure 123. The samples from Gruvberget–Sumåssjön plotted in an AFM–diagram (Irvine & Baragar 1971).

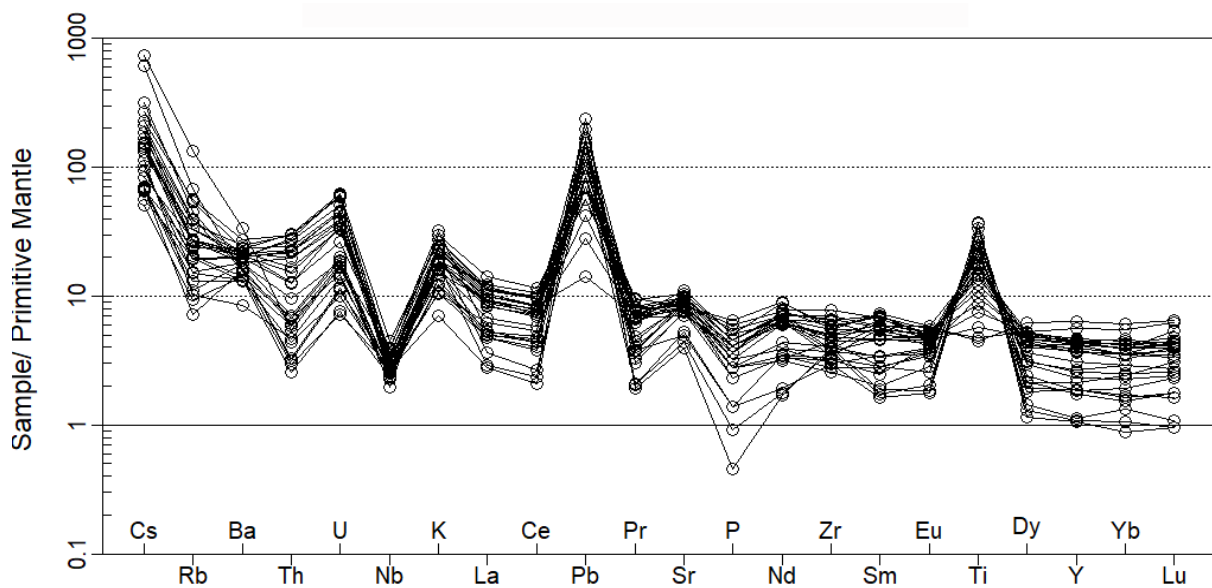


Figure 124. Primitive mantle normalised diagram for Gruvberget–Sumåssjön samples. Normalising values from Sun & McDonough (1989).

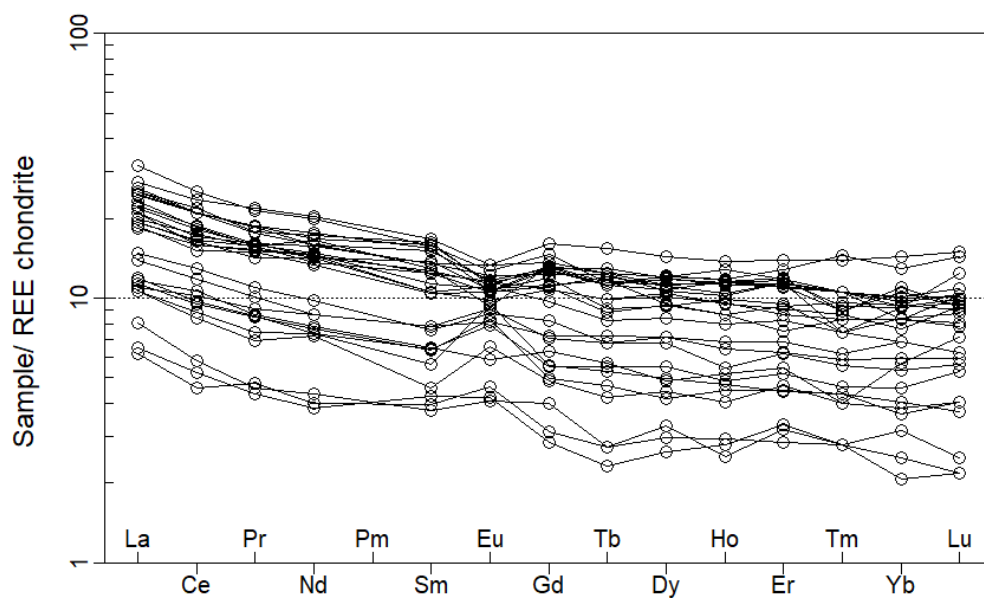


Figure 125. Chondrite normalised REE diagram for samples from Gruvberget–Sumåssjön. The samples are characterised by moderately enriched $(La/Yb)_N$ ratios in the range 1.85–3.28. Chondrite values are from Boynton (1984).

Most of the samples plot in the field of destructive-margin volcanic basalts (CAB and IAT) in the triangular Th-Hf-Nb diagram (fig. 126). In the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams the sample suite mostly group in the volcanic arc fields (figs. 127A and 127B).

Overall, the geochemical signature is similar to that of the Kramsta intrusion and both intrusions most likely formed in the same tectonomagmatic environment. The geochemical characteristics, with a negative Nb and positive Pb anomaly, and the incompatible trace-element ratios (figs. 126 and 127) favour an interpretation of the tectonomagmatic environment as that of a volcanic-arc, most probably related to an active margin. The ubiquitous positive Ti-anomaly that is observed in the sample suite (similar to the Kramsta intrusion) is best explained by accumulation of titanomagnetite.

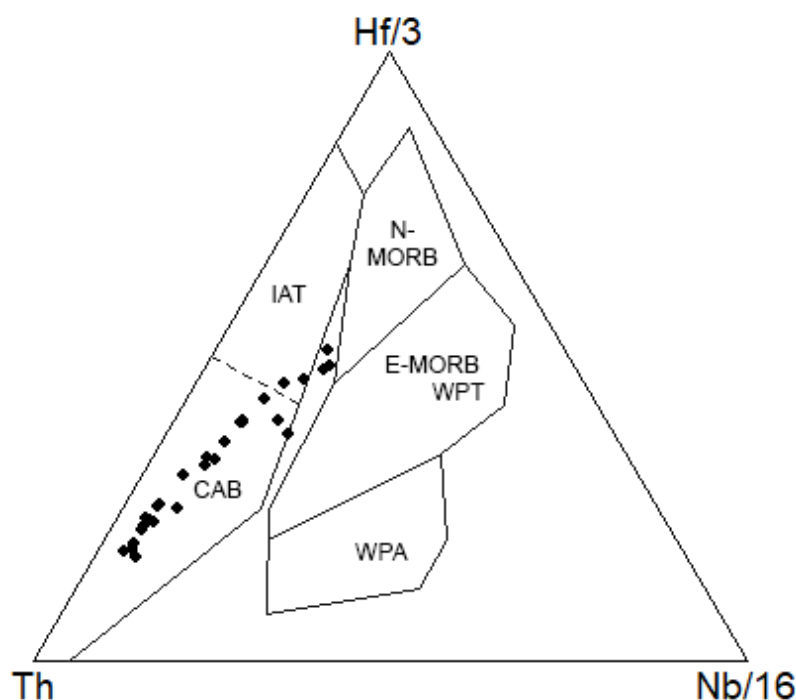


Figure 126. Gruvberget–Sumåssjön samples plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

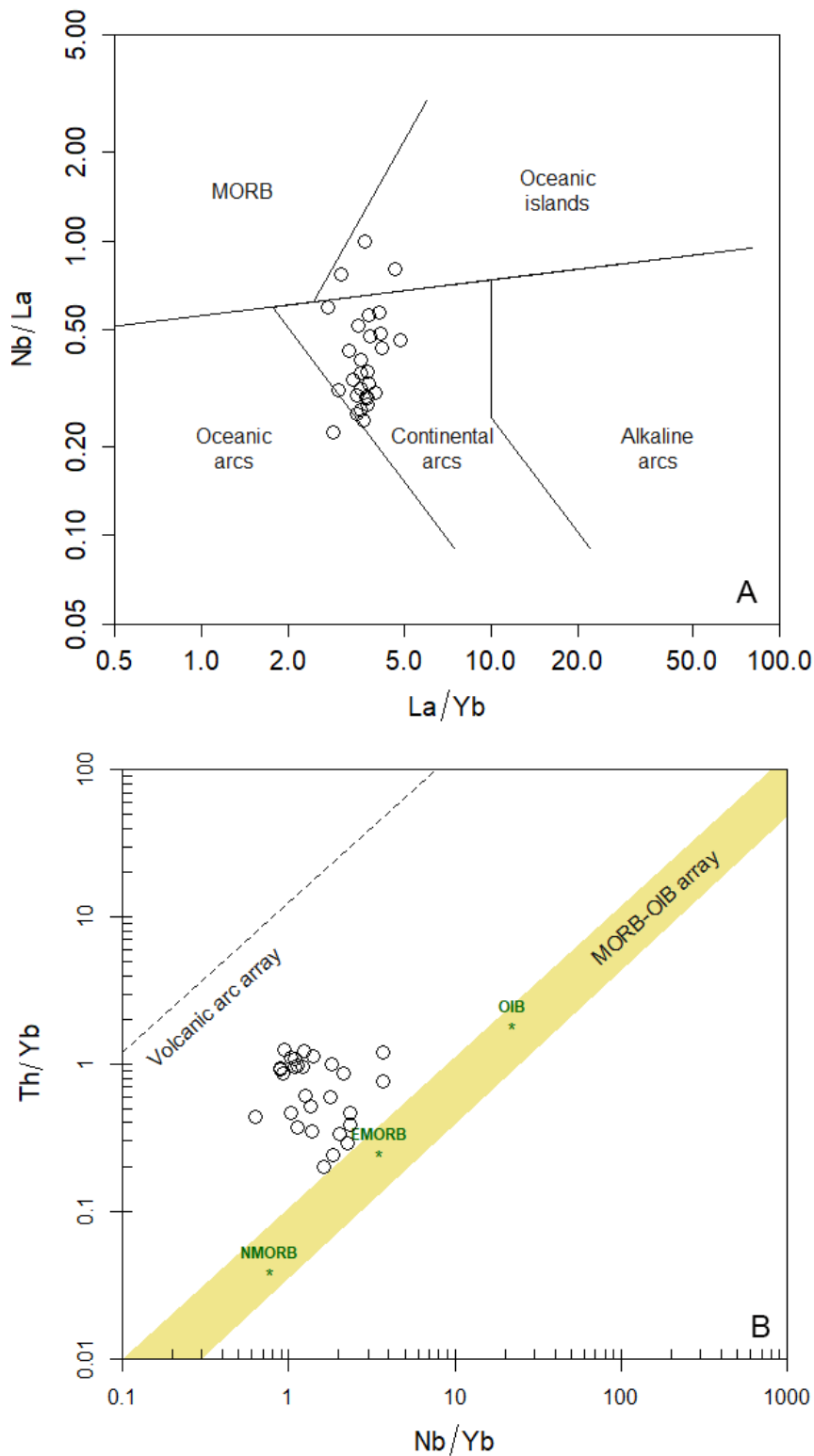


Figure 127. The Gruvberget–Sumåssjön samples plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Bläckmyran and Gråsjön

Bläckmyran is located approximately 2.5 km to the east of Gruvberget–Sumåssjön (fig. 95). Based on airborne and ground based magnetic measurements acquired during the late 1970s, a follow-up drilling program comprising 14 drillholes distributed along seven profiles with an internal

spacing of 60-120 metres were performed in the early 1980s. Exploration reports describe the western part of the deposit as a homogenous vanadiniferous magnetite mineralisation, while the eastern part is more complex due to faulting and intrusion of pegmatites. Despite this however, relatively high vanadium contents occur over large areas in the eastern part (Lagergren & Lindblom 1983).

Gråsjön, located to the east of Bläckmyran has not been drilled, but ground magnetic measurements were performed contemporaneously with Bläckmyran.

Ground-based geophysical measurements

Figure 128 shows a map of the ground magnetic data collected over the Bläckmyran and Gråsjön intrusions as well as an updated bedrock geology map over the area.

A series of approximately parallel, linear positive magnetic anomalies can be observed in the magnetic data above the Bläckmyran intrusion. These anomalies cover an area approximately 1 600 m long and 300 m wide with a strike of about 57°. The anomaly at Bläckmyran is relatively strong, compared to the other anomalies in this study. Here the maximum magnetic field values in the survey reach values as high as 15 000 nT above the background value and exceed 10 000 nT above the background value over an area of about 4 500 m². The highest magnetic field values appear to be located in the eastern half of the intrusion, close to its northwestern flank. Several zones with lateral displacements along some of these semi-parallel anomalies can potentially be interpreted as faults. Figure 13 shows a map of the average magnetic susceptibility within the upper 75 m of the model obtained by inverting the ground magnetic data. Here a series of lenses with high magnetic susceptibility can be observed within the intrusion which correlate well with the observed magnetic susceptibility values. The 3D susceptibility model obtained from the inversion indicates that the intrusion dips to the southeast (fig. 13), which is consistent with previous work by SGU and the available borehole data (Båk 1984).

Magnetic susceptibility logs of core from the BLA82004 and BLA82006 boreholes within the Bläckmyran intrusion can be found in appendix B. A map showing the location of these boreholes is shown in appendix B. Within BLA82004 there appears to be a somewhat variable magnetic susceptibility, where the highest magnetic susceptibilities occur close to the surface within a 20 m thick gabbro interval. Several pegmatite layers can be observed with relatively low magnetic susceptibilities. Within BLA82006 the magnetic susceptibilities within the gabbro appear to be relatively consistent, with the exception of a 20 m thick layer adjacent to the contact with the surrounding granitic rock, which has notably lower susceptibility (and lower inferred vanadium content).

The ground magnetic anomaly above the Gråsjön intrusion is approximately 2 000 m long and 300 m wide with a curved form (fig. 128). However, despite its relatively large size, the anomaly is relatively weak compared to the other anomalies in this study, reaching a maximum value of about 4 500 nT above the background value. In contrast to the nearby Gruvberget–Sumåssjön and Bläckmyran anomalies, the anomaly at Gråsjön appears to consist of broader, relatively low frequency peaks. This implies that the mineralisation within the Gråsjön intrusion is somewhat more diffuse than at Bläckmyran and Gruvberget–Sumåssjön. Figure 129 shows a map of the average magnetic susceptibility of the upper 75 m of the model obtained by inverting the ground-based measurements. Here it can be observed that, in general, relatively low magnetic susceptibility values are calculated for the intrusion, which is consistent with the magnetic susceptibility data collected at outcrop. In the 3D magnetic susceptibility model, the region with higher magnetic susceptibility within the intrusion appears to dip to the southeast (fig. 129), which is consistent with the nearby Gruvberget–Sumåssjön and Bläckmyran intrusions.

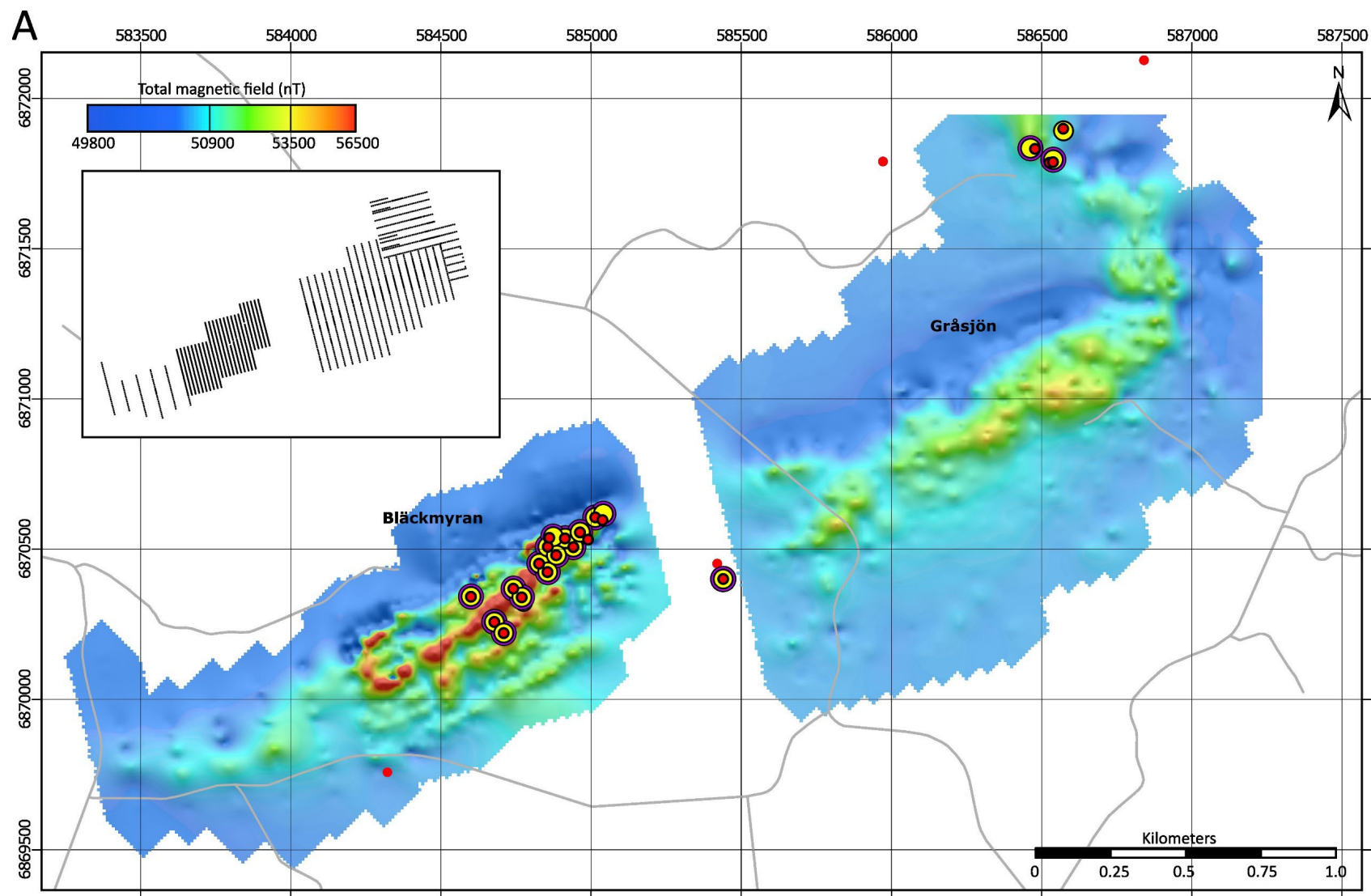


Figure 128. A. Map of the total magnetic field from ground measurements collected between 1981 and 1982 by SGU over the Bläckmyran and Gråsjön intrusions. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. The location of samples and boreholes are shown as different colored dots on the map. See figure 128B for the legend for these symbols. Note that the only boreholes in the figure are located in Bläckmyran but are obscured by the other symbols.

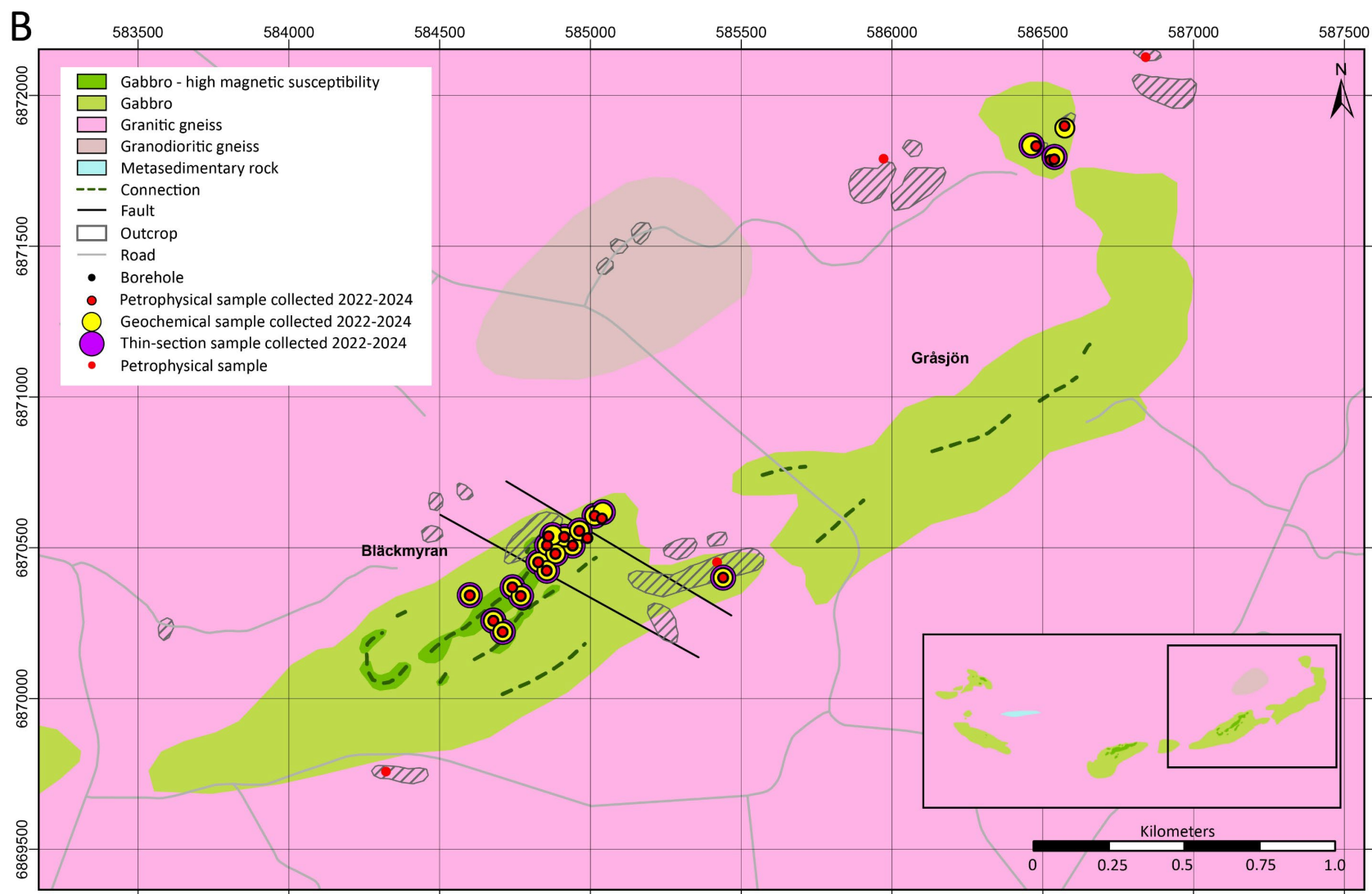


Figure 128 continued. B. Updated map of the bedrock geology around Bläckmyran and Gråsjön, interpreted from the ground magnetic field data and the available geological observations and samples. The location of samples and boreholes are shown as different colored dots on the map. The inset map shows the location of the map with regards to the other intrusions in the Gruvberget–Sumåssjön area. Note that the only boreholes in the figure are located in Bläckmyran but are obscured by the other symbols.

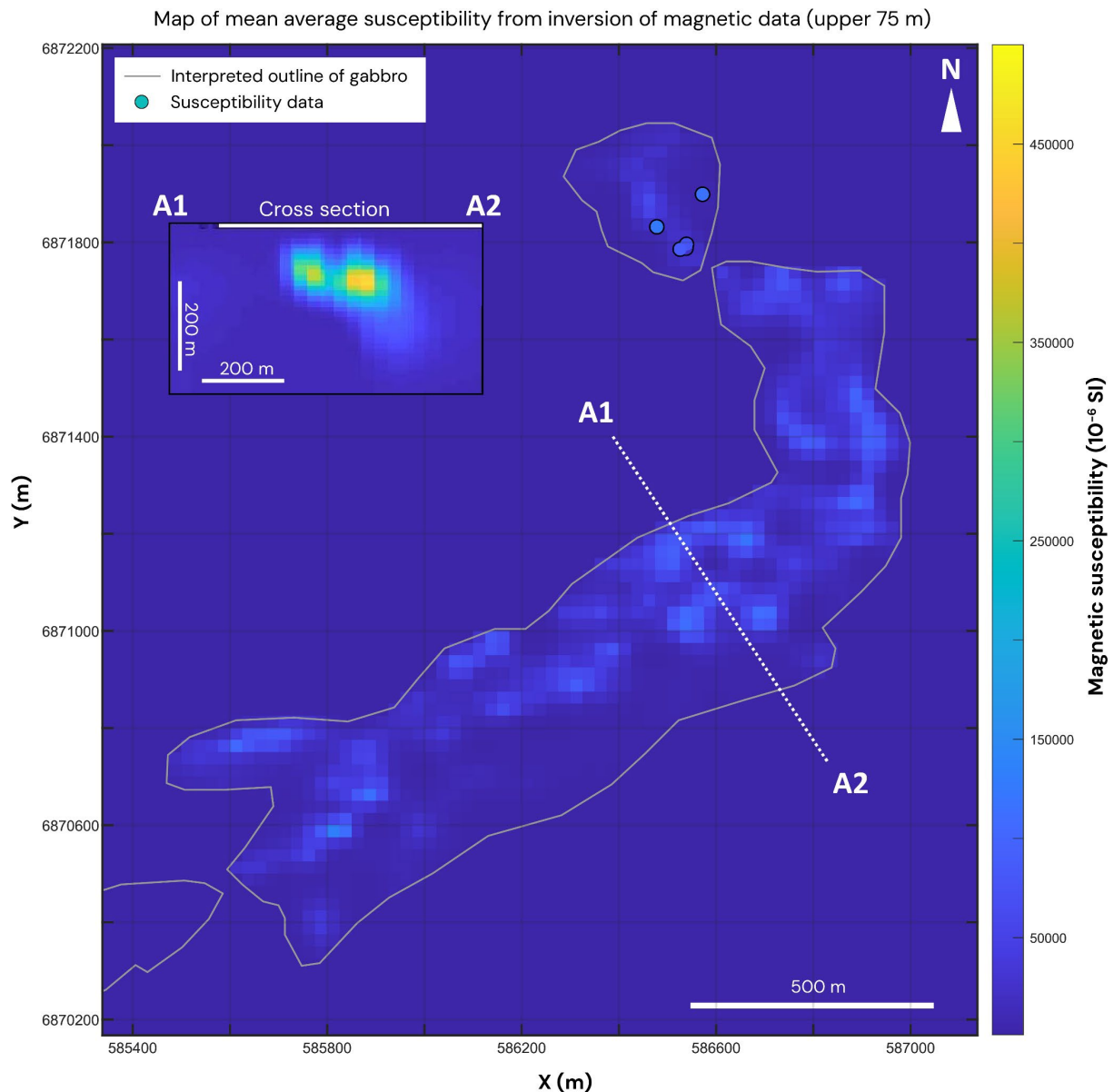


Figure 129. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Gråsjön intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

In this project 31 one-metre samples were collected from nine drill cores from Bläckmyran (e.g., figs. 131, 132, and 134). These samples were analysed for major and trace elements. In addition, three field samples were collected at Bläckmyran from old mining pits (Aggtjärnsgruvorna) at the northern slope of Gråsjöberget (fig. 130) and from outcrops (fig. 137).

At Gråsjön three field samples were taken from outcrop (fig. 138). Typically, selected from the most Fe-Ti-V mineralised outcrops. These samples are characterised by a relatively fine grain-size (fine to medium). In contrast, coarser and pegmatitic parts of the outcrop are often barren (fig. 137). Blebs consisting of massive sulphide (mainly pyrrhotite) are sometimes observed (fig. 133). The contact between the gabbroid and surrounding granite is manifested by a zone of hybridisation showing that the intruding gabbroid have partially melted the older foliated granitoid (figs. 135 and 136). The contact relation resembles that at Kramsta and several of the other investigated intrusions and indicates that these mafic intrusions postdate the granitic gneisses.



Figure 130. Abandoned pit measuring approximately 6 × 8 m at Gråsjöbergets gruva (Aggtjärnsgruvan 3) at Bläckmyran (6870542/584874). Waste-rocks comprise fine medium to medium grained vanadiniferous gabbro. Analysis of a sample from the heap gave the following: 34.40% Fe₂O₃, 5.16% TiO₂, and 2 470 ppm V. Photo: Helge Reginiussen.



Figure 131. Strongly mineralised section starting at 7.60 m depth in drill core BLA82011 from Bläckmyran. An assayed section from 7.60–8.58 m depth gave the following grades: 58.5% Fe_2O_3 , 7.99% TiO_2 , and 6 040 ppm V. Photo: Helge Reginiussen.



Figure 132. Close-up of Fe-Ti-V mineralised section starting at 39.42 m depth in drill core BLA82012 from Bläckmyran. The section from 39.28–40.26 m depth contains 45.50 % Fe_2O_3 , 6.82 % TiO_2 , and 4 720 ppm V. Photo: Helge Reginiussen.



Figure 133. Massive sulphide bleb (mainly pyrrhotite and minor chalcopyrite) in massive, fine- to medium-grained gabbroid in tray 2 in drill core BLA82006 at c. 19.70 m depth. The bleb is c. 4 cm in diameter. Photo: Helge Reginiussen.



Figure 134. Fine-grained, massive, homogenous, gabbroid in tray 6 in drill core BLA82003. Analysis of the section between the red arrows in compartment 4 (60.47–62.45 m) yielded 44.70% Fe_2O_3 , 6.50% TiO_2 , and 3 840 ppm V. Photo: Helge Reginiussen.



Figure 135. Lower part of drill core BLA82006 showing the contact between gabbroid and granite. The contact is a 2.5–3 m wide transition zone where a hybrid rock occurs between the undeformed massive gabbroid (uppermost compartment) and granitic gneiss below. The yellow rectangle shows the outline of figure 136. Photo: Helge Reginiussen.



Figure 136. Magnification of figure 135 showing details of the contact zone between undeformed, massive gabbroid (uppermost compartment) and granitic gneiss (lowermost two compartments). The zone is defined by a 2–3 m thick hybrid rock (middle compartments). Photo: Helge Reginiussen.



Figure 137. Gabbroid in outcrop at Bläckmyran (6870393/585448). At this locality the grainsize varies from medium to coarse, with occasional pegmatitic pockets and, hence the iron, titanium and vanadium contents are low (compared to more fine-grained varieties) with 21.20% Fe_2O_3 , 2.33% TiO_2 , and 947 ppm V. Photo: Helge Reginiussen.



Figure 138. Gabbroid outcrop at Gråsjön (6871832/586480). Photo: Helge Reginiussen.

Description of thin sections – ore minerals – Bläckmyran

In several thin sections from the Bläckmyran intrusion the Fe-Ti oxides make up a more or less well-developed interconnected framework with the silicate minerals found inside, e.g., the mineralised samples DCL230003A from drill core BLA82007 at 96.23–96.31 m depth and DCL230005A from drill core BLA82003 at 62.00–62.06 m depth, respectively (figs. C10, C11).

The texture of the larger grains of magnetite and ilmenite suggest that both were crystallising together at the magmatic stage (figs. 139, 140A–C, 141A–B). There is exsolved ilmenite as lamellae, laths and trellis, which follow crystallographic planes, in the magnetite, discernible in ordinary reflected light but using differential interference contrast (DIC) highlights them (figs. 139B–C, 140B–C, 141C–E). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are probably magnetite or ulvöspinel (figs. 139B–C, 140B–C, 141B–C, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the almost orthogonal tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), easily seen in ordinary reflected light and less obvious in DIC where they are beige, but no proper identification was done (figs. 139B–C, 140B–C, 141C–E). In the close-up images (figs. 140B–C, 141C–E) an additional feature is evident, here the amount of lamellae appear to decrease towards the contact with the magnetite grains. Adjacent to the contact essentially no lamellae can be observed when viewing with an optical microscope. This is best viewed in the differential interference contrast image but is also clearly seen in the plain reflected light but needs the correct orientation to be obvious. It is possible that a zone with fewer trellis and laths at the edges of the magnetite grains is present, however, this zone is thinner than the zone with fewer lamellae in the ilmenite grains (figs. 140B–C, 141C–E).

The ore minerals magnetite, ilmenite, pyrrhotite, chalcopyrite, and pyrite were identified in mineralised sample DCL222026B from drill core BLA82012 at 39.11–39.19 m (fig. 139, see fig. C8 for panorama). Sulphides occur mostly as small grains.

The ore minerals magnetite, ilmenite, pyrrhotite, chalcopyrite, and pentlandite were identified in mineralised sample DCL234001A from drill core BLA82006 at 58.90–58.95 m (fig. 140, see fig. C13 for panorama). There is some of the trellis-type exsolutions that have lots of small dark crystals, seen in ordinary reflected light, which are very bright in DIC. These could possibly be ulvöspinel or fluid inclusion related (figs. 140B–C, cf. Pochon *et al.* 2024). The sulphide minerals in this sample are relatively abundant compared with other thin sections in this study. A grain of sulphide minerals consisting of pyrrhotite, chalcopyrite, and pentlandite surrounded by magnetite and silicate minerals appears to be relatively unaltered (figs. 140D–E).

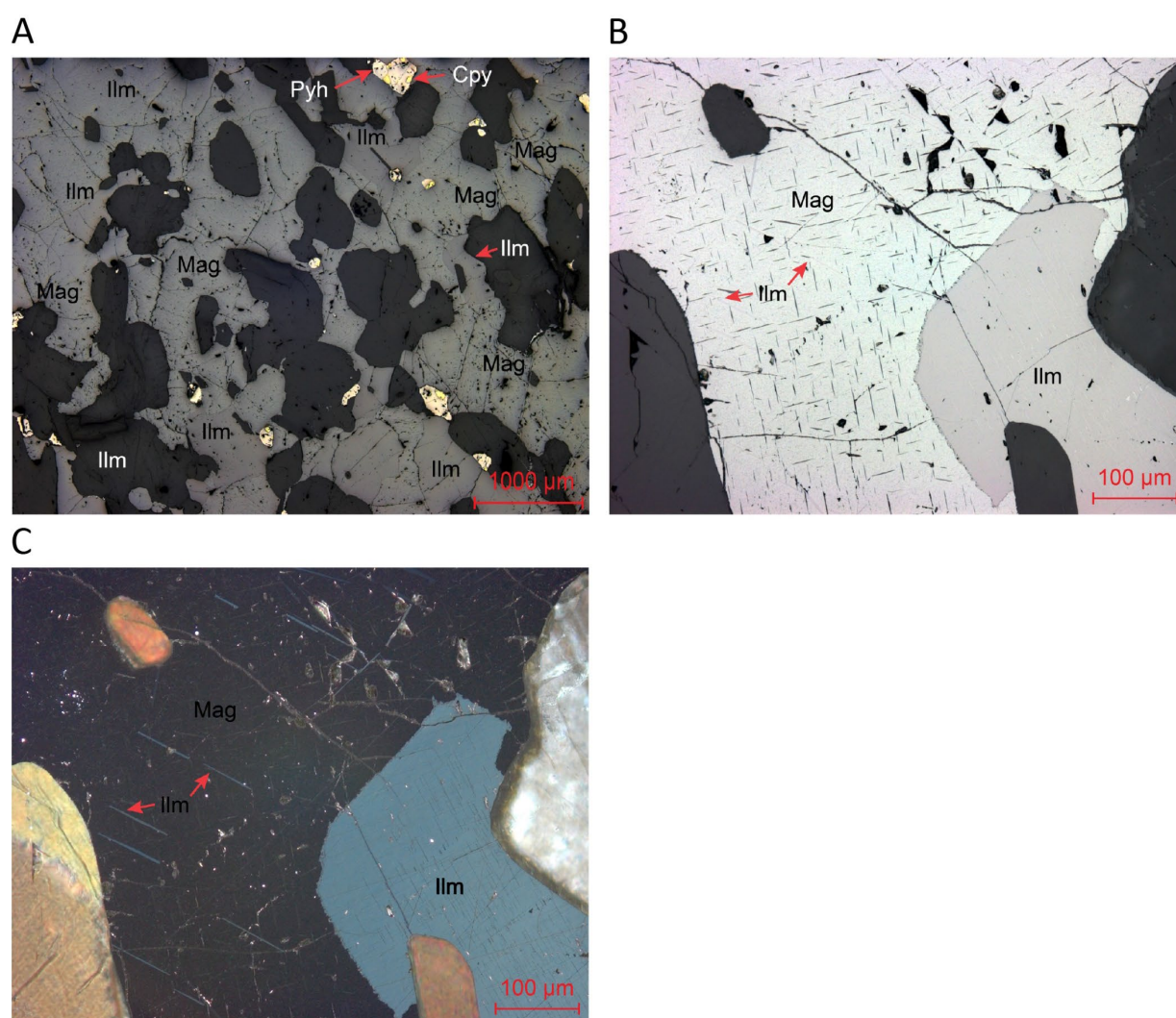


Figure 139. Ore minerals from the Bläckmyran intrusion, mineralised sample DCL222026B from drill core BLA82012 at 39.11–39.19 m (see fig. C8 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework with small crystals of pyrrhotite and chalcopyrite. Close-up images of **B.** magnetite with few thin ilmenite exsolution lamellae that are hard to see and lots of trellis-type that are darker exsolutions almost at right angle to each other. The ilmenite crystal has thin exsolution lamellae of hematite and unknown darker minerals, **C.** same area as in B. using differential interference contrast (DIC) objective that highlights the very faint ilmenite lamellae in magnetite and exsolved minerals in ilmenite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

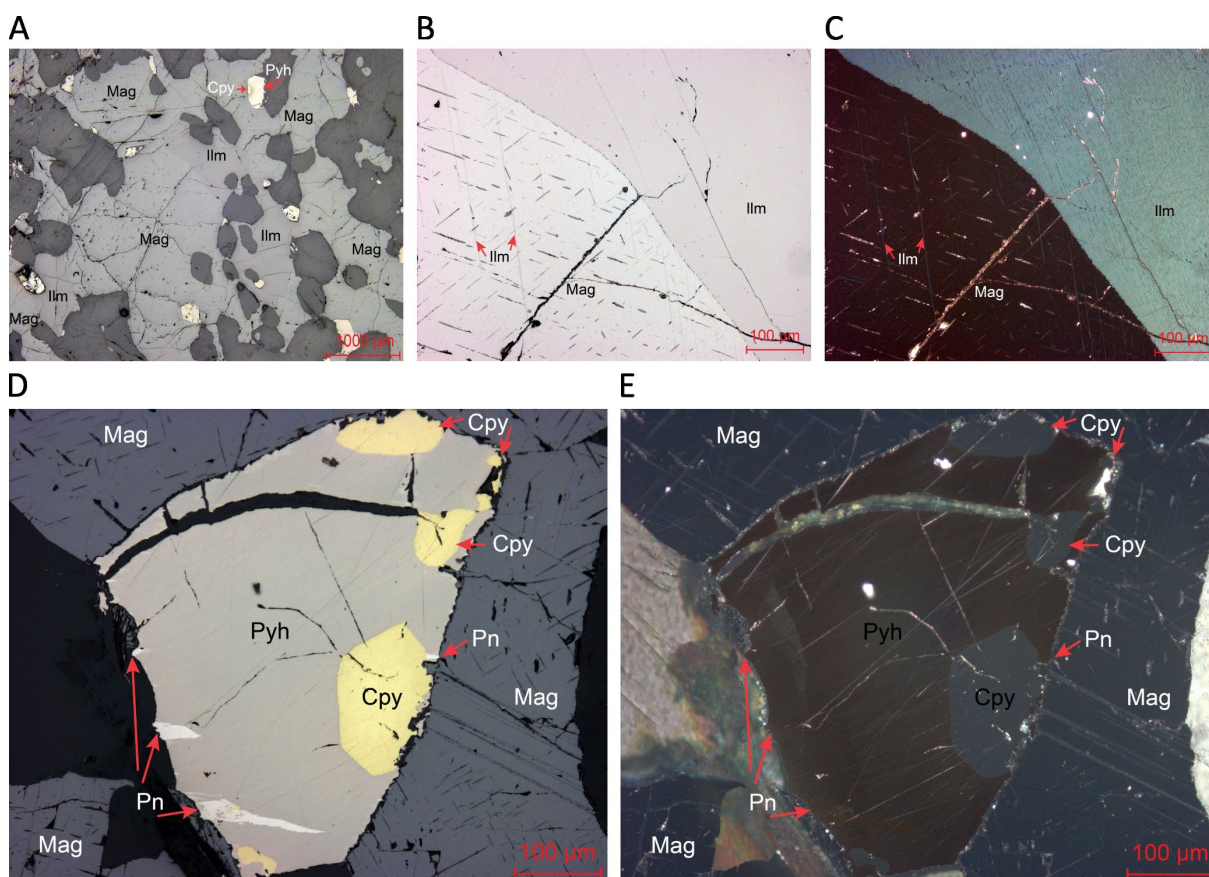


Figure 140. Ore minerals from the Bläckmyran intrusion, mineralised sample DCL234001A from drill core BLA82006 at 58.90–58.95 m (see fig. C13 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework with crystals of pyrrhotite and chalcopyrite. Close-up images of **B.** magnetite with few thin ilmenite exsolution lamellae and lots of trellis-type that are darker exsolutions. The ilmenite crystal has thin exsolution lamellae of hematite and unknown darker minerals, **C.** same area as in B. using differential interference contrast (DIC) objective that highlights the darker trellis with bright small crystals in magnetite and exsolved minerals in ilmenite. Grain of sulphide minerals consisting of pyrrhotite, chalcopyrite, and pentlandite surrounded by magnetite and silicate minerals, **D.** in plain reflected light and **E.** with DIC. Note that pentlandite has a faint reddish colour in DIC. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

The ore minerals magnetite, ilmenite, pyrrhotite, chalcopyrite, and pentlandite were identified in mineralised sample DCL234006A from drill core BLA82011 at 7.48–7.53 m (fig. 141, see fig. C15 for panorama). Two trails of miniscule sulphide crystals in an ilmenite crystal are interpreted as related to hair-thin fractures where some later sulphide-rich liquid migrated (fig. 141C). The sulphide minerals in this sample are relatively abundant compared with other thin sections in this study. A grain of sulphide minerals consisting of pyrrhotite, chalcopyrite, and pentlandite surrounded by magnetite and silicate appears to be relatively unaltered, with the exception of minor alteration of pyrrhotite along thin fractures and in parts of the contact with magnetite (fig. 141F).

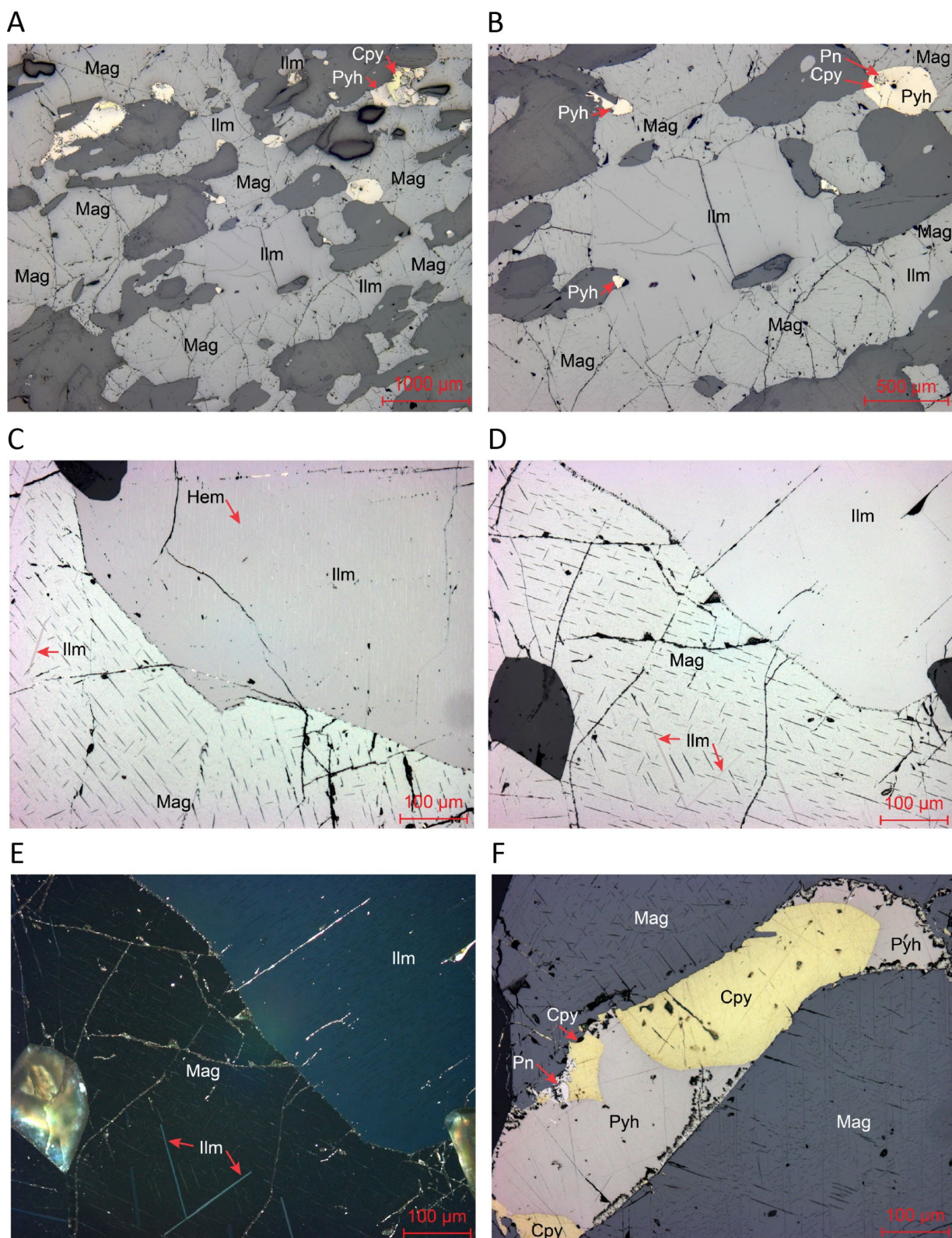


Figure 141. Ore minerals from the Bläckmyran intrusion, mineralised sample DCL234006A from drill core BLA82011 at 7.48–7.53 m (see fig. C15 for panorama). **A.** Overview of relations between magnetite and ilmenite in an opaque framework with crystals of pyrrhotite and chalcopyrite. **B.** Close-up of the central part of image A. with subhedral ilmenite in the centre. **C.** Close-up of subhedral ilmenite in contact with magnetite. Note two trails of miniscule sulphide crystals in the ilmenite crystal in probable hair-thin fractures and trellis of hematite. Contact between ilmenite and magnetite with a decrease of exsolution the closer to the contact, **D.** plain reflected light and **E.** using a differential interference contrast (DIC) objective. **F.** Grain of sulphide minerals consisting of pyrrhotite, chalcopyrite, and pentlandite surrounded by magnetite and silicate, minor alteration of pyrrhotite along thin fractures and parts of contact with magnetite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Bläckmyran

Although mostly well-preserved and with a preferred orientation of minerals, the mineralised sample DCL222026B from drill core BLA82012 at 39.11-39.19 m (panorama fig. C8), has alteration where fractured. Euhedral to anhedral hornblende is the main mafic mineral (figs. 142A–B). Hornblende has grain triple junctions at 120 degrees, an igneous granoblastic texture that signifies textural equilibrium (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Possible orthopyroxene occurs as minor component of anhedral interstitial grains with low order birefringence and close to straight extinction, partly to severely altered. Subhedral to anhedral plagioclase, some look dissolved with round shapes, embayments, and cusps when in contact with opaque minerals. Biotite has brownish red to light tan pleochroism.

Sample DCL222027B from drill core BLA81002 at 89.85-89.90 m is mostly well-preserved with some sericite-saussurite alteration and secondary green amphibole present. Subhedral to anhedral hornblende is the main mafic mineral (figs. 142C–D). Hornblende has grain triple junctions at 120 degrees. Anhedral to subhedral and round crystals of plagioclase is the other main silicate mineral in this sample.

Mineralised sample DCL223033A from drill core BLA81001 at 44.31–44.35 m (panorama fig. C9) is well-preserved with only minor alteration. Euhedral to anhedral hornblende is the main mafic silicate mineral. Subhedral to anhedral plagioclase is in places rimmed with opaque minerals and Fe-Ti oxides also as infilling of fractures within plagioclase (figs. 142E–F). Two generations of biotite are present, the first has brownish red pleochroism and the second brownish red to tan. They occur as interstitial grains with exsolution of opaque minerals. Hornblende, biotite, and Fe-Ti oxides are intergrown with no sign of reaction (figs. 143A–B).

The mineralised and well-preserved sample DCL223036A from drill core BLA81001 at 179.77–179.81 m has subhedral to anhedral hornblende as the main mafic silicate mineral (figs. 143C–D). Some rounded grains of subhedral to anhedral plagioclase are present. Opaque minerals occur as minor fracture fillings and rims of plagioclase. Large and small interstitial biotite grains with brownish red to greyish tan pleochroism occur. Some large biotite grains are oikocrysts with plagioclase chadacrysts and exsolution of opaque minerals. Possibly, a few prehnite crystals occur in biotite. A few subhedral apatite crystals are observed.

There is a possible mineral layering developed as differences in abundance of plagioclase, clinopyroxene, hornblende, and Fe-Ti oxides in irregular bands in mineralised well-preserved sample DCL223043A from drill core BLA82008 at 89.29-89.33 m. Bands are dominated by either hornblende + Fe-Ti oxides (figs. 143E–F) or by clinopyroxene + plagioclase (figs. 144A–B) in respective band. Subhedral to anhedral hornblende grains and interstitially grown crystals occur. Subhedral to anhedral clinopyroxene is present as interstitially grown grains, and oikocrysts with chadacrysts of hornblende, plagioclase, and Fe-Ti oxides. Subhedral to anhedral plagioclase with minor sericite-saussurite alteration is observed.

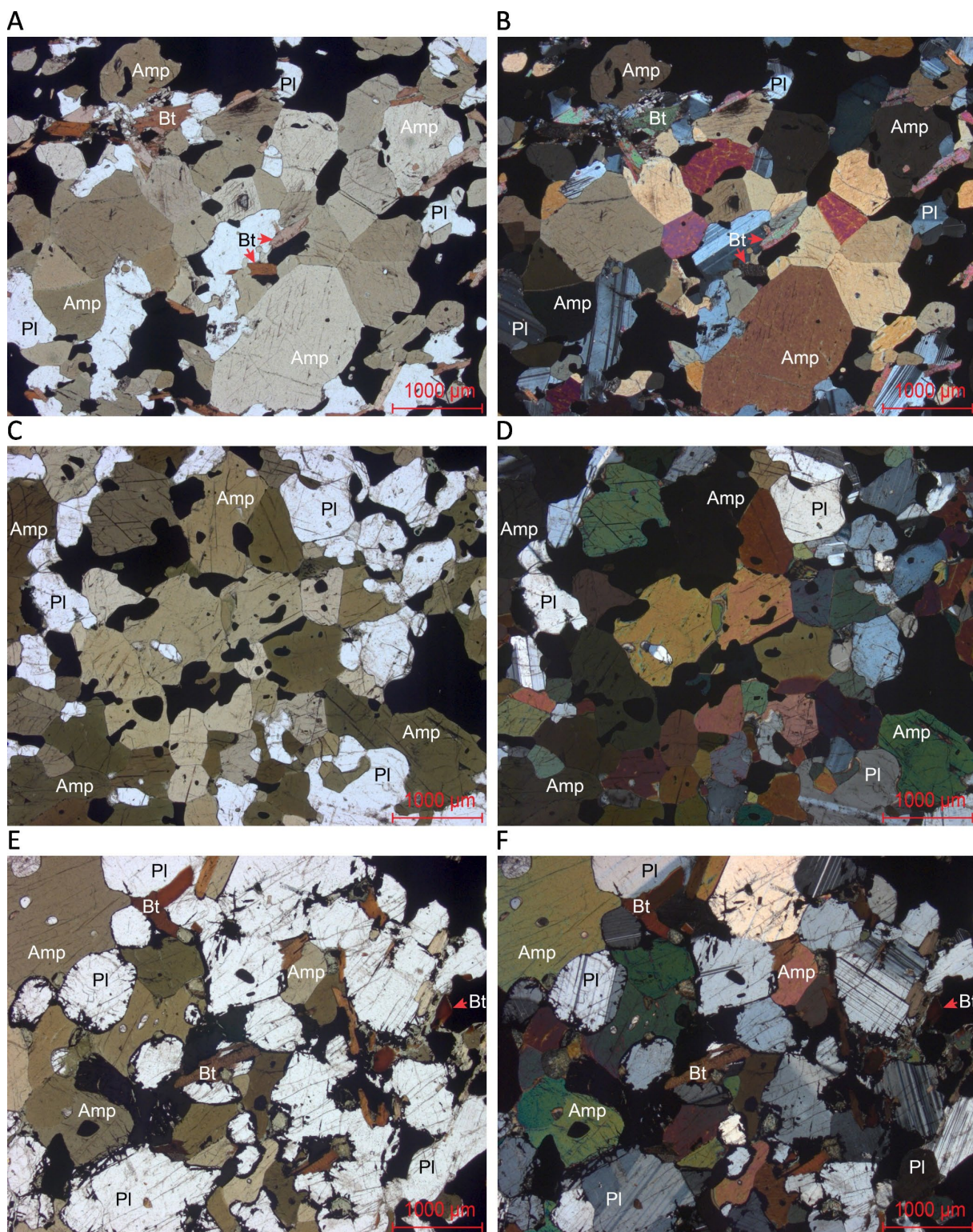


Figure 142. A. and B. Sample DCL222026B from drill core BLA82012 at 39.11–39.19 m, with subhedral hornblende grain triple junctions at 120 degrees. C. and D. Sample DCL222027B from drill core BLA81002 at 89.85–89.90 m, is a cumulate rock mainly comprising hornblende and plagioclase. E. and F. Sample DCL223033A from drill core BLA81001 at 44.31–44.35 m, with plagioclase in places rimmed with opaque minerals and infill of fractures. Left in ppl and right in xpl. Photo: Dick Claeson.

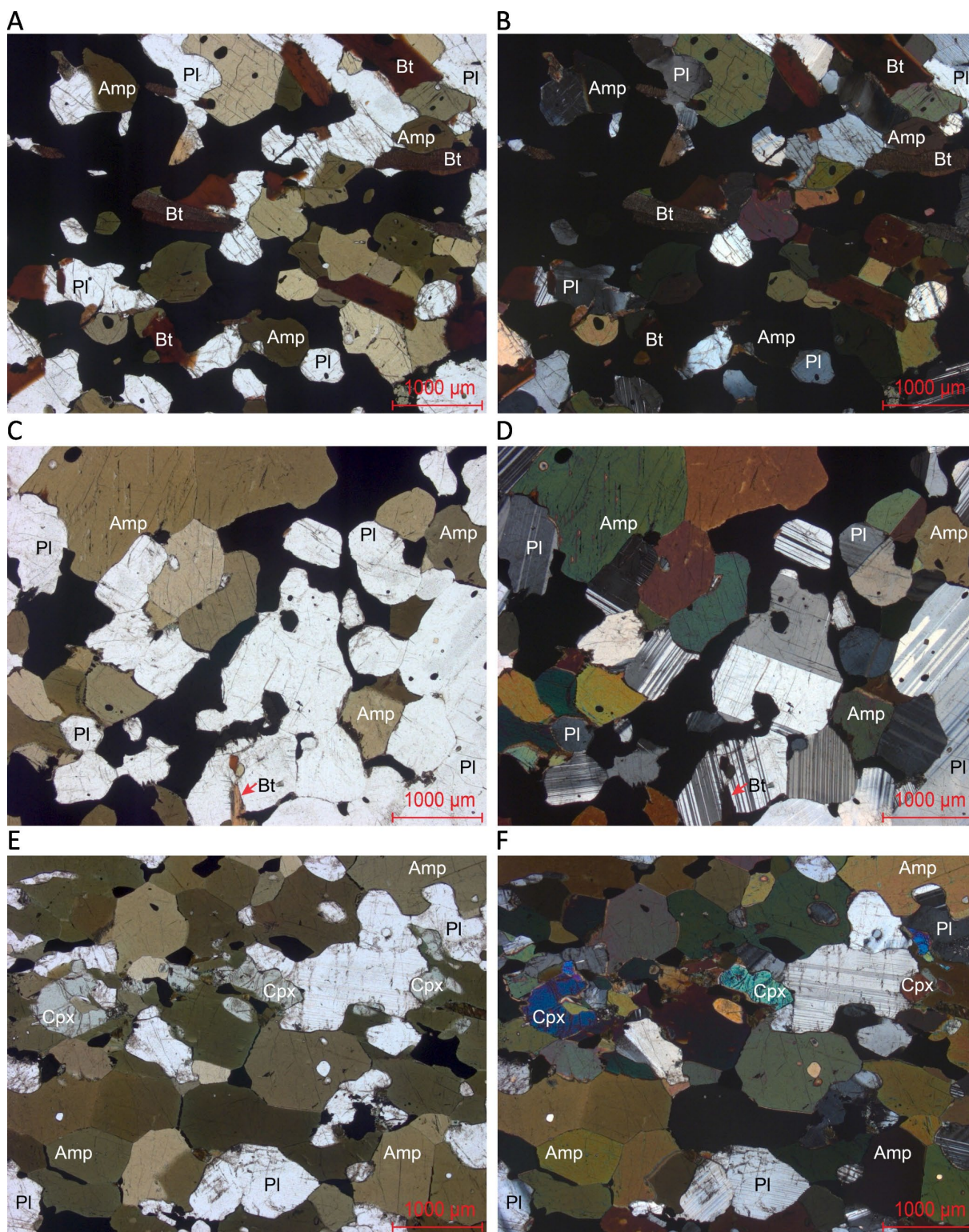


Figure 143. **A.** and **B.** Sample DCL223033A from drill core BLA81001 at 44.31–44.35 m, with intergrown hornblende, biotite, and Fe–Ti oxides. Note the difference in shape between these minerals and the rounded shape of plagioclase. **C.** and **D.** Sample DCL223036A from drill core BLA81001 at 179.77–179.81 m, having subhedral to anhedral hornblende and rounded plagioclase. **E.** and **F.** Sample DCL223043A from drill core BLA82008 at 89.29–89.33 m, with irregular bands of different mineral compositions, in this image band dominated by hornblende and Fe–Ti oxides is shown. Left in ppl and right in xpl. Photo: Dick Claeson.

Mineralised sample DCL230001A from drill core BLA82004 at 19.01–19.07 m is severely altered in part and well-preserved elsewhere, with subhedral to anhedral hornblende as the main mafic silicate mineral set in an opaque mineral framework (figs. 144C–D). Hornblende has grain triple junctions at 120 degrees, and an igneous granoblastic texture indicating textural equilibrium. Rare clinopyroxene with exsolution lamellae, and grains partly altered to secondary green amphibole are present. Plagioclase grains set in an opaque mineral framework can be observed, often with a rounded appearance, some severely altered to sericite-saussurite. Rare brownish red biotite crystals occur.

The well-preserved cumulate rock of sample DCL230002A from drill core BLA82004 at 61.33–61.37 m has subhedral to anhedral hornblende and anhedral clinopyroxene grains, interstitially grown, and oikocrysts as the main mafic silicate minerals (figs. 144E–F). Anhedral to subhedral plagioclase with minor sericite-saussurite alteration is observed. Hornblende has grain triple junctions at 120 degrees, and an igneous granoblastic texture indicating textural equilibrium (figs. 145A–B).

Sample DCL230004A from drill core BLA82007 at 153.23–153.27 m is a well-preserved cumulate rock with subhedral to anhedral hornblende, clinopyroxene, and plagioclase. All three minerals have irregular grain boundaries towards each other at places, reminiscent of a lobate texture (figs. 145C–D).

A strong preferred orientation of the minerals is present in mineralised sample DCL230006A from drill core BLA82002 at 7.52–7.58 m (panorama fig. C12). Alteration has occurred where the cumulate rock was fractured, elsewhere it is well-preserved. Subhedral to anhedral hornblende, subhedral to anhedral and rounded plagioclase, and subhedral biotite occurs in a framework of Fe-Ti oxides (figs. 145E–F). Some plagioclase crystals are severely altered to sericite-saussurite. Biotite has brownish red to tan pleochroism.

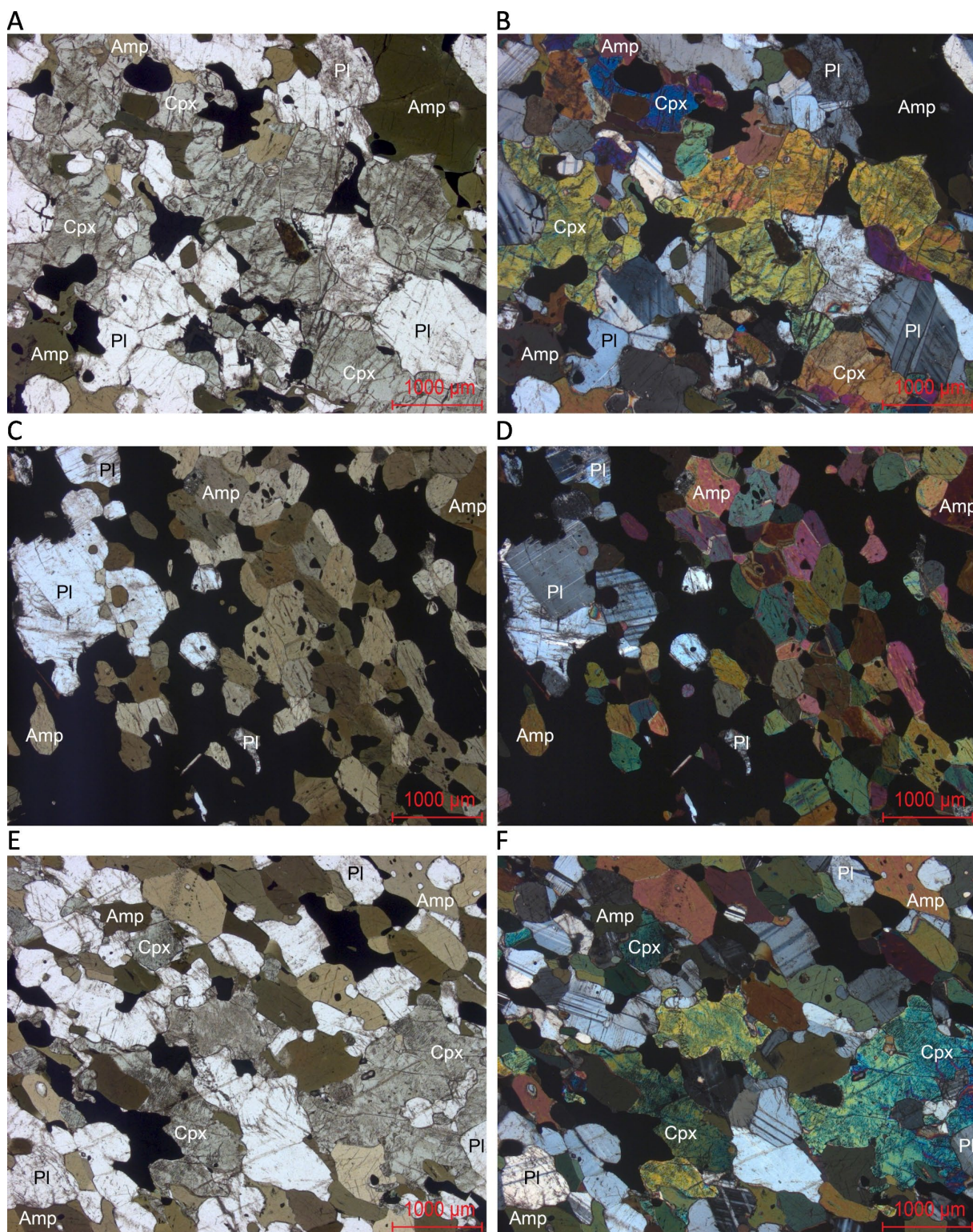


Figure 144. A. and B. Sample DCL223043A from drill core BLA82008 at 89.29–89.33 m, with irregular bands with different mineral compositions, here a band dominated by clinopyroxene and plagioclase is shown. C. and D. Sample DCL230001A from drill core BLA82004 at 19.01–19.07 m, hornblende and plagioclase set in framework of Fe-Ti oxides. E. and F. Sample DCL230002A from drill core BLA82004 at 61.33–61.37 m, cumulate rock with clinopyroxene, hornblende, plagioclase, and Fe-Ti oxides. Left in ppl and right in xpl. Photo: Dick Claeson.

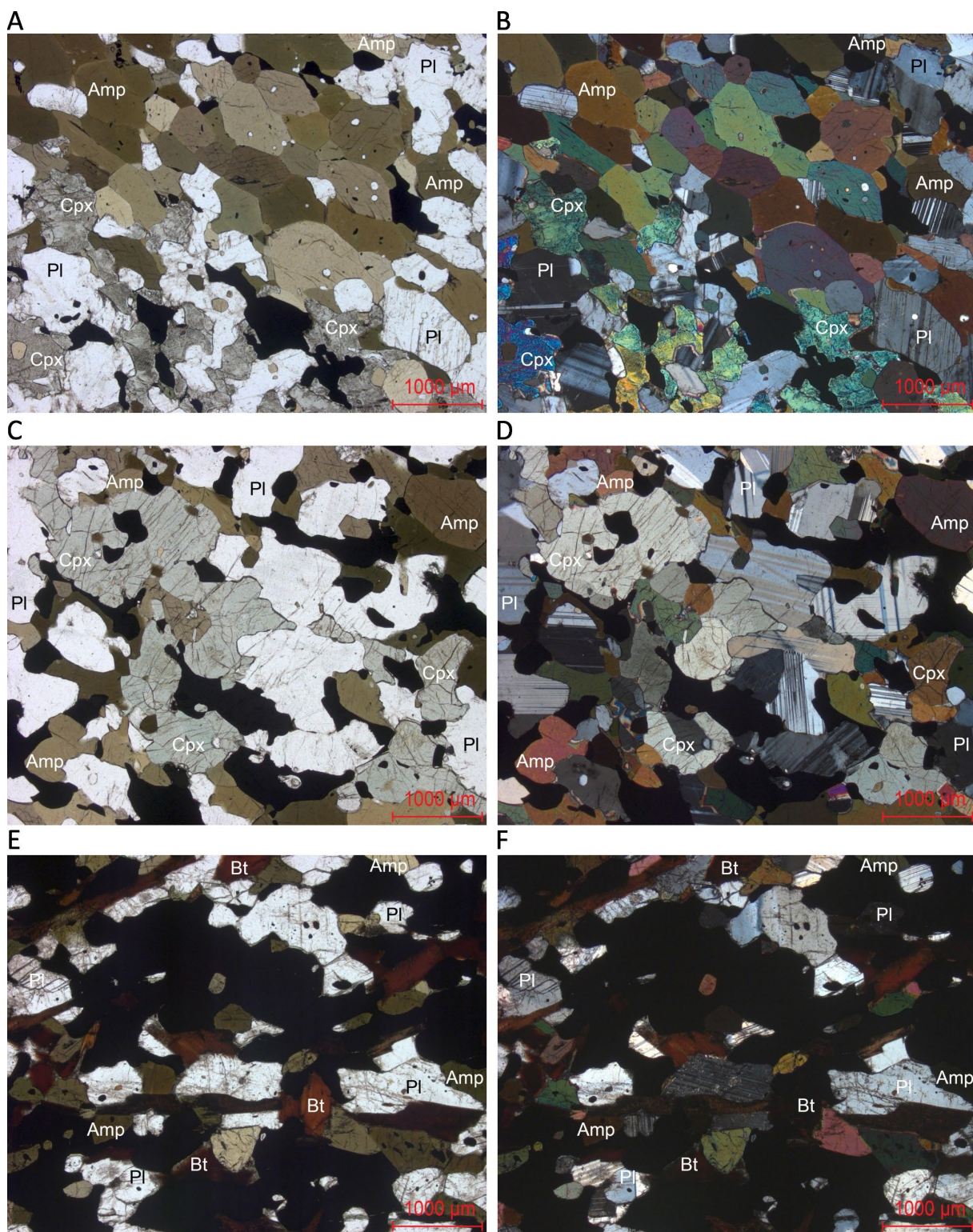


Figure 145. **A.** and **B.** Sample DCL230002A from drill core BLA82004 at 61.33–61.37 m, hornblende with grain triple junctions at 120 degrees. **C.** and **D.** Sample DCL230004A from drill core BLA82007 at 153.23–153.27 m. Irregular grain boundaries are observed between all three silicate minerals. **E.** and **F.** Sample DCL230006A from drill core BLA82002 at 7.52–7.58 m, having a framework of Fe–Ti oxides with rounded plagioclase grains and subhedral hornblende and biotite. Left in ppl and right in xpl. Photo: Dick Claeson.

The well-preserved cumulate rock of sample DCL230007A from drill core BLA82001 at 57.36–57.42 m consists of the silicate minerals hornblende, clinopyroxene, and plagioclase (figs. 146A–B). All minerals are subhedral to anhedral with clinopyroxene having some lamellae and opaque exsolutions. Hornblende has grain triple junctions at 120 degrees, otherwise rather rounded grains of the silicate minerals are observed.

Mineralised sample DCL234000A from drill core BLA82006 at 13.54–13.60 m is well-preserved with subhedral to anhedral hornblende as the main mafic silicate mineral (figs. 146C–F). Hornblende has grain triple junctions at 120 degrees. A poikilitic texture is present as one c. 3 × 5 mm large oikocryst of clinopyroxene, the only occurrence of clinopyroxene in this thin section (figs. 146C–D). Large plagioclase crystals have grey pigmentation of early-formed central parts, which is lacking in their late-formed outer part. Plagioclase crystals that formed entirely within an interstitial position lack pigmentation as well. Some plagioclase grains show bends or kinks, deformation twins, and undulose extinction due to deformation (figs. 146E–F). Plagioclase bending or kinking, formation of deformation twins, and undulose extinction while hot in a cumulate rock is thought to result from the process of compaction of a crystal pile or mush, where interstitial liquid is pressed out of the residual porosity of the cumulate rock (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). Plagioclase has minor spots of sericite-saussurite due to alteration. Minor biotite occurs as small to large grains with brownish red to tan pleochroism.

The mostly well-preserved mineralised sample DCL234001A from drill core BLA82006 at 58.90–58.95 m (panorama fig. C13), has subhedral to anhedral and rounded hornblende as the main mafic silicate mineral, with very minor secondary green amphibole (figs. 147A–B). Subhedral to anhedral and rounded plagioclase grains with some sericite-saussurite alteration are present. Some plagioclase crystals have fractures filled with opaque minerals and are rimmed by opaque minerals. Some plagioclase crystals are probably partly dissolved and replaced by Fe-Ti oxides that formed from a hydrous Fe-Ti-rich liquid. Subhedral biotite grains with brownish red to tan pleochroism are observed.

The sample DCL234002A from drill core BLA82006 at 81.47–81.53 m has partly severe alteration of plagioclase to sericite-saussurite, while the rest of the thin-section is well-preserved (figs. 147C–D). Euhedral to anhedral hornblende occurs as grains and interstitially grown crystals, with grain triple junctions at 120 degrees, and an igneous granoblastic texture indicating textural equilibrium. Subhedral to anhedral clinopyroxene occurs as interstitially grown grains, some with lamellae and opaque exsolutions. Subhedral to anhedral plagioclase crystals are present. Small grains of quartz with very weak undulose extinction are observed.

The mostly well-preserved mineralised sample DCL234003A from drill core BLA82009 at 37.60–37.65 m (panorama fig. C14), has euhedral to anhedral hornblende as the main mafic silicate mineral, with grain triple junctions at 120 degrees (figs. 147E–F). Subhedral to anhedral plagioclase grains, some sericite-saussurite alteration, fracture filling and rims of opaque minerals occur. Late-crystallised biotite grains with brownish red to tan pleochroism are present.



Figure 146. A. and B. Sample DCL230007A from drill core BLA82001 at 57.36–57.42 m, with rather rounded grains of the silicate minerals. C. and D. Relatively large oikocryst of clinopyroxene. E. and F. Note bend or kink between red arrows and to the right, deformation twins and undulose extinction. Hornblende with grain triple junctions at 120 degrees. Images from sample DCL234000A from drill core BLA82006 at 13.54–13.60 m. Left in ppl and right in xpl. Photo: Dick Claeson.

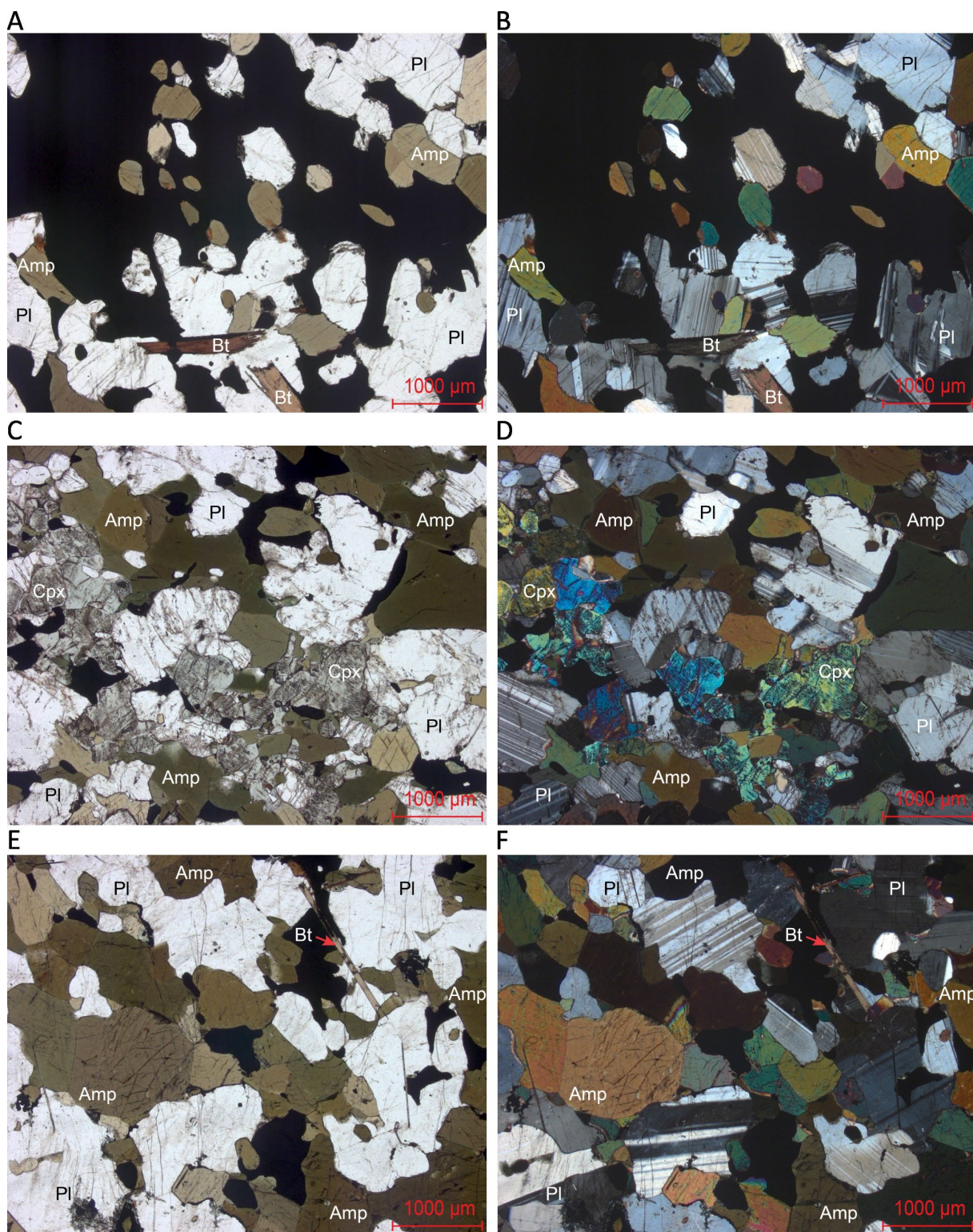


Figure 147. **A.** and **B.** Sample DCL234001A from drill core BLA82006 at 58.90–58.95 m, rounded hornblende and plagioclase in framework of Fe-Ti oxides. **C.** and **D.** Sample DCL234002A from drill core BLA82006 at 81.47–81.53 m, cumulate rock of hornblende, clinopyroxene, plagioclase, and Fe-Ti oxides. **E.** and **F.** Sample DCL234003A from drill core BLA82009 at 37.60–37.65 m, hornblende grain triple junctions at 120 degrees. Note late-crystallized biotite crystal. Left in ppl and right in xpl. Photo: Dick Claeson.

The well-preserved, mineralised sample DCL234004A from drill core BLA82009 at 81.81–81.86 m has subhedral to anhedral grains and interstitial hornblende as the main mafic silicate mineral (figs. 148A–B). Several hornblende grain triple junctions at 120 degrees occur. Plagioclase has subhedral to anhedral grains. A few apatite crystals are present. Rare quartz grains with none or very weak undulose extinction occur. A possible symplectite developed between opaque and possible quartz is observed at a few places in the thin section.

Mostly well-preserved mineralised sample DCL234005A from drill core BLA82009 at 130.65–130.70 m has subhedral to anhedral grains and interstitial hornblende as main mafic silicate mineral (figs. 148C–D). A few subhedral to anhedral clinopyroxene crystals some with lamellae and opaque exsolutions occur. Plagioclase is subhedral to anhedral. Very rare crystals of apatite and few small grains of quartz are present.

Mineralised and well-preserved with a strong preferred orientation of minerals, sample DCL234006A from drill core BLA82011 at 7.48–7.53 m (panorama fig. C15), has subhedral to anhedral grains and interstitial hornblende as main mafic silicate mineral (figs. 148E–F). Hornblende has grain triple junctions at 120 degrees. Subhedral to anhedral grains of plagioclase, some with inclusions of mostly hornblende and few biotite crystals occur. Biotite is relatively abundant with brownish red to tan pleochroism, some grains have exsolutions of opaque minerals. Rare, small grains of quartz occur.

The well-preserved, mineralised sample HRE220008A has subhedral to anhedral grains and interstitial hornblende as the main mafic silicate mineral (figs. 149A–B). Hornblende has grain triple junctions at 120 degrees, and an igneous granoblastic texture indicating textural equilibrium. There are possibly rare anhedral orthopyroxene crystals with low order birefringence and straight extinction. Subhedral to anhedral plagioclase crystals have some parts that have been dissolved and replaced by opaque minerals.

Mineralised and well-preserved cumulate rock of sample HRE220009A (panorama fig. C16), has subhedral to anhedral and rounded hornblende as main mafic silicate mineral (figs. 149C–D). Hornblende has grain triple junctions at 120 degrees, and an igneous granoblastic texture. Subhedral to anhedral and rounded plagioclase crystals occur, some with inclusions of hornblende and biotite. Biotite with brownish red to tan pleochroism exists, with some grains as aggregates. Rare crystals of prehnite are found in biotite.

Mostly well-preserved cumulate rock of sample HRE220037A has clinopyroxene and hornblende as main mafic silicate minerals (figs. 149E–H). Subhedral to anhedral hornblende occurs as grains, interstitially grown, and aggregates. Subhedral to anhedral grains of clinopyroxene are found, where some have lamellae and opaque exsolutions. Late-crystallised rims of hornblende grew on several of the clinopyroxene crystals. Most of these rims are followed by Fe-Ti oxides, moving away from clinopyroxene and thus few Fe-Ti oxide grains are in contact with clinopyroxene. A few subhedral to anhedral grains of olivine, intergrown with clinopyroxene. Two generations of biotite, first red to brownish red pleochroism and second brownish red to tan, occur as grains and interstitially grown crystals, some with exsolution of opaque minerals. Biotite, hornblende, and Fe-Ti oxides form aggregates. A rare, elongated, prismatic apatite crystal (cf. Brown *et al.* 2013), c. 55 µm wide and more than 1.4 mm long, is present in a pocket of fine-grained minerals (figs. 149G–H). This pocket is interpreted as one of the very last to crystallise in the cumulate rock.

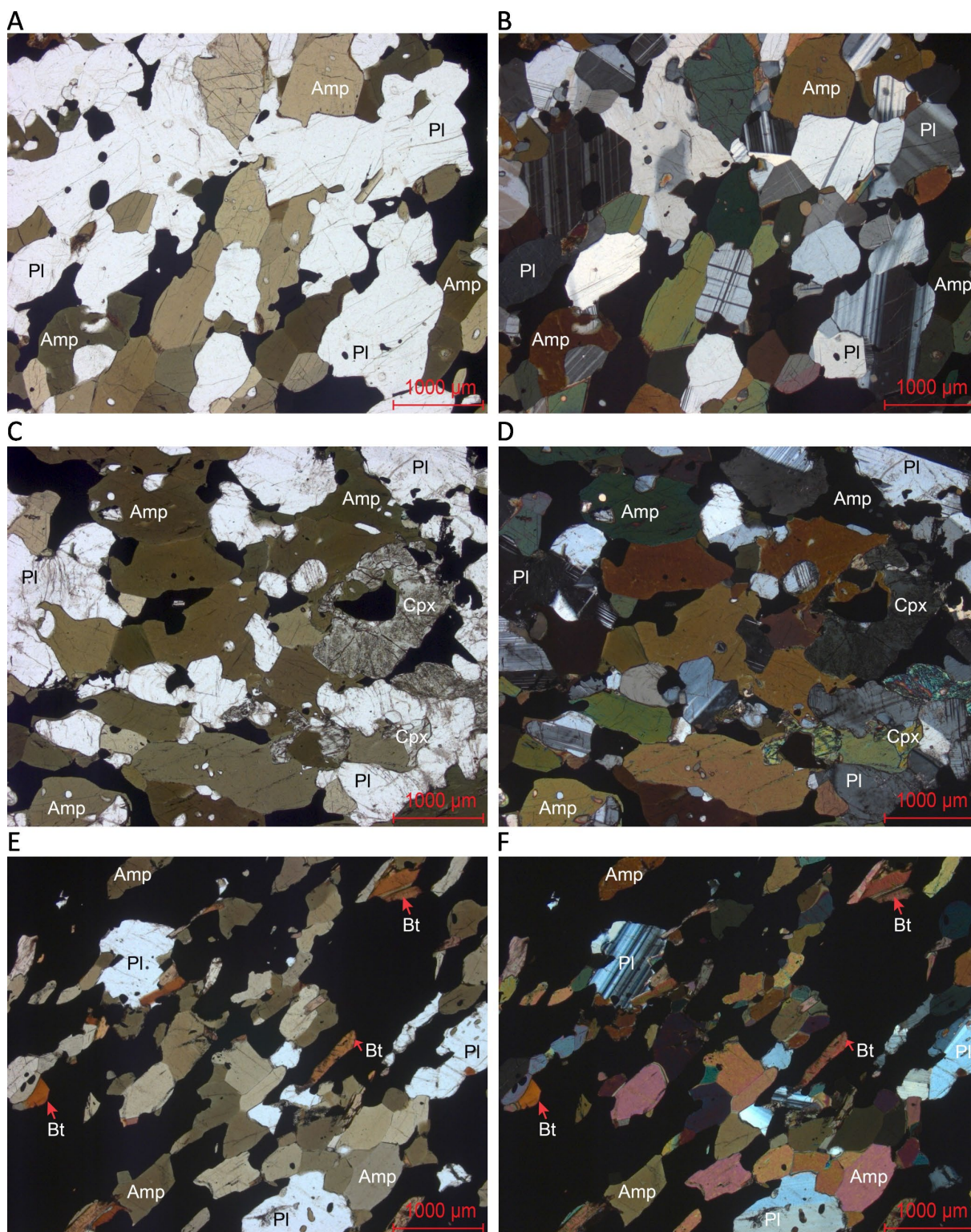


Figure 148. **A.** and **B.** Sample DCL234004A from drill core BLA82009 at 81.81–81.86 m, hornblende and plagioclase main silicate minerals, hornblende with grain triple junctions at 120 degrees. **C.** and **D.** Sample DCL234005A from drill core BLA82009 at 130.65–130.70 m, hornblende, plagioclase, and minor clinopyroxene in cumulate rock. **E.** and **F.** Sample DCL234006A from drill core BLA82011 at 7.48–7.53 m, strong preferred orientation of minerals in framework of Fe–Ti oxides. Left in ppl and right in xpl. Photo: Dick Claeson.

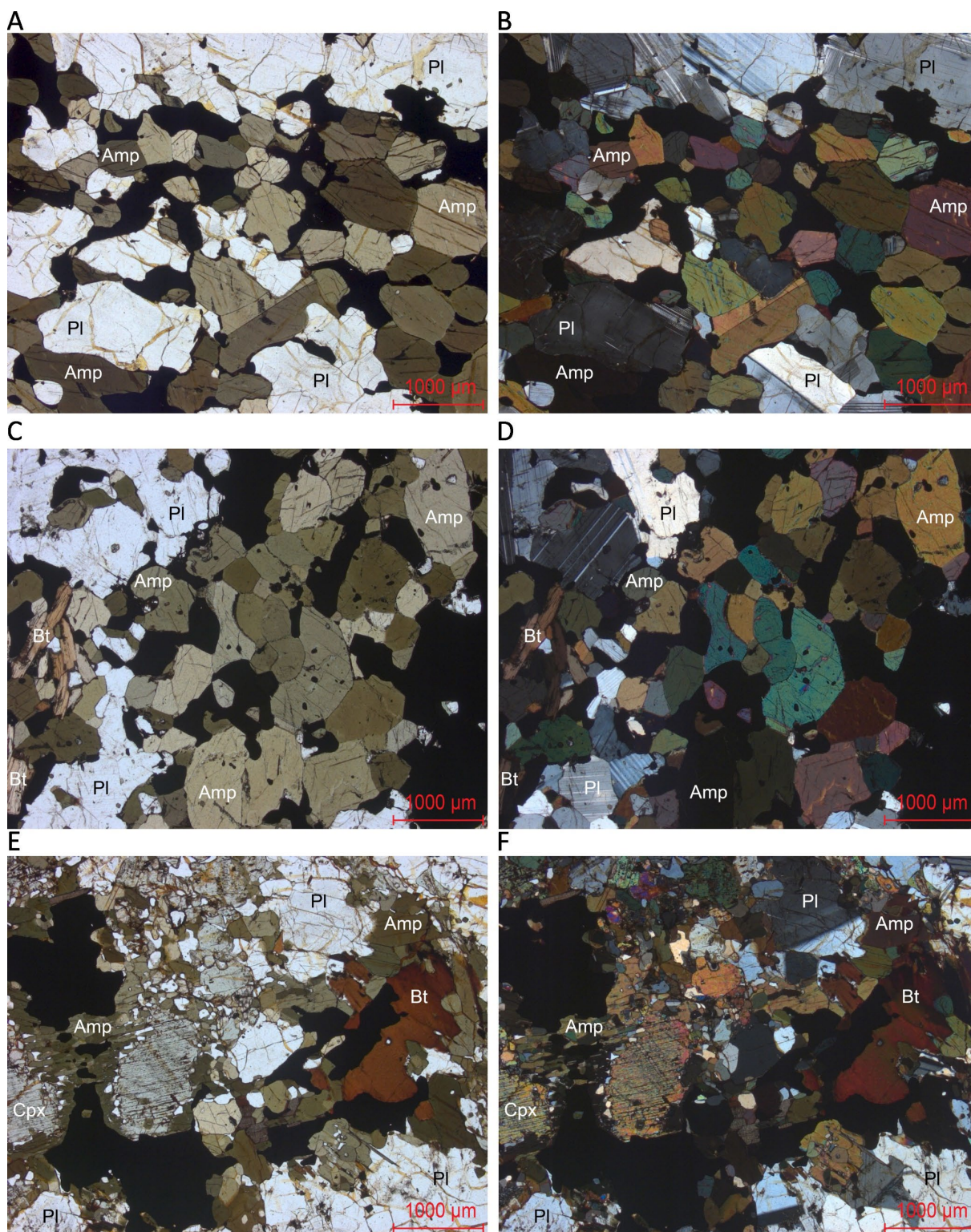


Figure 149. A. and B. Mineralised gabbroid cumulate with hornblende grain triple junctions at 120 degrees and partly dissolved plagioclase, replaced by Fe-Ti oxides. Sample HRE220008A (6870542/584874). C. and D. Mineralised gabbroid cumulate with euhedral to anhedral hornblende and aggregate of biotite. Sample HRE220009A (6870618/585041). E. and F. Late-crystallised rims of hornblende on clinopyroxene. Aggregate of biotite, hornblende, and Fe-Ti oxides. Sample HRE220037A (6870401/585440). Left in ppl and right in xpl. Photo: Dick Claeson.

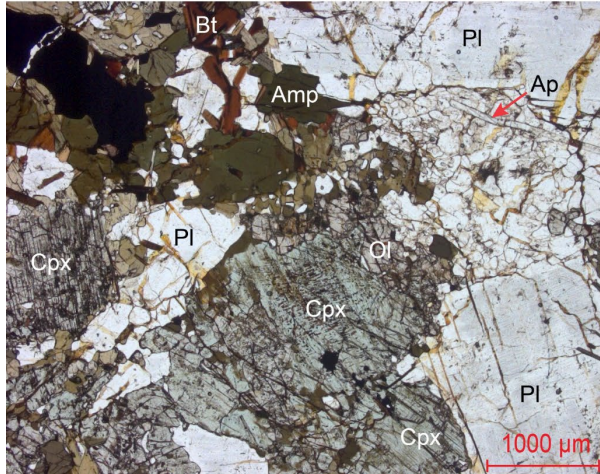
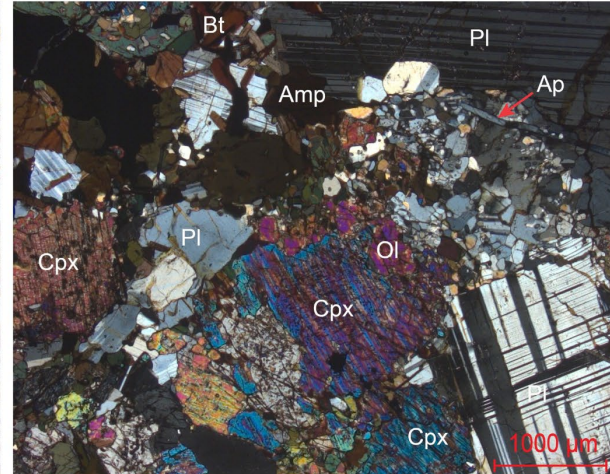
G**H**

Figure 149 continued. G. and H. Elongated, prismatic apatite crystal continues out of view, high-lighted by red arrow, in a very late crystallising pocket. Olivine intergrown with clinopyroxene. Sample HRE220037A (6870401/585440). Left in ppl and right in xpl. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Gråsjön

Hornblende is the main mafic silicate mineral in sample HRE220010A with euhedral to anhedral, small to large grains (figs. 150A–B). Hornblende has grain triple junctions at 120 degrees, an igneous granoblastic texture. There is minor alteration to green amphibole of clinopyroxene. Clinopyroxene is subhedral to anhedral and occurs as small grains to interstitially grown, often with lamellae and opaque exsolutions. Subhedral to anhedral plagioclase has patchy to severe sericite-saussurite alteration. A few small quartz grains exist. Rare biotite grains are severely altered to chlorite.

There are roughly equal amounts of hornblende and clinopyroxene in the well-preserved sample HRE230027A, with minor weathering alteration (figs. 150C–D). Euhedral to anhedral hornblende with grain triple junctions at 120 degrees exist at several locations of the thin section. The granoblastic texture minimises the combined surface energy of the grains (figs. 150E–F). In igneous layered intrusions it signifies textural equilibrium (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Anhedral olivine occurs as grains and interstitially grown crystals. Subhedral to anhedral clinopyroxene with lamellae and opaque exsolutions is present, and few large oikocrysts with chadacrysts of opaque minerals, plagioclase, and hornblende are observed. Subhedral to anhedral plagioclase is generally well-preserved. Rare, small grains of quartz occur.

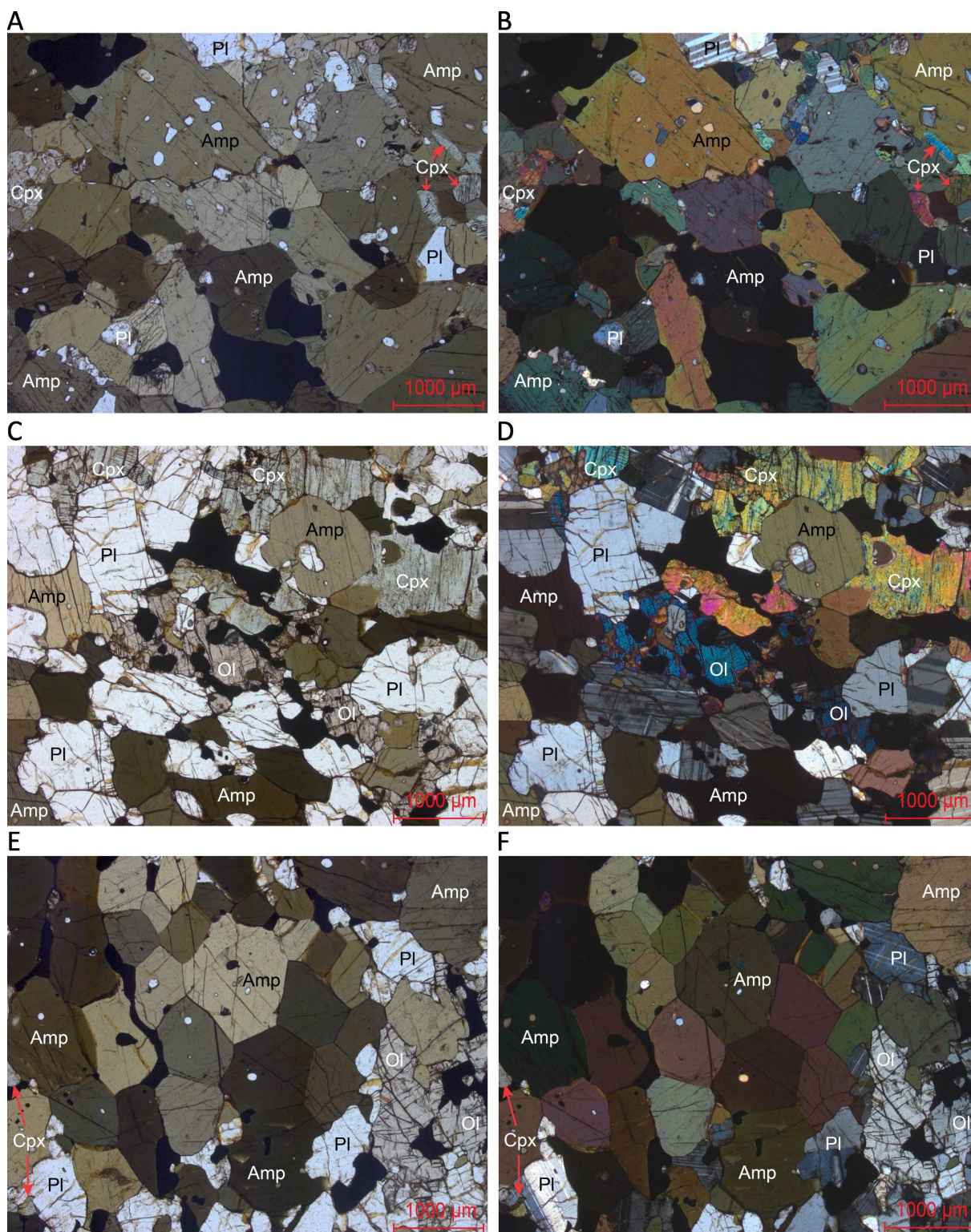


Figure 150. A. and B. Cumulate rock of large hornblende crystals with clinopyroxene and plagioclase interstitially and as inclusions in hornblende. Note the hornblende grain triple junctions at 120 degrees. Sample HRE220010A (6871796/586539). C. and D. Clinopyroxene, hornblende, olivine, and plagioclase in cumulate rock. E. and F. A large olivine crystal and interstitial clinopyroxene in a part dominated by hornblende and plagioclase. Euhedral to subhedral hornblende crystals and some clearly interstitially grown. Several hornblende grain triple junctions at 120 degrees in the centre among subhedral crystals. Sample HRE230027A (6871834/586463). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data from Bläckmyran and Gråsjön

Previous geochemical analyses of the 14 drill cores from Bläckmyran were performed at Swedish Mineralprocesses AB (Minpro AB) during 1981-1983 which included the elements Fe and V. Analogue data from these cores ($n = 202$) has been digitised as part of this project. The linear relationship between Fe and V in these analyses is excellent (fig. 151) with a Pearson coefficient (r) of 0.96. When the new analyses of gabbroids ($n = 34$) collected in this project are included, the Pearson coefficient (r) is 0.97.

Variations in vanadium contents with depth in the drill cores are shown in figure 152. Note that the lengths of the sections used in the old analyses are much longer and variable (2.10 m to 11.50 m) compared to the one-metre sections used in the current project.

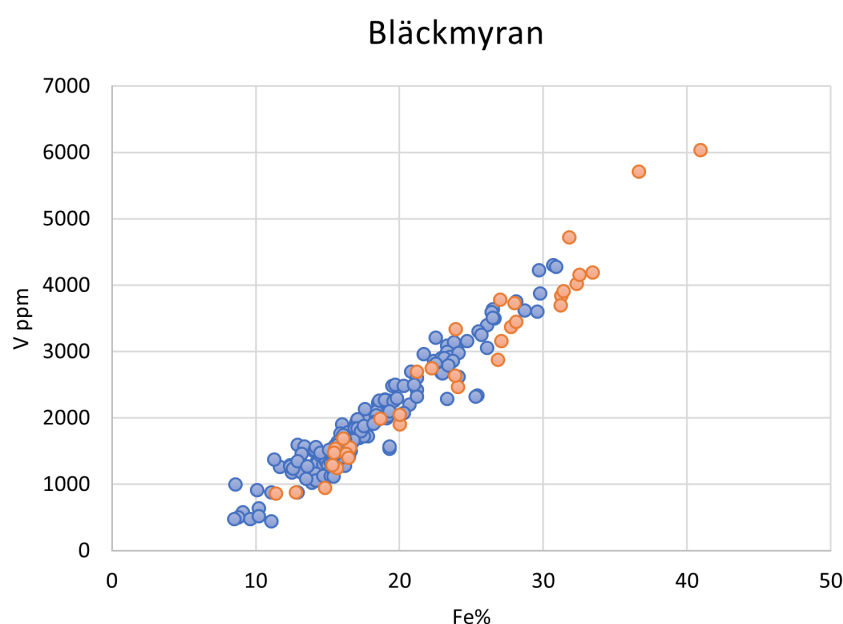


Figure 151. Fe and V contents in gabbroids at Bläckmyran. Blue dots are drill core analyses from 1981–1983 ($n = 202$) and the orange are analyses obtained in the current project from drill cores ($n = 31$) and field samples ($n = 3$). The positive correlation is very good with a Pearson coefficient (r) for the whole dataset of 0.97. The average V:Fe ratio is 0.01.

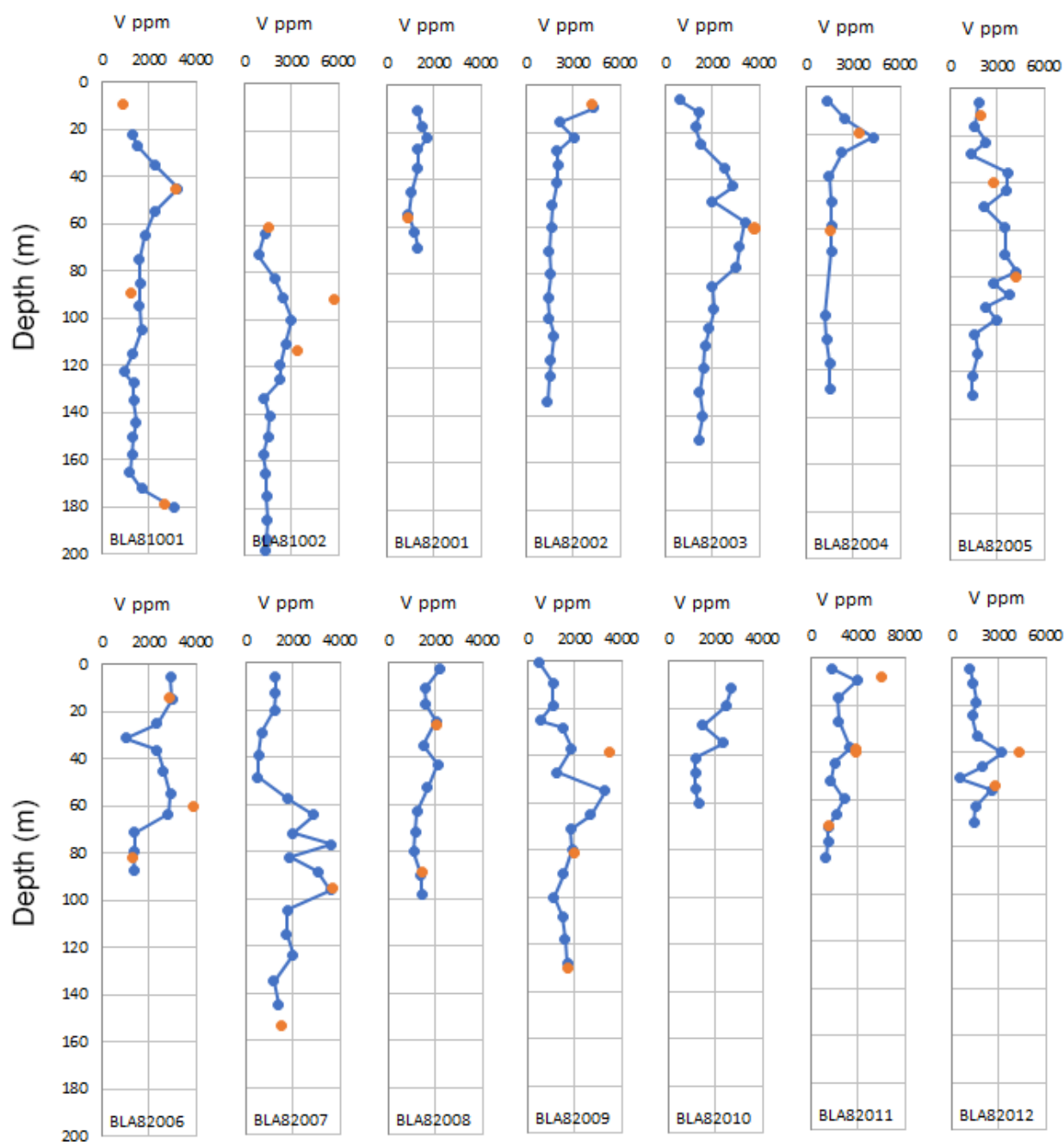


Figure 152. Variations in vanadium contents with depth in Bläckmyran drill cores. Blue dots are drill core analyses from 1981–1982 and the orange (n = 31) are analyses obtained in the current project. The lengths of the sections used in the old analyses are much longer and variable (2.10 m to 11.50 m) compared to the one-metre sections used in the current project. Note that the scale on the X-axis (V ppm) is not the same for all samples.

The total sample suite analysed in the current project comprises 34 samples from Bläckmyran (31 drill core samples and three field samples) and three samples from Gråsjön. Harker diagrams with major element oxides against SiO_2 and vanadium against selected major element oxides and trace elements are shown in figures 153 and 154.

The samples from Bläckmyran and Gråsjön show compositional variations from barren gabbro to strongly Fe-Ti-V mineralised ore with ranges of selected oxides (in %) as follows:

SiO_2 (17.70–50.90), Al_2O_3 (9.29–16.80), Fe_2O_3 (16.30–58.50, average: 32.85), CaO (3.75–10.45), Na_2O (1.06–2.83), MgO (2.10–7.19), K_2O (0.30–1.37), MnO (0.15–0.27), P_2O_5 (0.02–0.87), and TiO_2 (1.76–7.99, average: 4.73).

Vanadium varies from 184–6 040 ppm with an average of 2 628 ppm, 33 samples have more than 1 000 ppm V. Ni contents vary between 1 and 311 ppm, Zn (105–345 ppm), Co (29–199 ppm), Cu (4–539 ppm), and Cr (3–453 ppm).

Scandium contents are in the range 15–56 ppm, with average 33 ppm. Yttrium varies between 6 and 71 ppm, average 15 ppm.

The ΣREE (not including scandium and yttrium) are generally low, varying from 12 to 203 ppm (average 40 ppm). The sample with highest ΣREE value stands out. This sample also has highest yttrium (71 ppm) and is from an evolved sample from Gråsjön with 51% SiO_2 .

In the Bläckmyran dataset (exclusive of the three Gråsjön samples) Fe_2O_3 ($r = -0.99$) and TiO_2 ($r = -0.99$) show strong negative correlations against SiO_2 , while CaO ($r = 0.96$) has strong positive correlation (Table 10).

Vanadium shows good positive correlations with TiO_2 ($r = 0.97$), Fe_2O_3 ($r = 0.98$), Co ($r = 0.95$), Ni ($r = 0.93$), Cu ($r = 0.91$), Zn ($r = 0.88$), In ($r = 0.85$), Ge ($r = 0.85$), and Ga ($r = 0.79$) (Table 10).

Good negative correlations are observed between V and SiO_2 ($r = -0.97$), CaO ($r = -0.95$), and Y ($r = -0.88$).

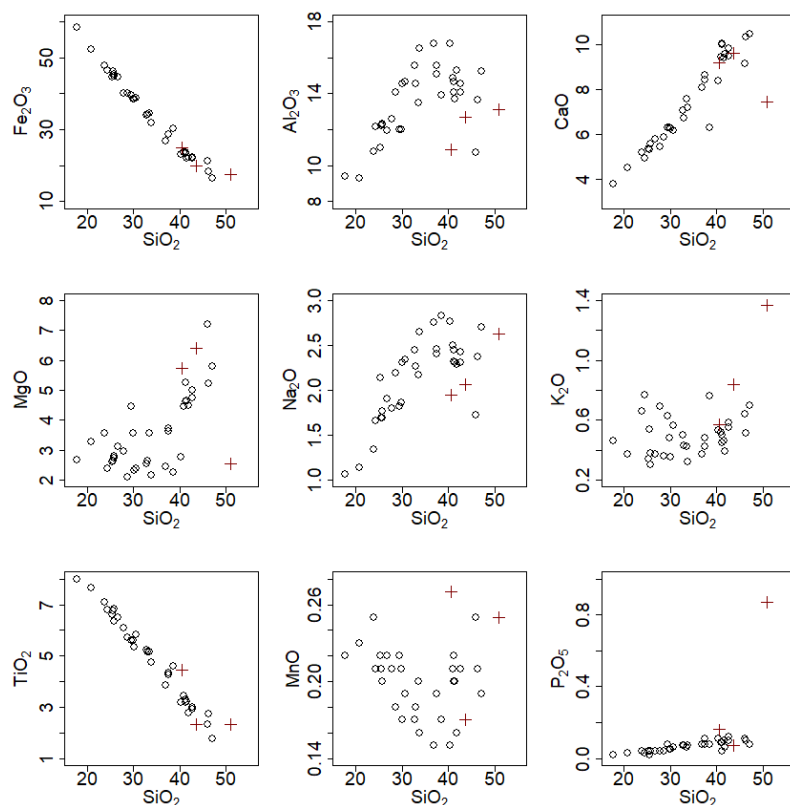


Figure 153. Harker diagrams for major elements vs. SiO_2 in Bläckmyran drill cores and field samples (black circles) and Gråsjön (red crosses). All concentrations are in %.

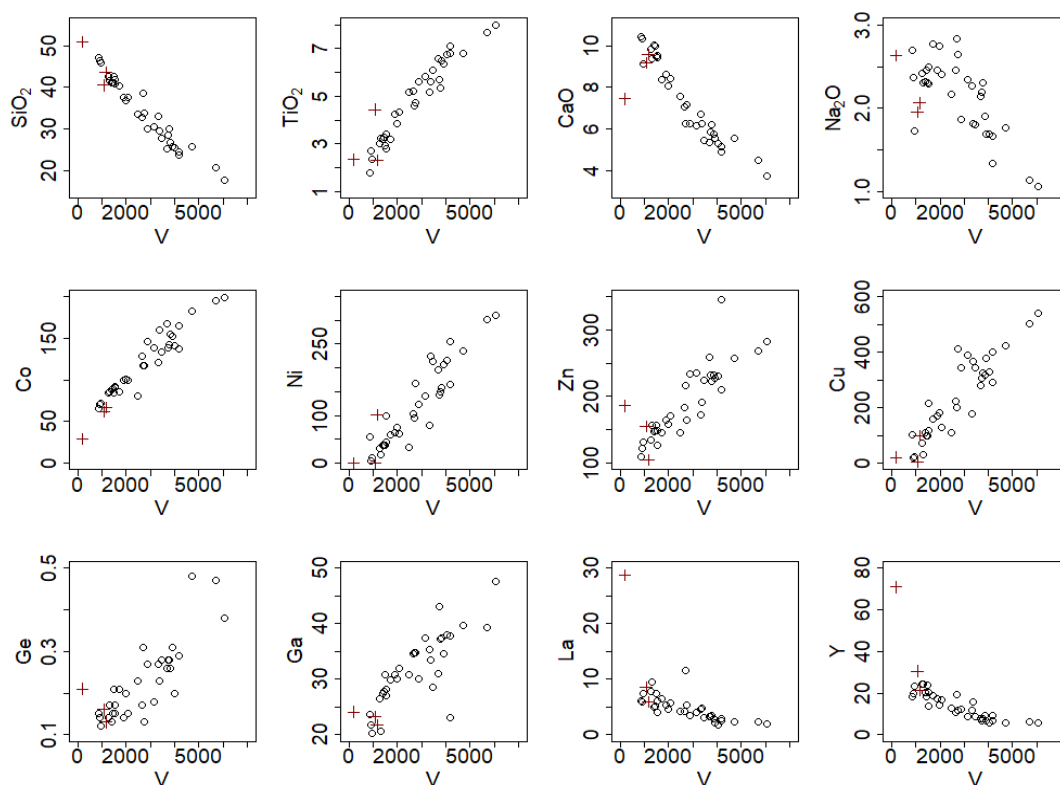


Figure 154. Harker diagrams for vanadium (ppm) vs. selected major and trace elements in Bläckmyran drill cores and field samples (black circles) and Gråsjön (red crosses). Major element oxide concentrations are in %. Trace elements are reported as ppm. The Gråsjön samples appears more evolved and are in the lower end in terms of Fe-Ti-V contents.

Table 10. Pearson correlation matrix for selected elements from Bläckmyran. The three samples from Gråsjön are not included in the calculations.

	V	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	Ce	Co	Cu	Ga	Ge	In	La	Ni	Y	Zn
V	1																
SiO₂	-0.97	1															
TiO₂	0.97	-0.99	1														
Al₂O₃	-0.64	0.62	-0.63	1													
Fe₂O₃	0.98	-0.99	0.99	-0.68	1												
CaO	-0.95	0.96	-0.96	0.60	-0.96	1											
Na₂O	-0.74	0.73	-0.72	0.91	-0.78	0.67	1										
Ce	-0.74	0.78	-0.74	0.43	-0.77	0.68	0.64	1									
Co	0.95	-0.94	0.94	-0.65	0.95	-0.92	-0.72	-0.69	1								
Cu	0.91	-0.90	0.87	-0.49	0.89	-0.88	-0.63	-0.72	0.92	1							
Ga	0.79	-0.74	0.74	-0.28	0.74	-0.73	-0.40	-0.56	0.77	0.78	1						
Ge	0.85	-0.76	0.77	-0.61	0.78	-0.78	-0.63	-0.50	0.81	0.71	0.62	1					
In	0.85	-0.80	0.81	-0.46	0.82	-0.84	-0.52	-0.44	0.83	0.85	0.87	0.72	1				
La	-0.71	0.77	-0.73	0.42	-0.75	0.64	0.64	0.99	-0.68	-0.71	-0.54	-0.48	-0.42	1			
Ni	0.93	-0.91	0.89	-0.63	0.92	-0.89	-0.74	-0.72	0.94	0.95	0.72	0.75	0.80	-0.71	1		
Y	-0.88	0.90	-0.88	0.41	-0.88	0.87	0.56	0.90	-0.82	-0.84	-0.71	-0.66	-0.66	0.87	-0.82	1	
Zn	0.88	-0.89	0.90	-0.66	0.90	-0.89	-0.69	-0.61	0.91	0.83	0.72	0.75	0.78	-0.59	0.86	-0.75	1

In the AFM diagram all samples show strong Fe-enrichment (fig. 155). Primitive mantle normalised trace-element compositions are shown in figure 156. A characteristic feature is the negative Nb anomaly, and positive Pb and Ti anomalies.

Chondrite normalised REE patterns from Blackmyran drill core and outcrops are subparallel (except for Eu-anomalies) and show low to moderate LREE enrichment (fig. 157) with $(La/Yb)_N$ in the range 1.61–4.07. The $(La/Sm)_N$ values are 1.38–2.43 indicating some degree of fractionation between the light REEs. The heavy REEs are slightly fractionated shown by $(Gd/Yb)_N$ ratios (0.99–1.44) and $(Dy/Yb)_N$ ratios (0.92–1.34). Although the absolute REE contents vary between the samples, the general subparallel REE patterns are interpreted as a result of different degrees of fractional crystallisation.

Half of the samples in the dataset ($n = 17$) show negative Eu/Eu*, spanning the interval 0.81–0.99 while the remaining half have positive Eu/Eu* (in the range 1.07–2.01).

The three samples from Gråsjön show a broadly similar pattern with $(La/Yb)_N$ in the range 1.58–2.77, although one evolved sample has higher total REEs than the rest of the sample suite (fig. 157).

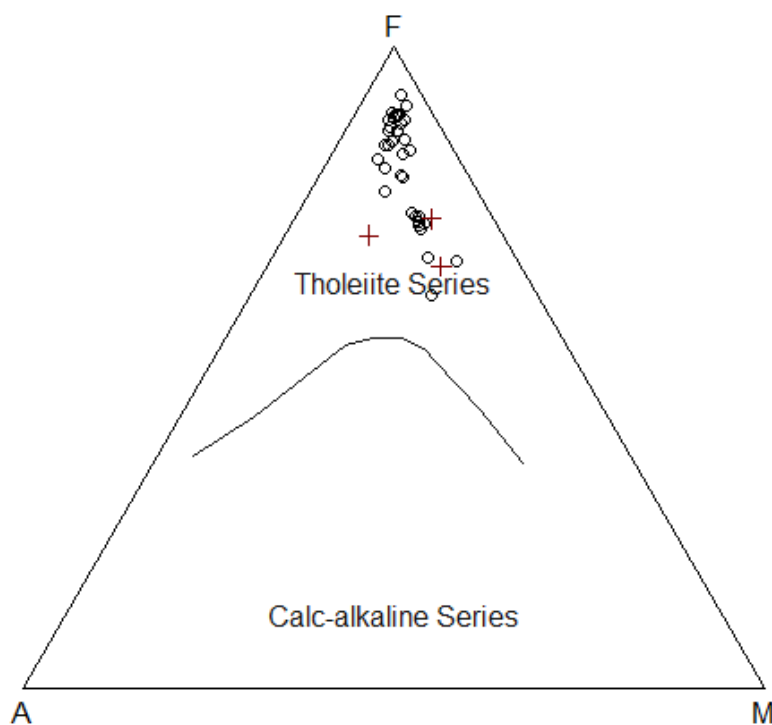


Figure 155. The samples from Bläckmyran (black circles) and Gråsjön (red crosses) plotted in an AFM-diagram (Irvine & Baragar 1971).

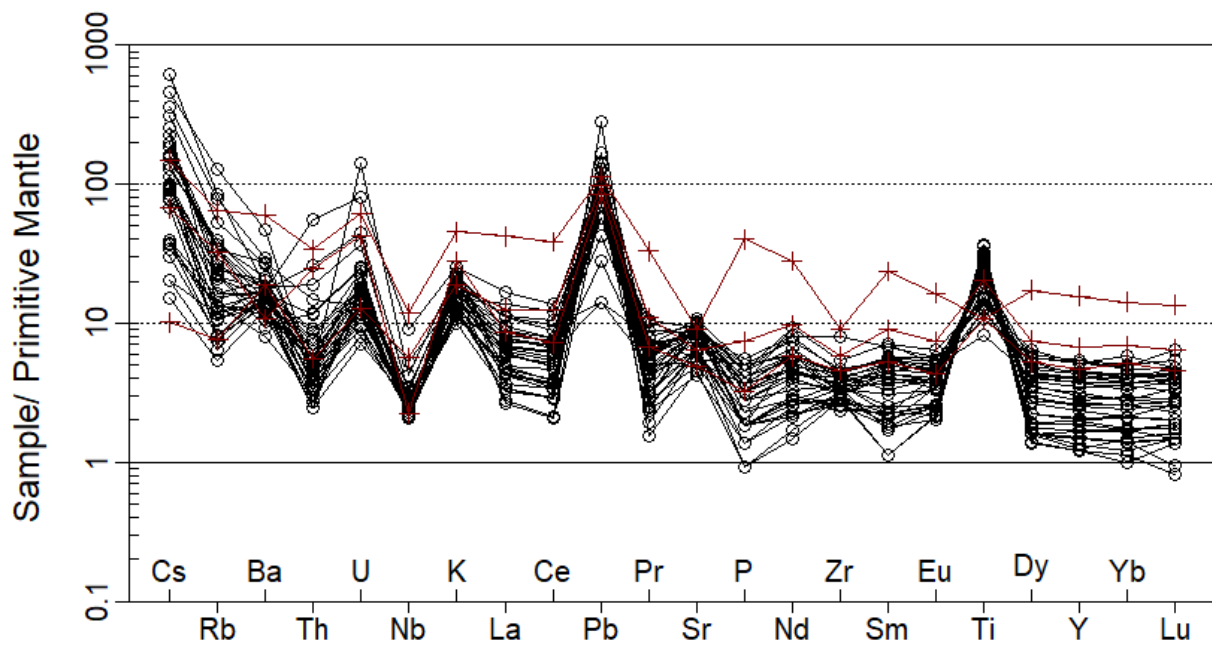


Figure 156. Primitive mantle normalised diagram for Bläckmyran drill core and field samples (black circles) and Gråsjön (red crosses). Normalising values from Sun & McDonough (1989).

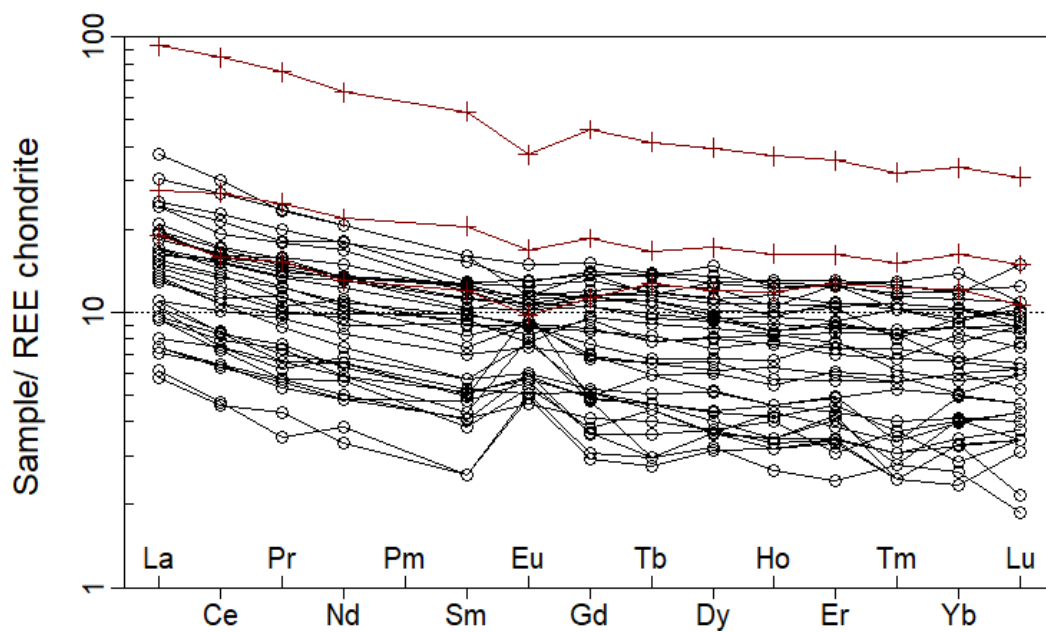


Figure 157. Chondrite normalised REE diagram for samples from drill core and field samples from Bläckmyran (black circles) and Gråsjön (red crosses). The samples are characterised by flat patterns with moderate $(La/Yb)_N$ ratios. Chondrite values are from Boynton (1984).

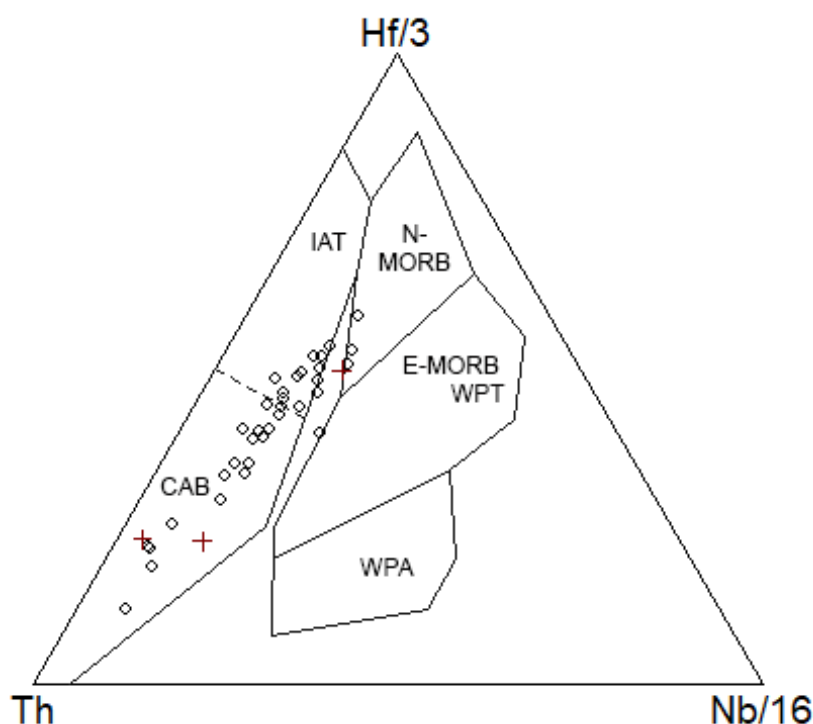


Figure 158. Bläckmyran samples (black circles) and Gråsjön (red crosses) plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

Most of the samples plot in the field of destructive plate volcanic basalts (CAB and IAT) in the triangular Th-Hf-Nb diagrams (fig. 158) while a few straddle the border towards, and even plot within, the N-MORB and E-MORB fields. A predominantly volcanic arc signature is supported by the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 159A and 159B), although a few samples have elevated Nb/La ratios and cluster in the OIB-field close to the MORB boundary. Overall, the geochemical signature resembles that of the Gruvberget–Sumåssjön and Kramsta intrusions and the Bläckmyran gabbroids probably formed in the same tectonomagmatic environment. Hence, geochemical characteristics, with a negative Nb and positive Pb anomaly, and the incompatible trace-element ratios (figs. 158 and 159) favour an interpretation of the tectonomagmatic environment as that of a volcanic-arc, most probably a continental arc. The characteristic positive Ti-anomaly that is observed in the sample suite (similar to the Gruvberget–Sumåssjön and Kramsta intrusions) is interpreted to be a result of the accumulation of titanomagnetite.

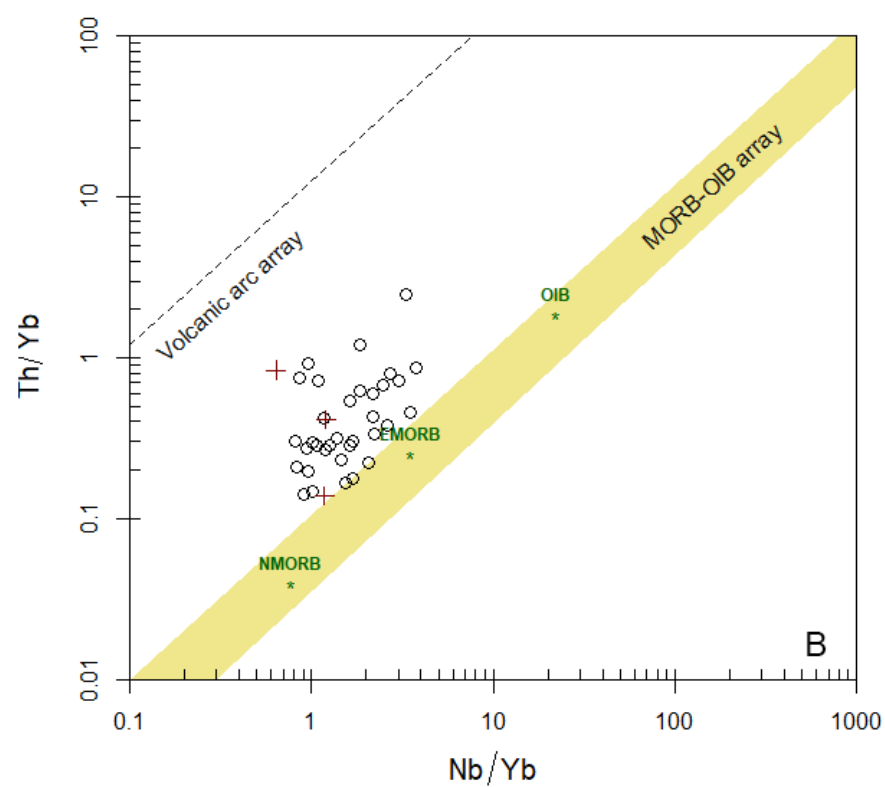
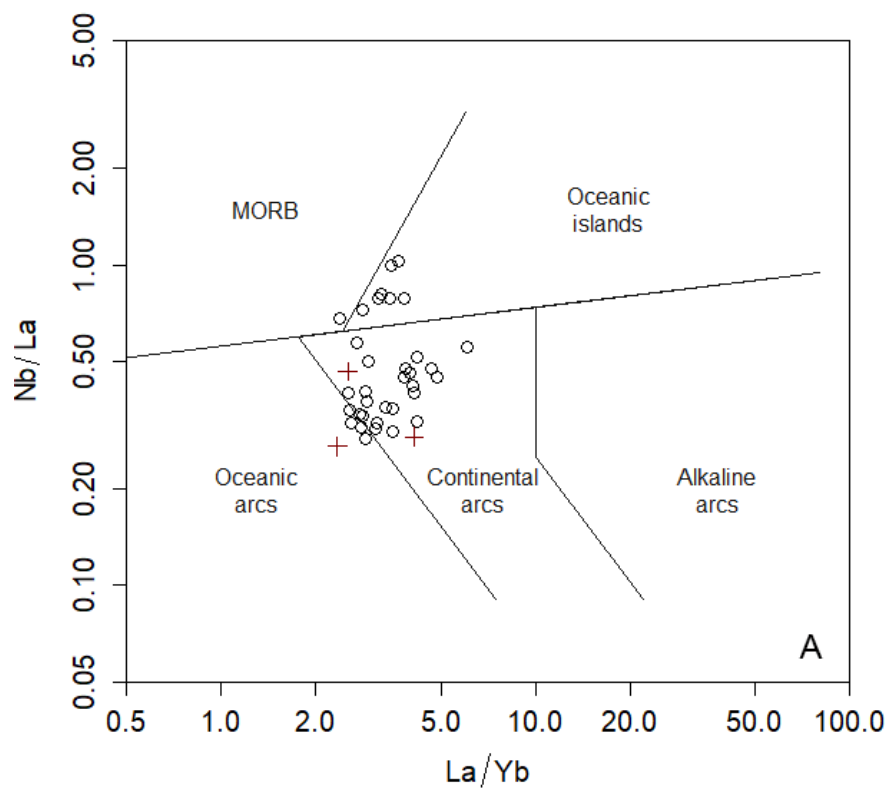


Figure 159. Bläckmyran (black circles) and Gråsjön (red crosses) plotted in diagrams for geotectonic discrimination **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Masugnsberget and Blistra

Mining activities at Masugnsberget started at Gåcktjärns järngruva in the early 1730s but ended quickly. Intermittent mining activity occurred in 1784 and 1823. The last recorded activity was in the 1870s (Wik *et al.* 2009).

Sampling and analyses of waste-rock at Masugnsberget in 1980 showed high grades of vanadium and subsequent airborne magnetic measurements showed a significant positive anomaly. This was followed up with ground measurements in 1981–1982 (fig. 160) and a drilling program in 1983. Four profiles comprising a total of seven drillholes were drilled with an internal spacing of 70–80 m. The work led to the discovery of a 200 m long and c. 10–30 m wide vanadium mineralised zone (Lagergren 1983). At the nearby Blistra occurrence, magnetic ground measurements were conducted, but no drilling was performed.

Ground-based geophysical measurements

Figure 160 shows a map of the ground based magnetic measurements collected over the Masugnsberget and Blistra intrusions, as well as an updated bedrock geology map for the area.

The anomaly associated with the Masugnsberget intrusion appears to include a zone in the northeastern part of the intrusion with several relatively continuous high amplitude anomalies. This area has previously been investigated by drilling. The zone with these higher amplitude anomalies has a length of about 700 m, width of about 250 m and strike of approximately 115°. Within this area the highest magnetic field values reach about 12 000 nT above the background value, which is interpreted to coincide with the highest levels of mineralisation in the intrusion. In this area the continuous positive magnetic anomalies imply a lens- or sheet-like geometry for the mineralisation, as noted in previous studies (Lagergren 1983). To the southwest of this zone are several additional areas with elevated magnetic field values, interpreted to be a series of smaller intrusions with lower levels of mineralisation. Figure 161 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained by inverting the ground magnetic data. Here the highest magnetic susceptibility values are shown in the northeastern part of the intrusion, adjacent to the northeastern contact. Within the 3D susceptibility model the zone with high susceptibility values beneath the intrusion appears to dip to the southwest (fig. 161), which is consistent with drill core data and results from previous studies (Lagergren 1983).

Magnetic susceptibility logs of core from the MAB83006 and MAB83007 boreholes within the Masugnsberget intrusion can be found in appendix B. A map showing the location of these boreholes is shown in appendix B. Within the MAB83006 borehole there appears to be a 10–15 m thick interval at about 60 m depth with relatively high magnetic susceptibilities and vanadium content. The magnetic susceptibility within the MAB83007 well is relatively constant throughout the entire logged interval.

The area with ground magnetic anomalies above the Blistra intrusion is some 1 200 m long, 250 m wide and has an approximate strike of 115° (fig. 160). This appears to include a series of semi-parallel, relatively low amplitude and low frequency magnetic field anomalies. The highest magnetic field values reach some 5 500 nT above the background value. These values appear to be located close to the central northeastern edge of the intrusion. Figure 162 shows a map of the average magnetic susceptibility within the upper 75 m of the model obtained by inverting the ground magnetic data. Here the highest susceptibility values appear to be located on the northeastern edge of the intrusion. Within the 3D inversion model, it appears that the intrusion dips to the southwest (fig. 162).

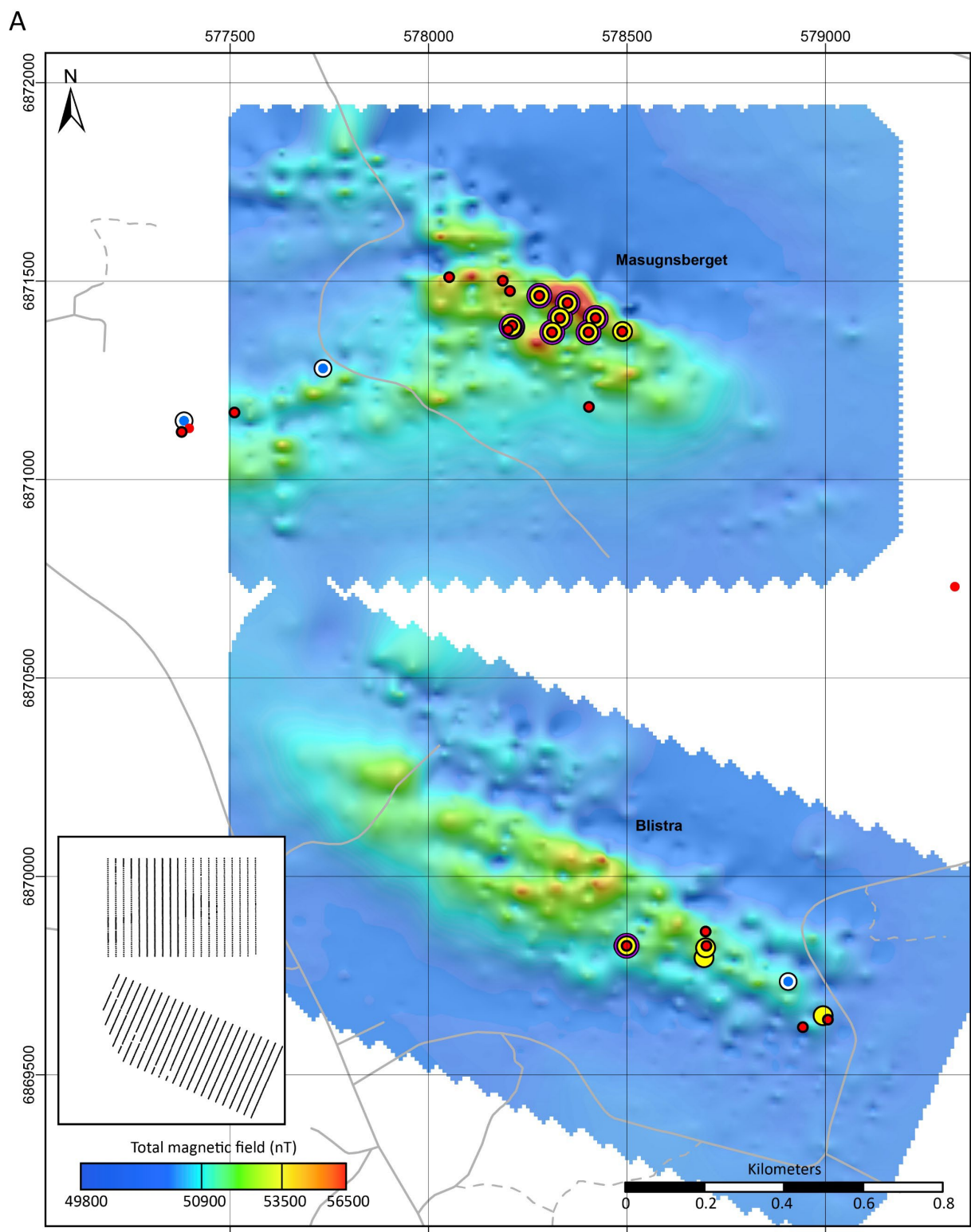


Figure 160. A. Map of the total magnetic field from ground measurements collected by SGU in 1982 from the Masugnsberget and Blistra intrusions. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. The location of geological observations, samples, boreholes, and magnetic susceptibility measurements at outcrop are shown as different coloured dots on the map. See figure 160B for the legend for these symbols. Note that the only boreholes in the figure are located in Masugnsberget but are obscured by the other symbols.

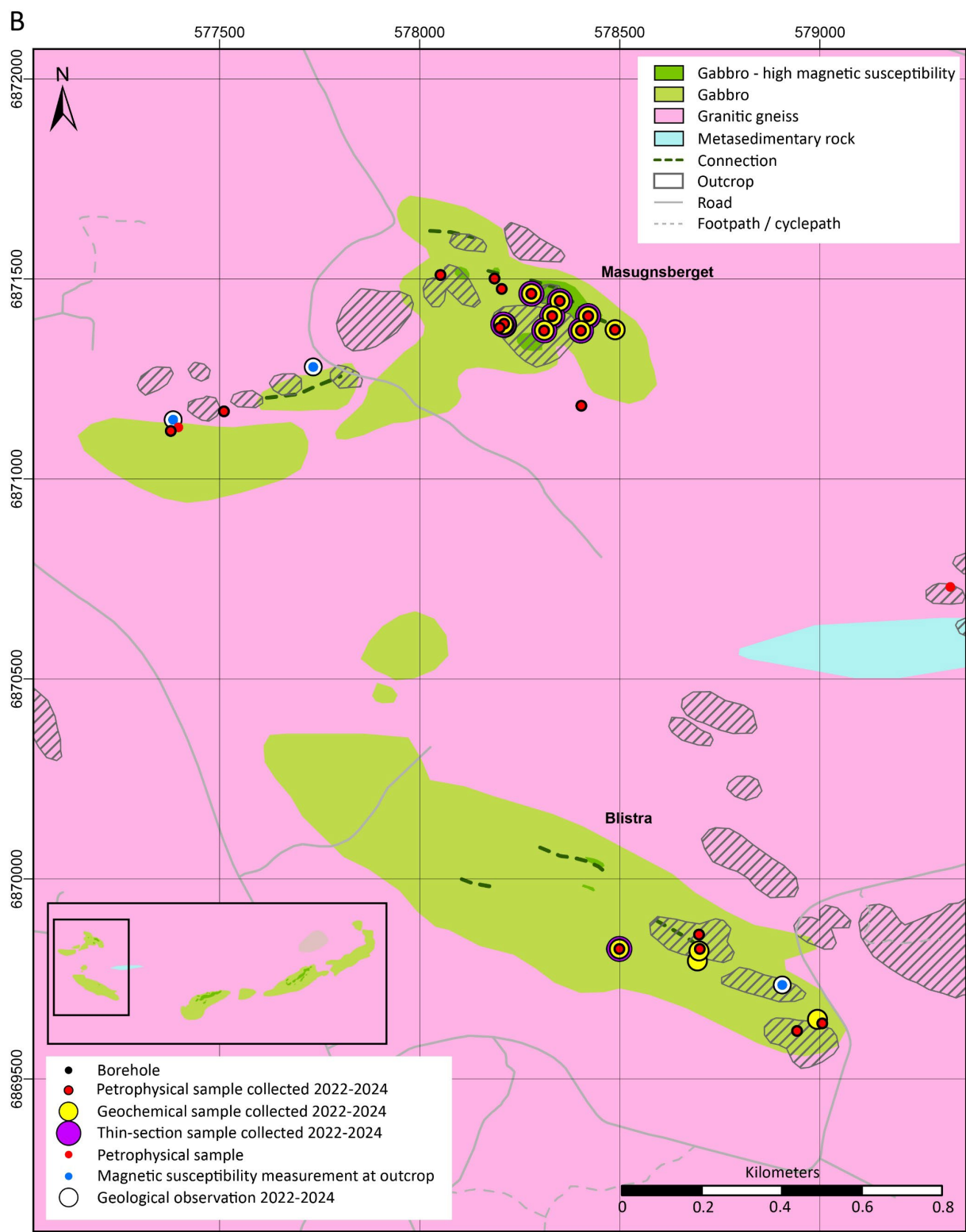


Figure 160 continued. B. Updated map of the bedrock geology around the Masugnsberget and Blistra intrusions, interpreted from the ground magnetic field data and the available geological observations and samples. The location of geological observations, samples, boreholes, and magnetic susceptibility measurements at outcrop are shown as different coloured dots on the map. The inset map shows the location of the map with regards to the other intrusions in the Gruvberget–Sumåssjön area. Note that the only boreholes in the figure are located in Masugnsberget but are obscured by the other symbols.

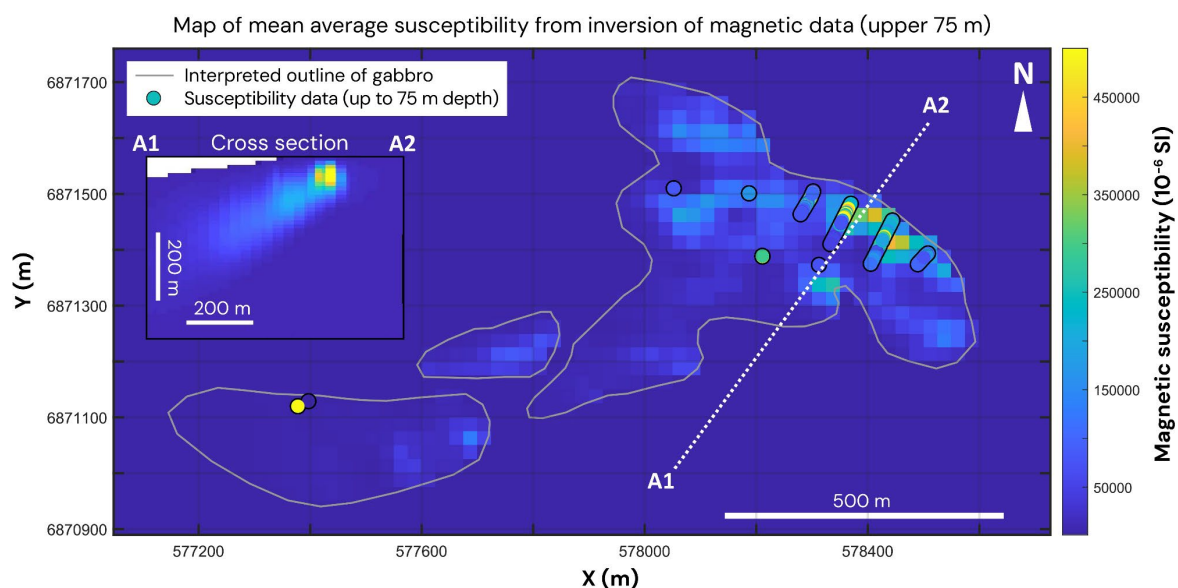


Figure 161. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Masugnsberget intrusion. All magnetic susceptibility measurements collected up to a depth of 75 m (measurements on core and at the surface) are shown as dots. In cases where only geochemical data is available from drill cores, magnetic susceptibilities have been calculated using the relationship described in the petrophysics section of the report. These calculated susceptibilities are shown together with the magnetic susceptibility measurements as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale.

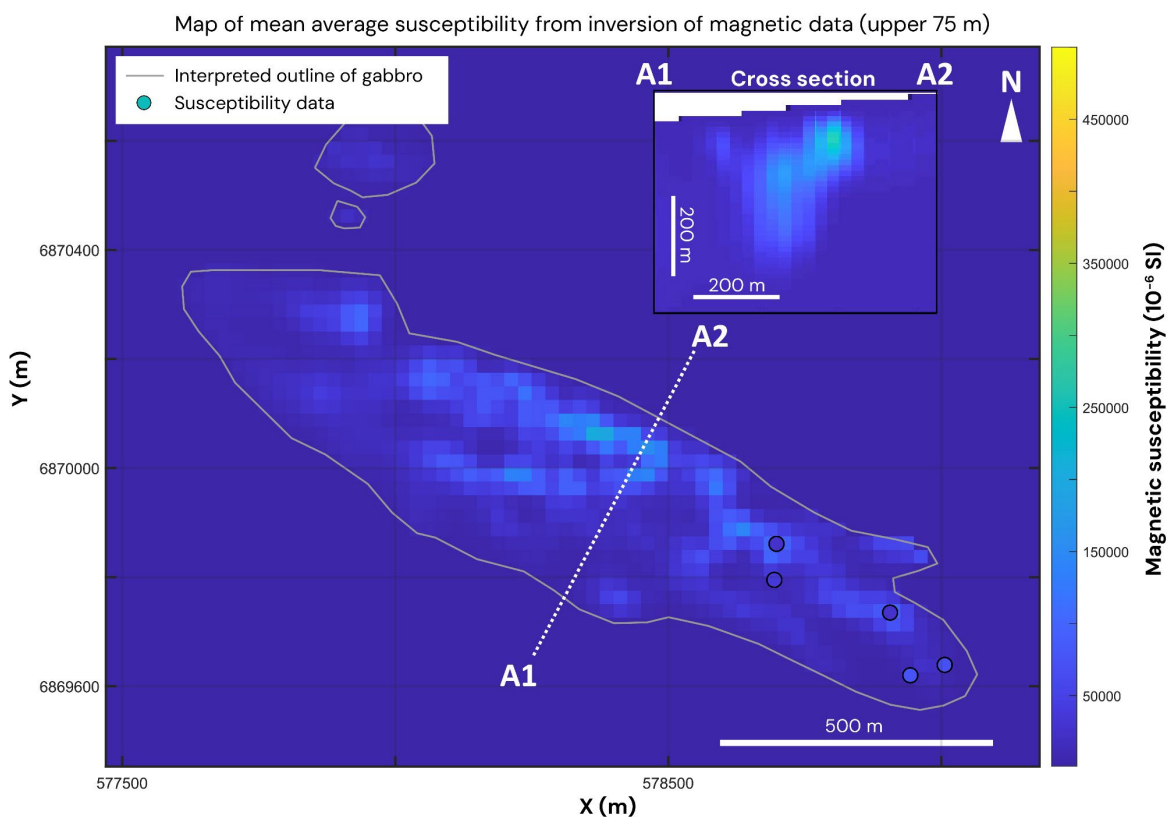


Figure 162. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Blistra intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

In the current project all the seven drill cores from 1983 were sampled and analysed for major and trace elements including a total of 19 sections, each comprising c. 1 m of core (fig. 167). In addition, three samples, which contained 1 435, 3 110, and 4 330 ppm vanadium respectively, were collected from an old mining pit at Gåcktjärns järngruva (fig. 163). Two outcrops (fig. 164) and two small mining pits (fig. 165) at Blistra (Blistra gruva 1 and Blistra gruva 2) were sampled with a total of four samples (e.g., fig. 166).



Figure 163. A. Mining pit at Gåcktjärns järngruva at Masugnsberget (6871389/578211). The pit is approximately 10 × 15 m. B. Sample of Fe-Ti-V mineralised gabbroid from waste-rock adjacent to the pit. Photo: Helge Reginiussen.



Figure 164. Gabbroid outcrop at Blistra (6869820/578698). Assay from a sample taken at this outcrop returned 28.80% Fe_2O_3 , 3.92% TiO_2 , and 2 120 ppm V. Photo: Helge Reginiussen.



Figure 165. Sampling of waste-rock from the old pit at Blistra gruva 1 (6869825/578489). Photo: Helge Reginiussen.



Figure 166. Sample of waste-rock comprising mineralised gabbroid from the pit at Blistra gruva 1 (6869825/578489). Analysis shows 28.80% Fe_2O_3 , 3.97% TiO_2 , and 1 800 ppm V. Photo: Helge Reginiussen.



Figure 167. Tray 6 of drill core MAS83006 from Masugnsberget containing fine- to medium-grained, massive, homogeneous, gabbroid. Such fine- to medium-grained varieties often have the highest V contents. Analysis of the section between the red arrows in compartment 5 (59.38–60.36 m) yielded 37.40% Fe_2O_3 , 5.48% TiO_2 , and 3 240 ppm V. Photo: Helge Reginiussen.

Description of thin sections – ore minerals – Masugnsberget

The ore minerals magnetite, ilmenite, pyrrhotite, pyrite, and chalcopyrite were identified in sample DCL222001B from drill core MAB83003 at 28.64–28.68 m (fig. 168, see fig. C17 for panorama). The texture of the larger grains of magnetite and ilmenite suggest that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock (figs. 168A–C). There is plenty of exsolved ilmenite as laths and trellis in the magnetite (fig. 168B). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are likely to be magnetite or ulvöspinel (figs. 168D, G, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), however, this could not be confirmed. The sulphide grains in sample DCL222001B are, compared to other intrusions in this study, relatively large but still a minor component (figs. 168A, C). Most grains are either pure pyrrhotite or infillings of pyrite, but some are coprecipitations of pyrrhotite and chalcopyrite (fig. 168C).

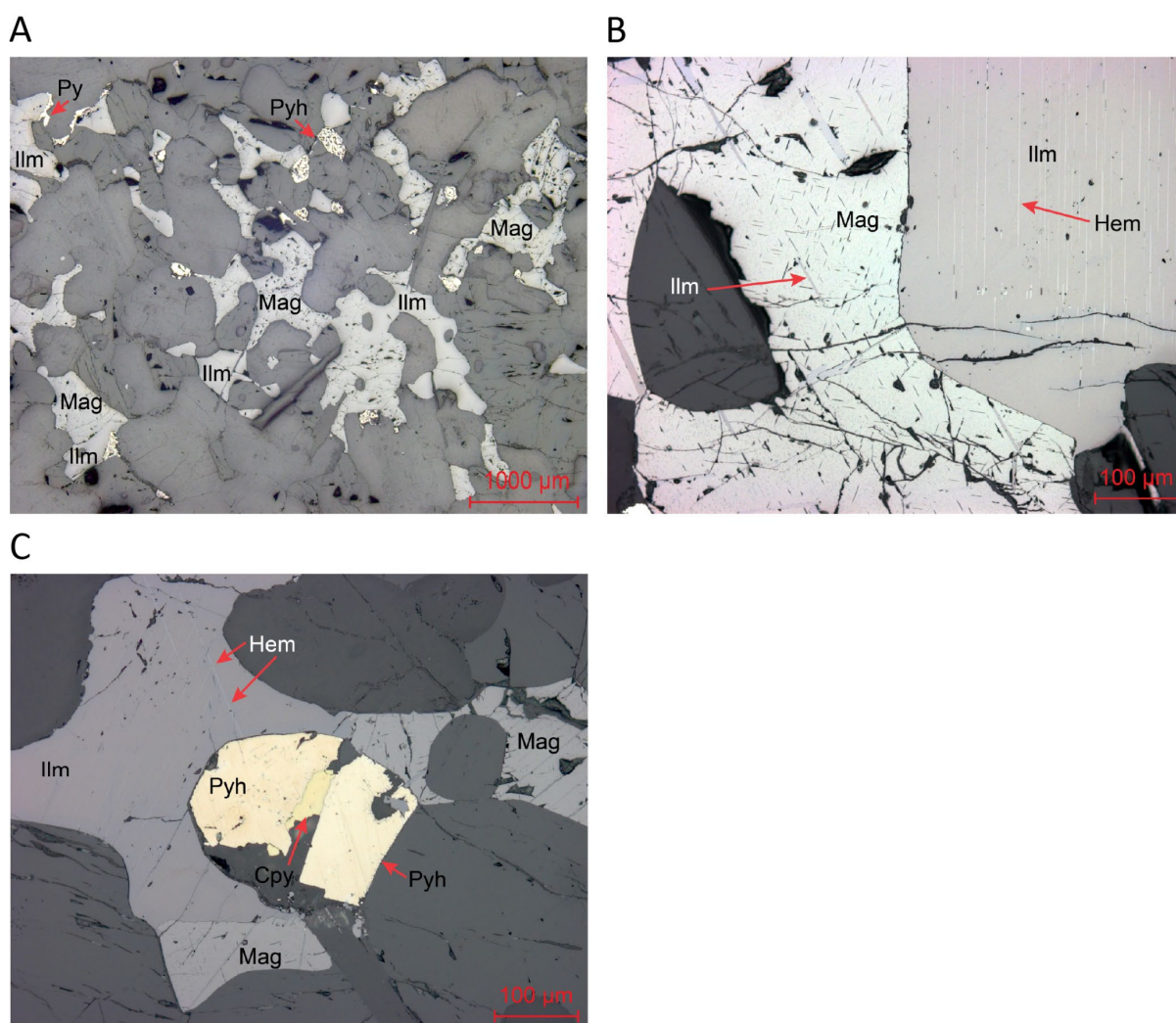


Figure 168. Ore minerals from the Masugnsberget intrusion, mineralised sample DCL222001B from drill core MAB83003 at 28.64–28.68 m (see fig. C17 for panorama). **A.** Overview of relations between magnetite, ilmenite, pyrrhotite, and pyrite in interstitial opaque framework. **B.** Close-up of relations between large magnetite and ilmenite grains, note ilmenite as trellis exsolutions along crystallographic planes, lath-shaped exsolutions within magnetite and thin hematite exsolution lamellae in both minerals. **C.** Close-up of thin hematite exsolutions along two crystallographic planes in ilmenite, and a grain of chalcopyrite sandwiched between two of pyrrhotite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

The ore minerals magnetite, ilmenite, pyrrhotite, and chalcopyrite were identified in mineralised sample DCL223026A from drill core MAB83001 at 29.68–29.72 m (fig. 169, see fig. C19 for panorama). Large grains of both magnetite and ilmenite occur in a framework of opaque minerals (fig. 169A). Exsolved ilmenite occurs as trellis and laths in the magnetite (figs. 169B–C). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are most likely magnetite or ulvöspinel (fig. 169C). Both ulvöspinel and pleonaste are possibly present among the tiny trellis-type exsolutions in the magnetite, where pleonaste would be the darkest ones but this could not be confirmed using the optical microscope.

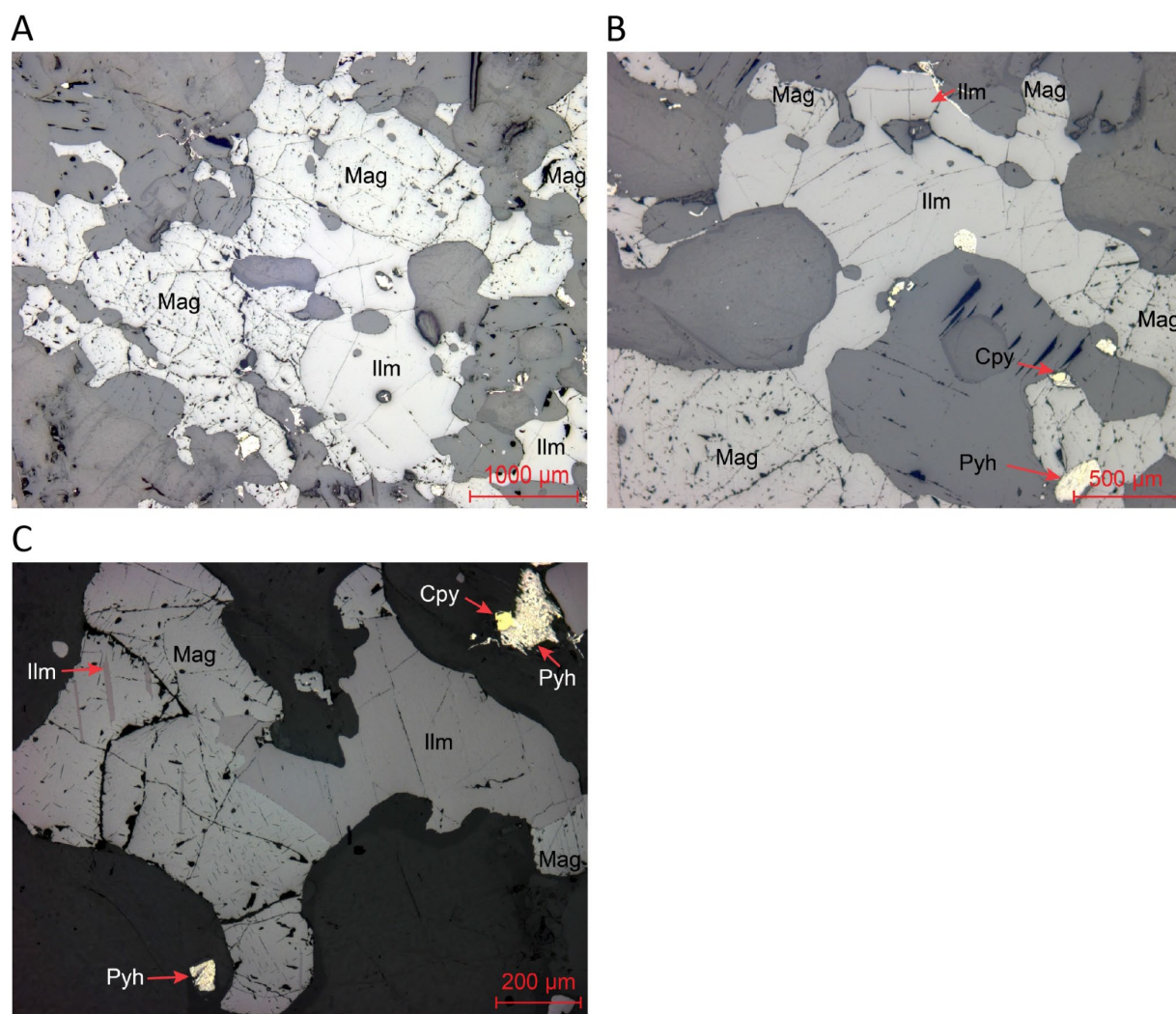


Figure 169. Ore minerals from the Masugnsberget intrusion, mineralised sample DCL223026A from drill core MAB83001 at 29.68–29.72 m (see fig. C19 for panorama). **A.** Overview of relations between magnetite and ilmenite in opaque framework. Close-up images of **B.** relations between large magnetite and ilmenite grains and small pyrrhotite and chalcopyrite grains, **C.** ilmenite as trellis exsolutions along crystallographic planes and lath-shaped exsolutions within magnetite, note thin exsolution lamellae in both minerals. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Masugnsberget

The well-preserved, mineralised sample DCL222001B from drill core MAB83003 at 28.64–28.68 m (panorama fig. C17), has hornblende as the main mafic silicate mineral (figs. 170A–D).

Euhedral to subhedral hornblende occurs as grains and interstitially grown crystals. Hornblende has grain triple junctions at 120 degrees at several locations of the thin section. A granoblastic texture is present that in igneous layered intrusions signifies textural equilibrium (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Well-preserved subhedral to anhedral plagioclase grains occur. There are two generations of biotite, the first has red to light brown pleochroism and the second brownish red to tan. Some interstitially grown biotite crystals have exsolutions of opaque minerals. Biotite, hornblende, and Fe-Ti oxides form aggregates. Few quartz grains with slightly undulose extinction occur.

The mineralised sample DCL222002B from drill core MAB83004 at 86.20–86.25 m (panorama fig. C18), is well-preserved with clinopyroxene, hornblende, olivine, and biotite as mafic silicate minerals (figs. 170E–F). Clinopyroxene is subhedral to anhedral and has lamellae and opaque exsolutions. Anhedral interstitially grown olivine and mostly interstitial subhedral to anhedral hornblende occurs. Subhedral to anhedral plagioclase crystals display slight sericite-saussurite alteration in patches and some have bends or kinks, deformation twins, and undulose extinction due to compaction while hot in a crystal mush. Two generations of biotite are present, the first has red to light brown pleochroism and the second brownish red to tan. Some interstitial biotite crystals have exsolutions of opaque minerals. A few quartz grains have slightly undulose extinction.

Subhedral to anhedral hornblende forms aggregates with biotite and Fe-Ti oxides in sample DCL222003B from drill core MAB83004 at 20.21–20.28 m (figs. 171A–B). Glomerocrysts of mainly clinopyroxene are present in the well-preserved cumulate rock (figs. 171C–D). Subhedral to anhedral clinopyroxene has lamellae and opaque exsolutions. The olivine is anhedral and grown interstitially. Subhedral to anhedral plagioclase has minor sericite-saussurite alteration in patches. Pigmentation of plagioclase cores is lacking in their rims. There are two generations of biotite, the first has red to light brown pleochroism and the second brownish red to tan, some crystals have exsolution of opaque minerals. Rare but relatively large alkali feldspar crystals, euhedral to subhedral apatite grains, and quartz grains with weak undulose extinction occur.

Generally, sample DCL223022A from drill core MAB83002 at 6.47–6.51 m is a well-preserved fine-grained cumulate rock (figs. 171E–F). Alteration is limited to fractures, with secondary green amphibole and chlorite formed in their proximity. Subhedral to anhedral hornblende, possibly few small grains of olivine, subhedral to anhedral clinopyroxene with lamellae and opaque exsolutions are present. Subhedral to anhedral, small and relatively large plagioclase crystals occur. The two generations of biotite have distinct pleochroism, the first has red to light brown pleochroism and the second dark tan to light tan, some crystals have exsolution of opaque minerals. Aggregates of biotite, hornblende, and Fe-Ti oxides occur. Rare but relatively large alkali feldspar crystals, a few subhedral apatite grains, and quartz grains with weak undulose extinction occur.



Figure 170. A. and B. Euhedral to subhedral hornblende is the main mafic mineral. Note hornblende grain triple junctions at 120 degrees. Aggregates of biotite, hornblende, and Fe-Ti oxides. C. and D. Aggregates of hornblende and Fe-Ti oxides, with less biotite than in A–B. Images from sample DCL222001B from drill core MAB83003 at 28.64–28.68 m. E. and F. Sample DCL222002B from drill core MAB83004 at 86.20–86.25 m, with mostly interstitial olivine, clinopyroxene, hornblende, and biotite. Left in ppl and right in xpl. Photo: Dick Claeson.

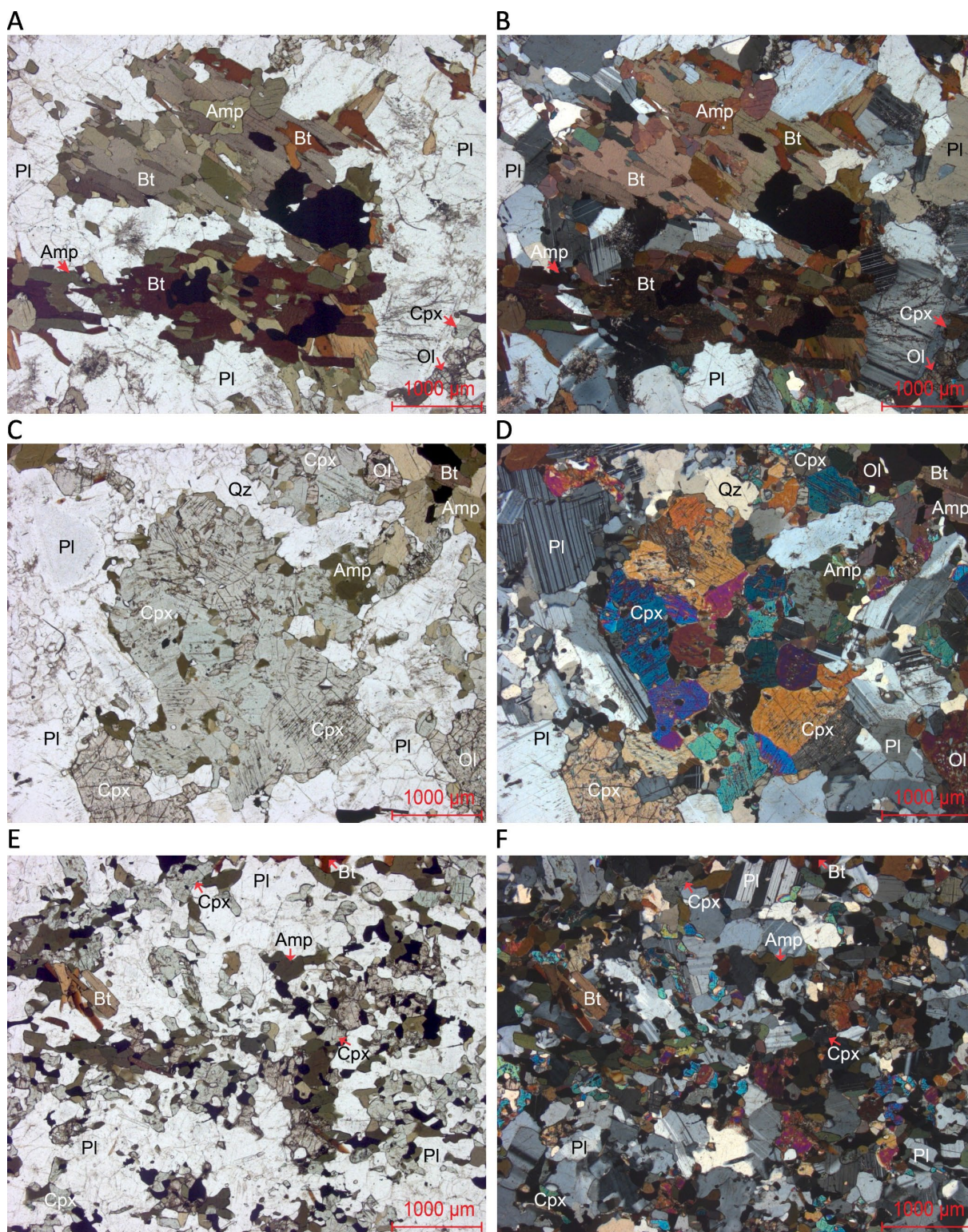


Figure 171. A. and B. Aggregates of biotite, hornblende, and Fe-Ti oxides. C. and D. Glomerocryst of mainly clinopyroxene crystals. Images from sample DCL222003B from drill core MAB83004 at 20.21–20.28 m. E. and F. Sample DCL223022A from drill core MAB83002 at 6.47–6.51 m, a fine-grained cumulate rock with aggregates of biotite, hornblende, and Fe-Ti oxides. Left in ppl and right in xpl. Photo: Dick Claeson.

Euhedral to subhedral hornblende is the main mafic silicate mineral of sample DCL223024A from drill core MAB83002 at 66.67–66.72 m (figs. 172A–B). Several of the hornblende grains display triple junctions at 120 degrees, an igneous granoblastic texture in the cumulate rock. Subhedral to anhedral plagioclase and few biotite grains with brownish red to light brown pleochroism occur. Few anhedral apatite and quartz grains with weak undulose extinction are present.

Well-preserved, mineralised sample DCL223026A from drill core MAB83001 at 29.68–29.72 m has a preferred orientation of minerals (panorama fig. C19), and euhedral to anhedral hornblende is the main mafic silicate mineral (figs. 172C–F). Hornblende crystals display grain triple junctions at 120 degrees, an igneous granoblastic texture indicating textural equilibrium in cumulate rocks (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). The plagioclase crystals are for the most part anhedral to subhedral and the rounded and embayed appearance of the anhedral crystals is probably due to dissolution and subsequent replacement by a late-stage interstitial hydrous Fe-Ti-rich liquid. This liquid formed Fe-Ti oxide in its place rather than hornblende. Plagioclase has minor alteration to sericite-saussurite along fractures. Biotite has brownish red to light brown pleochroism. Apatite occurs as grains and aggregates and quartz grains have slightly undulose extinction.

The cumulate rock of sample DCL223028A from drill core MAB83001 at 66.93–66.97 consists mainly of clinopyroxene, hornblende, olivine, biotite, and orthopyroxene as mafic silicates and plagioclase as felsic (figs. 173A–D). Subhedral to anhedral clinopyroxene has lamellae and opaque exsolutions. Subhedral to anhedral hornblende occurs as grains, interstitially grown crystals, and in aggregates with biotite and Fe-Ti oxides. Olivine occurs as anhedral to subhedral grains and interstitially grown crystals. Rare orthopyroxene crystals have low order birefringence and straight extinction. Subhedral to anhedral plagioclase grains are well-preserved. Two generations of biotite occur, the first has brownish red to brown pleochroism and the second brownish red to tan.

Clinopyroxene is the main mafic mineral of the well-preserved sample DCL234009A from drill core MAB83006 at 15.86–15.93 m (figs. 173E–F). The clinopyroxene is subhedral-anhedral and has lamellae and opaque exsolutions. Minor amounts of subhedral to anhedral hornblende occur as grains and interstitially grown crystals. Cores of subhedral to anhedral plagioclase crystals have darker pigmentation than their rims lack. Small interstitial plagioclase crystals lack pigmentation. The relatively abundant biotite occurs as two generations, the first has brownish red to brown pleochroism and the second brownish red to tan. Anhedral apatite grains and quartz grains with weak undulose extinction occur.

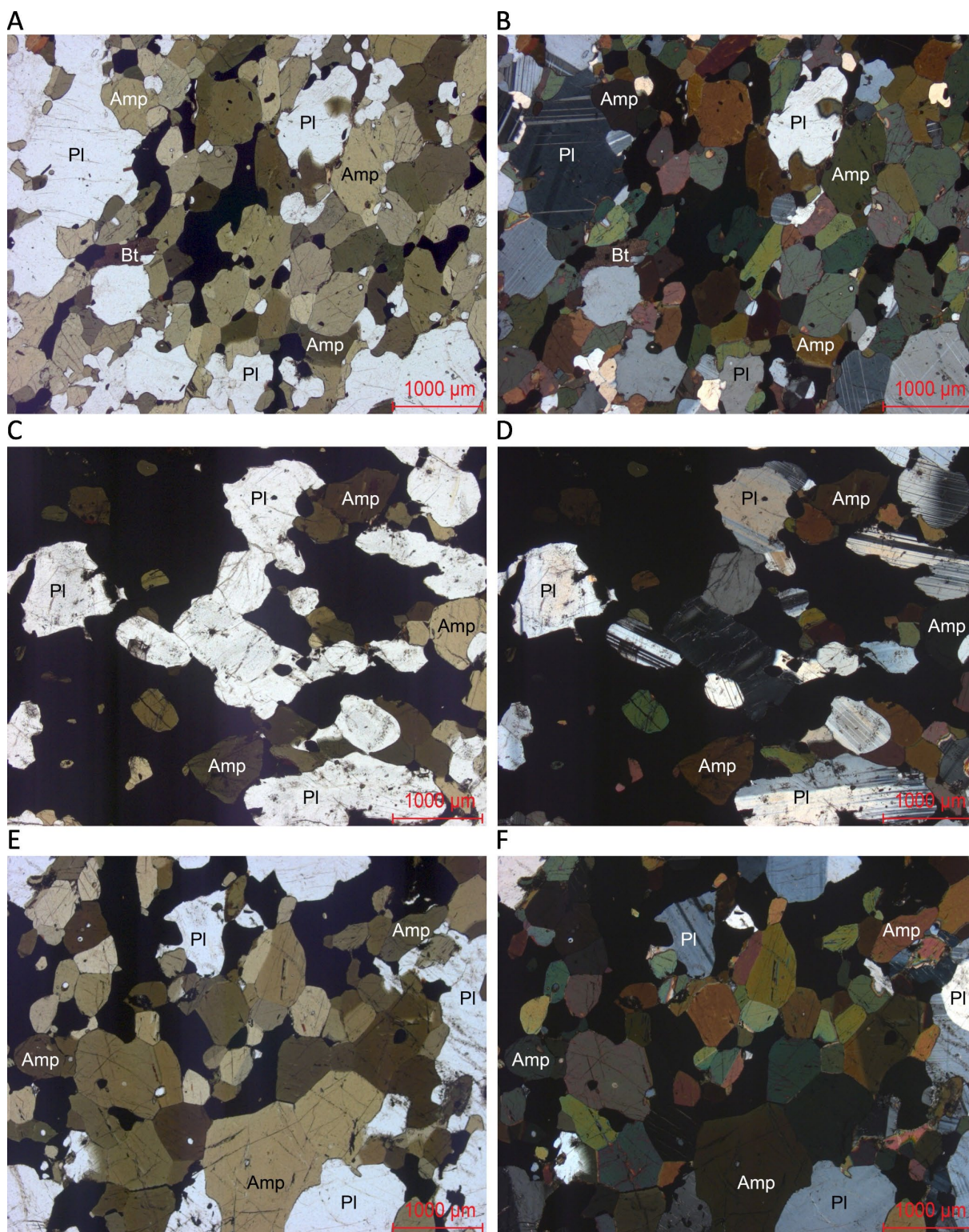


Figure 172. **A.** and **B.** Sample DCL223024A from drill core MAB83002 at 66.67–66.72 m, euhehedral to subhehedral hornblende with triple junctions at 120 degrees. **C.** and **D.** Rounded and embayed plagioclase crystals indicate dissolution and replacement by Fe–Ti oxides. **E.** and **F.** Euhehedral to anhedral hornblende, grain triple junctions at 120 degrees. Images from sample DCL223026A from drill core MAB83001 at 29.68–29.72 m. Left in ppl and right in xpl. Photo: Dick Claeson.

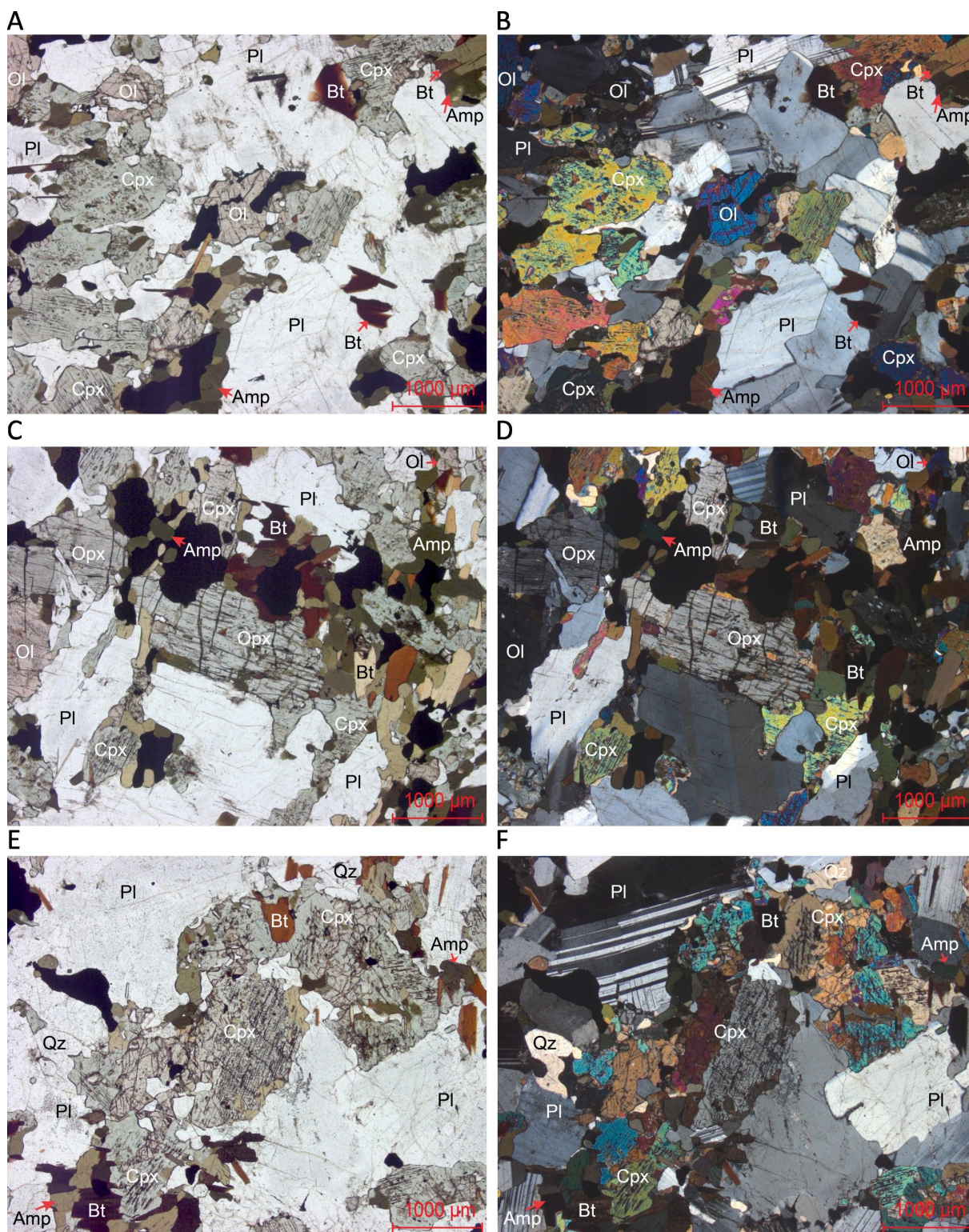


Figure 173. A. and B. Cumulate rock with clinopyroxene, olivine, and hornblende as main mafic silicates. C. and D. Rare orthopyroxene grains. Aggregates of hornblende, biotite, and Fe-Ti oxides. Images from sample DCL223028A from drill core MAB83001 at 66.93–66.97 m. E. and F. Clinopyroxene main mafic silicate. Note pigmentation pattern in large plagioclase. Sample DCL234009A from drill core MAB83006 at 15.86–15.93 m. Left in ppl and right in xpl. Photo: Dick Claeson.

Subhedral to anhedral hornblende is the main mafic silicate mineral in sample DCL234008A from drill core MAB83006 at 60.45-60.50 m (figs. 174A–D). Hornblende, biotite, and Fe-Ti oxides form aggregates. Hornblende, with grain triple junctions at 120 degrees, an igneous granoblastic texture indicating textural equilibrium, occurs. The cumulate rock is well-preserved but for minor alteration of plagioclase to sericite-saussurite in patches. There are rare crystals of olivine, clinopyroxene, and a few orthopyroxene crystals that are partly consumed and replaced by hornblende. Two generations of biotite occur, the first has brownish red to light brown pleochroism and the second brownish red to tan. Rare quartz grains with weak undulose extinction are present.

The well-preserved, mineralised sample DCL234010A from drill core MAB83005 at 176.45–176.51 m (panorama fig. C20), has subhedral to anhedral clinopyroxene as the main mafic mineral (figs. 174E–F). The clinopyroxene grains have lamellae and opaque exsolutions. Subhedral to anhedral minor hornblende occurs as grains and interstitially grown crystals. Subhedral to anhedral plagioclase have patchy sericite-saussurite alteration, some severe. Abundant biotite of two igneous generations is present, the first has brownish red to brown pleochroism and the second brownish red to light tan. Few relatively large aggregates of alkali feldspar and quartz grains with weak undulose extinction are late crystallising minerals. Aggregates of hornblende, biotite, and Fe-Ti oxides occur.

Subhedral to anhedral grains of clinopyroxene, hornblende, olivine, and minor biotite are the main mafic silicate minerals of the well-preserved mineralised sample HRE220001A (figs. 175A–B). The clinopyroxene has lamellae and opaque exsolutions. Hornblende has grain triple junctions at 120 degrees, an igneous granoblastic texture indicating textural equilibrium occur. Fe-Ti oxides are strongly linked to the presence of hornblende. Plagioclase occurs as subhedral to anhedral grains. Few quartz grains with slightly undulose extinction are present.

The well-preserved, mineralised sample HRE230053A has clinopyroxene, orthopyroxene, and hornblende as the main mafic minerals and minor olivine (figs. 175C–D). Clinopyroxene has lamellae and opaque exsolutions. Hornblende is closely associated with Fe-Ti oxides. Plagioclase is subhedral to anhedral. Small, rare crystals of brownish red biotite and quartz crystals occur.

Euhedral to anhedral hornblende is the main mafic silicate mineral of the well-preserved sample HRE230053B (figs. 175E–F). Hornblende has grain triple junctions at 120 degrees, an igneous granoblastic texture indicating textural equilibrium (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Relatively few interstitial crystals of mostly small, anhedral plagioclase are present. Biotite has brownish red to tan pleochroism and is abundant, where the largest crystals have lots of quartz crystals included. Quartz is relatively abundant and has slightly undulose extinction.

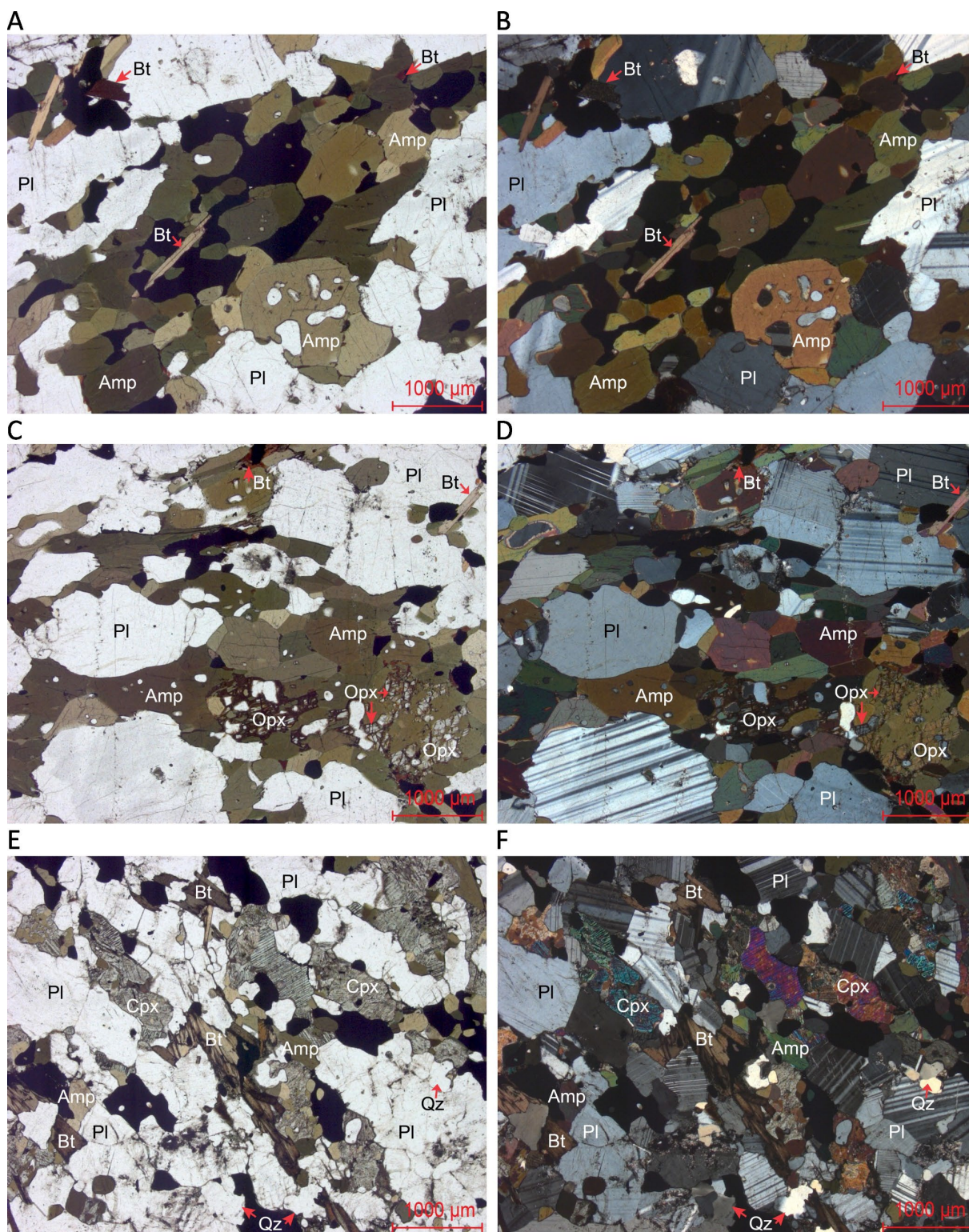


Figure 174. A. and B. Aggregates of hornblende, biotite, and Fe-Ti oxides. C. and D. Orthopyroxene crystals that are partly consumed and replaced by hornblende. Euhedral to anhedral hornblende, grain triple junctions at 120 degrees. Images from sample DCL234008A from drill core MAB83006 at 60.45–60.50 m. E. and F. Sample DCL234010A from drill core MAB83005 at 176.45–176.51 m, cumulate rock with clinopyroxene as main mafic silicate mineral. Left in ppl and right in xpl. Photo: Dick Claeson.

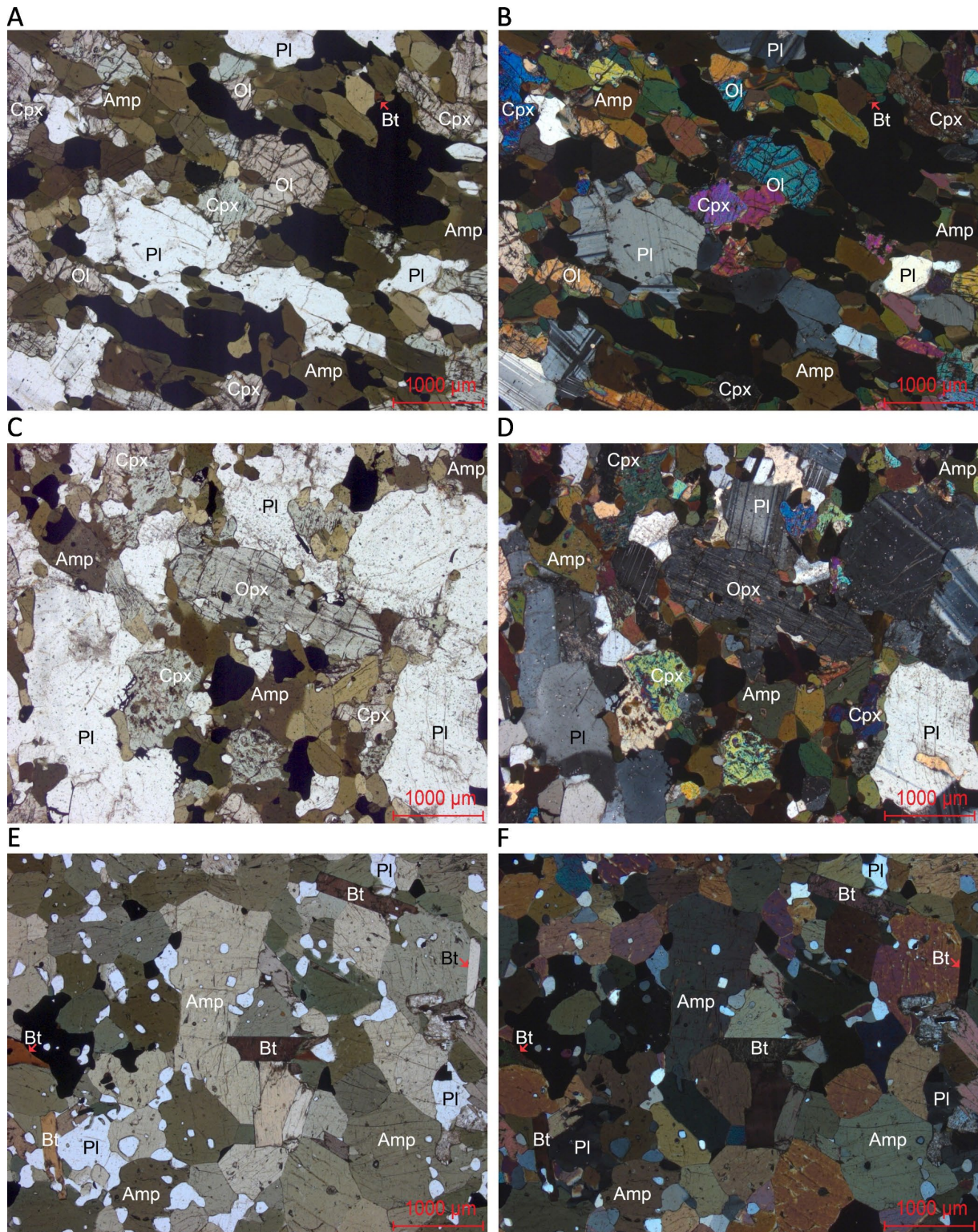


Figure 175. A. and B. Close relation between hornblende and Fe-Ti oxides. Sample HRE220001A (6871385/578211). C. and D. Two pyroxenes and hornblende are the main mafic silicate minerals. Sample HRE230053A (6871386/ 578209). E. and F. Euhedral to subhedral hornblende with grain triple junctions at 120 degrees. Mostly interstitial plagioclase crystals. Sample HRE230053B (6871386/ 578209). Left in ppl and right in xpl. Photo: Dick Claeson.

Description of thin sections – ore minerals – Blistra

The ore minerals magnetite, ilmenite, and few small grains of pyrrhotite were identified in mineralised sample HRE220035A (fig. 176, see fig. C7 for panorama). The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock (fig. 176). There is also plenty of exsolved ilmenite as trellis and few laths in the magnetite (figs. 176B–C). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are most likely magnetite or ulvöspinel (figs. 176B–C, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but optical microscopy was deemed inadequate for proper identification.

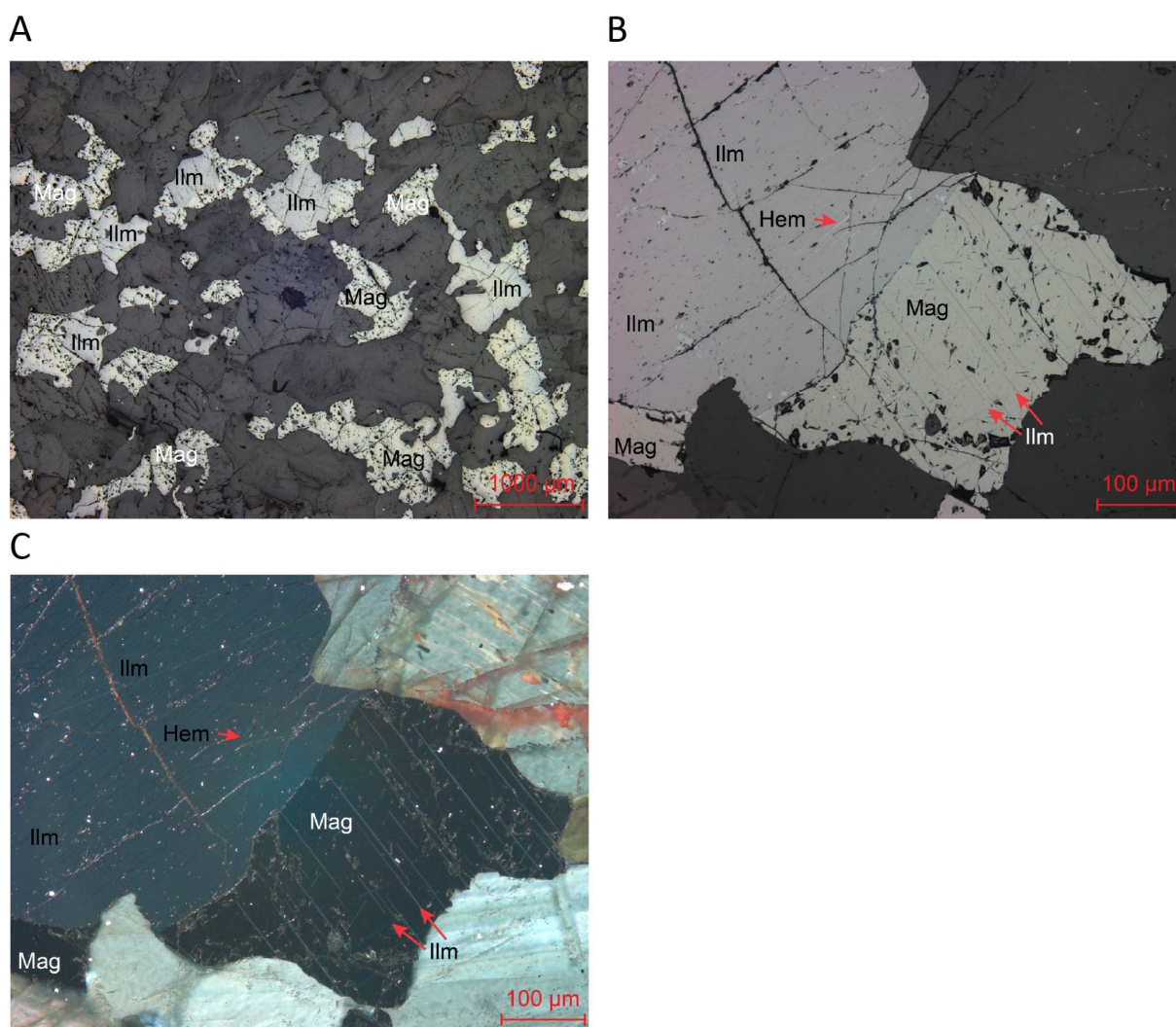


Figure 176. Ore minerals from the Blistra intrusion, mineralised sample HRE220035A (see fig. C7 for panorama). **A.** overview of relations between magnetite and ilmenite in opaque interstitial framework. Close-up images of relations between magnetite and ilmenite, ilmenite as trellis exsolutions along crystallographic planes within magnetite, and hematite exsolution lamellae in ilmenite, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals – Blistra

Subhedral-anhedral grains of clinopyroxene, with lamellae and opaque exsolutions, is the main mafic silicate mineral of the well-preserved, mineralised sample HRE220035A (panorama fig. C7). Only minor hornblende and olivine occur in this sample (fig. 177). Subhedral to anhedral grains of plagioclase with patchy sericite-saussurite alteration occur, where a few elongated crystals have weak bends or kinks due to deformation within a crystal mush. Plagioclase grains are lacking pigmentation at the edges, which formed late and from interstitial liquids. Biotite is relatively abundant with two generations, the first generation has brownish red to brown pleochroism and the second brownish red to tan to pale green. Rare quartz grains with marginally undulose extinction occur. The Fe-Ti oxides often occur in aggregates with biotite and hornblende.

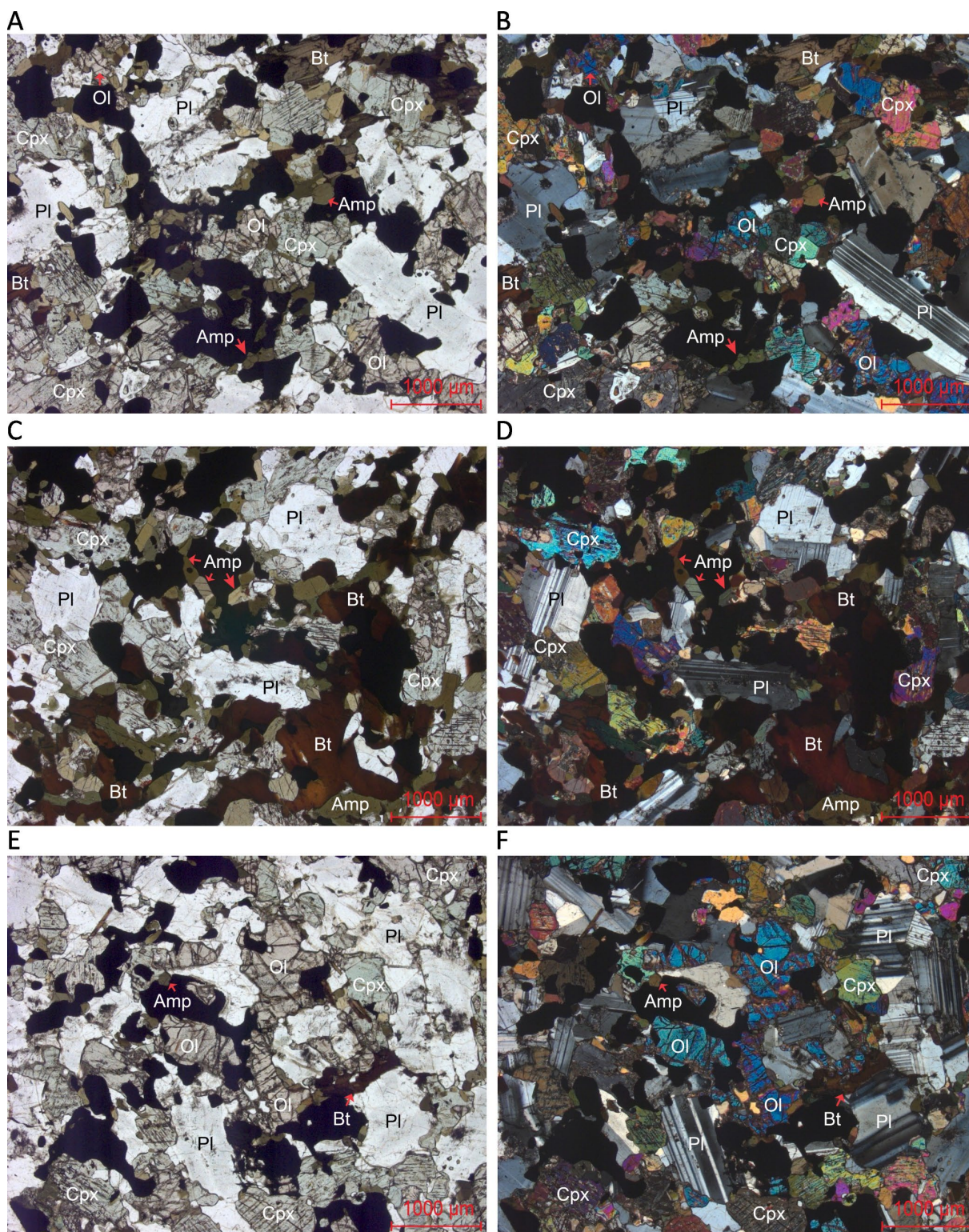


Figure 177. A. and B. The elongated plagioclase crystal to the right has weakly developed bends or kinks, deformation twins, and undulose extinction. Note pigmentation pattern of plagioclase. C. and D. Aggregates of biotite, hornblende, and Fe-Ti oxides. E. and F. Part of thin section with less hydrous minerals and more olivine. All images sample HRE220035A (6869825/578499). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data from Masugnsberget and Blistra

The drill cores from Masugnsberget were analysed for the elements Fe and V at Swedish Mineralprocesses AB (Minpro AB) in 1983. Analogue data from these cores ($n = 79$) has been digitised within this project.

The linear relationship between Fe and V in these analyses is excellent (fig. 178) with a Pearson coefficient (r) of 0.97. Inclusion of the new analyses of gabbroids from Masugnsberget ($n = 22$) obtained in this project does not change the Pearson coefficient. Note that the Blistra samples are not included here.

Variations in vanadium contents with depth in the drill cores are shown in figure 179. In general, the analyses from 1983 are in good agreement with the new analyses.

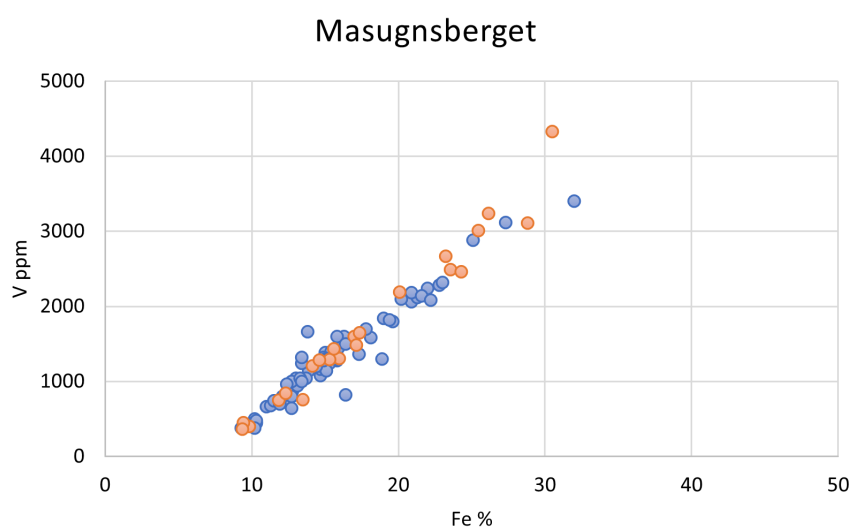


Figure 178. Fe and V contents in gabbroids at Masugnsberget. Blue dots are drill core analyses from 1983 ($n = 79$) and the orange are analyses obtained in the current project from drill cores ($n = 19$) and field samples ($n = 3$). The Pearson coefficient (r) for the whole dataset is 0.97. The average V:Fe ratio is 0.01.

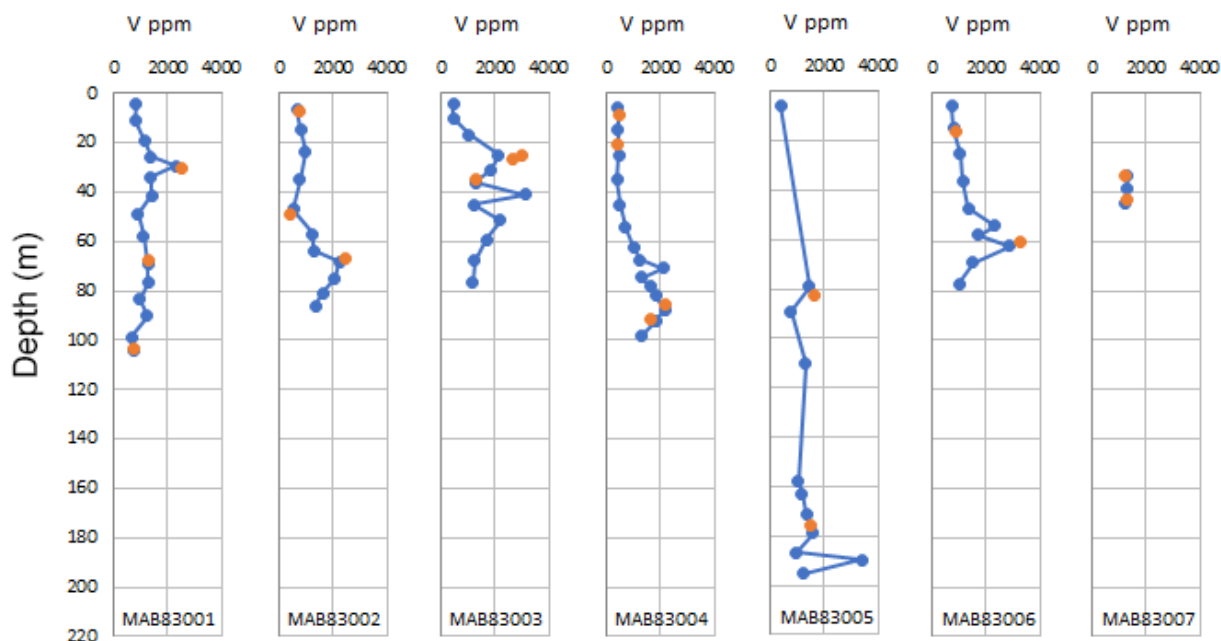


Figure 179. Variations in vanadium contents with depth in Masugnsberget drill cores. Blue dots are drill core analyses from 1983 and the orange (n = 19) are analyses obtained in the current project.

The sample suite analysed in the current project comprises 22 samples from Masugnsberget (19 drill core samples and three field samples) and four field samples from Blistra. Harker diagrams with major element oxides against SiO_2 are shown in figure 180 and vanadium is plotted against selected major element oxides and trace elements in figure 181.

The samples show compositional variations from unmineralised gabbro to strongly Fe-Ti-V mineralised with ranges of selected oxides (in %) as follows: SiO_2 (30.00–52.40), Al_2O_3 (8.18–15.15), Fe_2O_3 (13.35–43.60, average: 25.27), CaO (5.87–10.25), Na_2O (1.30–2.84), MgO (2.24–6.73), K_2O (0.46–1.52), MnO (0.17–0.27), P_2O_5 (0.07–0.40), and TiO_2 (1.57–5.82, average: 3.49).

Vanadium varies from 366 to 4 330 ppm with an average of 1695 ppm, 18 samples have more than 1 000 ppm V. Ni contents vary between 11 and 152 ppm, Zn (109–235 ppm), Co (45–146 ppm), Cu (23–276 ppm), and Cr (10–226 ppm).

Scandium contents are in the range 18–56 ppm, averaging 41 ppm. Yttrium varies between 13 and 44 ppm, with an average of 24 ppm.

The ΣREE (not including scandium and yttrium) are generally low, varying from 31 to 118 ppm (average 65 ppm).

In the Masugnsberget dataset (exclusive of the Blistra samples) Fe_2O_3 ($r = -0.99$) and TiO_2 ($r = -0.97$) show strong negative correlations against SiO_2 , while CaO ($r = 0.78$) has positive correlation while the other oxides have more scattered patterns (fig. 180 and Table 11).

Vanadium shows good positive correlations with Fe_2O_3 ($r = 0.98$), TiO_2 ($r = 0.94$), Co ($r = 0.97$), Zn ($r = 0.88$), Cu ($r = 0.85$), Ga ($r = 0.82$), and Ni ($r = 0.80$); (fig. 181 and Table 11).

Good negative correlations are observed between V and SiO_2 ($r = -0.97$), Y ($r = -0.81$), La ($r = -0.81$), and Ce ($r = -0.80$).

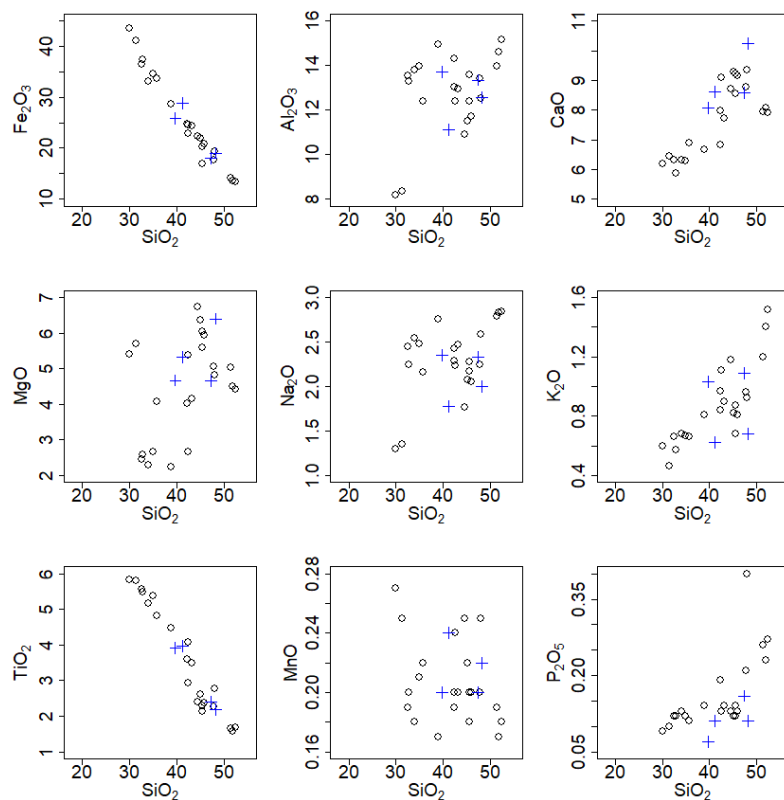


Figure 180. Harker diagrams for Masugnsberget and Blistra. Masugnsberget samples are shown with black circles (n = 22). Blue crosses are Blistra samples (n = 4). All concentrations are in %.

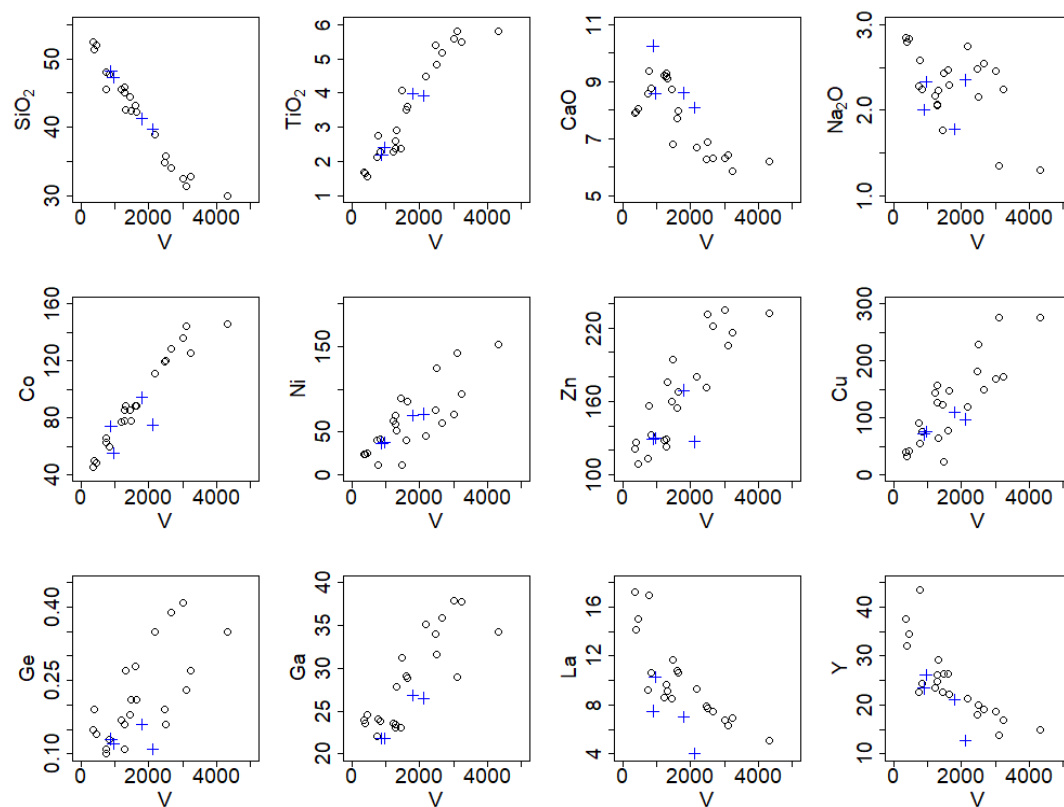


Figure 181. Harker diagrams for vanadium (ppm) vs. selected major and trace elements in Masugnsberget samples (black circles) and Blistra (blue crosses). Major element oxide concentrations are in %. Trace elements are reported as ppm.

Table 11. Pearson correlation matrix for selected elements from Masugnsberget. Blistra samples are not included.

	V	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	Ce	Co	Cu	Ga	Ge	In	La	Ni	Y	Zn
V	1																
SiO₂	-0.97	1															
TiO₂	0.94	-0.97	1														
Al₂O₃	-0.50	0.43	-0.32	1													
Fe₂O₃	0.98	-0.99	0.97	-0.50	1												
CaO	-0.78	0.78	-0.85	0.00	-0.79	1											
Na₂O	-0.56	0.51	-0.38	0.94	-0.55	0.08	1										
Ce	-0.80	0.83	-0.70	0.49	-0.78	0.50	0.64	1									
Co	0.97	-0.99	0.95	-0.48	0.98	-0.75	-0.53	-0.83	1								
Cu	0.85	-0.82	0.74	-0.69	0.85	-0.50	-0.73	-0.78	0.85	1							
Ga	0.82	-0.84	0.90	0.05	0.82	-0.89	-0.03	-0.56	0.81	0.48	1						
Ge	0.71	-0.69	0.69	-0.06	0.66	-0.68	-0.08	-0.55	0.71	0.36	0.82	1					
In	0.57	-0.63	0.58	-0.19	0.60	-0.44	-0.24	-0.48	0.64	0.43	0.58	0.55	1				
La	-0.81	0.84	-0.71	0.52	-0.80	0.48	0.67	0.99	-0.85	-0.80	-0.56	-0.54	-0.53	1			
Ni	0.80	-0.75	0.65	-0.76	0.79	-0.45	-0.81	-0.76	0.78	0.95	0.39	0.31	0.50	-0.78	1		
Y	-0.81	0.84	-0.74	0.42	-0.80	0.62	0.60	0.96	-0.83	-0.80	-0.60	-0.52	-0.44	0.95	-0.77	1	
Zn	0.88	-0.90	0.91	-0.31	0.89	-0.77	-0.36	-0.62	0.88	0.63	0.86	0.73	0.68	-0.64	0.61	-0.62	1

In the AFM diagram all samples show similarities to the Kramsta, Gruvberget–Sumåssjön, and Bläckmyran intrusions with a strong Fe-enrichment and tholeiitic affinity (fig. 182). Primitive mantle normalised trace-element compositions are shown in figure 183. A characteristic feature is the pronounced negative Nb anomaly, and positive Pb and Ti anomalies, which are very similar to the previously described intrusions.

Chondrite normalised REE patterns from drill core and field samples show relatively flat, subparallel patterns (fig. 184), reflecting different degrees of fractional crystallisation.

The Masugnsberget samples (not including Blistra) have moderate LREE enrichment with $(La/Yb)_N$ in the range 1.92–3.05. Slight fractionation among the LREEs is shown by $(La/Sm)_N$ between 1.58 and 2.40 and slight fractionation among the heavy REEs are shown by $(Gd/Yb)_N$ ranging from 1.03 to 1.48 and $(Dy/Yb)_N$ in the range 0.94 to 1.22. 19 samples show negative (Eu/Eu^*) , spanning the interval 0.70–0.96 while three have positive Eu/Eu^* (in the range 1.02 to 1.09).

The four Blistra samples have similar patterns with $(La/Yb)_N$ in the interval 1.81–2.47.

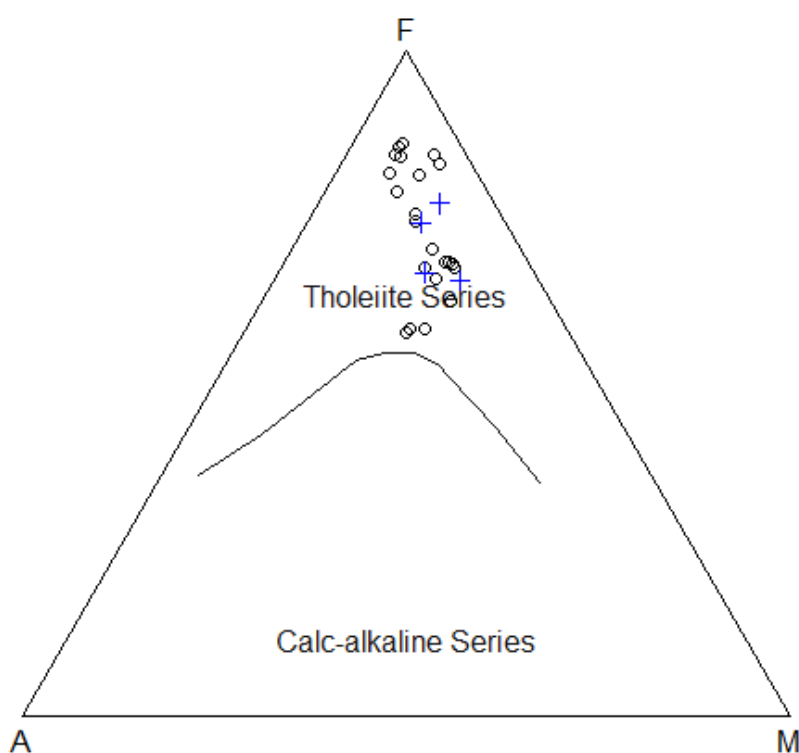


Figure 182. The samples from Masugnsberget (black circles) and Blistra (blue crosses) plotted in an AFM-diagram (Irvine & Baragar 1971).

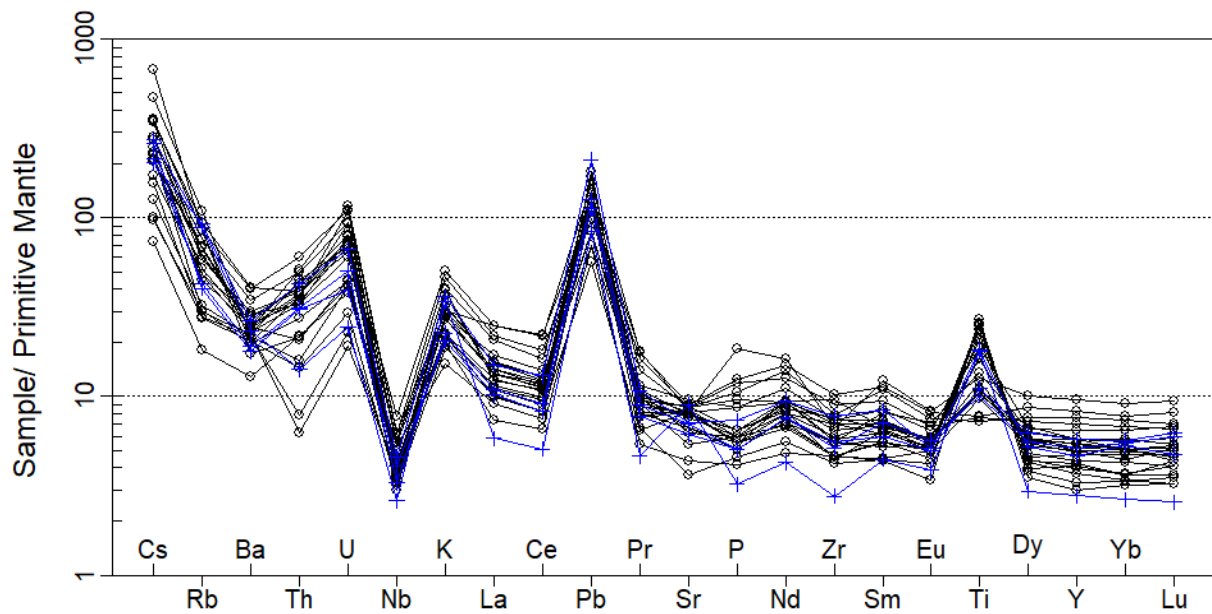


Figure 183. Primitive mantle normalised diagram for Masugnsberget samples (black circles) and Blistra (blue crosses). Normalising values from Sun & McDonough (1989).

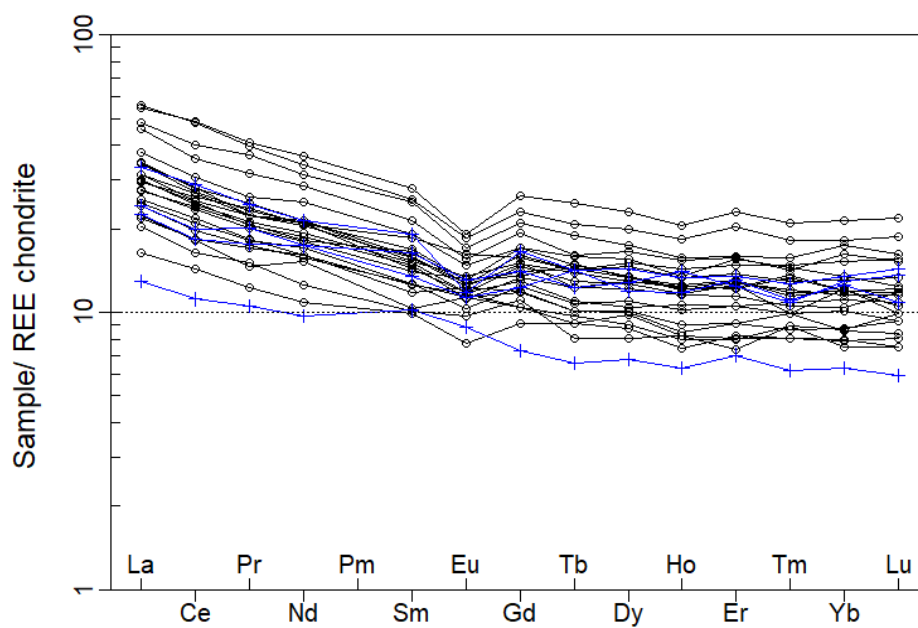


Figure 184. Chondrite normalised REE diagram for samples from Masugnsberget (black circles) and Blistra (blue crosses). The samples have rather flat patterns with low to moderate $(La/Yb)_N$ ratios. Chondrite values are from Boynton (1984).

In the Th-Hf-Nb diagram (fig. 185) all but one sample plot in the field of Island arc calc-alkaline basalt (CAB). The distinct volcanic arc signature is reflected by the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 186A and 186B). Overall, the geochemical signature resembles that of the Kramsta, Gruvberget–Sumåssjön, and Bläckmyran gabbroids and Masugnsberget probably formed in the same tectonomagmatic environment. The geochemical features, with a strong negative Nb and positive Pb anomaly, coupled with the incompatible trace-element ratios (figs. 185 and 186) favour an interpretation of the tectonomagmatic environment as that of a volcanic-arc, most probably related to an active margin. The characteristic positive Ti-anomaly that is observed in the sample suite (similar to the Kramsta, Gruvberget–Sumåssjön and Bläckmyran intrusions) is interpreted to be a result of the accumulation of titanomagnetite.

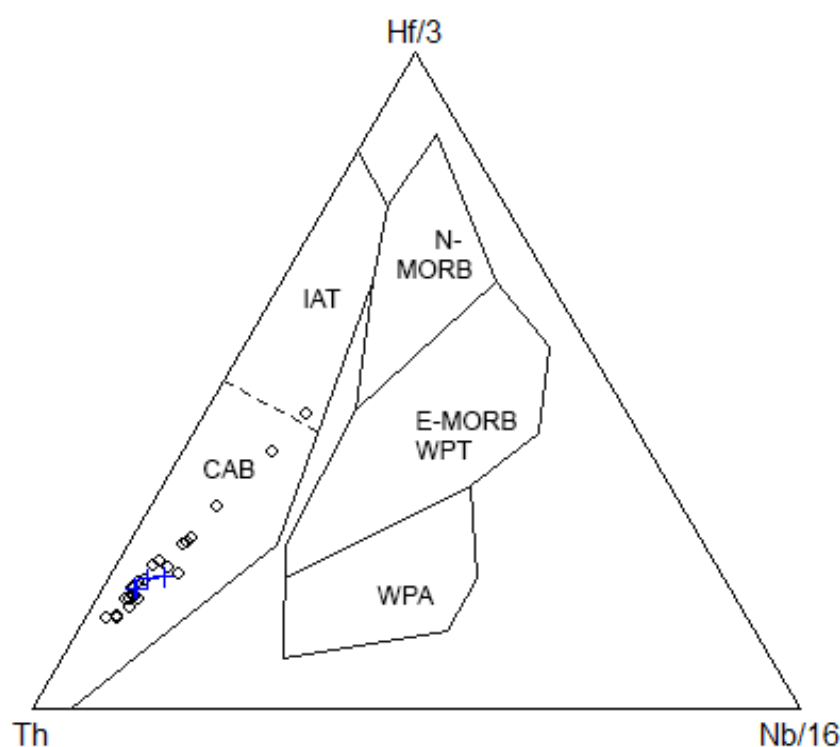


Figure 185. Masugnsberget samples (black circles) and Blistra (blue crosses) plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

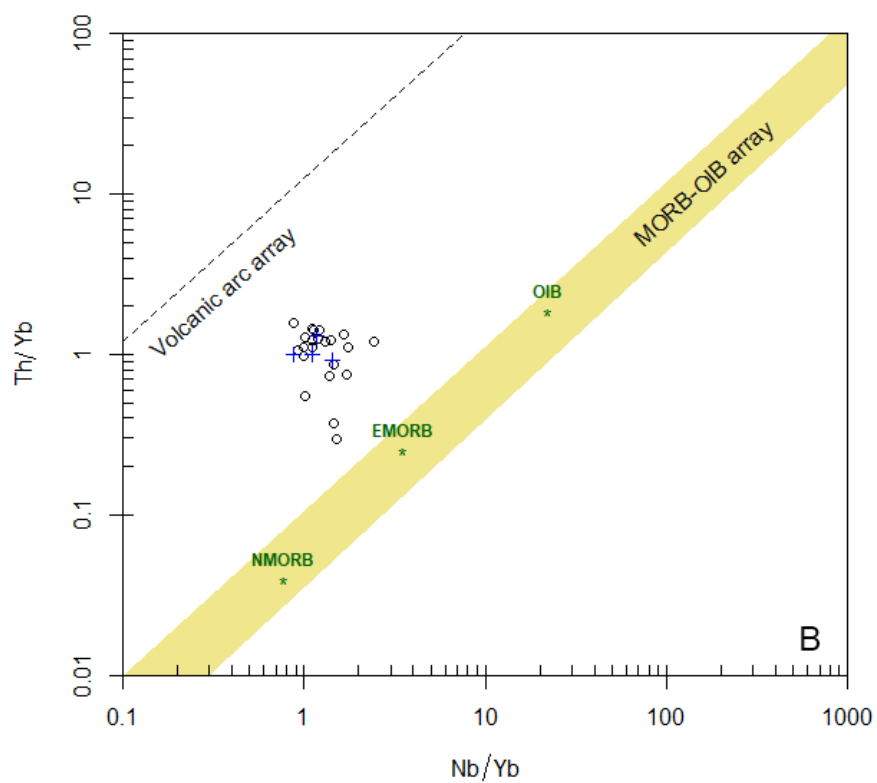
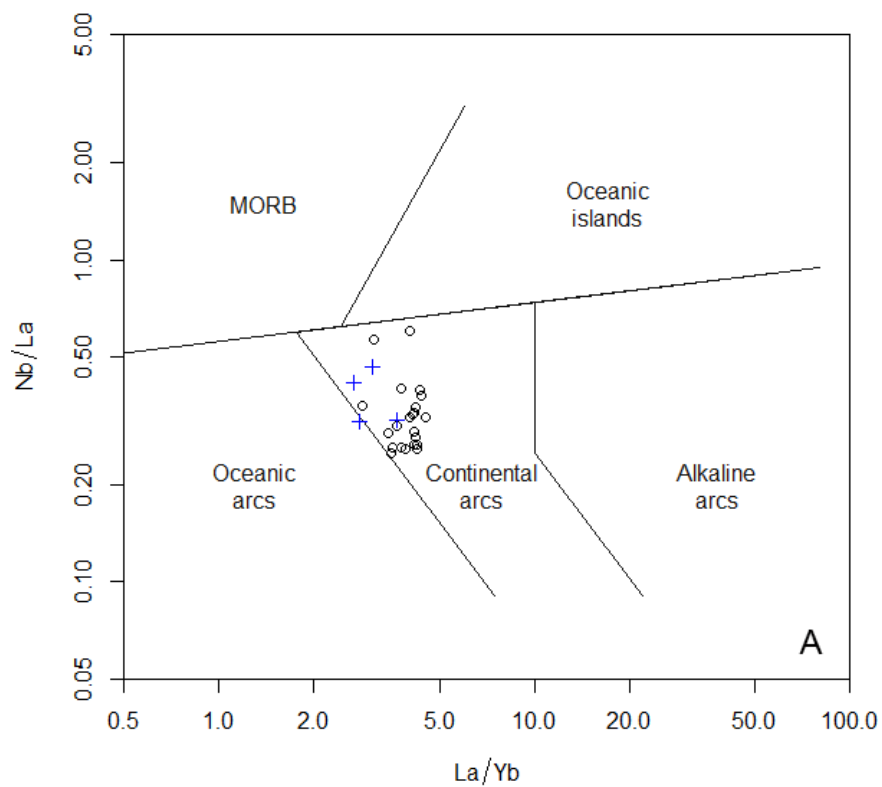


Figure 186. Masugnsberget (black circles) and Blistra (blue crosses) plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

The area north of Gruvberget–Sumåssjön

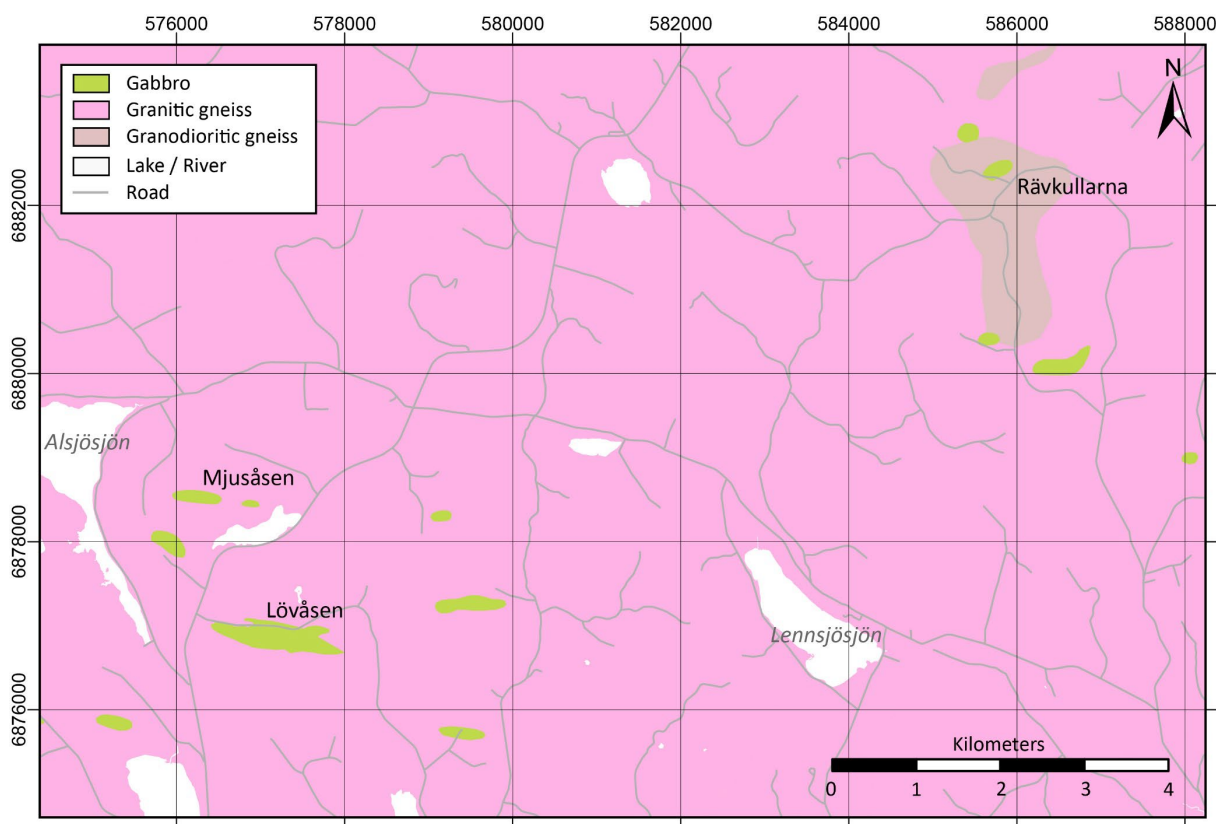


Figure 187. Bedrock geology map showing the area north of Gruvberget–Sumåssjön. The names of the mafic intrusions referred to in the report are shown as black text. Names of some lakes are shown as grey italic text.

In the area north of Gruvberget–Sumåssjön there is a small cluster of magnetic anomalies which can be observed on airborne magnetic measurements (see fig. 16). Some of these anomalies are documented to be associated with mafic intrusions and have been sampled as part of this project, such as the intrusions around Mjusåsen (fig. 187). In this area the largest magnetic anomaly lies immediately to the south of Mjusåsen and is referred to in this study as Löväsen (fig. 187). Given the understanding of the local geology and the shape and orientation of the anomaly, it is assumed that it is a mafic intrusion. Hence, ground based magnetic measurements were performed over this area to provide more information about the structure and geometry of the anomaly. The survey at Löväsen covers an area of approximately 0.8 km² with a typical profile spacing of about 35 m.

Lövåsen and Mjusåsen

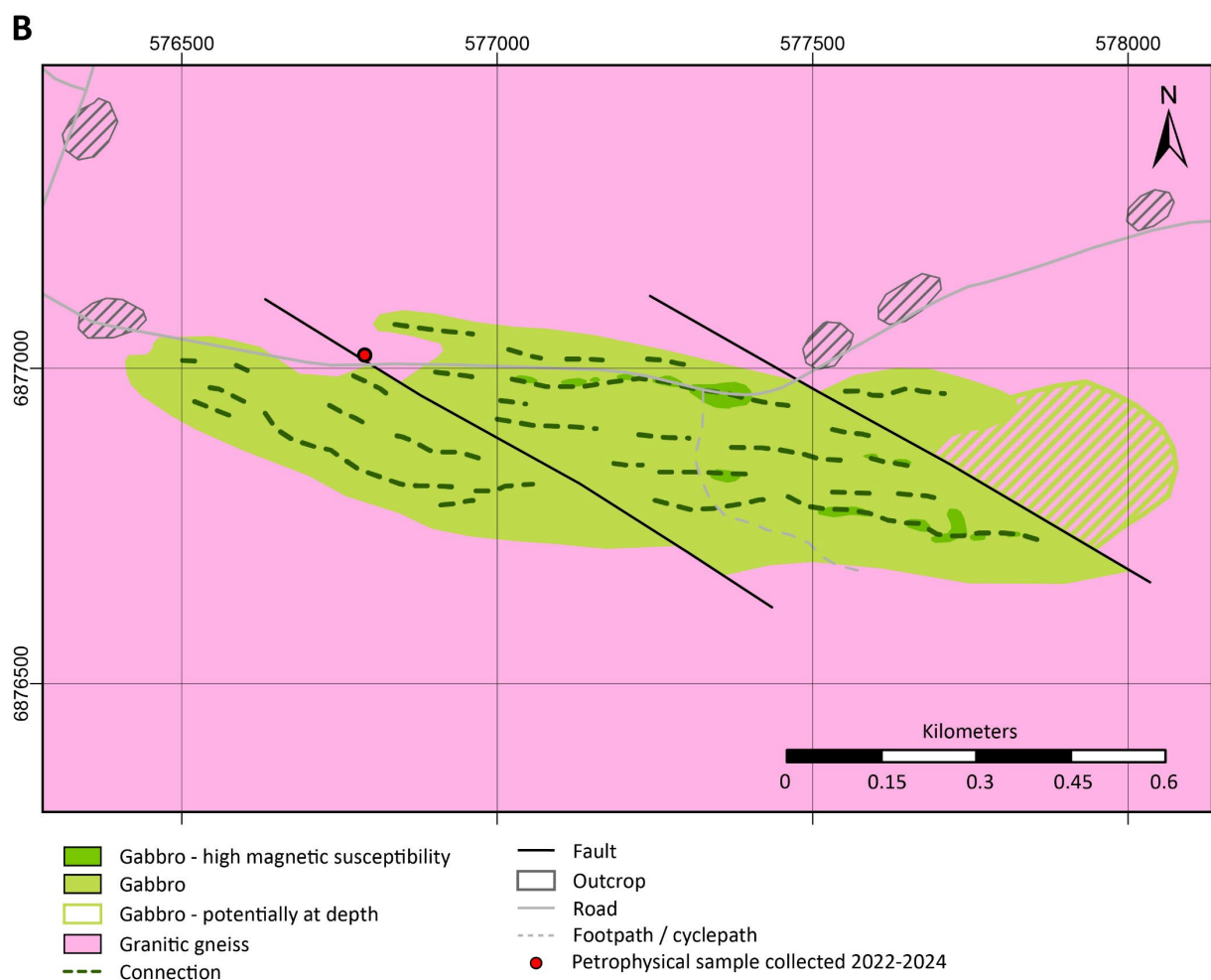
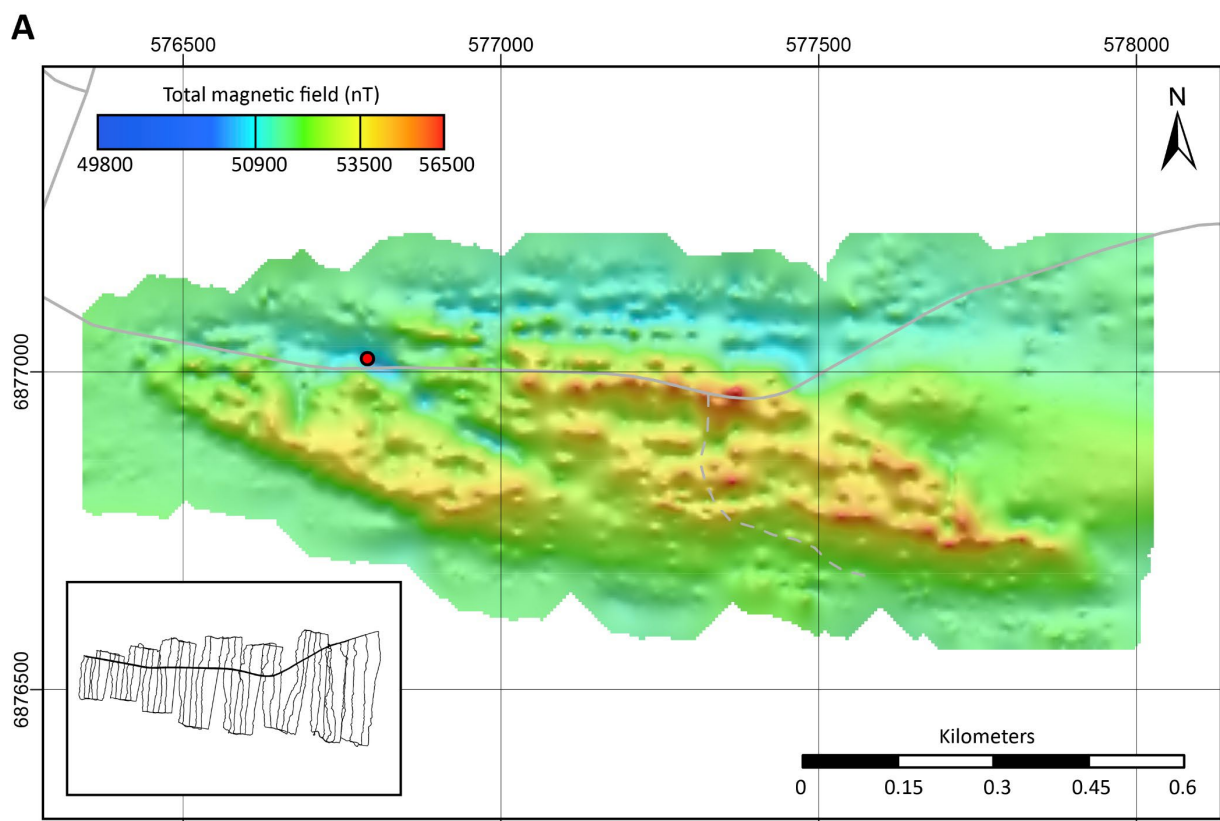
Ground-based geophysical measurements

Figure 188 shows the ground magnetic data collected over the anomaly at Lövåsen. Here a series of relatively consistent and parallel magnetic anomalies can be observed striking approximately east–west. The overall size of the zone containing magnetic anomalies is relatively large with a length of about 1 400 m and width of 300 m. The greatest magnetic field values appear to be located within linear anomalies located on the southern and northern flanks of the structure. In these areas the magnetic field values reach a maximum of about 5 400 nT above the background value. Despite the relatively continuous nature of the anomalies, there are two zones where the anomalies terminate abruptly or are laterally displaced. These are interpreted to be faults which offset parts of the structure. Both of these faults appear to have a northwest–southeast strike. In the case of the easternmost fault, the character of the magnetic anomalies changes from relatively high frequency on the western side to relatively low frequency on the eastern side. A potential interpretation of this is that the magnetic strata have been downthrown on the eastern side and presently lie at a greater depth than the strata on the western side of the fault.

It should be noted that due to the lack of outcrops within the survey area it was not possible to confirm that this anomaly is associated with a mafic intrusion. However, gabbro was observed in a boulder located on the northern flank of the structure. Figure 188 shows an updated bedrock geology map for the area around Lövåsen, where it has been interpreted to be a mafic intrusion.

Figure 189 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained by inverting the ground based magnetic data. Here the highest magnetic susceptibility values are observed to be located on the northern flank of the structure. Within the 3D inversion model, the high susceptibility body appears to be located at the surface. However, on the eastern flank of the structure the higher susceptibility values appear to be located at depth. Furthermore, there appears to be two discrete vertical offsets in the inversion model (fig. 189), which correlate well with the position of the interpreted faults on the bedrock geology map shown in figure 188.

► **Figure 188.** **A.** Map of the total magnetic field from ground measurements collected as part of this study over the anomaly at Lövåsen (interpreted to be a mafic intrusion). The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Lövåsen anomaly, interpreted from the ground magnetic field data and the available geological observation and sample, which is shown as a red dot in both A and B.



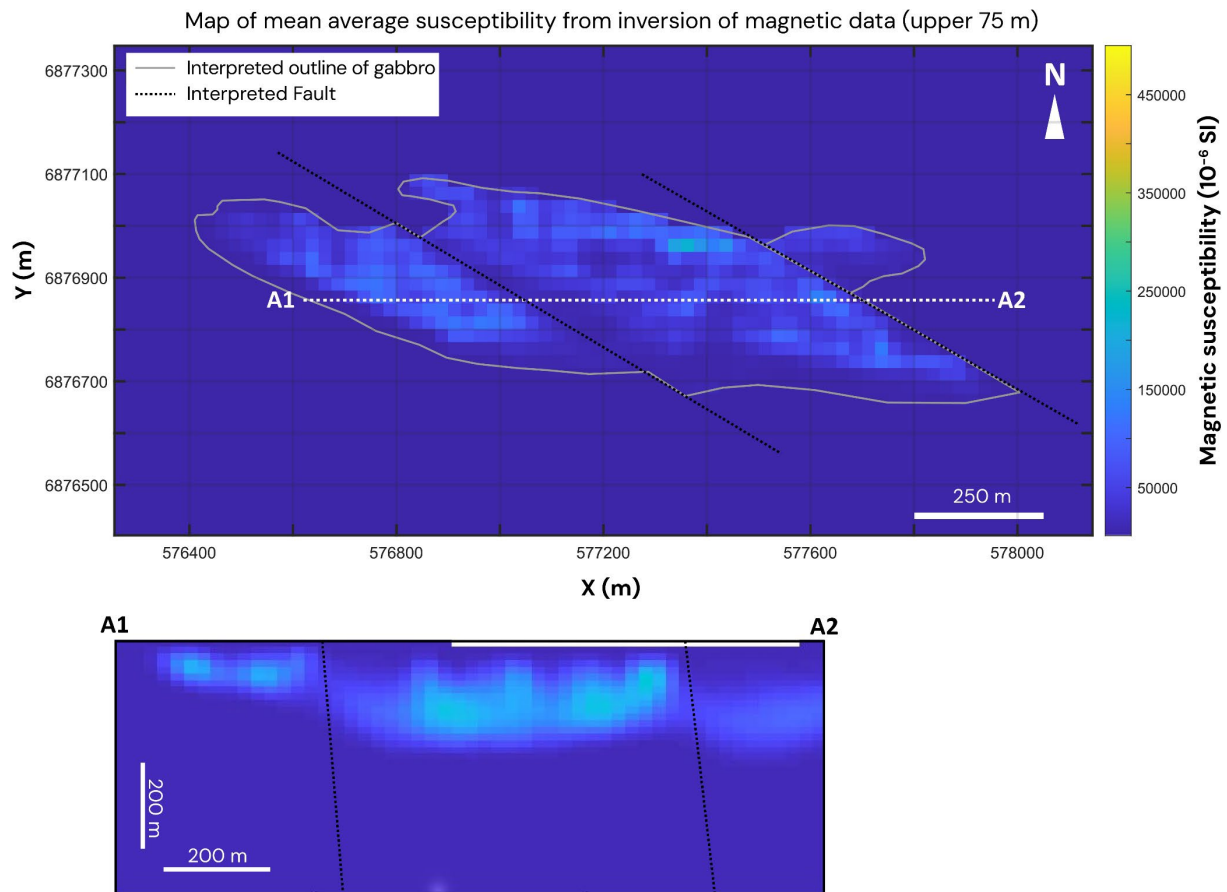


Figure 189. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Lövåsen intrusion. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

Lövåsen is located approximately 5 km north of Hedvigsfors and Masugnsberget (fig. 187). The degree of bedrock exposure is extremely low, and the object was identified from aeromagnetic measurements. Despite significant efforts to find outcrops none were discovered. However, a large, presumably locally derived boulder comprising a gabbroic rock was found and sampled (fig. 190).

At Mjusåsen, two kilometres further to the north, several outcrops containing massive gabbroid rocks occur along a newly constructed road (figs. 191 and 192). Geochemical analyses show elevated contents of vanadium (435-709 ppm), albeit much lower than Masugnsberget and Blistra to the south.



Figure 190. Gabbroic boulder at Lövåsen (6877021/576790). Photo: Helge Reginiussen.



Figure 191. A. Fresh, massive, medium-grained, gabbroid in outcrop at Mjusåsen (6878508/576441). B. Close-up of sampled gabbro. Photo: Helge Reginiussen.

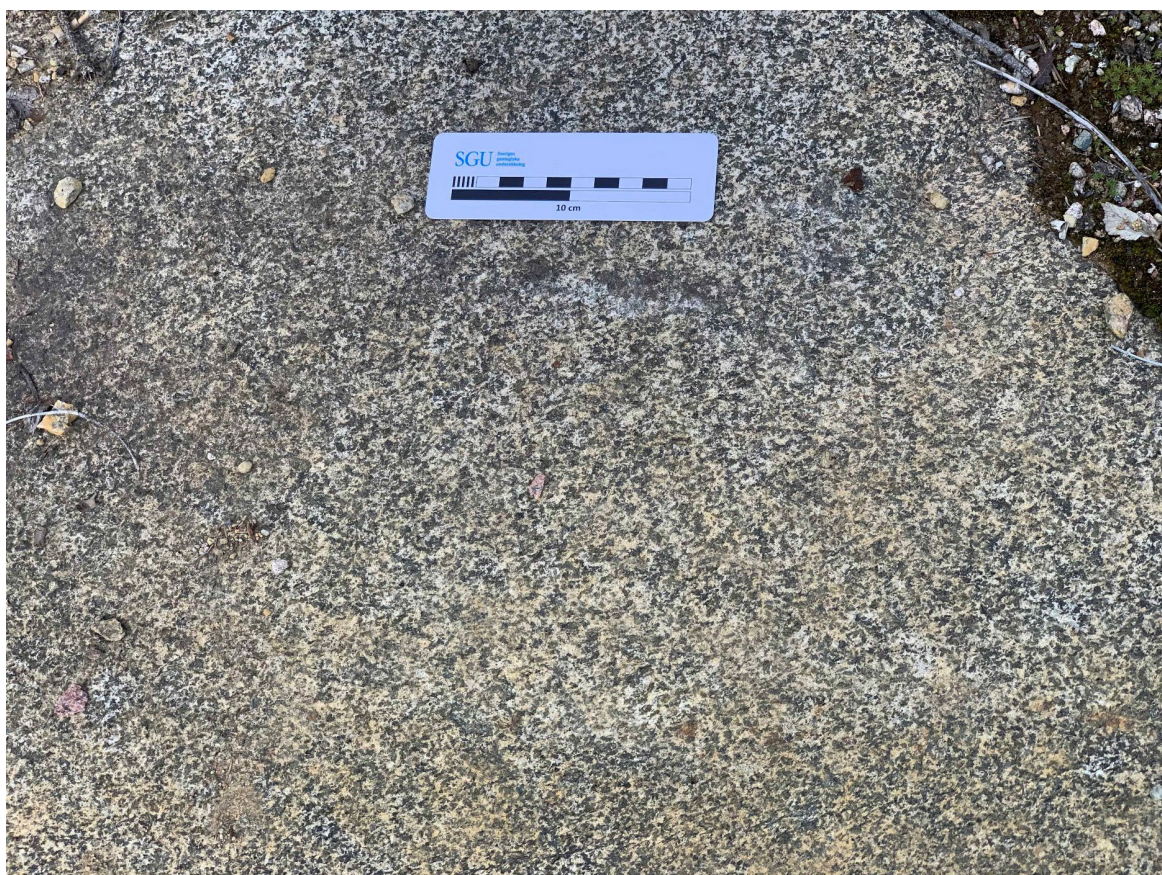


Figure 192. Undeformed, medium-grained gabbroid in outcrop at Mjusåsen (6878579/576309). Photo: Helge Reginiussen.

Description of thin sections – silicate minerals – Lövåsen

A large local boulder was sampled at Lövåsen, HRE230047A ($1 \times 1 \times 2$ metre). Clinopyroxene is the main mafic mineral and occurs as interstitially grown, euhedral to anhedral, small to large grains, with lamellae and opaque exsolutions (fig. 193). There are two generations of relatively abundant biotite, where the first formed has brownish red to light brown pleochroism and the later brownish red to light tan. Olivine is a minor mineral and is seen included in large clinopyroxene grains or as interstitially grown crystals. Hornblende is rare and is intergrown with clinopyroxene and as rims. Some green amphibole is possibly fixed to fractures and as alteration of clinopyroxene close to fractures (figs. 193C–D).

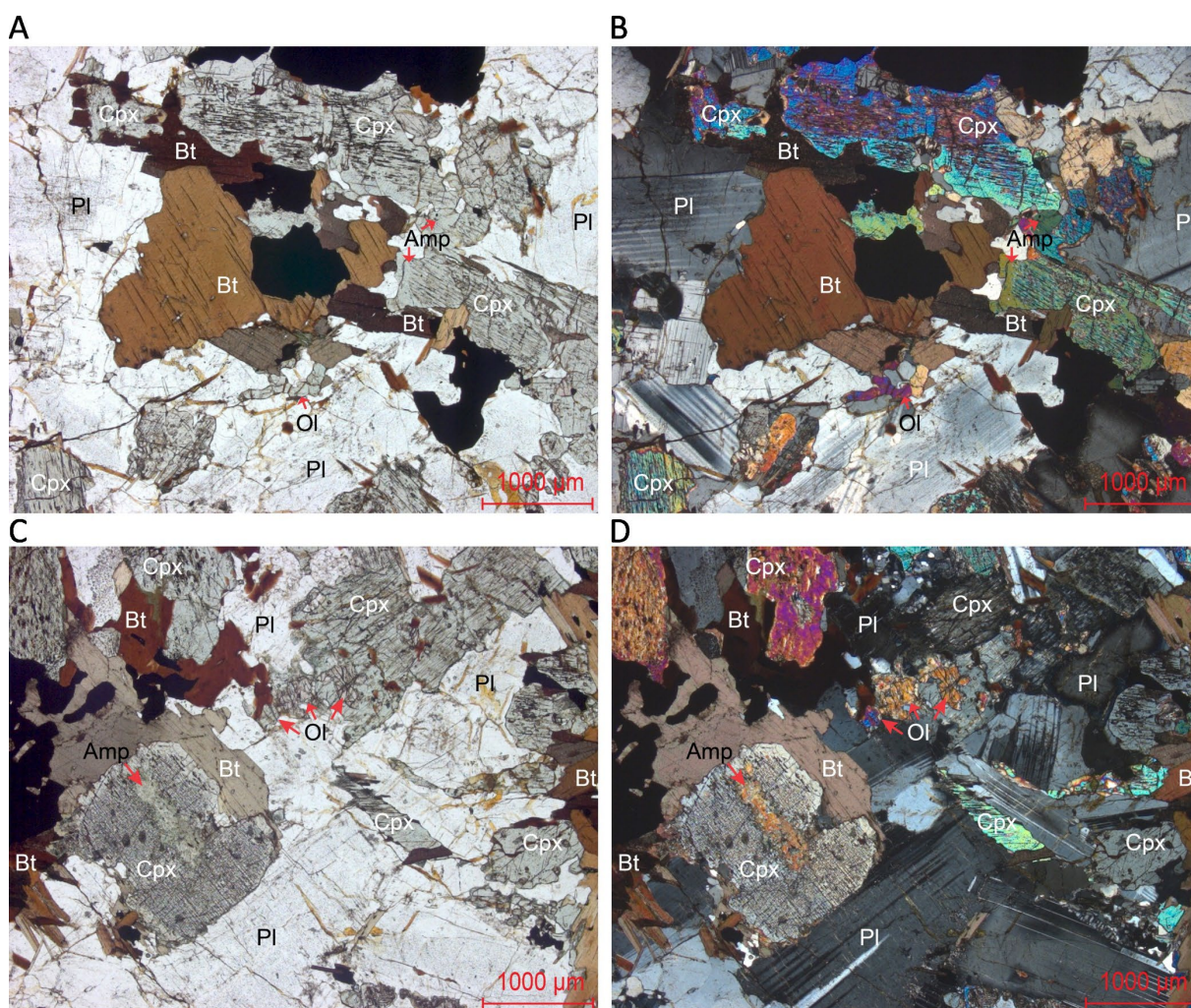


Figure 193. A. and B. Relatively abundant biotite, plagioclase, and clinopyroxene with minor interstitial olivine and hornblende as rims and discrete small grains. Large clinopyroxene at top displays twinning, lamellae, and exsolution. C. and D. Clinopyroxene is altered in central part to amphibole and outer parts lack exsolutions. Olivine is mostly included in large clinopyroxene. All images sample HRE230047A (6877021/576790). Left in ppl and right in xpl. Photo: Dick Claeson.

Description of thin sections – silicate minerals - Mjusåsen

There are roughly equal amounts of the main mafic silicate minerals hornblende and clinopyroxene in sample HRE220052A. Late-formed aggregates of biotite, hornblende, and Fe-Ti oxides, along with clinopyroxene, olivine, and plagioclase, form a cumulate rock (figs. 194A–D). Hornblende is subhedral to anhedral and occurs as small to large grains, interstitially grown crystals, and aggregates. Anhedral olivine has small to large grains. Subhedral to anhedral clinopyroxene occurs as interstitially grown grains, with lamellae and opaque exsolutions. A few crystals are partly altered to secondary green amphibole. Subhedral to anhedral plagioclase occurs as small to large grains with minor patchy sericite-saussurite alteration. There are two generations of biotite, the first has brownish red to red pleochroism and the second brownish red to tan, and is relatively abundant. Several of the well-developed hornblende have grain triple junctions at 120 degrees, an igneous granoblastic texture in layered intrusions that signifies textural equilibrium (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b).

Sample HRE220053A is mostly well-preserved, although some weathering is seen together with minor alteration of clinopyroxene to secondary green amphibole and with minor patchy sericite-saussurite alteration of plagioclase. Roughly equal amounts of the main mafic silicate minerals hornblende and clinopyroxene are observed. Large subhedral clinopyroxene has lamellae and opaque exsolutions (figs. 194E–F). Hornblende is present as grains, interstitially grown crystals, and in aggregates with biotite and opaque. Anhedral olivine has small to large grains. Biotite has brownish red to light tan pleochroism and is relatively abundant. A rare biotite oikocryst with chadacrysts of Fe-Ti oxides occurs. Small to large grains of quartz with weak undulose extinction occur. Minor amounts of igneous myrmekite are observed.

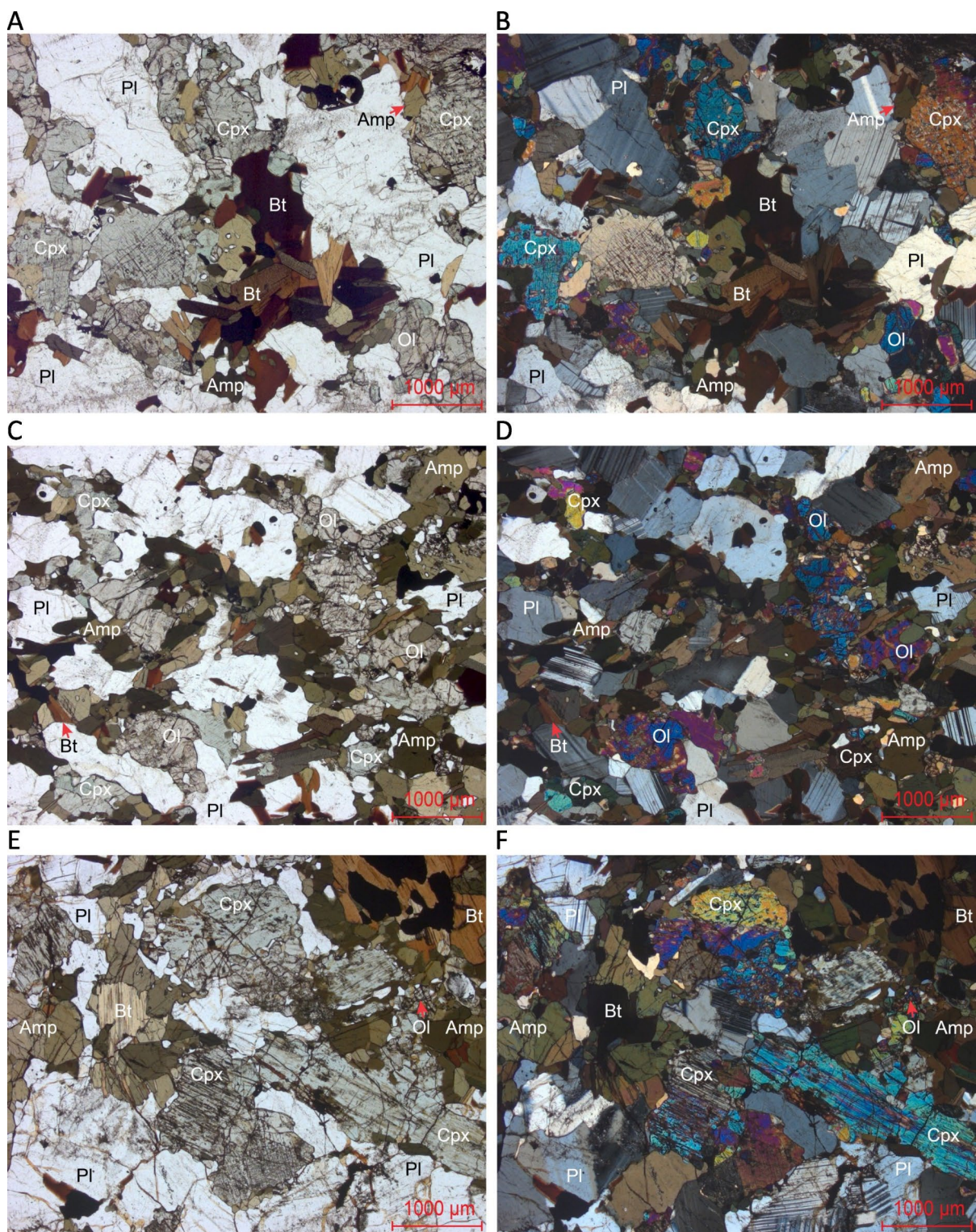


Figure 194. A. and B. Aggregate of biotite, hornblende, and Fe-Ti oxides, with clinopyroxene, olivine, and plagioclase making up a cumulate rock. C. and D. Several well-developed hornblende grain triple junctions at 120 degrees. Sample HRE220052A (6878492/576482). E. and F. Large subhedral clinopyroxene with lamellae and opaque exsolution. Biotite oikocryst with chadacrysts of Fe-Ti oxides in the northeastern corner of the image. Sample HRE220053A (6878508/576441). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data from Lövåsen and Mjusåsen

The primitive mantle normalised (fig. 195) patterns of the three samples show strong negative Nb-anomaly and positive Pb anomaly. The primitive mantle normalised patterns as well as the subparallel REE patterns (fig. 196) are similar to the patterns of Kramsta, Gruvberget–Sumåssjön, Bläckmyran and Masugnsberget. Also, in the Th-Hf-Nb diagram (fig. 197) all samples plot in the field of Island arc calc-alkaline basalt (CAB). The volcanic arc signature is again evident by the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 198A and 198B).

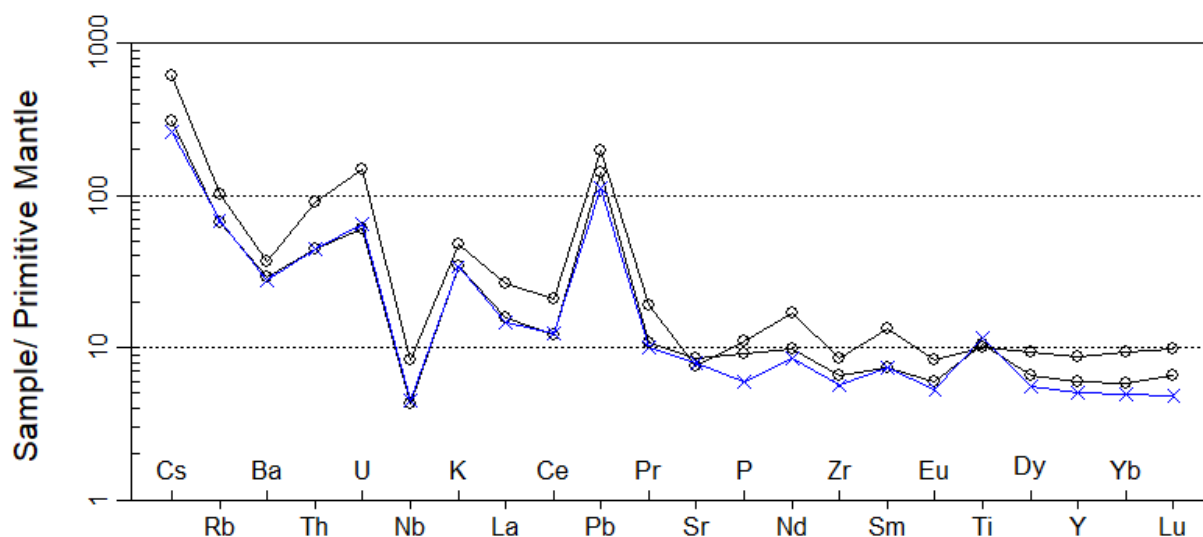


Figure 195. Primitive mantle normalised diagram for Mjusåsen (black circles) and Lövåsen (blue 'X'). Normalising values from Sun & McDonough (1989).

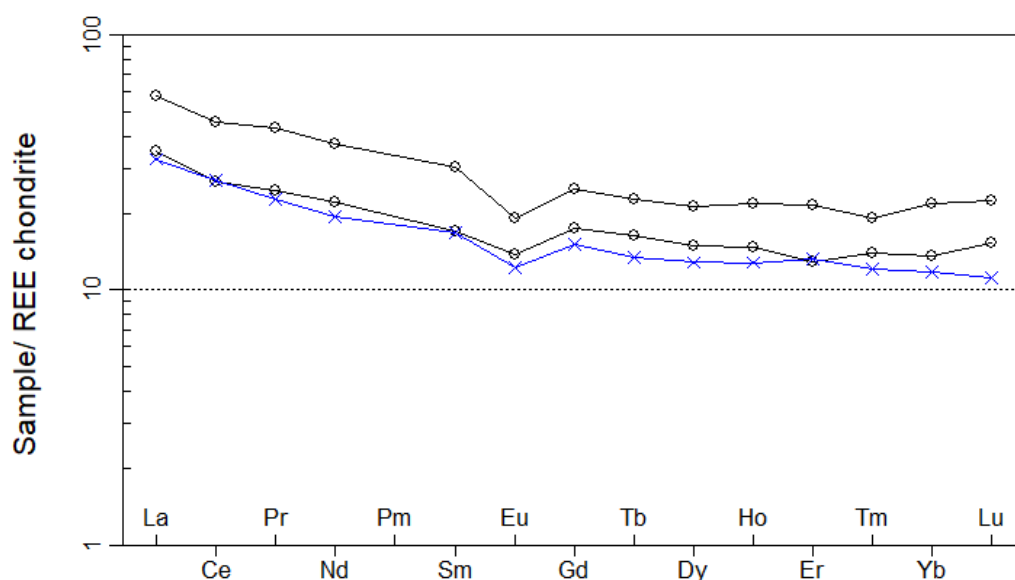


Figure 196. Chondrite normalised REE diagram for Mjusåsen (black circles) and Lövåsen (blue 'X'). Chondrite values are from Boynton (1984).

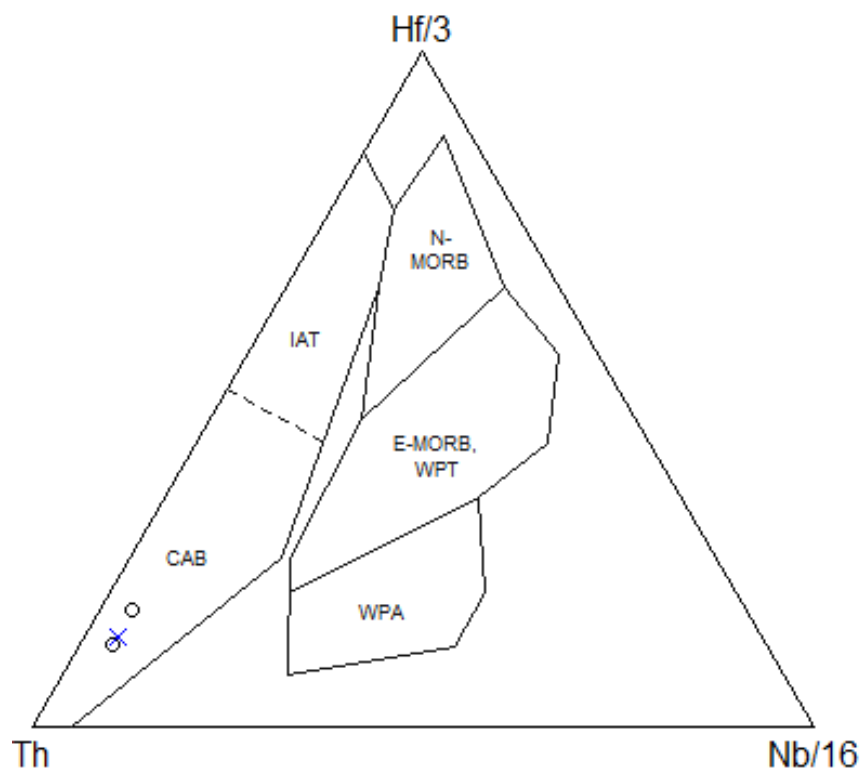


Figure 197. Mjusåsen samples (black circles) and Lövåsen (blue 'X') plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

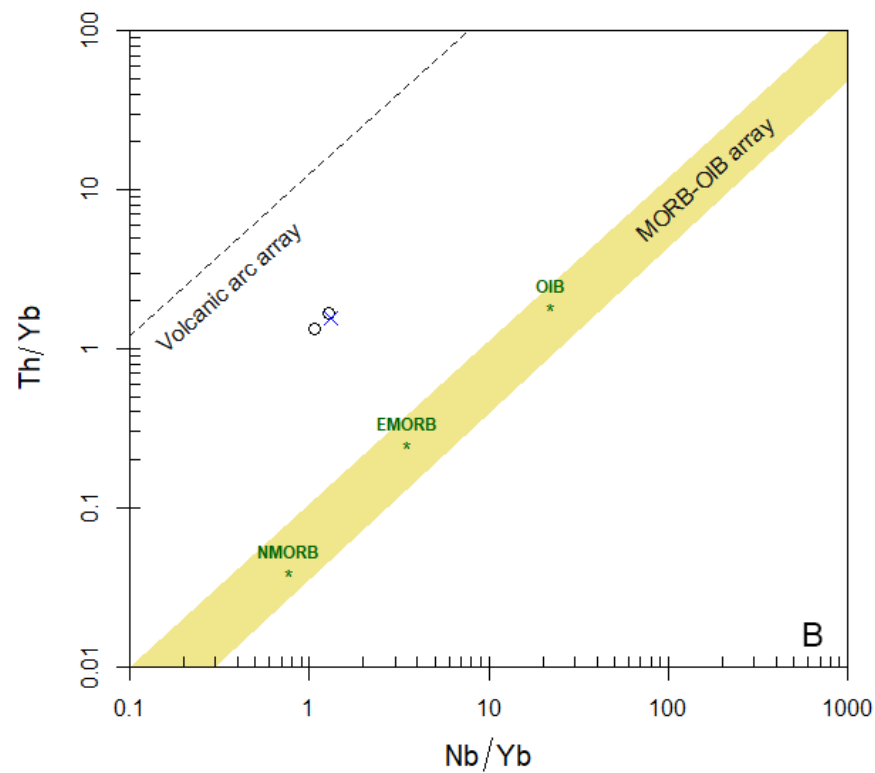
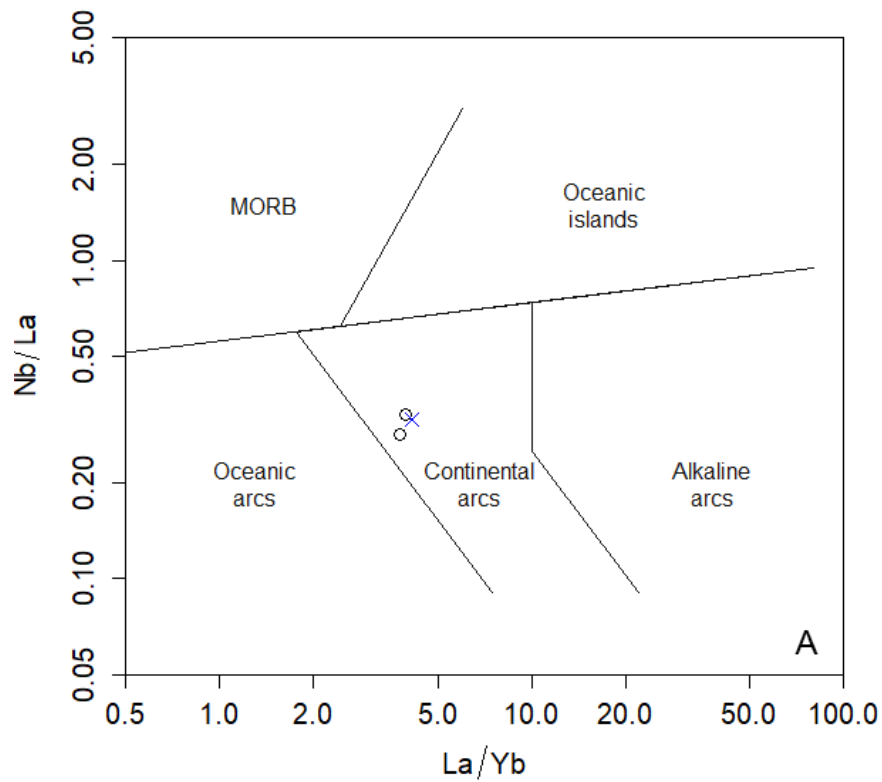


Figure 198. Mjusåsen samples (black circles) and Lövåsen (blue 'X') plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Rävkullarna

Geological observations

At Rävkullarna, located approximately 10-12 km directly north of Gråsjön (fig. 187), a medium-grained, massive gabbroic to intermediate rock was observed in a small outcrop close to a forest road (fig. 199). A geochemical analysis shows elevated SiO_2 content (58.20%), rather high Zr (201 ppm) and low contents of vanadium (15 ppm), iron (14.40%), and titanium (1.24%) compared to the vanadiniferous gabbroids further south.



Figure 199. Outcrop at Rävkullarna (6882342/585707). Photo: Helge Reginiussen.

Description of thin sections – silicate minerals

An evolved cumulate designated dioritoid in the field has roughly equal amounts of hornblende and clinopyroxene as main mafic minerals (fig. 200). Clinopyroxene is subhedral to anhedral as small to large grains and interstitially grown crystals, with lamellae and opaque exsolutions. There are also minor olivine crystals. Plagioclase is subhedral to anhedral with small to large grains. The rock has relatively abundant, faintly undulose quartz and minor amounts of igneous myrmekite. Grains of magnetite and ilmenite along with sulphides as rare droplets are the opaque minerals. The rock is massive and lacks signs of deformation or metamorphism apart from very minor sericite-saussurite alteration of plagioclase.

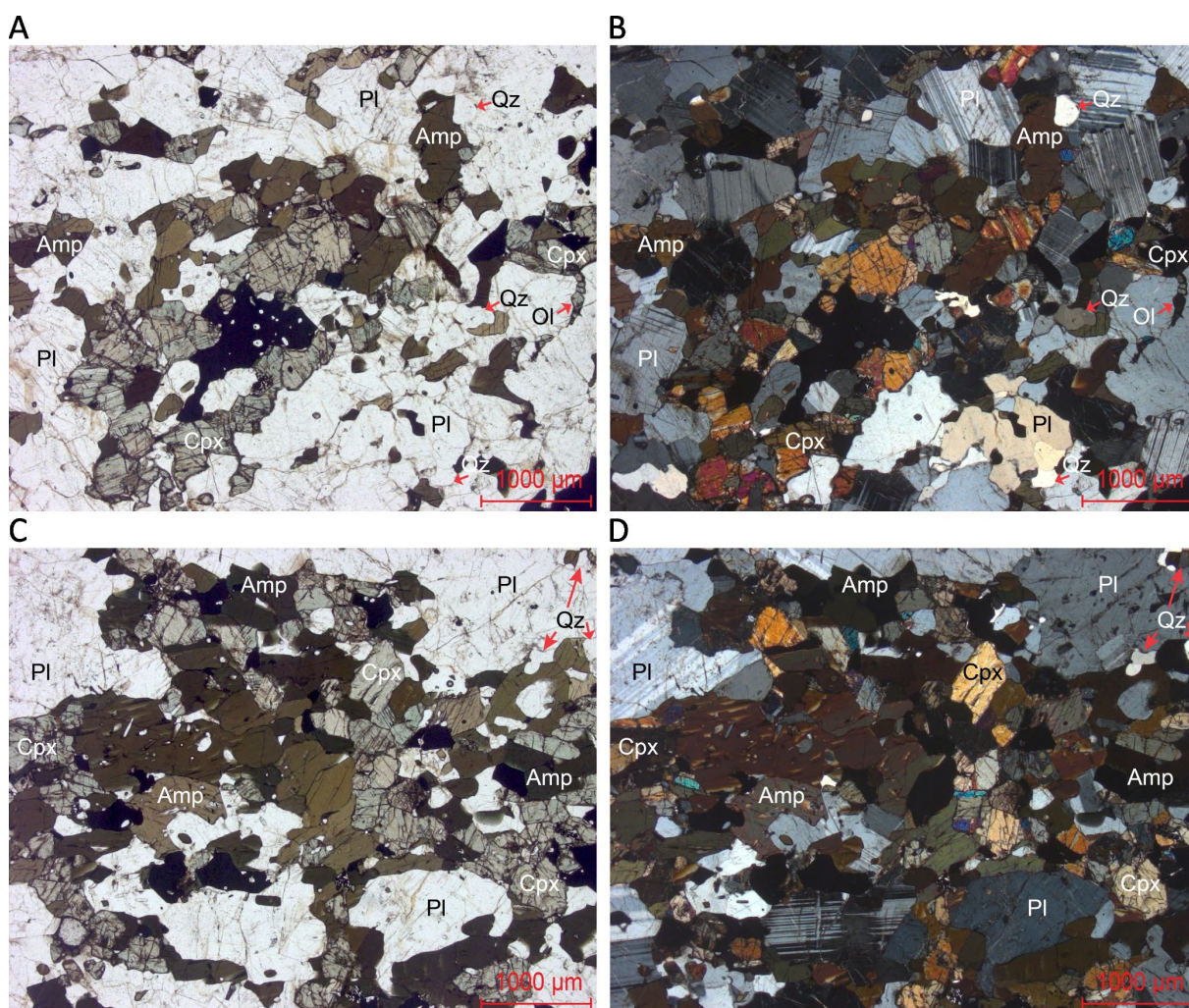


Figure 200. A. to D. Dioritoid cumulate rock with roughly equal amounts of hornblende and clinopyroxene as main mafic minerals, rare olivine, small and large plagioclase crystals, and relatively abundant quartz. Sample HRE220051A (6882342/585707). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data

The analysed sample shows LILE enrichment, distinct negative Nb and Ti anomalies and positive Pb anomaly in a primitive mantle normalised diagram (fig. 201). Weak LREE/HREE enrichment ($(La/Yb)_N = 2.79$) is evident in a chondrite normalised REE diagram (fig. 202). The Mjusåsen and Lövåsen samples are plotted for reference in the diagrams 201-204.

The patterns in figures 201 and 202 resemble the gabbroids at Mjusåsen and Lövåsen and are similar to arc-type basalts. However, in the Rävkillarna sample the SiO_2 content (58.20%) and ΣREE are relatively high (194 ppm) compared to that of the other gabbroids suggesting more advanced fractionation.

In the Th-Hf-Nb diagram (fig. 203) the sample plots in the field of Island arc calc-alkaline basalt (CAB). The volcanic arc signature is evident by the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 204A–B).

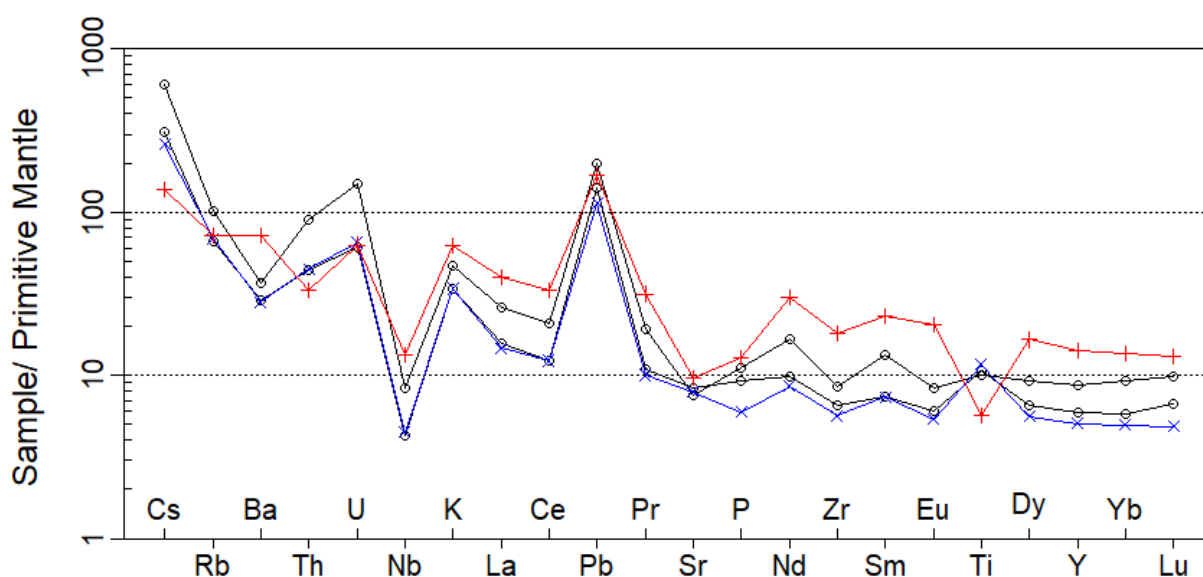


Figure 201. Primitive mantle normalised diagram for the sample from Rävkillarna (red cross). Mjusåsen samples (black circles) and Lövåsen (blue 'X') are plotted for reference. Normalising values from Sun & McDonough (1989).

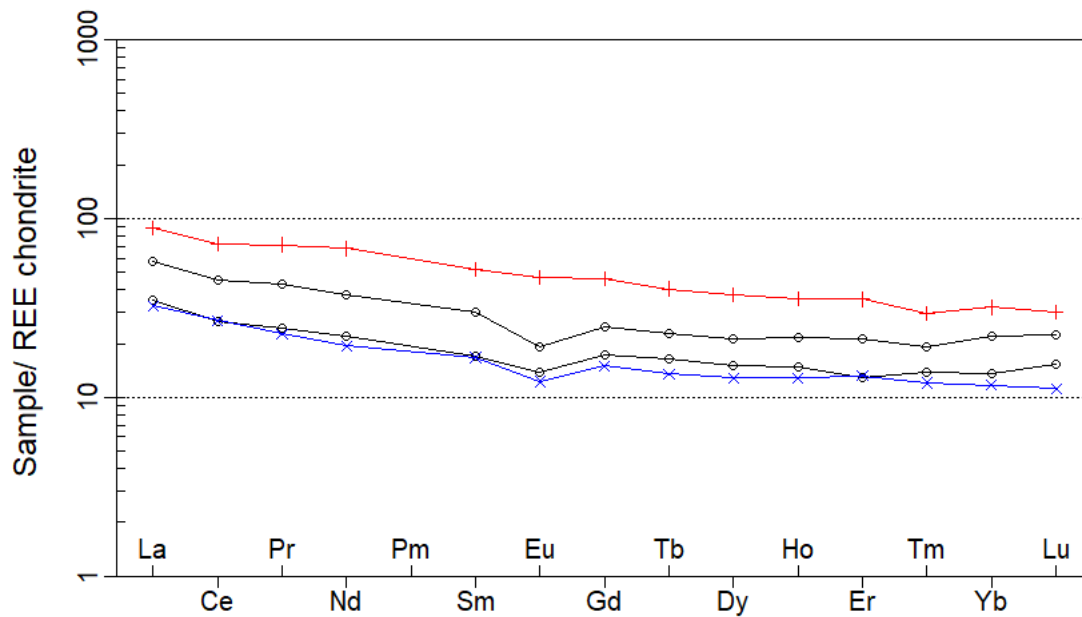


Figure 202. Chondrite normalised REE diagram for the sample from Rävkillarna (red cross). Mjusåsen samples (black circles) and Lövåsen (blue 'X') are plotted for reference. Chondrite values are from Boynton (1984).

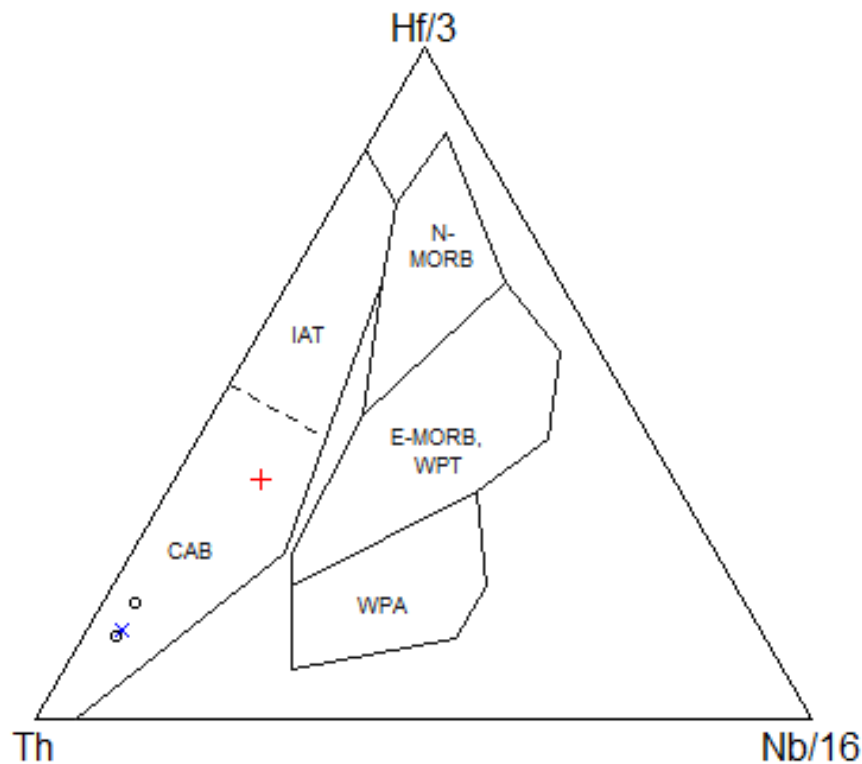


Figure 203. The Rävkillarna sample (red cross) plotted in a triangular diagram for geotectonic discrimination (Wood 1980). The Mjusåsen (black circles) and Lövåsen (blue 'X') samples are plotted for reference. Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

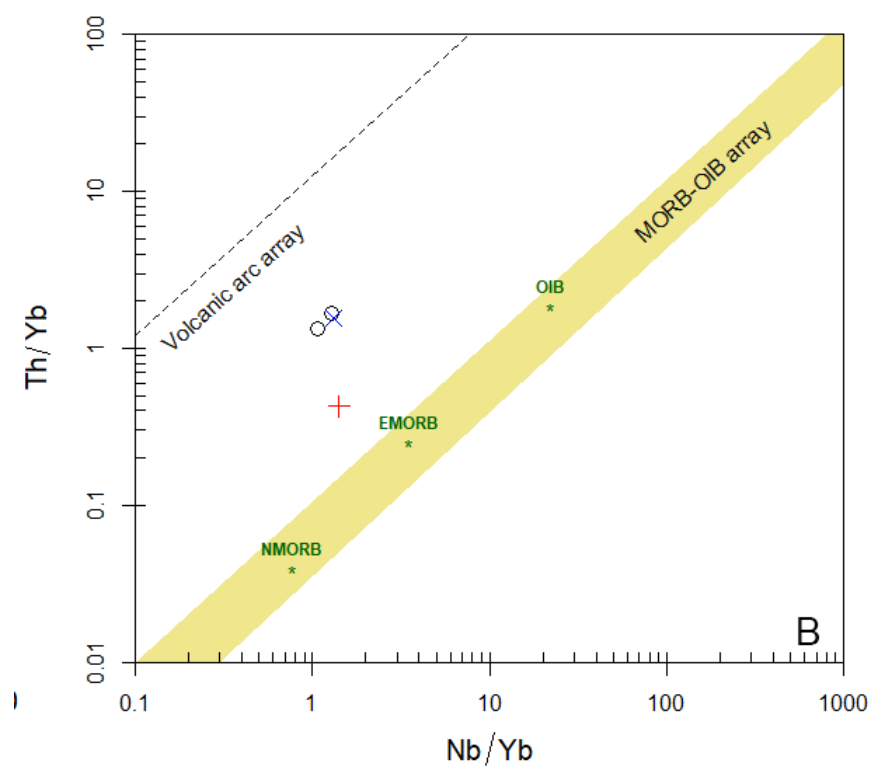
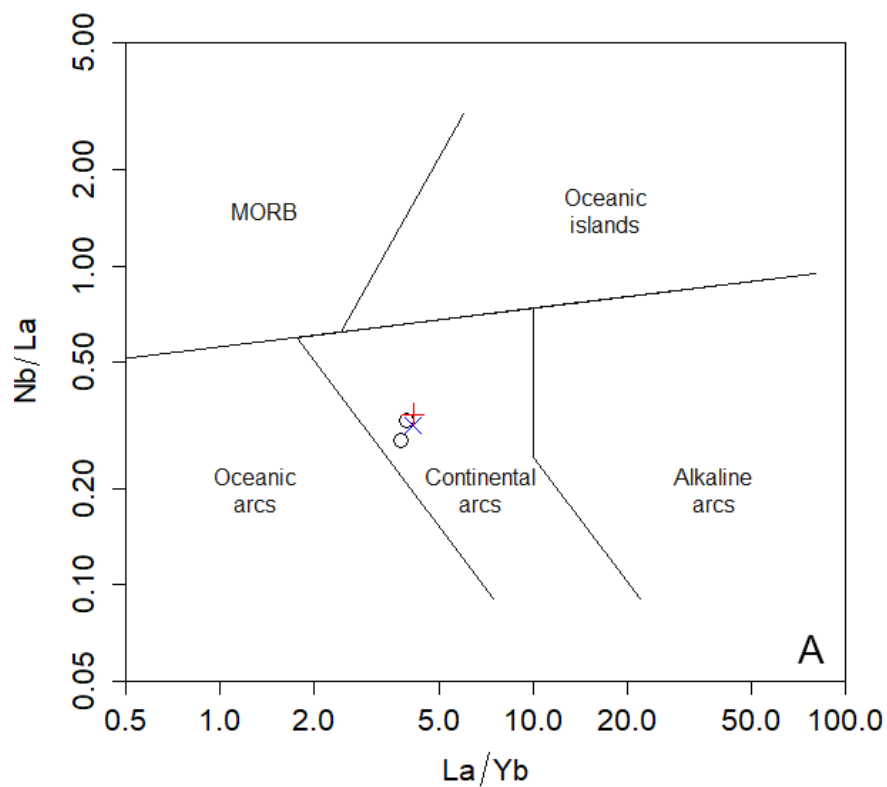


Figure 204. The Rävskullarna sample (red cross) plotted in diagrams for geotectonic discrimination. The Mjusåsen (black circles) and Lövsåsen (blue 'X') samples are plotted for reference. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Storåsen, Kullberget, Tallåsen, and Kattuggelberget

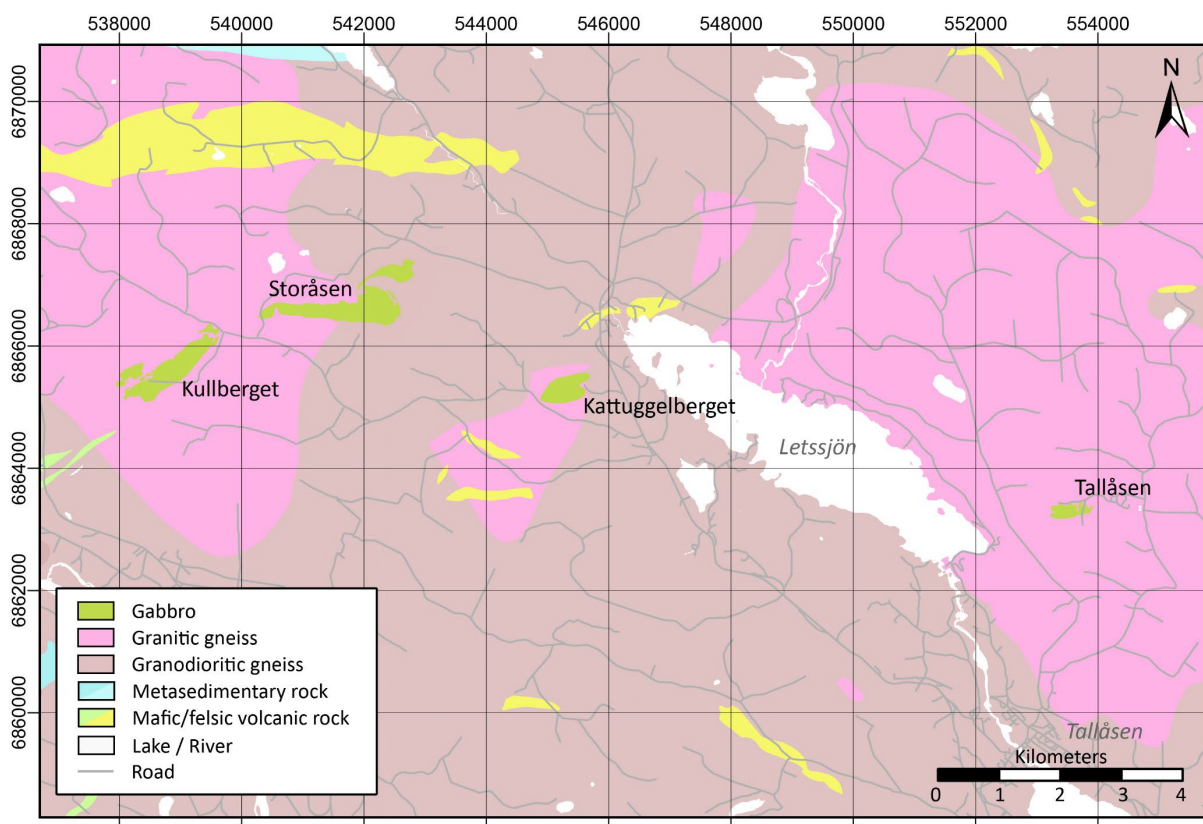


Figure 205. Bedrock geology map showing the area around the Storåsen, Kullberget, Tallåsen, and Kattuggelberget intrusions. The names of the mafic intrusions referred to in the report are shown as black text. Names of some lakes or towns are shown as grey italic text.

These objects are located 10–20 km northwest of Ljusdal (fig. 205). The presence of mafic intrusions in this area was documented as early as 1956 (Lundegårdh 1957). High contents of vanadium and titanium were noted during sampling of the gabbroid at Kullberget in 1978. Boulder-hunting was also done in 1980 in the area to the east of Storåsen (Persson 1982).

No drill cores are available from the area, but in the current project new sampling of outcrops and old mining pits was performed for geochemistry, thin sections, and petrophysics.

SGU collected airborne magnetic data over this area in 1979, where several strong magnetic anomalies could clearly be observed. To further investigate the anomalies SGU collected several ground magnetic profiles over the Storåsen and Kullberget intrusions. Unfortunately, not all these data are present in the archive, but as part of our project four ground magnetic profiles from Kullberget collected in 1980 (Persson 1982), have been digitised and located geographically. Persson (1982) documents that magnetic anomalies similar in magnitude to those observed at Gruvberget–Sumåssjön were observed at Kullberget and Storåsen, indicating the potential for significant mineralisation at these sites. However, due to the relatively sparse line spacing and significant uncertainty in position, these data were not utilised in this project. Instead, new ground magnetic data were collected over the Kullberget and Storåsen intrusions in 2024. These new data were collected with a nominal line spacing of 40 m and cover areas of approximately 1.4 km² and 1.6 km² for the Kullberget and Storåsen intrusions, respectively. In addition to this, about 0.25 km² of ground magnetic data were also collected over the Tallåsen intrusion in 2023.

Kullberget

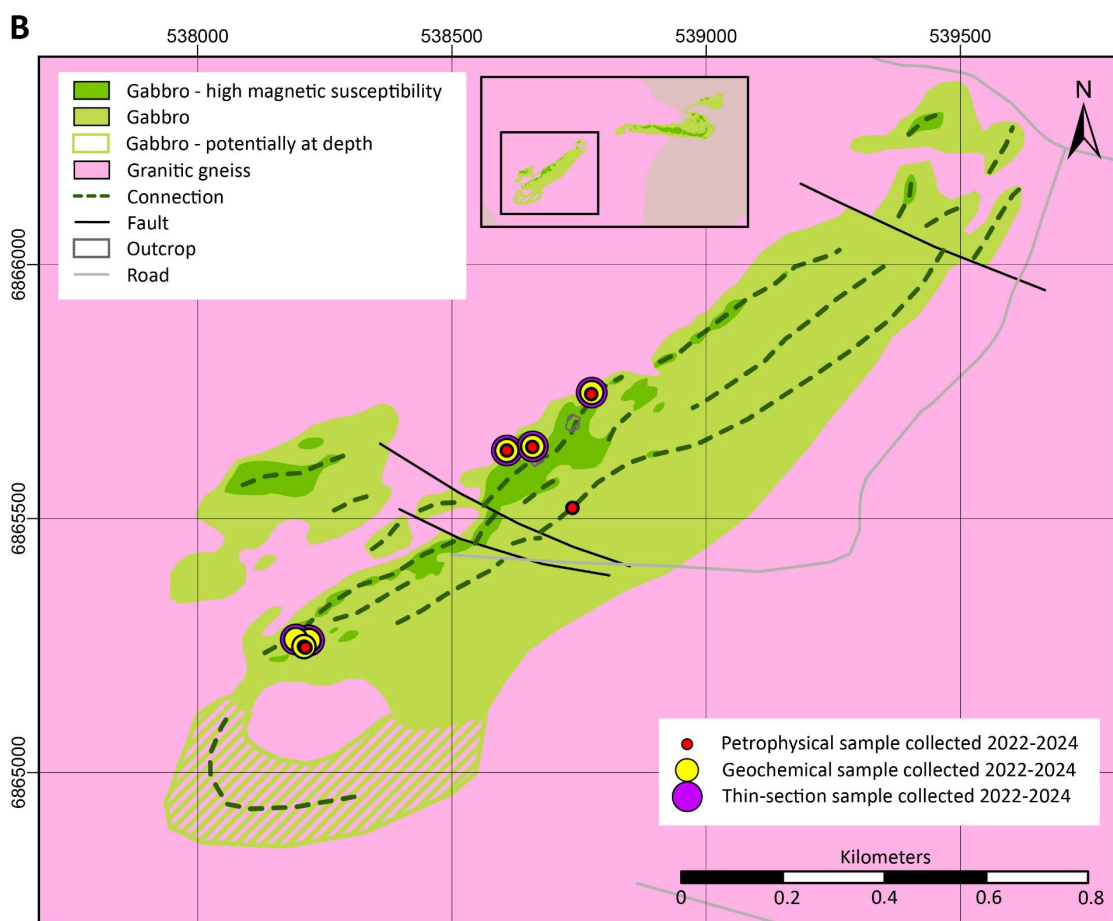
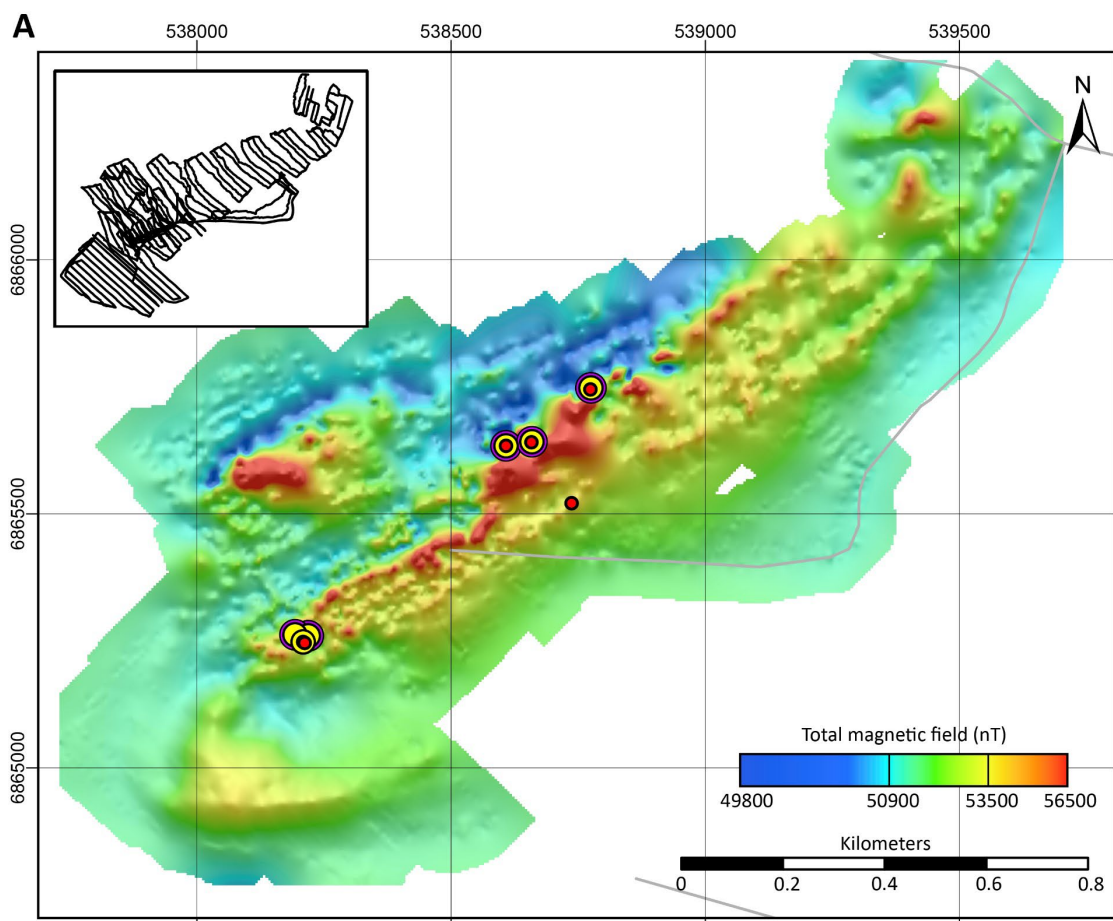
Ground-based geophysical data

Figure 206 shows a map of the ground magnetic data collected from the Kullberget intrusion as well as an updated bedrock geology map for the area around the intrusion. On inspection of the newly acquired magnetic data two distinct anomalies can be observed. This suggests that the Kullberget intrusion consist of two separate bodies. The largest of the two anomalies has a length of about 1.6 km, width of about 250 m and strike of about 53°. The magnetic anomaly from the larger intrusion is relatively strong compared to the others in this project, reaching magnetic field values of up to about 13 500 nT above the background value. The smaller anomaly lies to the northwest of the main anomaly with a similar strike and is about 300 m long and 150 m wide. Within the anomaly from this smaller intrusion the magnetic field reaches values as high as 12 000 nT above the background value.

Within the anomaly for the main intrusion a series of smaller, approximately linear, positive anomalies can be observed. In the northern part of the intrusion, three approximately parallel linear anomalies are distinctly visible with a separation of about 50–100 m. In the southern part of the anomaly these smaller positive linear anomalies appear to be more closely spaced. Within these smaller positive anomalies, the strongest magnetic field values appear to lie consistently along the northwestern flank of the intrusion. These continuous positive anomalies can be interpreted to be lenses or layers within the intrusion which are more mineralised, when compared to the other parts of the intrusion. Furthermore, the highest levels of mineralisation appear to occur in a layer which lies adjacent to the northwestern flank of the intrusion. This is consistent with the presence of abandoned mines at Kullberget, which appear to be located along this northwestern flank. In the smaller intrusion, the highest magnetic field values also appear to occur on the northwestern flank of the intrusion. In some places these relatively continuous linear anomalies appear to be laterally displaced, which can be interpreted to be due to the presence of faults. To the south of the main intrusion there is an area where the magnetic field appears to be lower in frequency. This is interpreted to indicate that the intrusion lies at a greater depth below the surface in this area.

Figure 207 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained from inverting the ground magnetic data. Here the highest magnetic susceptibilities appear to lie consistently along the northwestern flanks of both the main and smaller intrusions. On inspection of the susceptibility model in 3D it appears that the layers with high magnetic susceptibility dip to the southeast in both the main and smaller intrusions (fig. 207).

► **Figure 206.** **A.** Map of the total magnetic field from ground measurements collected as part of this study from the Kullberget intrusion. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Kullberget intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of samples are shown as coloured dots in both A and B.



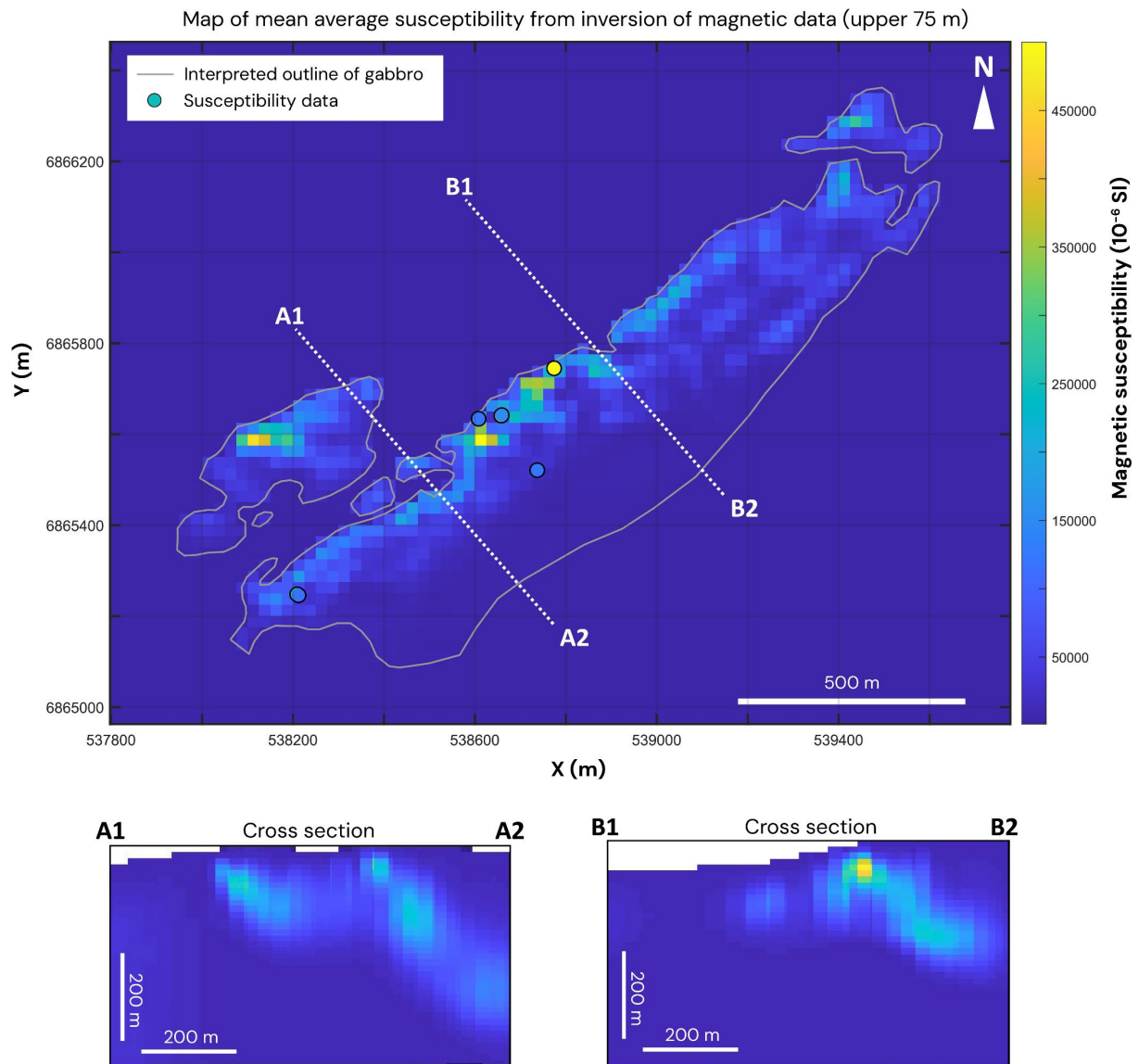


Figure 207. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Kullberget intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. Cross sections (A1–A2 and B1–B2) through the magnetic susceptibility model obtained from the inversion are shown below to the map. The locations of the cross sections are denoted on the map as dotted white lines. The dots, map and sections are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

At Kullberget sampling was done from outcrops (fig. 208) and in waste-rock heaps close to small historic mining pits named Kullberget 1, Kullberget 2, and Kullberget 3 (fig. 209).



Figure 208. Sampling of massive gabbroid in outcrop at Kullberget (6865262/538193). Photo: Helge Reginiussen.



Figure 209. Sampling of mineralised gabbroid in waste-rock heaps at the Kullberget 3 pit on the western slope of Kullberget hill (6865634/538608). Photo: Helge Reginiussen.

Description of thin sections – ore minerals

The ore minerals magnetite, ilmenite, pyrrhotite, and chalcopyrite were identified in mineralised sample HRE220023A (fig. 210, see fig. C32 for panorama). The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock (figs. 210A–B). Ilmenite has exsolved hematite lamellae, but these are much fewer in this sample compared with similar rocks of this investigation and may indicate that there was less Fe incorporated (figs. 210B–C). There is exsolved ilmenite as trellis in the magnetite (figs. 210B–C). Both ulvöspinel and pleonaste are probably present among the trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but optical microscopy was deemed inadequate for proper identification. An indicated ilmenite-pleonaste-magnetite symplectite is present for most of the contact between ilmenite and magnetite (figs. 210B–C). The width of the symplectite is from zero to three μm , which is comparable to other similar symplectites that have been reported (e.g., McEnroe *et al.* 2000).

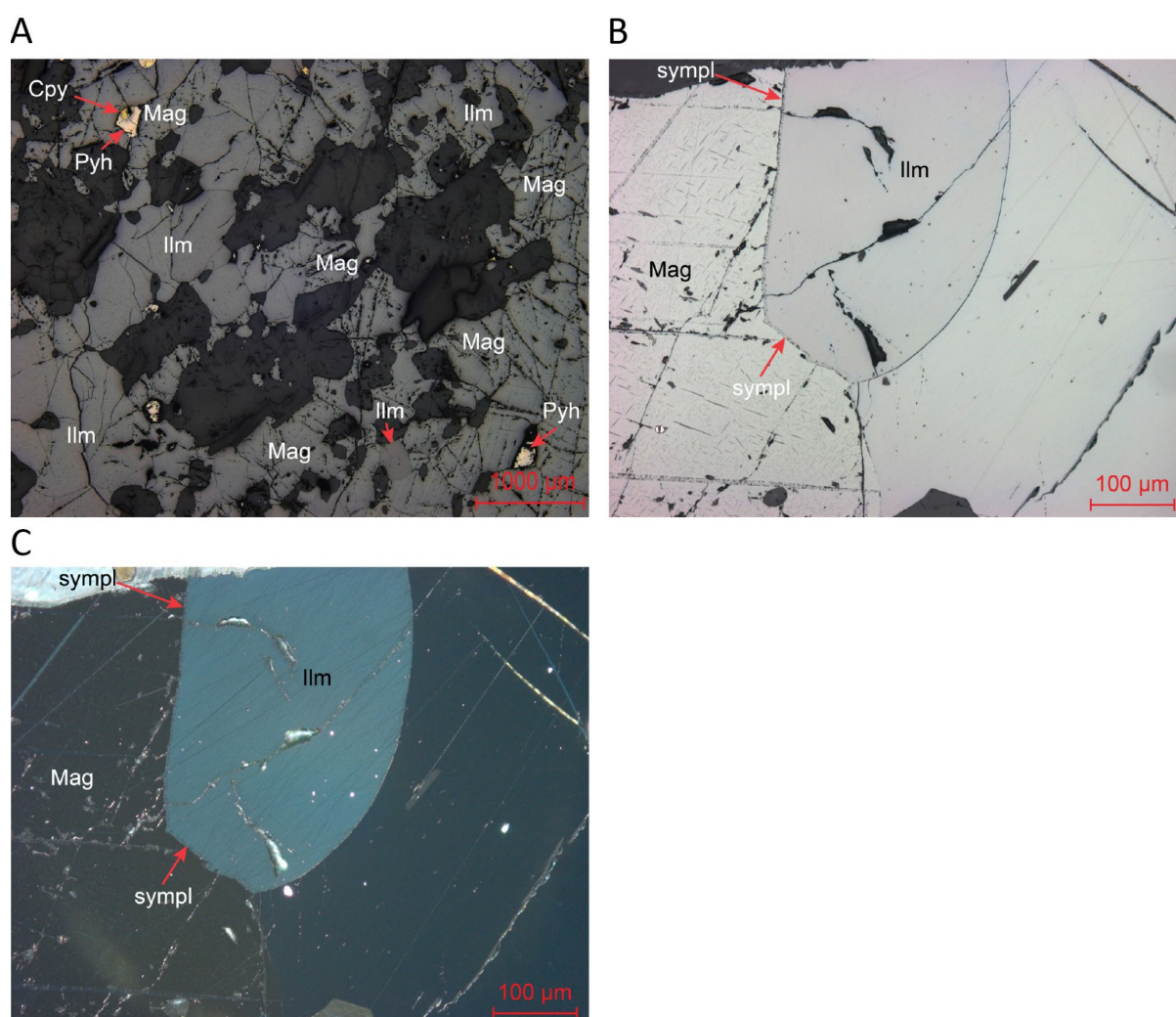


Figure 210. Ore minerals from the Kullberget intrusion, mineralised sample HRE220023A (see fig. C32 for panorama). **A.** Overview of relations between magnetite and ilmenite in opaque framework, with minor pyrrhotite and chalcopyrite. Close-up images of relations between magnetite and ilmenite, ilmenite, ulvöspinel, and pleonaste as trellis exsolutions in magnetite, and almost no hematite exsolution lamellae in ilmenite, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. Note the thin ilmenite-pleonaste-magnetite symplectite (symp) present for most of the contact between ilmenite and magnetite. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals

A lot of late-forming interstitial Fe-Ti-oxides are present in sample HRE220021A (panorama fig. C31). The only mafic silicate is subhedral to anhedral hornblende, in small to large grains and interstitially grown crystals, with a few aggregates (figs. 211A–B). Note the hornblende grain triple junction at 120 degrees in the centre of figures 211A–B and the same is present between plagioclase crystals. This granoblastic texture signifies a high degree of textural equilibrium (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Note the opaque minerals as thin fracture fillings in some of the plagioclase crystals (figs. 211A–B). A more hydrous mineral assemblage is present in sample HRE220022A, with relatively abundant biotite and hornblende along with clinopyroxene, olivine, and plagioclase (figs. 211C–D).

All images of sample HRE220023A are exclusively from the right part of the mineralised panorama figure C32. Clinopyroxene, hornblende, and olivine are the main mafic minerals and biotite is rare, however, biotite is relatively abundant in the magnetite-ilmenite framework part. Plagioclase is the main felsic mineral (fig. 212). Hornblende is subhedral to anhedral with many grain triple junctions at 120 degrees. For the most part where Fe-Ti-oxides are present, the main mafic mineral is hornblende whereas in portions of the thin section lacking Fe-Ti-oxide, clinopyroxene and olivine are more common. Plagioclase is irregularly distributed in this part of the section (fig. C32), where present it has no, or very minor reaction or dissolution features present when in direct contact with opaque minerals (figs. 212C–F). For the most part plagioclase is surrounded by hornblende crystals or Fe-Ti-oxides and none of the other mafic silicates are present in the thin section. Even when there is a miniscule distance between e.g., clinopyroxene and plagioclase, hornblende occurs except for very rare places where they are in contact (figs. 212C–F). This is due to hornblende crystallising as a late-forming mineral and thus in interstitial positions where porosity was still present.

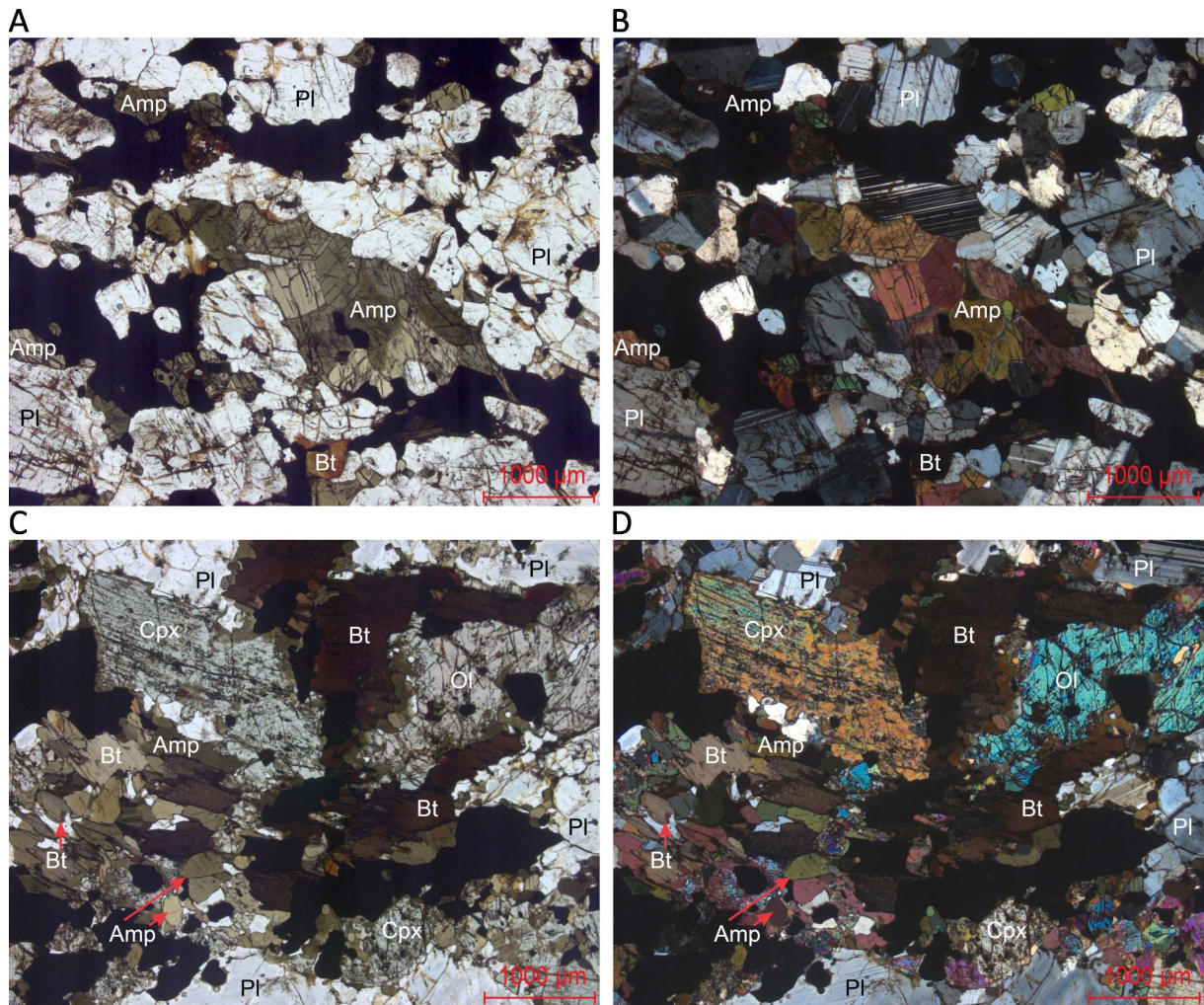


Figure 211. **A.** and **B.** Hornblende and plagioclase have grain triple junctions at 120 degrees, e.g., close to the centre of the images. Sample HRE220021A (6865634/538608). **C.** and **D.** Relatively abundant biotite and hornblende along with clinopyroxene, olivine, and plagioclase. Sample HRE220022A (6865642/538659). Left in ppl and right in xpl. Photo: Dick Claeson.

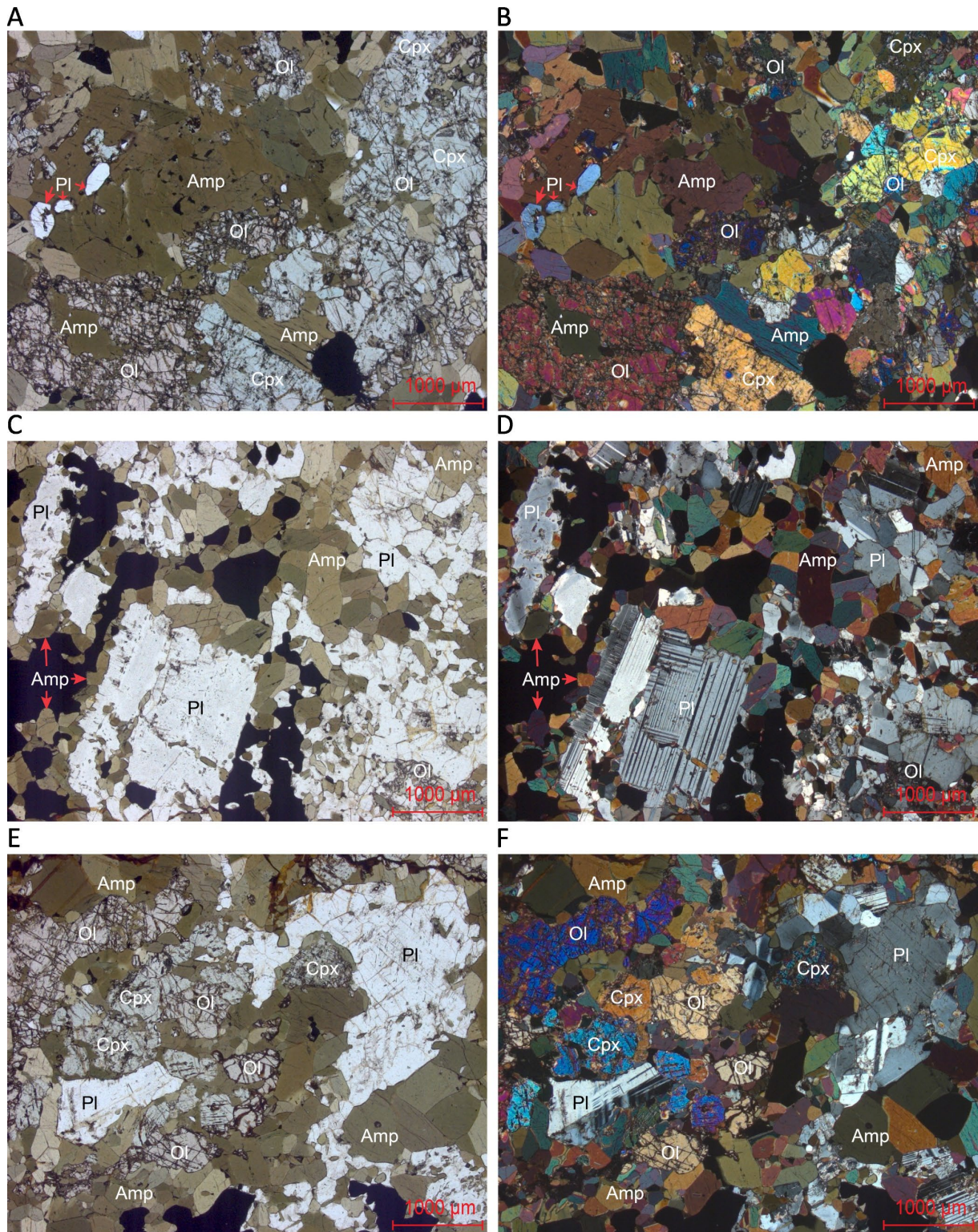


Figure 212. A. and B. Part dominated by mafic minerals clinopyroxene, hornblende, and olivine with rare plagioclase crystals. C. and D. Hornblende dominate in proximity to Fe-Ti oxides and between plagioclase and Fe-Ti oxides. Several hornblende and plagioclase grain triple junctions at 120 degrees, a granoblastic texture. E. and F. Intergrown clinopyroxene, hornblende, and olivine, with mostly hornblende in contact with plagioclase. All images sample HRE220023A (6865748/538775). Left in ppl and right in xpl. Photo: Dick Claeson.

Storåsen

Ground-based geophysical data

Figure 213 shows the ground magnetic data collected over the Storåsen intrusion together with an updated interpretation of the bedrock geology around the intrusion. Here the magnetic anomalies appear to indicate that, at the surface, there are two separate intrusions. However, there is potential that these two separate intrusions are linked at depth. In the western part of the larger anomaly, the high magnetic field amplitudes form a somewhat continuous and linear anomaly with an approximately east–west strike. In the eastern part of the larger intrusion, the high anomaly values appear to bend round to form a curved geometry. The larger anomaly has a length of about 2.1 km and width of about 200 m in the west, which increases to about 500 m in the east. The anomaly is relatively strong compared to the others within the project, where the magnetic field values reach up to 14 500 nT above the background value in places. The smaller anomaly lies to the north of the eastern end of the larger anomaly and has a curved geometry. This smaller anomaly has a length of about 450 m and width of about 100 m.

Within both the smaller and larger anomalies, there appears to be a number of smaller continuous positive anomalies which can be correlated over distances of up to a few hundred metres. These are perhaps clearest in the eastern part of the large intrusion, where these have a concentric geometry, following the curve of the outermost, strongest magnetic anomaly. In the western part of the anomaly these small positive anomalies are approximately linear with an east–west strike. These small positive anomalies can be interpreted to be due to layers or lenses within the intrusion which have a greater degree of mineralisation. Within the intrusion the strongest magnetic field values appear to be present in the central part of the main intrusion.

Figure 214 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained by inverting the ground magnetic data. Here the highest average magnetic susceptibilities appear to lie along the edge of the intrusion in the eastern part. On inspection of the model in 3D it appears that the region with high susceptibilities dips to the north in the central and western parts of the larger intrusion. Whereas in the area with the concentric magnetic anomaly pattern, there appears to be a bowl like geometry, where the southern flank dips to the north and the northern flank dips to the south. The smaller intrusion to the north of the main intrusion, appears also to dip to the south (fig. 214).

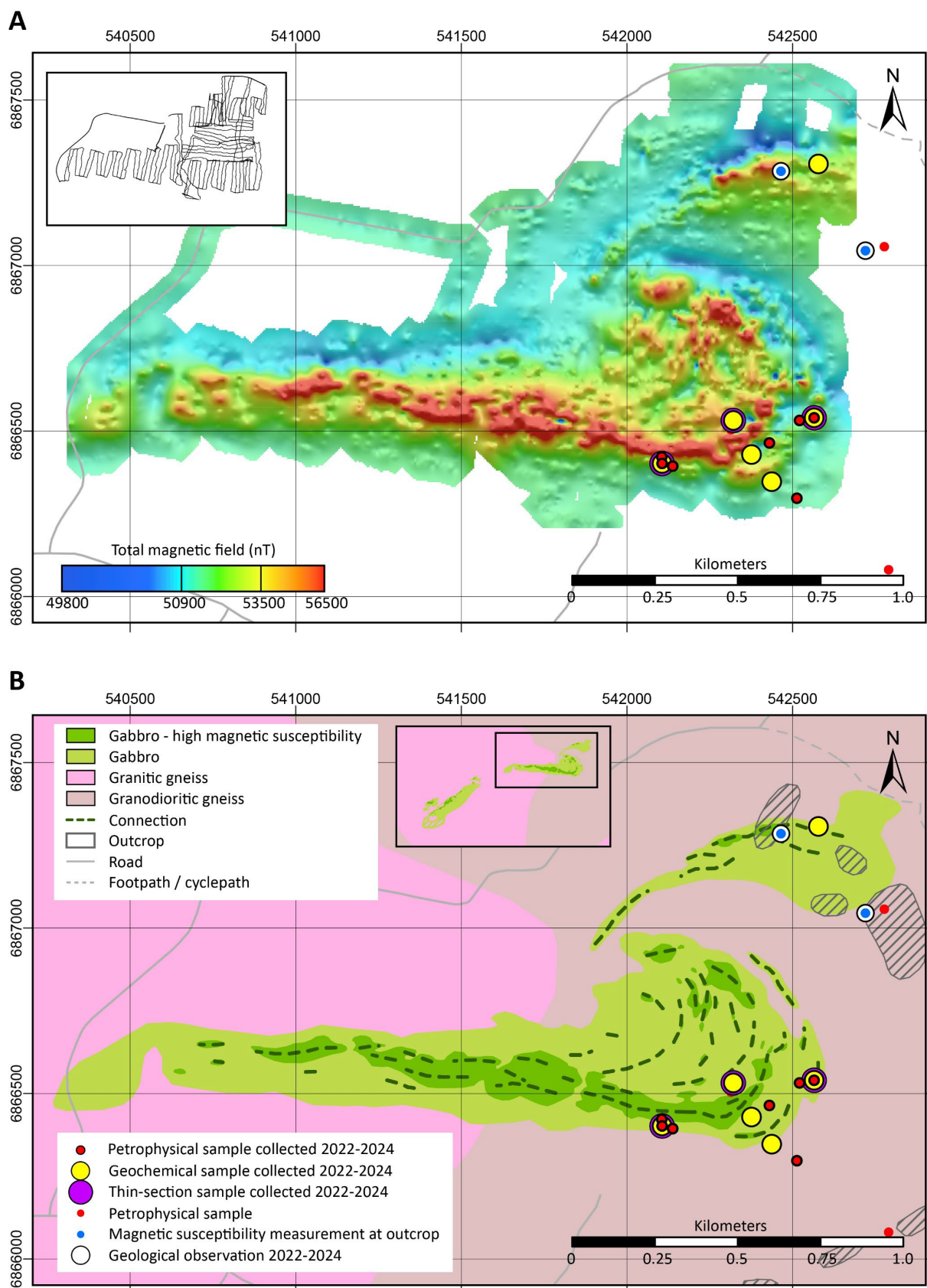


Figure 213. A. Map of the total magnetic field from ground measurements collected as part of this study over the Storåsen intrusion. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Storåsen intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of geological observations, samples, and magnetic susceptibility measurements at outcrop are shown as coloured dots in both A and B.

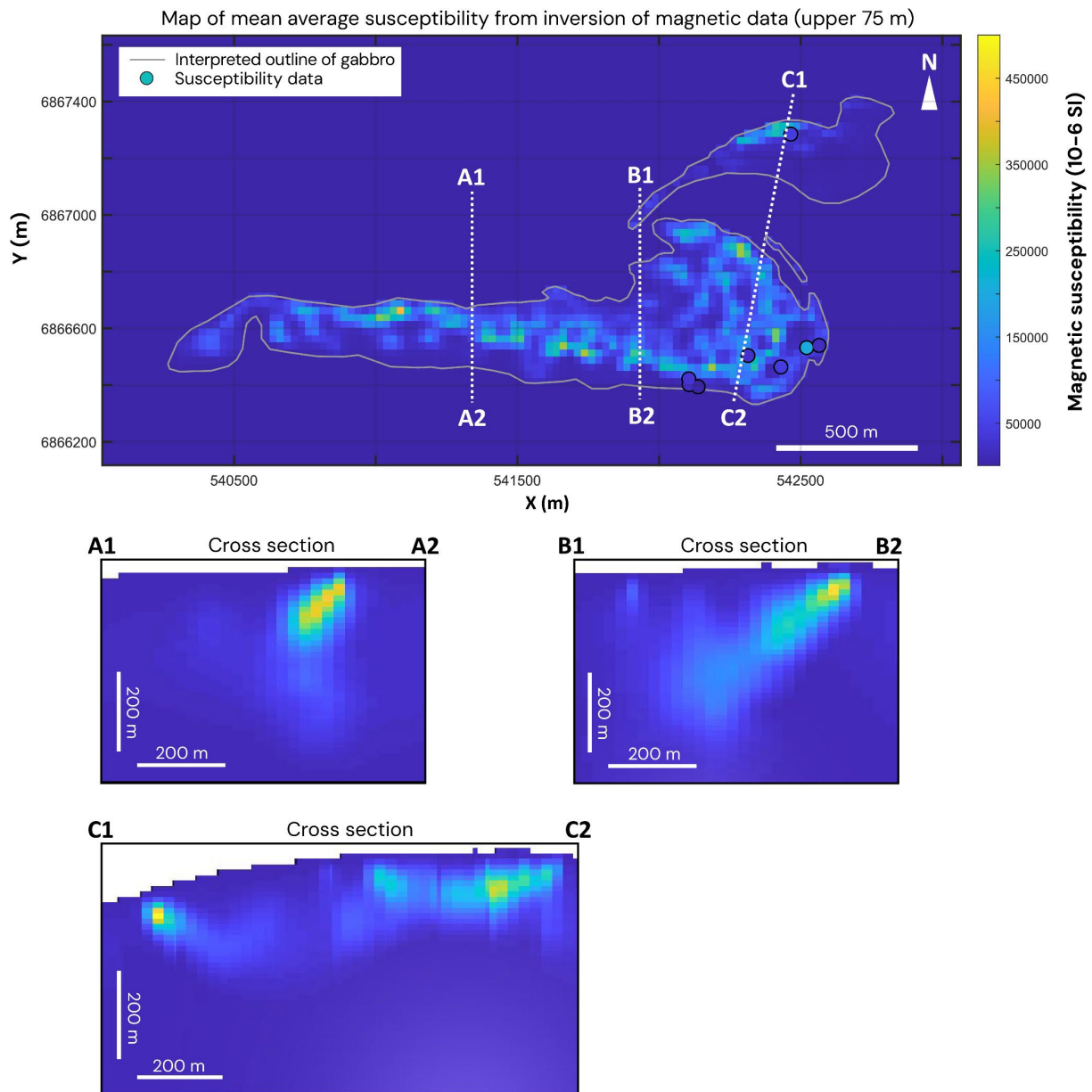


Figure 214. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Storåsen intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. Cross sections (A1–A2, B1–B2 and C1–C2) through the magnetic susceptibility model obtained from the inversion are shown below to the map. The locations of the cross sections are denoted on the map as dotted white lines. The dots, map and sections are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

At Storåsen, the degree of outcrop is limited, but outcrops with apparently undeformed, well-preserved gabbroid with primary magmatic textures were found (figs. 215, 216). Complex textures with large variations in grain size are observed (fig. 217B). The enveloping granitoid is light reddish, foliated and megacryst-bearing (fig. 219).

Pegmatitic, dendritic amphibole crystals, almost resembling harrisitic crescumulate texture were observed at one locality, which indicate a water-rich magma (fig. 217A).

The contact relations to the surrounding granite appear to be intrusive manifested by back-veining of partially melted granitic material, magma mingling, and hybridisation (fig. 218).



Figure 215. Gabbroid outcrop at Storåsen with diffuse modal layering (6866532/542521). Photo: Helge Reginiussen.



Figure 216. Massive, undeformed gabbroid in outcrop at Storåsen (6866419/542101). Photo: Helge Reginiussen.



Figure 217. A. Large, blade-formed, dendritic amphibole crystals at Storåsen (6867285/542465). B. The grain size can vary from fine-grained to pegmatitic within the same outcrop (6867285/542465). Photo: Helge Reginiussen.



Figure 218. Intrusive contact at Storåsen between gabbroid and reddish granite showing back-veining (6866402/542106). Photo: Helge Reginiussen.



Figure 219. Foliated, megacryst-bearing granitoid in outcrop at Storåsen. The contact to the gabbro is not exposed at this outcrop but is inferred to be within tens of metres (6866347/542437). Photo: Helge Reginiussen.

Description of thin sections – silicate minerals

The grain size is variable in sample HRE220032A from Storåsen (figs. 220A–D). In the fine-grained parts, clinopyroxene, olivine, and hornblende are tightly crystallised together between glomerocrysts of mostly plagioclase (figs. 220A–B). Biotite is generally scarce and has a brownish red to tan pleochroism. Aggregates with greater amounts and larger biotite grains together with hornblende and opaque minerals are present (figs. 220C–D). These aggregates mainly consist of hydrous minerals with Fe-Ti-oxides and minor plagioclase, formed at a late-stage of the evolution of the cumulate rock with plenty of H₂O in the Fe-Ti-rich interstitial liquid. Large euhedral to subhedral hornblende have grain triple junctions at 120 degrees (figs. 220C–D). The granoblastic texture minimises the combined surface energy of the grains and in igneous layered rocks signifies textural equilibrium that the cumulate has reached (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). There are larger oikocrysts of hornblende with chadacrysts of clinopyroxene, olivine, and plagioclase in the sample. Subhedral to anhedral plagioclase grains with minor sericite-saussurite alteration are present.

Bends or kinks are present in several of the larger plagioclase crystals in sample HRE230069A (figs. 220E–F). Bending or kinking of plagioclase in a cumulate rock is considered to result from the process of compaction of the hot crystal pile or mush, where interstitial liquid is pressed out of the residual porosity of the crystal mush (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011). Formation of deformation twins and undulose extinction in plagioclase is also attributed to this process (e.g., Holness *et al.* 2017). Clinopyroxene is the main mafic silicate and has grains that are subhedral to anhedral, small to large and has exsolutions of lamellae and opaque minerals. Hornblende occurs mostly as small grains and interstitially grown crystals along rims. Anhedral small grains of olivine are present.

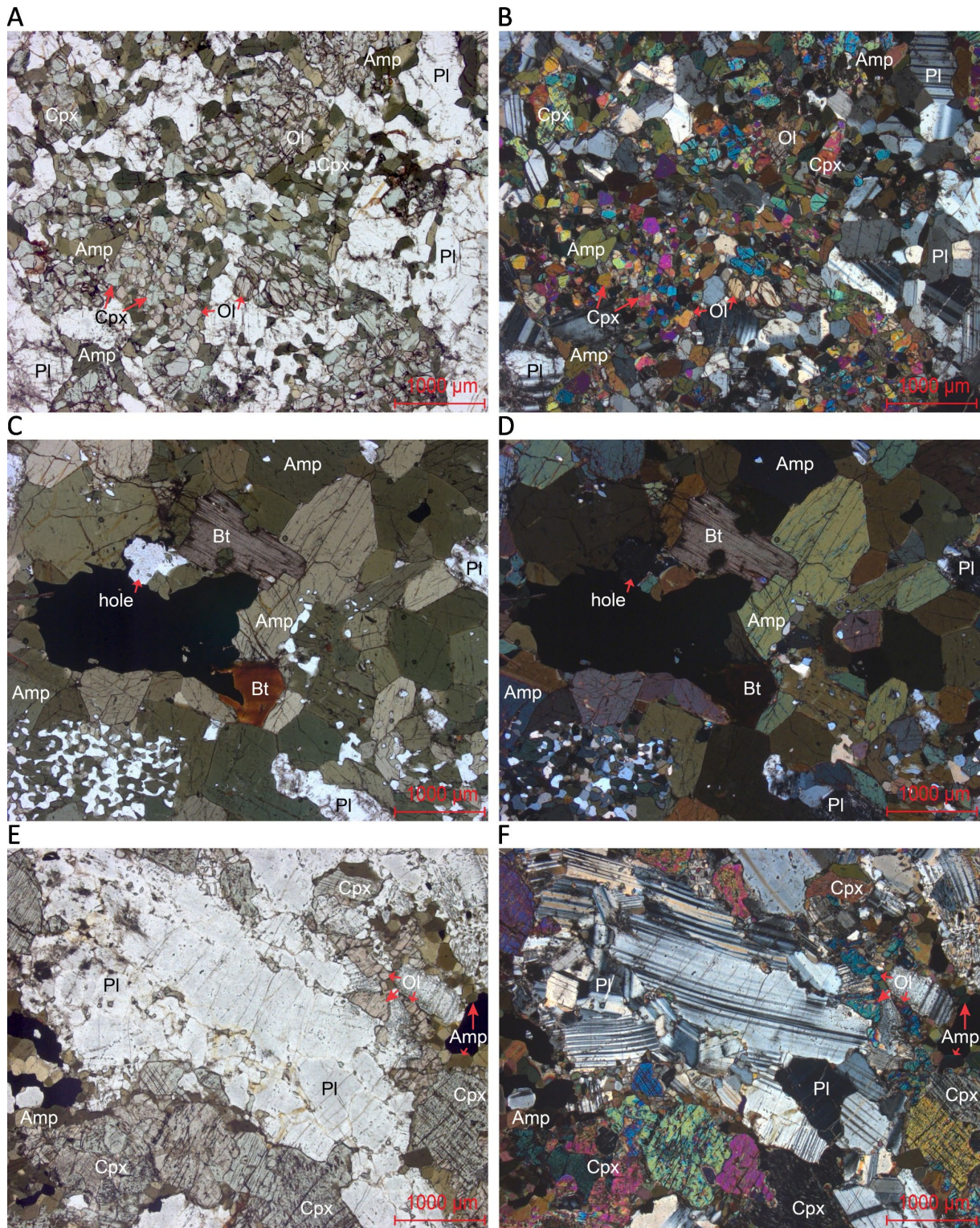


Figure 220. A. and B. Fine-grained clinopyroxene, olivine, and hornblende, between glomerocrysts of mostly plagioclase. C. and D. Large euhedral to subhedral hornblende with biotite and Fe-Ti-oxide crystals. Intergrown plagioclase and hornblende in left lower corner. Several hornblende grain triple junctions at 120 degrees. Sample HRE220032A (6866402/542106). E. and F. Bends or kinks, deformation twins, and undulose extinction are present across several of the large plagioclase. Sample HRE230069A (6866532/542321). Left in ppl and right in xpl. Photo: Dick Claeson.

Tallåsen

Ground-based geophysical data

The ground magnetic data collected as part of this project over the Tallåsen intrusion is shown in figure 221 together with an updated map of the bedrock geology around the intrusion. The anomaly associated with the Tallåsen intrusion appears to be about 500 m long and 200 m wide with an approximately east–west strike. The anomaly is relatively weak, when compared to the others in this study, where the highest magnetic field values reach a maximum of about 4 200 nT above the background. However, these strongest values appear to be confined to a small positive anomaly which is approximately 140 m long, located in the eastern part of the intrusion. Hence, the highest levels of mineralisation in this intrusion are interpreted to be associated with these higher magnetic field values.

Figure 222 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained by inversion of the ground magnetic data. Here the highest magnetic susceptibility values are located in the eastern part of the intrusion, however, these average values are still relatively low compared to the other inversion results in this study. A section through the 3D magnetic susceptibility model is shown in figure 222 where the higher susceptibility values in the eastern part of the intrusion appear to dip to the north.

Geological observations

At Tallåsen (fig. 223) two mining pits are located in close proximity. Sampling of medium-grained gabbroic rocks was done in the adjoining waste-rock heaps, but both analyses returned very low vanadium contents; 151 and 121 ppm, respectively.

Description of thin sections – silicate minerals

Interstitial hornblende is present between all other silicates in the cumulate rock from Tallåsen (figs. 224A–B). Larger, euhedral to anhedral grains of hornblende with central opaque minerals make up aggregates, where the silicate has several grain triple junctions at 120 degrees, an igneous granoblastic equilibrium texture (figs. 224C–D). Clinopyroxene and olivine occurs as subhedral to anhedral, small to large grains. The clinopyroxene has lamellae, opaque exsolutions, and occasional twinning. Rare large orthopyroxene crystal is anhedral, has low order birefringence and straight extinction. Plagioclase is subhedral to anhedral as small and large grains. Their rims usually lack the pigmentation seen in the central portion of the crystals and formed late interstitially.

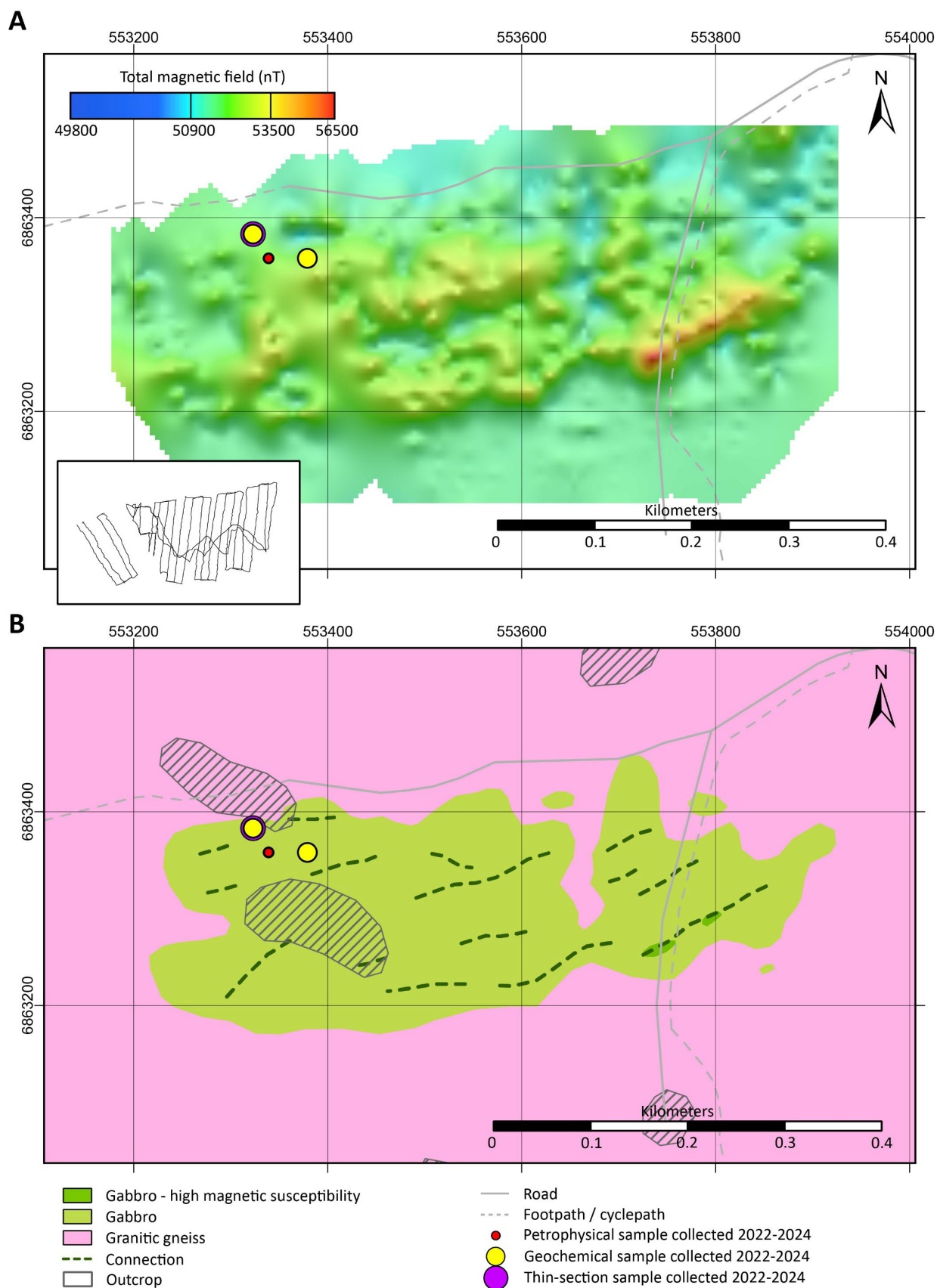


Figure 221. A. Map of the total magnetic field from ground measurements collected as part of this study over the Tallåsen intrusion. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Tallåsen intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of samples are shown as coloured dots in both A and B.

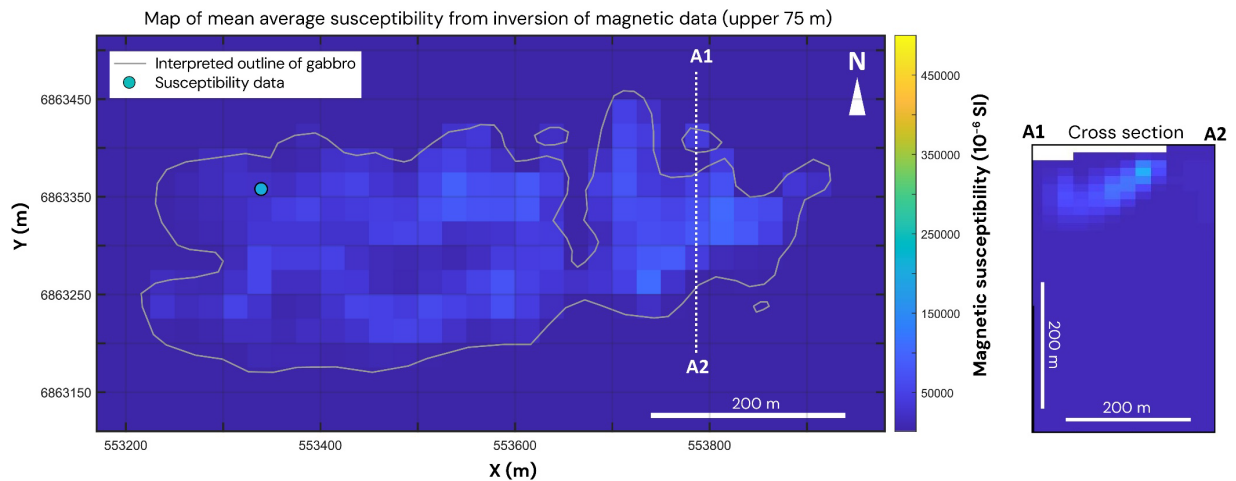


Figure 222. A map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Tallåsen intrusion. The magnetic susceptibility measurement collected at the surface is shown as a dot. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dot, map and section are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.



Figure 223. Waste-rock heap at Tallåsen (6863383/553323). Photo: Helge Reginiussen.

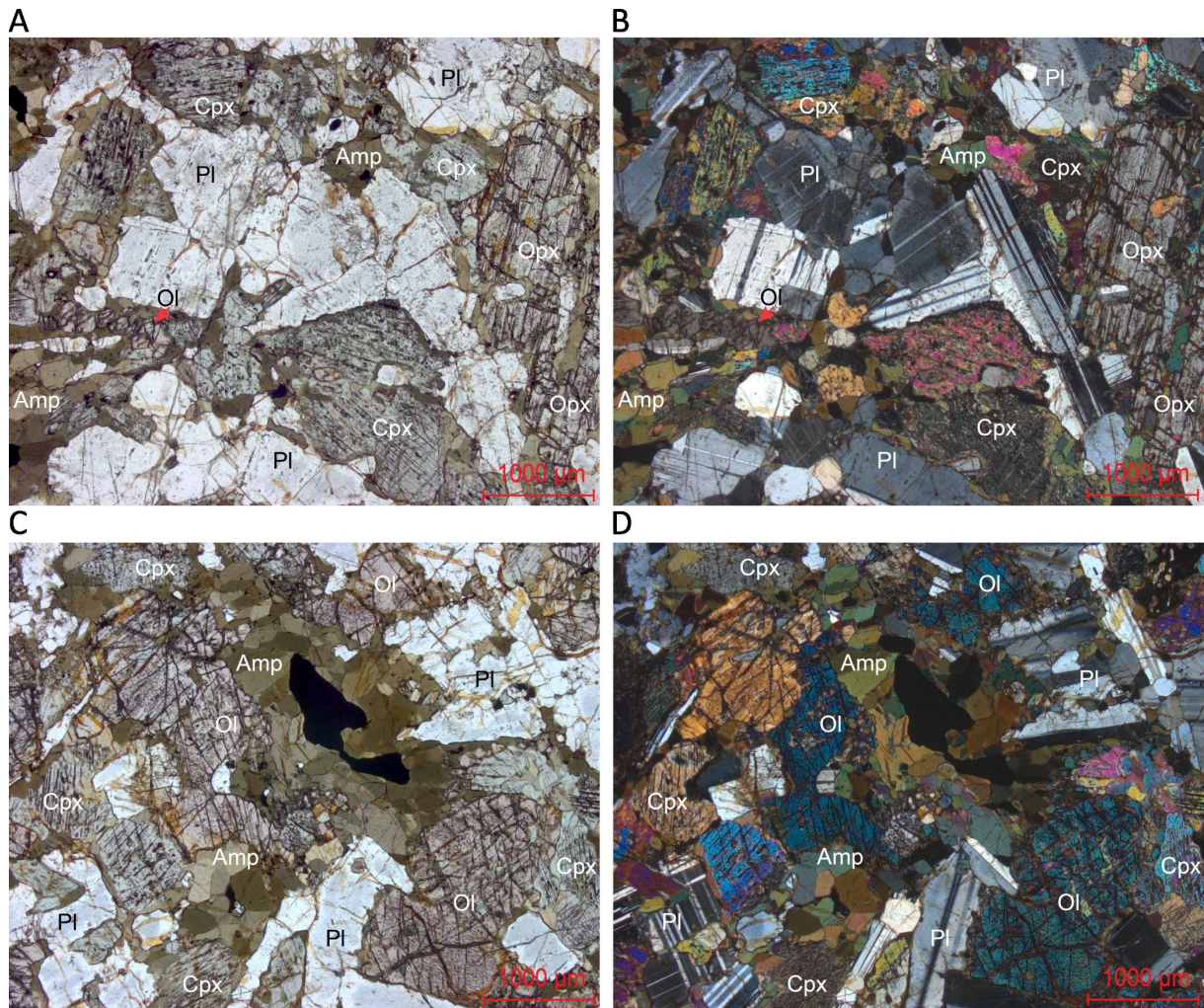


Figure 224. A. and B. Interstitial hornblende present between all other silicates in the cumulate rock. Rare large anhedral orthopyroxene crystal to the right. Note strong pigmentation in central parts of large plagioclase crystals and less in the perimeter. C. and D. The Fe-Ti oxides are surrounded by hornblende in aggregates within a cumulate of clinopyroxene, olivine, and plagioclase. Sample HRE230071A (6863383/553323). Left in ppl and right in xpl. Photo: Dick Claeson.

Kattuggelberget

Geological observations

Kattuggelberget is a hill located approximately 3 km southeast of Storåsen (fig. 205). Near the top of the hill both gabbroic outcrops and boulders occur. The dominant rock in outcrop is a gabbroic rock with subophitic texture (fig. 225). Fine-grained, rust coloured gabbroic boulders of presumed local origin show very high magnetic susceptibility. One sample each from boulders and outcrop was analysed. Assays of the outcrop sample returned 15.50% Fe_2O_3 , 1.48% TiO_2 , and 437 ppm V. Not surprisingly the boulders have higher grades with 54.30% Fe_2O_3 , 4.48% TiO_2 , and 982 ppm V.



Figure 225. Gabbroid at Kattuggelberget showing subophitic texture (6865124/545112). Photo: Helge Reginiussen.

Description of thin sections – ore minerals

The ore minerals magnetite, ilmenite, pyrrhotite, and relatively abundant chalcopyrite were identified in mineralised sample HRE220033A (fig. 226, see fig. C33 for panorama). The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock. Note the different steely grey ilmenite in reflected light compared with other samples of this study (figs. 226A–B). Ilmenite has exsolved hematite lamellae, but these are less frequent in this sample compared with most other similar rocks of this study, which may indicate that there was less Fe incorporated and might also explain the different colouration of ilmenite (figs. 226B–C). There is exsolved ilmenite as trellis in the magnetite (figs. 226B–C). There is a high probability that both ulvöspinel and pleonaste are present among the trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but the optical microscopy was deemed inadequate for proper identification.

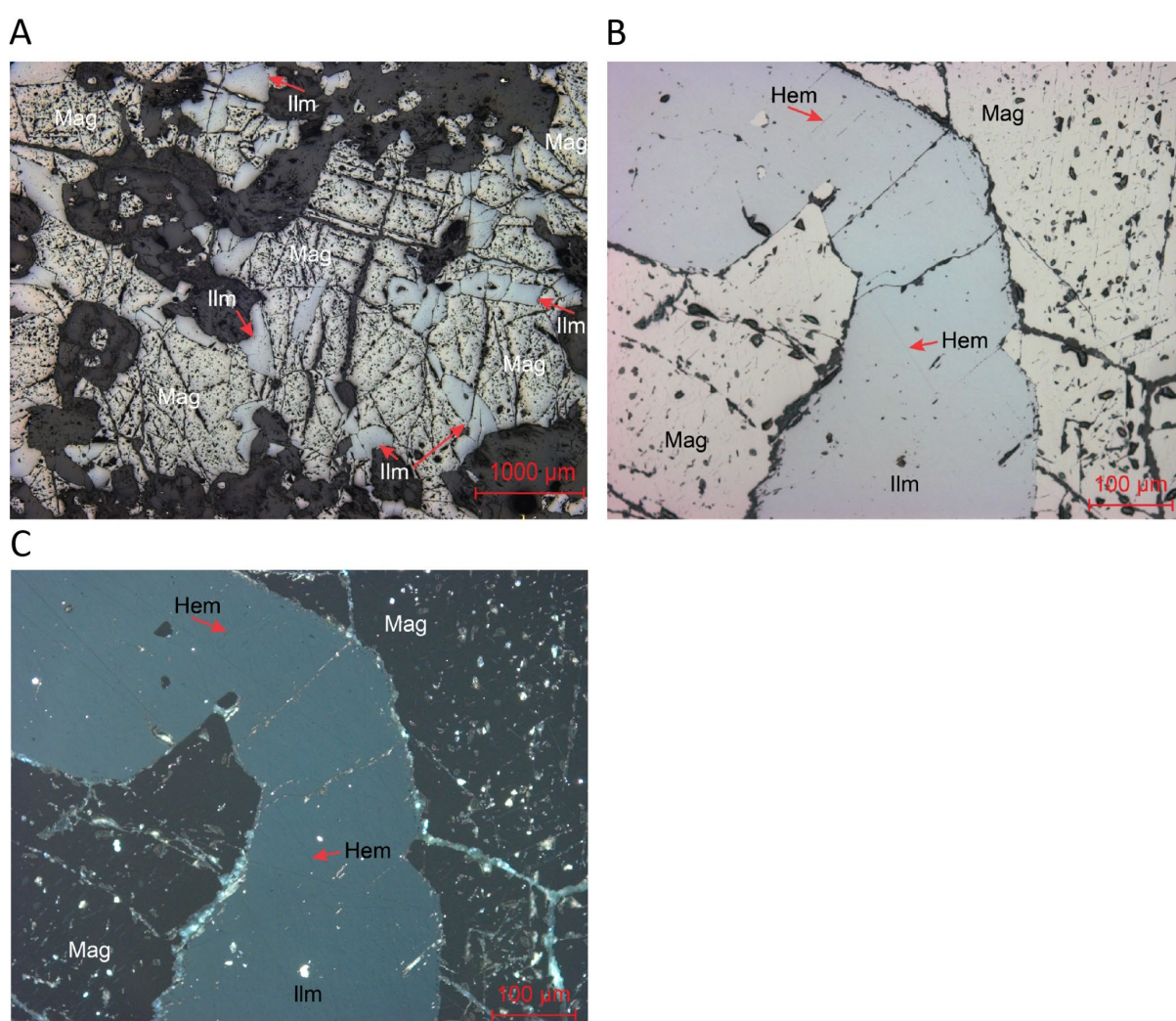


Figure 226. Ore minerals from the Kattuggelberget intrusion, mineralised sample HRE220033A (see fig. C33 for panorama). **A.** Overview of relations between magnetite and ilmenite in opaque framework, note the different steely grey colour of ilmenite of this sample. Close-up images of relations between magnetite and ilmenite, ilmenite as trellis exsolutions in magnetite, and very few hematite exsolution lamellae in ilmenite, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals

Sample HRE220033A is from a large boulder of fine-grained gabbro with high magnetic susceptibility (around 0.7 SI) at an outcrop on Kattuggelberget (panorama fig. C33). The mineralised rock is dominated by Fe-Ti oxides and the silicate minerals are mainly hornblende and plagioclase with minor clinopyroxene (fig. 227). There are rare severely altered crystals that could have been clinopyroxene. Both clinopyroxene and plagioclase, but not the main mafic mineral hornblende, have textures that are consistent with them having been partly digested, probably due to encountering a slightly later formed H₂O- and Fe-rich liquid that mineralised the rock (fig. 227).

The sample HRE220033B is from an outcrop at Kattuggelberget and is medium- to coarse-grained, with relatively low magnetic susceptibility. In the thin-section there is some patchy sericite-saussurite alteration and some alteration of grains which are most likely clinopyroxene (fig. 228). Grain-size variation among clinopyroxene, hornblende, and plagioclase occur, where all three have fine-grained and medium-grained parts and typically crystallised in the same proportions (figs. 228A–B). There are roughly equal amounts of hornblende and clinopyroxene. Euhedral to anhedral hornblende occur as small to large grains and aggregates with Fe-Ti oxide crystals. There are few anhedral olivine crystals. Rare biotite has brown to tan pleochroism and minor alteration into chlorite + prehnite.

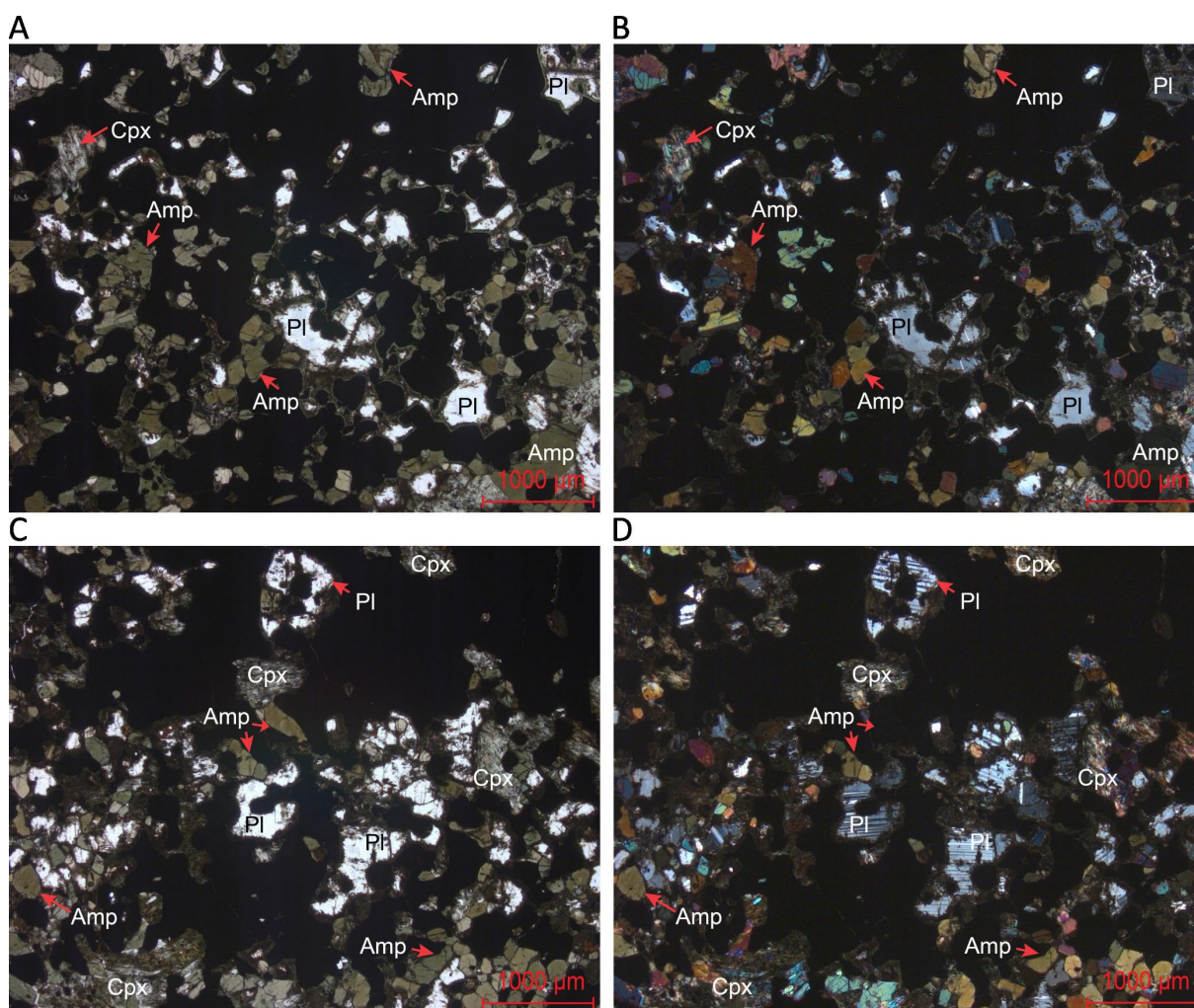


Figure 227. Mineralised cumulate rock dominated by Fe-Ti oxides and the silicate minerals are mainly hornblende and plagioclase with few clinopyroxene. All images sample HRE220033A (6865124/545117). Left in ppl and right in xpl. Photo: Dick Claeson.

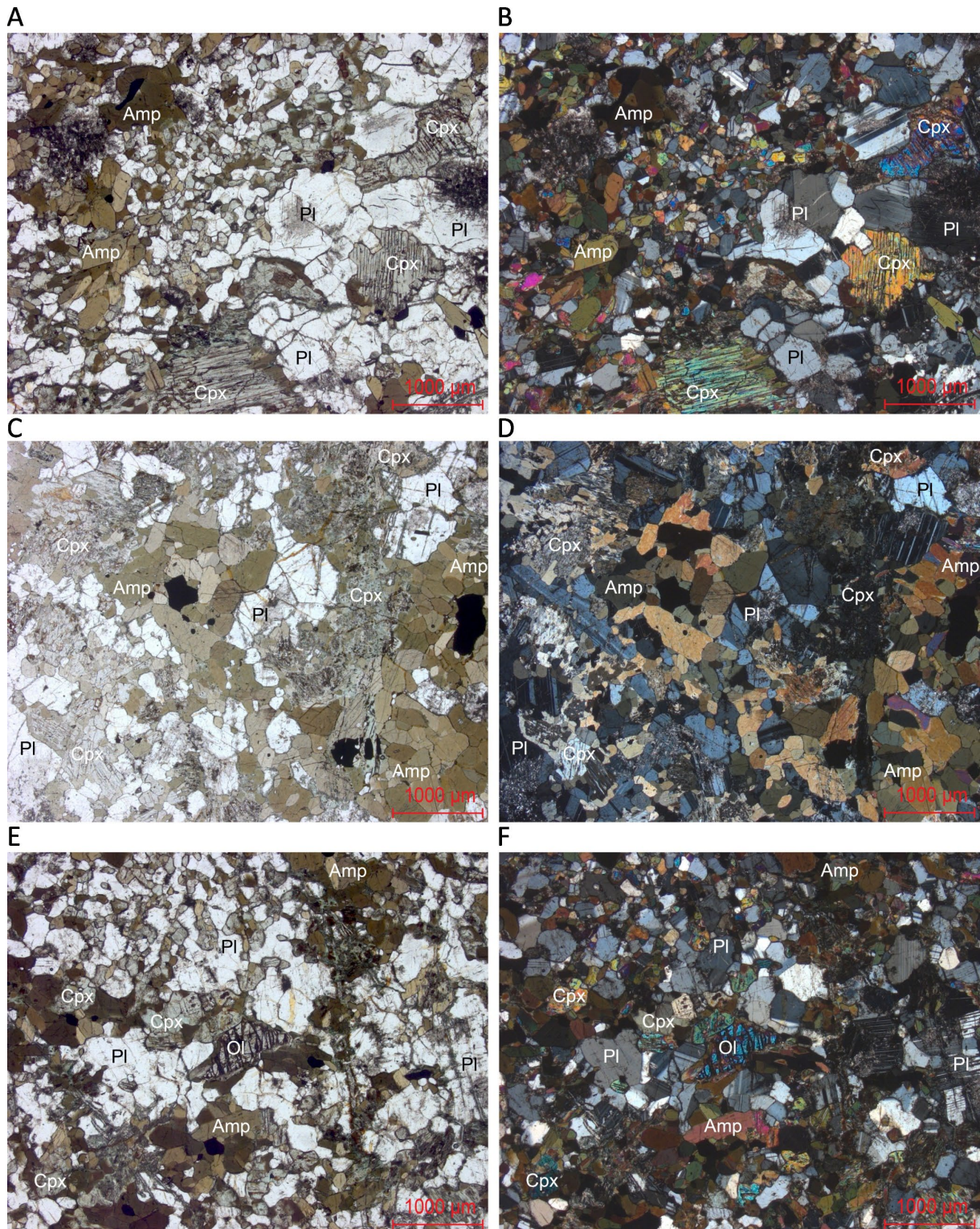


Figure 228. A. and B. Grain-size variation among clinopyroxene, hornblende, and plagioclase, all three have fine-grained and medium-grained parts. C. and D. Hornblende as aggregates with Fe-Ti oxide, note granoblastic texture. E. in ppl and F. Rare olivine crystal in centre of image surrounded by clinopyroxene, hornblende, and plagioclase. All images sample HRE220033B (6865124/545117). Left in ppl and right in xpl. Photo: Dick Claeson.

Geochemical data from Storåsen, Kullberget, Tallåsen, and Kattuggelberget

The vanadium and iron contents are plotted in figure 229. Most of the samples analysed have rather low Fe and V contents. In Harker diagrams the sample suite displays good correlations between SiO_2 and Fe_2O_3 . Correlation between TiO_2 and SiO_2 is also evident (fig. 230). Harker diagrams for vanadium (ppm) vs. selected major and trace elements are shown in figure 231.

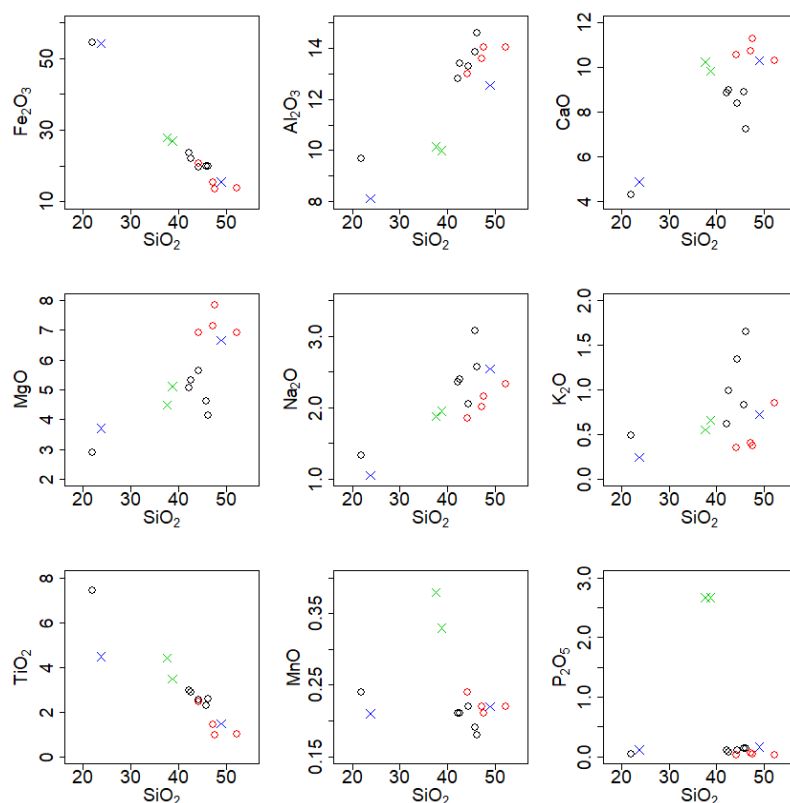
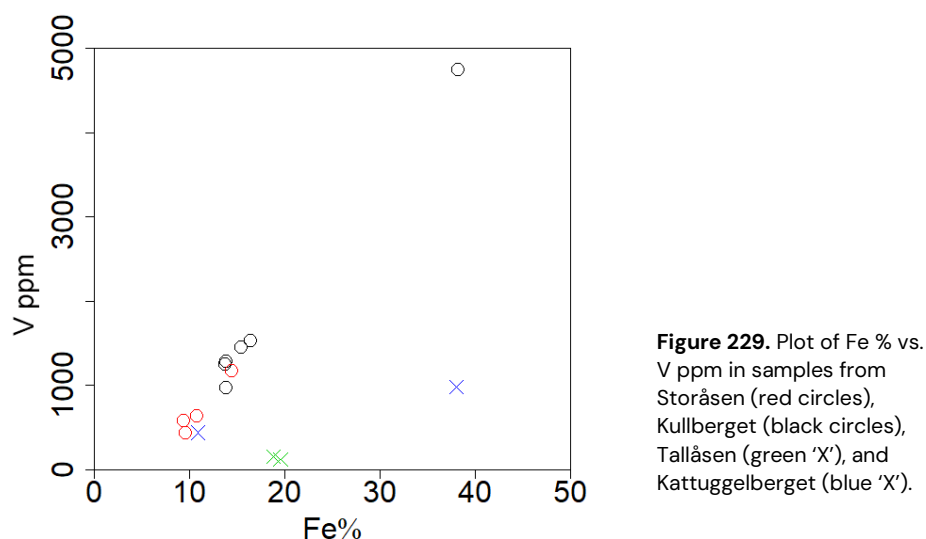


Figure 230. Harker diagrams for major element oxides in samples from Storåsen (red circles), Kullberget (black circles), Tallåsen (green 'X'), and Kattuggelberget (blue 'X'). All concentrations are in %.

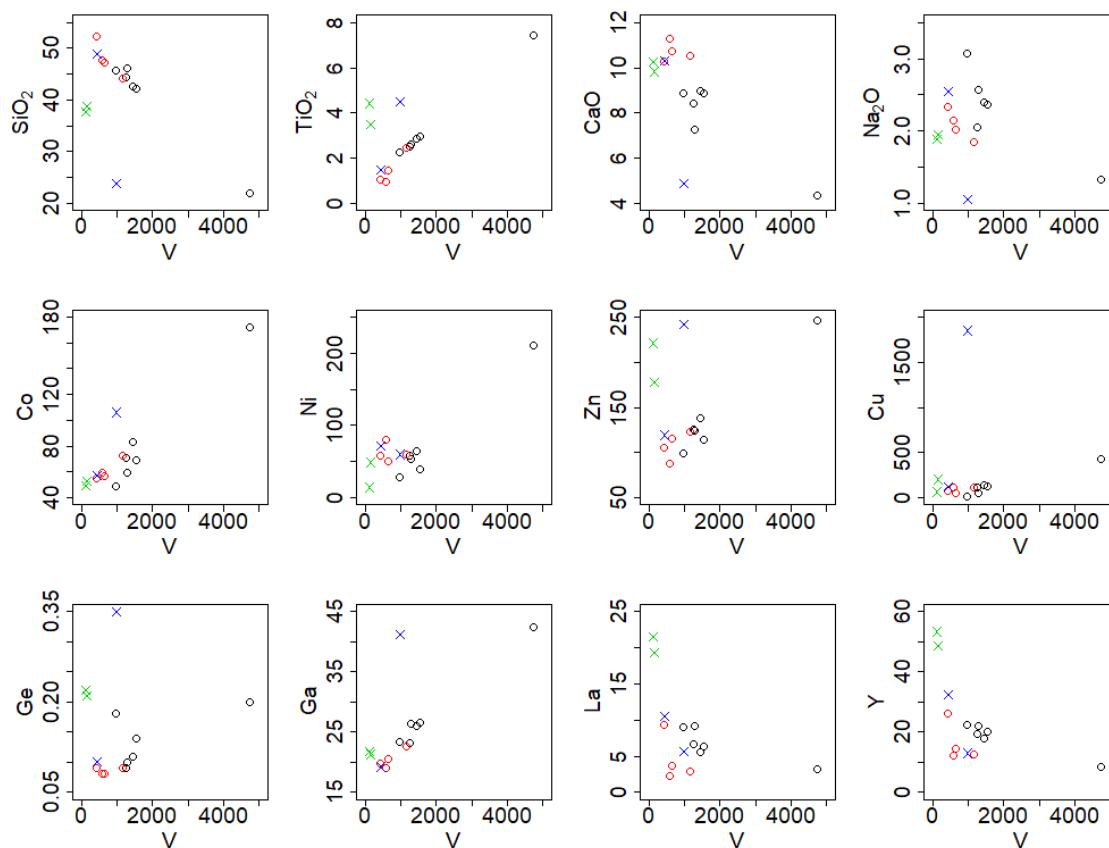


Figure 231. Harker diagrams for vanadium (ppm) vs. selected major and trace elements in samples from Storåsen (red circles), Kullberget (black circles), Tallåsen (green 'X'), and Kattuggelberget (blue 'X'). Major element oxide concentrations are in %. Trace elements are reported as ppm.

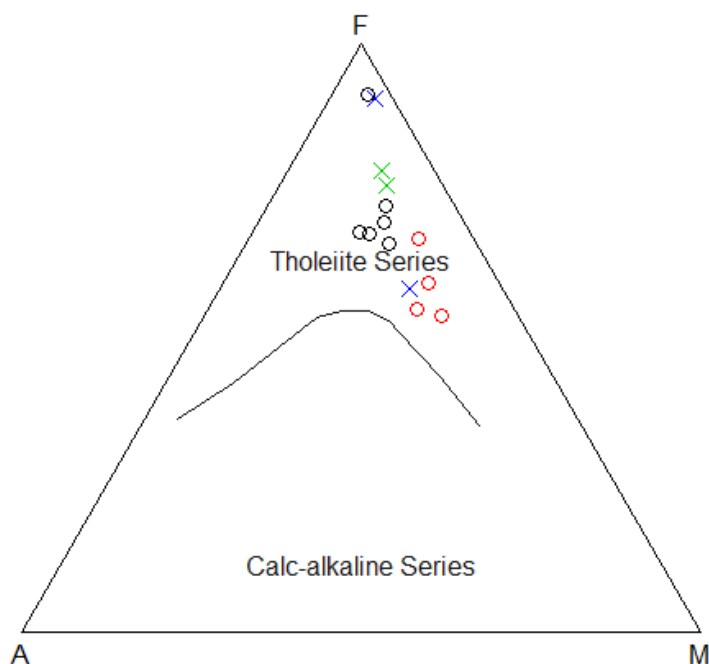


Figure 232. The samples from Storåsen (red circles), Kullberget (black circles), Tallåsen (green 'X'), and Kattuggelberget (blue 'X') plotted in an AFM-diagram (Irvine & Baragar 1971).

In the AFM diagram all samples show strong Fe-enrichment with similarities to the Kramsta, Gruvberget–Sumåssjön, Bläckmyran, and Masugnsberget intrusions (fig. 232).

Primitive mantle normalised trace-element compositions are shown in figure 233. A characteristic feature is the pronounced negative Nb anomaly, and positive Pb and Ti anomalies very similar to the previously described intrusions, although the two samples from Tallåsen show somewhat different patterns compared to the other sampled gabbroids.

Storåsen, Kullberget, and Kattuggelberget have relatively flat, broadly similar REE patterns (fig. 234), although Eu anomalies differ between samples. Subparallel patterns within the individual sample groups most probably reflect fractionation. Details are as follows (Σ REE does not include yttrium and scandium):

- Storåsen: Σ REE = 23–124 ppm. $(\text{La}/\text{Yb})_{\text{N}} = 1.11\text{--}1.77$, $(\text{La}/\text{Sm})_{\text{N}} = 1.19\text{--}1.97$, $(\text{Gd}/\text{Yb})_{\text{N}} = 0.88\text{--}1.14$, and $(\text{Dy}/\text{Yb})_{\text{N}} = 0.84\text{--}1.13$.
- Kullberget: Σ REE = 21–62 ppm. $(\text{La}/\text{Yb})_{\text{N}} = 1.86\text{--}2.61$, $(\text{La}/\text{Sm})_{\text{N}} = 1.50\text{--}2.80$, $(\text{Gd}/\text{Yb})_{\text{N}} = 0.88\text{--}1.32$, and $(\text{Dy}/\text{Yb})_{\text{N}} = 0.87\text{--}1.15$.
- Kattuggelberget: Σ REE = 37–78 ppm. $(\text{La}/\text{Yb})_{\text{N}} = 1.85\text{--}2.26$, $(\text{La}/\text{Sm})_{\text{N}} = 1.86\text{--}2.06$, $(\text{Gd}/\text{Yb})_{\text{N}}$ and $(\text{Dy}/\text{Yb})_{\text{N}}$ ratios are 1.12–1.11 and 0.96–1.01, respectively.

However, the two samples from Tallåsen stand out with much higher total REE contents (Σ REE = 156–172 ppm) and higher LREE/HREE ratios ($(\text{La}/\text{Yb})_{\text{N}} = 3.78\text{--}3.83$) than the rest of the sample suite. These two samples also show significant fractionation among the HREEs by having high $(\text{Gd}/\text{Yb})_{\text{N}}$ and $(\text{Dy}/\text{Yb})_{\text{N}}$ ratios (2.71–2.72 and 1.80–1.83, respectively). Note that in spite of being enriched in REE these samples are not particularly evolved as reflected by relatively low SiO_2 contents (37.60–38.70%), suggesting that the REE signature may be inherited from the source.

In the Th-Hf-Nb diagram (fig. 235) all samples plot in the field of Island arc calc-alkaline basalt (CAB).

The distinct volcanic arc signature is reflected by the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 236A–B). Overall, the geochemical signature resembles that of the Kramsta, Gruvberget–Sumåssjön, Masugnsberget, and Bläckmyran gabbroids and the gabbroids probably formed in the same tectonomagmatic environment.

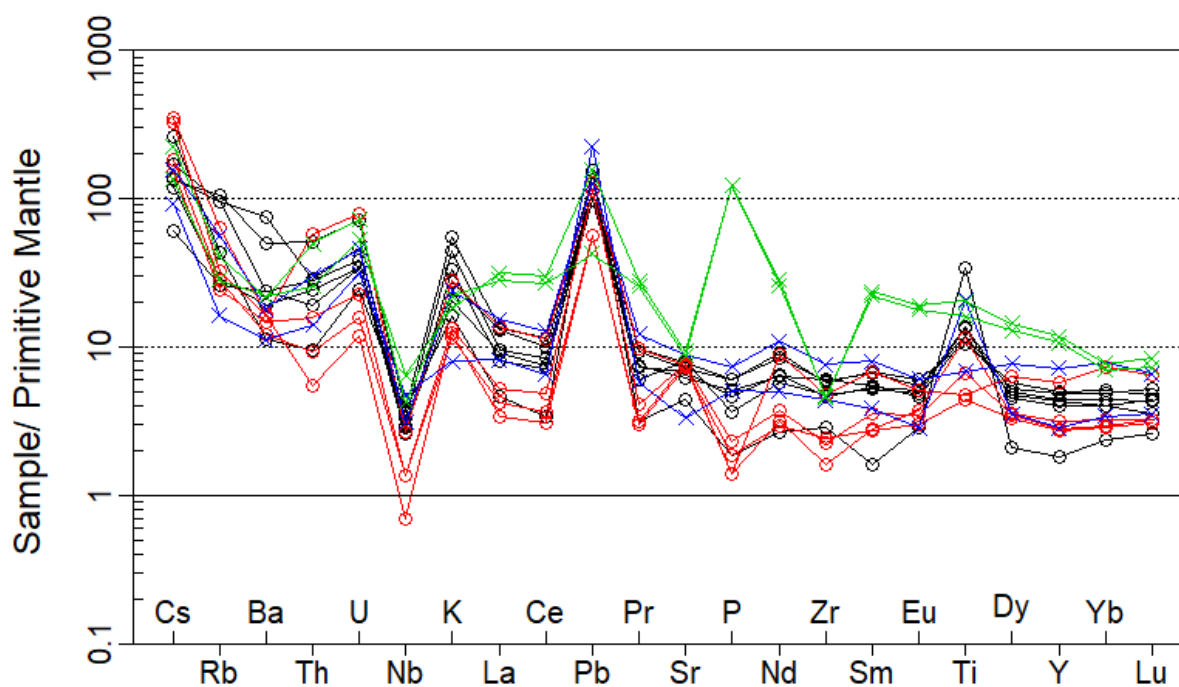


Figure 233. Primitive mantle normalised diagram for samples from Storåsen (red circles), Kullberget (black circles), Tallåsen (green 'X'), and Kattuggelberget (blue 'X'). Normalising values from Sun & McDonough (1989).

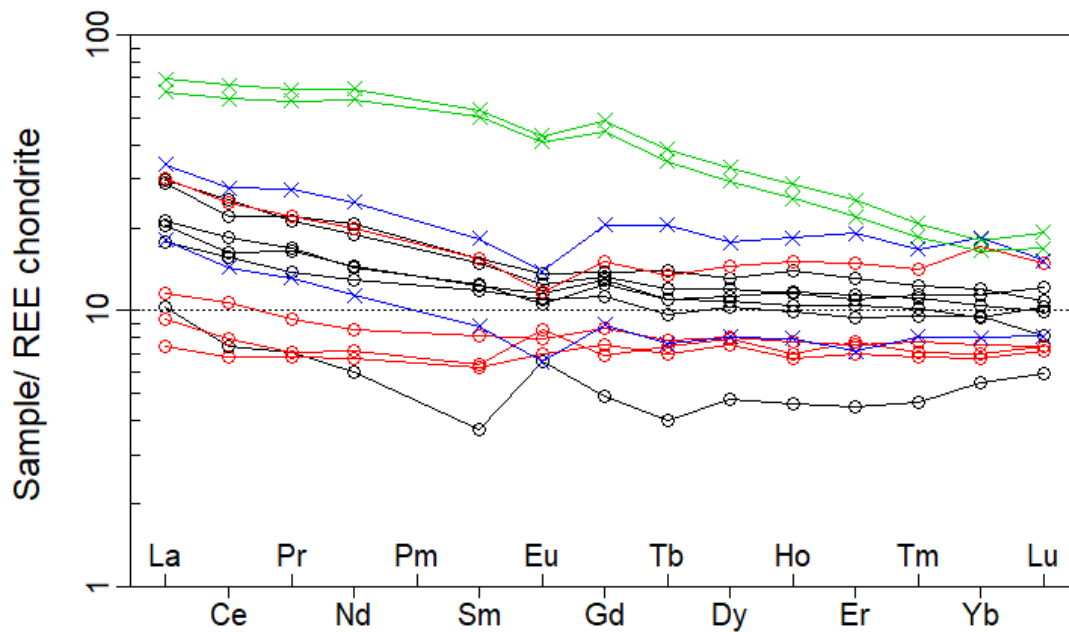


Figure 234. Chondrite normalised REE diagram for samples from Storåsen (red circles), Kullberget (black circles, Tallåsen (green 'X'), and Kattuggelberget (blue 'X'). Chondrite values are from Boynton (1984).

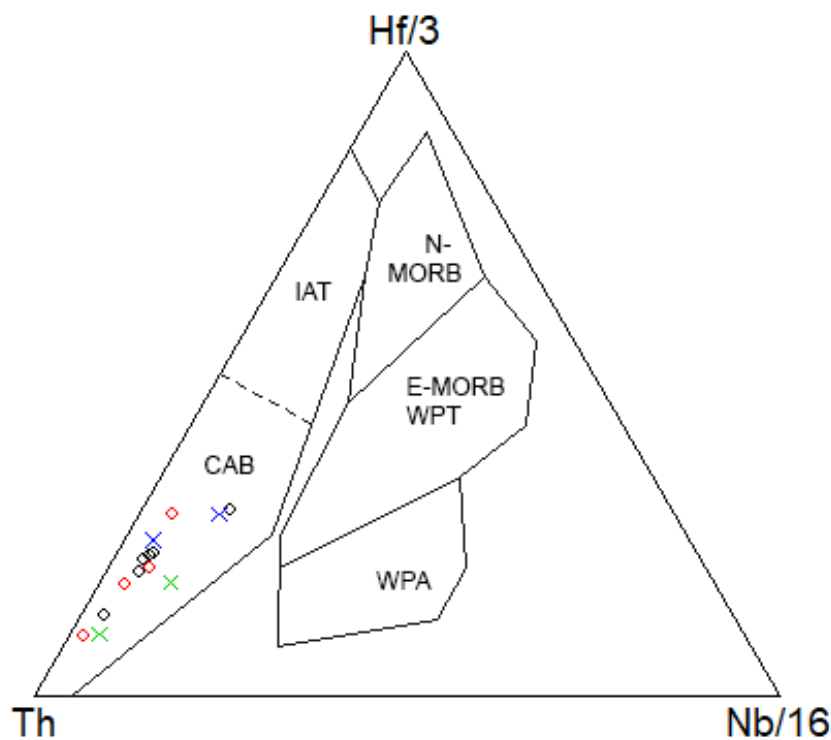


Figure 235. Storåsen (red circles), Kullberget (black circles), Tallåsen (green 'X'), and Kattuggelberget (blue 'X') plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

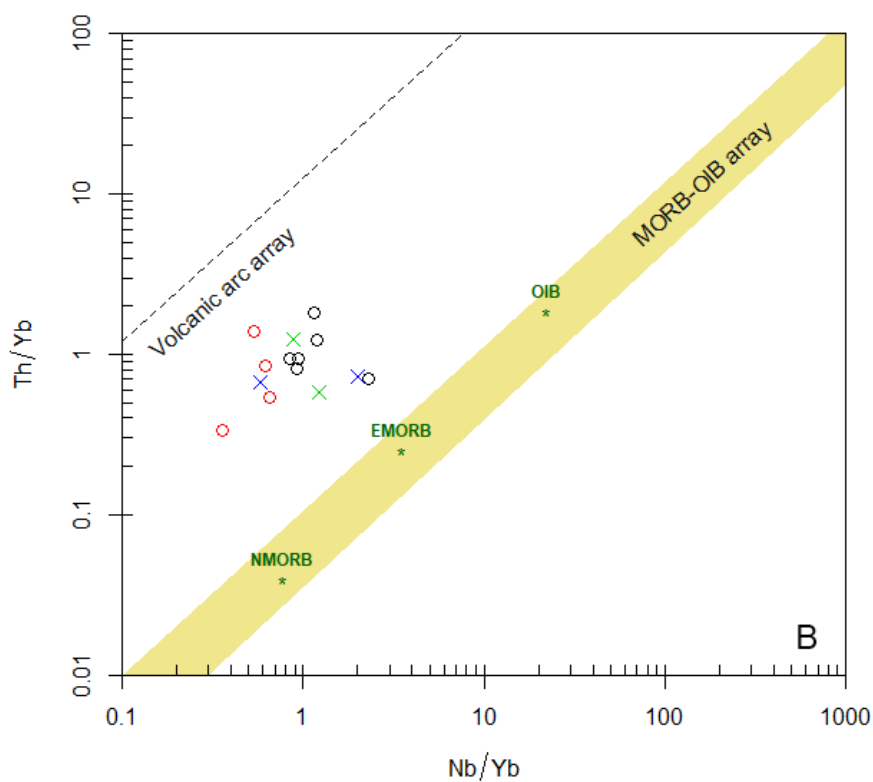
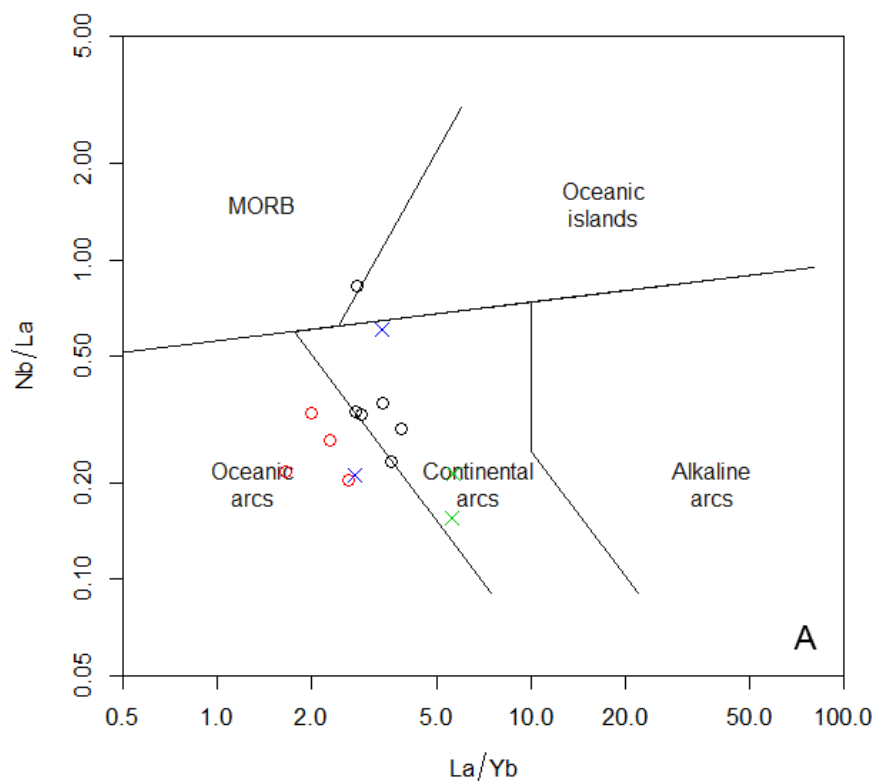


Figure 236. Storåsen (red circles), Kullberget (black circles), Tallåsen (green 'X'), and Kattuggelberget (blue 'X') plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

The Simesvallen area

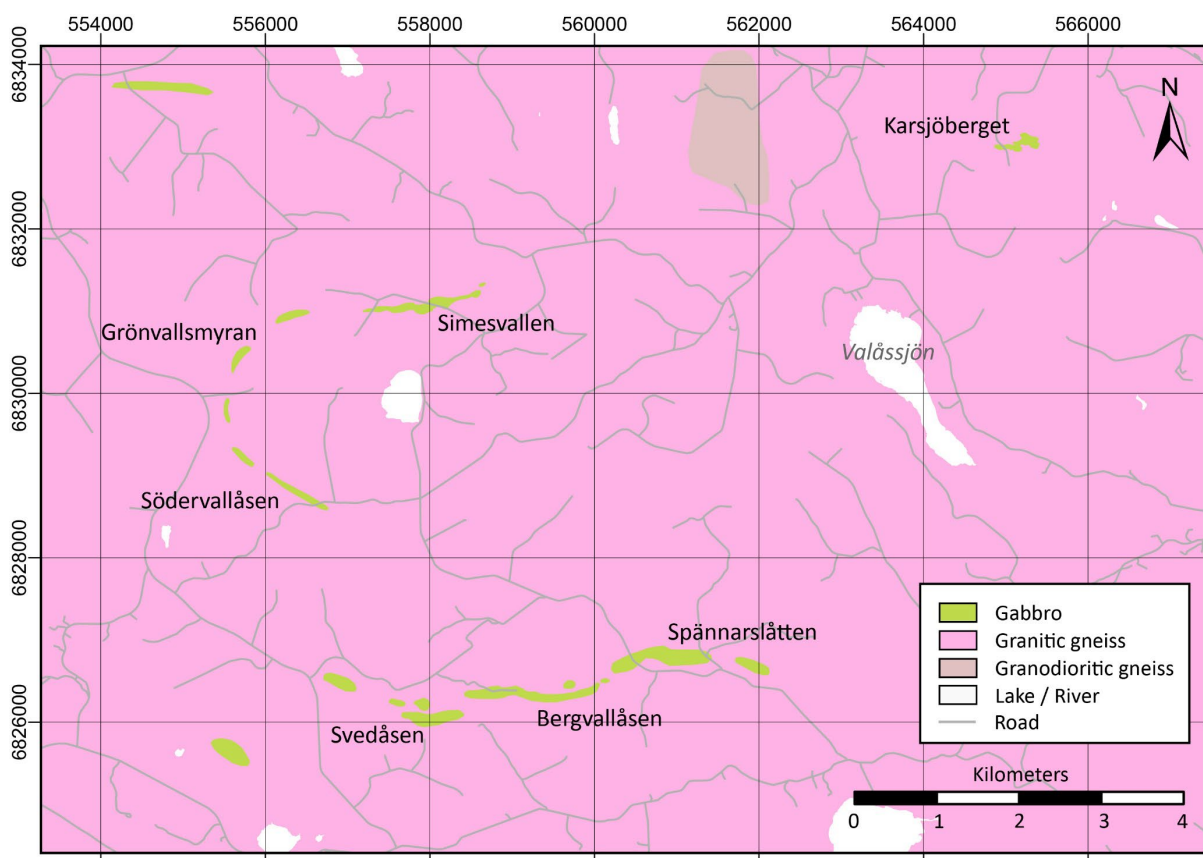


Figure 237. Bedrock geology map showing the area around the Simesvallen intrusion. The names of the mafic intrusions referred to in the report are shown as black text. Names of some lakes are shown as grey italic text.

Simesvallen is located approximately 12 km south of Järvsö (fig. 237). According to Wik *et al.* (2009), test-mining for iron was done in the area without success during the 19th century. The deposit was further investigated by SGU and SGAB using aeromagnetic measurements and boulder hunting in 1979–1980. Follow-up geophysical ground measurements (Persson & Holdar 1982) and drilling of 10 drillholes with a total length of 990 metres constrained a tonnage of 2.5 million tonnes with a grade of 0.19% V (Persson & Lindblom 1983). Despite extensive new road construction in connection with a wind power park the degree of outcrop in the area is low.

As part of SGU's airborne measurements in 1979 the magnetic anomalies at the Simesvallen, Svedåsen, Bergvallåsen, and Spännarslåtten sites were identified and highlighted for further investigation (Holdar 1980). At Simesvallen a total of 30 ground magnetic profiles were collected by SGU in 1982, with a spacing of 50-100 m covering an area of approximately 2 km² (Persson & Holdar 1982). A total of 35 profiles were collected over the Svedåsen, Bergvallåsen, and Spännarslåtten sites in 1983 (Persson 1983). As part of this project the available ground magnetic profiles were digitised and located geographically. However, it is important to note that, due to the quality of the analogue data available, the uncertainty in the position is relatively large with errors up to 100 m in some places.

As part of this study ground magnetic data were collected over a small magnetic anomaly, identified from airborne magnetic measurements, located to the northeast of the Simesvallen intrusion. This is referred to as Karsjöberget (fig. 237) and is interpreted in this study to be a small mafic intrusion. The measurements over this intrusion covered an area of about 0.2 km² with a nominal line spacing of 40 m.

Simesvallen

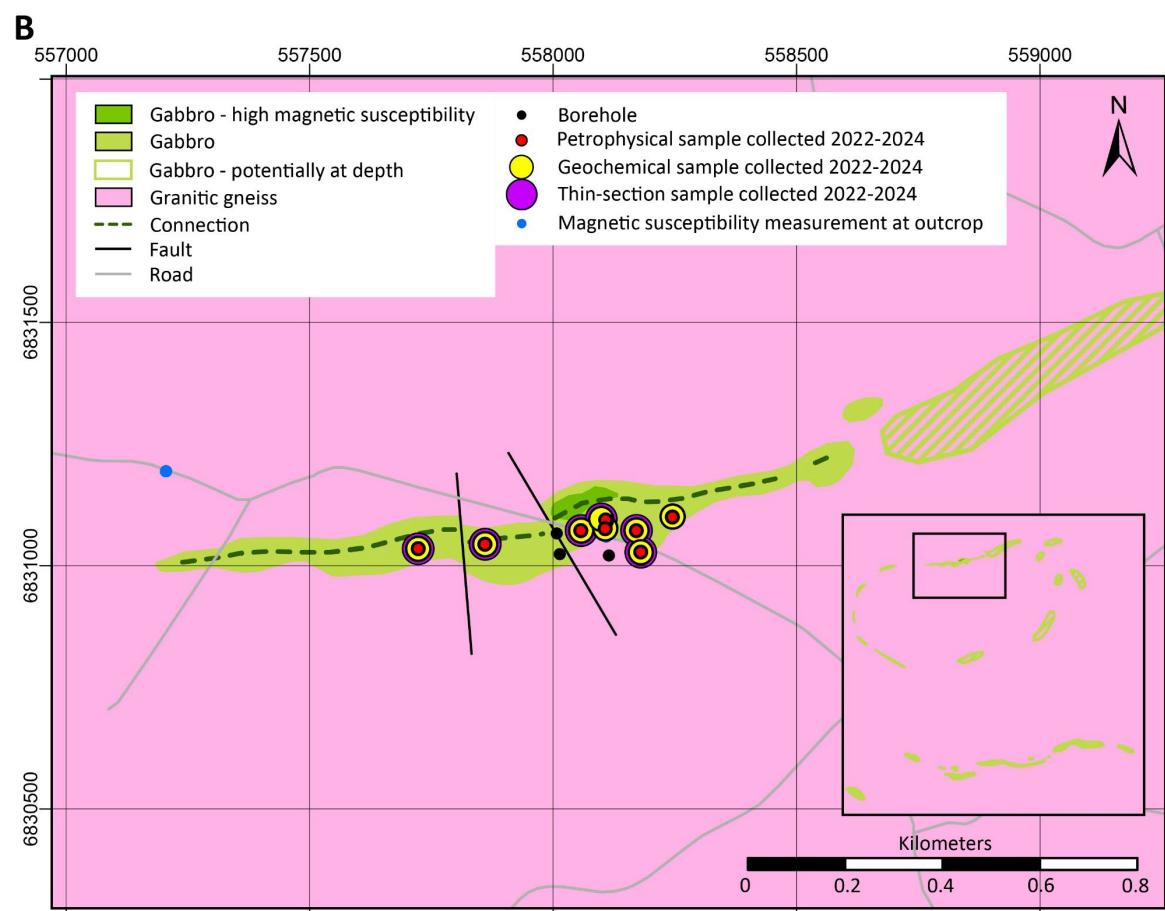
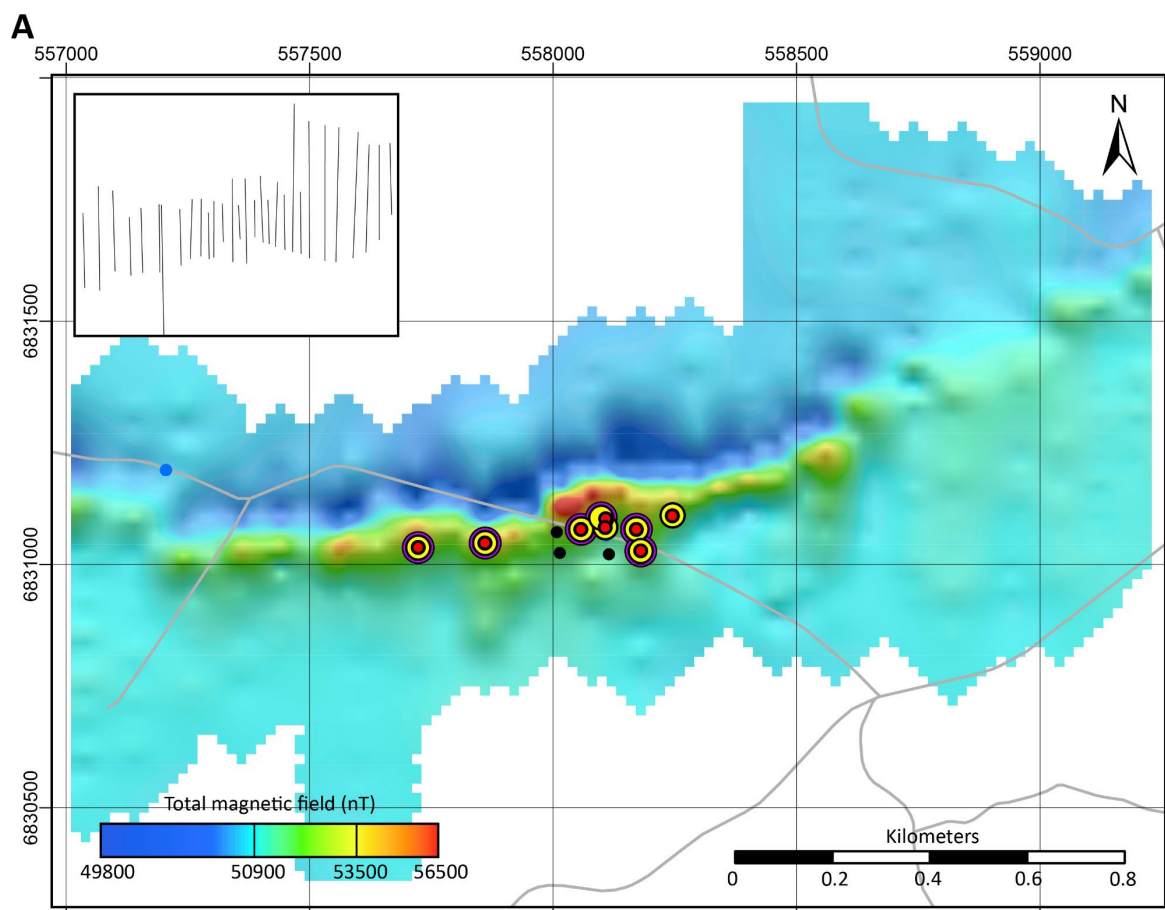
Ground-based geophysical data

Figure 238 shows the ground magnetic data from the Simesvallen intrusion together with an updated interpretation of the bedrock geology around the intrusion. The data shows a single approximately linear positive magnetic anomaly which is about 1 400 m long, 150 m wide and has a strike of about 80°. Within the central part of the anomaly the magnetic field is strongest, reaching values of up to about 7 500 nT above the background values. As the magnetic anomaly is rather focused, with a single positive anomaly, the intrusion appears to have a planar or sheet like geometry. 2D geophysical modelling of the intrusion performed in 1982 concluded that the intrusion dips to the south with a dip of about 50° (Persson & Holdar 1982). This is consistent with the results from 10 boreholes, which were drilled between 1982 and 1983 to further investigate the deposit (Persson & Lindblom 1983). These boreholes confirmed that the deposit has a sheet-like geometry and dips to the south by about 40° (Persson & Lindblom 1983). The positive anomaly is laterally displaced at several points along its length, which are interpreted here to be due to faulting.

Figure 239 shows the average magnetic susceptibilities within the upper 75 m of the model obtained by inversion of the ground magnetic data. Here the high susceptibility values clearly lie in a relatively focused zone, parallel to the strike of the intrusion, where the highest values lie somewhat centrally within the intrusion. In the 3D susceptibility model, the high susceptibility feature associated with the intrusion clearly dips to the south (see fig. 239). A clear positive anomaly can also be observed in the gravity data for the Simesvallen intrusion (fig. 17).

Magnetic susceptibility logs of core from the SIM82001, SIM82003 and SIM83001 boreholes within the Simesvallen intrusion can be found in appendix B. A map showing the location of these boreholes is shown in appendix B. In the logs for SIM82001 and SIM82003 the gabbro interval is clearly distinguishable from the underlying and overlying granitic rocks in the magnetic susceptibility log. In the SIM83001 borehole the highest magnetic susceptibility values appear to be present at the surface. It is clear on comparison of the geochemical data and the calculated geochemical curves from the magnetic susceptibility that the correlation for these boreholes is not as strong as for the other boreholes in this study. This could be due to the fact that only a quarter of the core was left in the archive for the majority of the gabbro sections in these boreholes, which could have affected the accuracy of the susceptibility logging.

► **Figure 238. A.** Map of the total magnetic field from ground measurements collected in 1982 over the Simesvallen intrusion, which were digitised as part of this study. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Simesvallen intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of boreholes, samples and magnetic susceptibility measurements at outcrop are shown as coloured dots in both A and B.



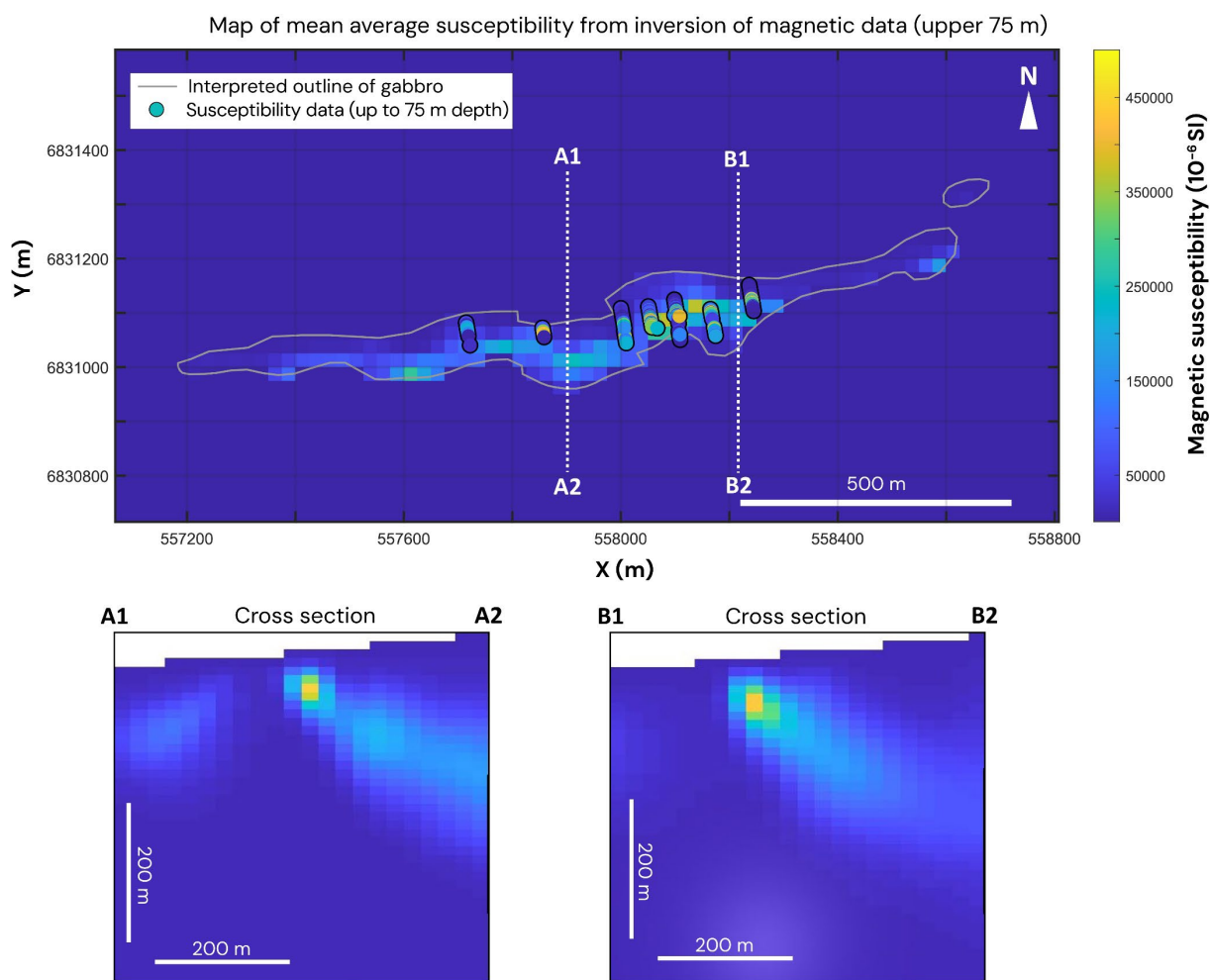


Figure 239. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Simesvallen intrusion. All magnetic susceptibility measurements collected up to a depth of 75 m (measurements on drill core and at the surface) are shown as dots. In cases where only geochemical data is available in boreholes, magnetic susceptibilities have been calculated using the relationship described in the petrophysics section of the report. These calculated susceptibilities are shown together with the magnetic susceptibility measurements as dots. Cross sections (A1–A2 and B1–B2) through the magnetic susceptibility model obtained from the inversion are shown below to the map. The locations of the cross sections are denoted on the map as dotted white lines. The dots, map and sections are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

A sample was collected from mineralised, fine-medium to medium-grained gabbroic waste-rock at the rim of at a partially waterfilled and overgrown, abandoned pit close to the road at Simesvallsberget (fig. 240). A massive, gabbroic rock outcrops adjacent to the road, 30 to 40 m from the abandoned pit (fig. 241). Five drill cores (with a total of eight 1 m sections) from Simesvallen were sampled and analysed in the current project (fig 242).



Figure 240. Partially waterfilled old mining pit at Simesvallen measuring approximately 8 × 10 m (6831096/558099). Photo: Helge Reginiussen.



Figure 241. A. Gabbroid outcropping close to the road at Simesvallen (6831063/558112). **B.** Close-up of the outcrop in A. Photo: Helge Reginiussen.



Figure 242. Drill core from Simesvallen (SIM82006, tray 2) showing slight modal layering in gabbroid. Analysis of a one metre section starting at 27.9 m (red arrow) contains 30.00% Fe_2O_3 , 5.15% TiO_2 , and 1 895 ppm V. The shown section is c. 40 cm. Photo: Helge Reginiussen.

Description of thin sections – ore minerals

The ore minerals magnetite, ilmenite, pyrrhotite, and pyrite were identified in mineralised sample DCL222005B from drill core SIM82006 at 27.76–27.80 m (fig. 243, see fig. C5 for panorama). Sulphides are more abundant than typically seen in other intrusions in this project. The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage (figs. 243A–C). There is plenty of exsolved ilmenite as laths and trellis in the magnetite (fig. 243A). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are likely to be magnetite or ulvöspinel (figs. 243B–C, cf. Haggerty 1991, Tan *et al.* 2016a). A large ilmenite crystal with thin exsolution lamellae and small grains of hematite and other unknown darker minerals which appear as small round grains and as tips and parts of lamellae can be observed (figs. 243B–C). Using a differential interference contrast (DIC) objective highlights the unknown darker minerals as brighter spots and parts of lamellae, whereas hematite here is dark (fig. 243C). The tips and parts of lamellae could be magnetite or ulvöspinel. Whether some of these round grains are magnetite, ulvöspinel or other included minerals, or fluid inclusions, cannot be distinguished (cf. Pochon *et al.* 2024). There is a high probability that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b).

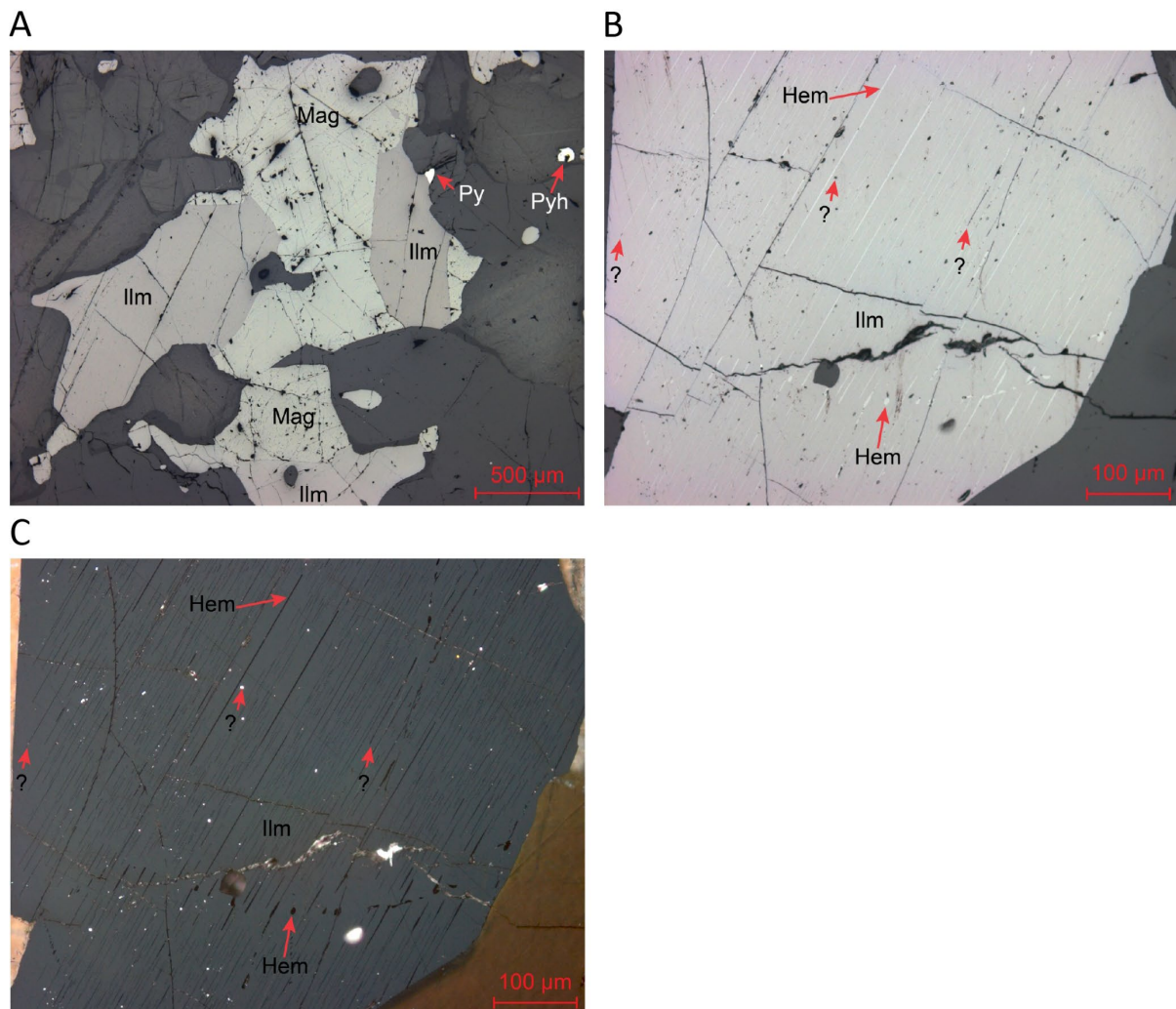


Figure 243. Ore minerals from the Simesvallen intrusion, mineralised sample DCL222005B from drill core SIM82006 at 27.76–27.80 m (see fig. C5 for panorama). **A.** Overview of relations between magnetite and ilmenite in an interstitial opaque framework. Close-up images of **B.** large ilmenite crystal with thin exsolution lamellae and small grains of hematite and unknown darker minerals as small round grains, and tips and parts of lamellae, **C.** same area as in B. using differential interference contrast (DIC) objective that highlights the darker minerals in B. as bright spots and brighter parts of lamellae, whereas hematite here is dark. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

The ore minerals magnetite, ilmenite, and rare, small sulphide crystals were identified in mineralised sample HRE220011A (fig. 244, see fig. C6 for panorama). A few larger plagioclase grains are present in the thin section, but the rock appears to be ultramafic in nature. The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage (fig. 244). There is a lot of exsolved ilmenite as laths and trellis in the magnetite, which follow crystallographic planes (figs. 244B–C). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are likely magnetite or ulvöspinel (figs. 244B–C, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolutions in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but no SEM-work has been done to identify the smallest exsolved minerals and optical microscopy was deemed inadequate for proper identification. In the closeup images there are two additional observations to make. Firstly, there appears to be a decrease in the amount of lamellae observed in the outer parts of the ilmenite grains, close to the contact with magnetite grains. Adjacent to the contact, lamellae are no longer observed when viewing with an optical microscope (figs. 244B–C). However, on inspection of the grain contacts between

two ilmenite grains, thin exsolution lamellae are observed in both grains all the way up to the contact (figs. 244B–C). These two observations are best made in the differential interference contrast image but can also be seen clearly in the plain reflected light image. It is possible that a zone with fewer trellis and laths at the edges of the magnetite grains is also seen, however, this zone is thinner than the zone with lower levels of lamellae in the ilmenite grains (figs. 244B–C). An explanation for the lack of exsolution occurrences in the contact zones could be that at the point of igneous crystallisation, the ilmenite and the magnetite are so close to each other that a miniscule amount of interstitial liquid present will lead to the uptake preferred by each mineral i.e., Fe moves preferably into magnetite and Ti into ilmenite during the competing growth and thus there will be much less material to exsolve. The lack of change of exsolved lamellae towards the contact of another ilmenite crystal is not that of competing for specific elements, because both ilmenite grains will take the same amount of material in the liquid during crystallisation and have similar amounts to exsolve moving down in temperature. This also shows the cumulate nature of the rock and that late-stage interstitial liquids were definitely Fe-Ti-rich.

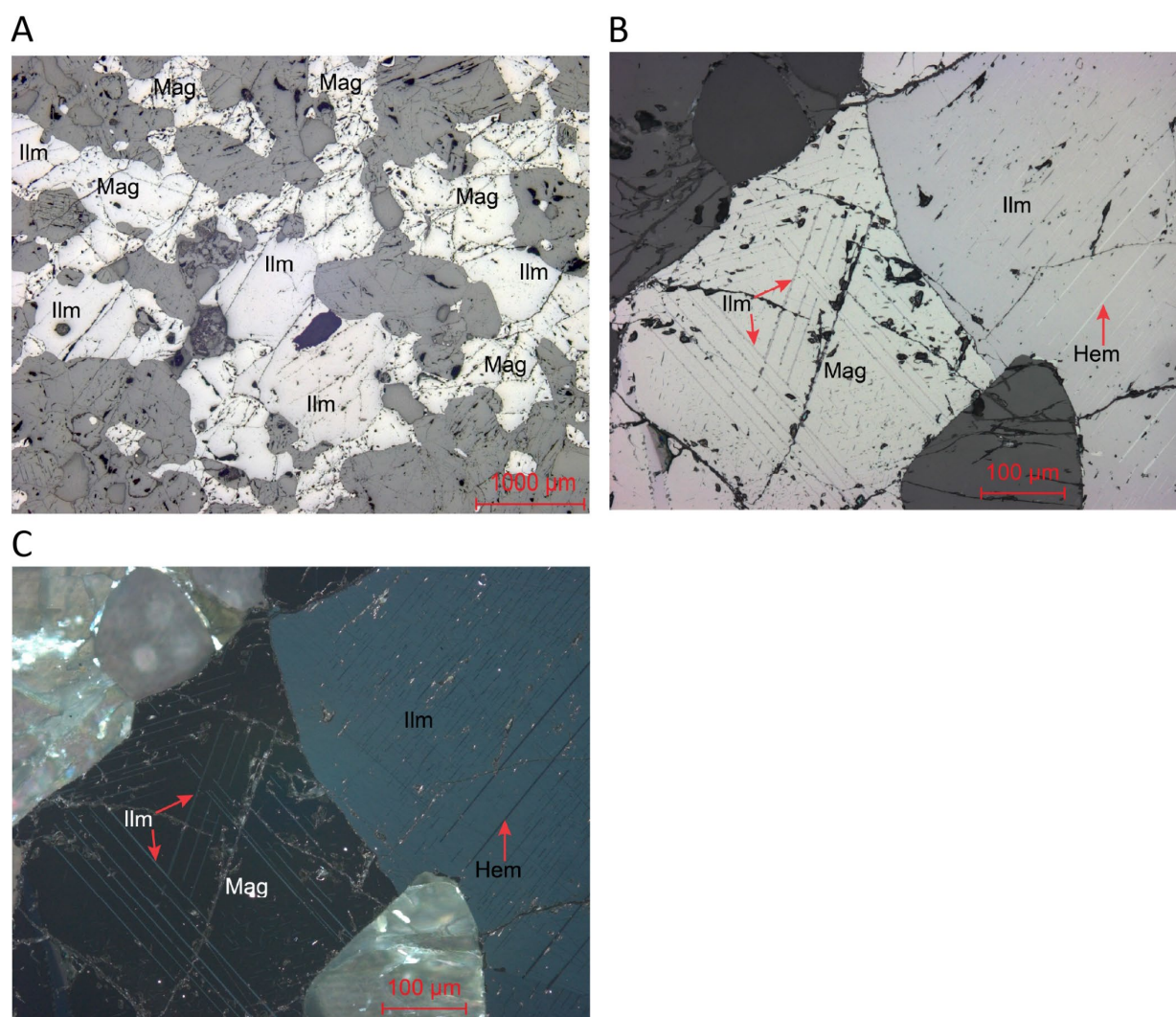


Figure 244. Ore minerals from the Simesvallen intrusion, ultramafic mineralised sample HRE220011A (see fig. C6 for panorama). **A.** Overview of relations between magnetite and ilmenite in an interstitial opaque framework. Close-up images of **B.** ilmenite crystal with thin exsolution lamellae of hematite and unknown darker minerals and magnetite with lamellae of ilmenite, **C.** same area as in B. using differential interference contrast (DIC) objective. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals

In sample DCL222005B from drill core SIM82006 at 27.76–27.80 m (panorama fig. C5), hornblende and clinopyroxene are the main mafic minerals of the gabbroic cumulate (figs. 245A–D). Subhedral to euhedral hornblende and subhedral clinopyroxene occur as grains and interstitially. Some clinopyroxene have lamellae and exsolution of opaque minerals. Plagioclase is subhedral to anhedral with opaque minerals occurring interstitially. A granoblastic texture with grain triple junctions at 120 degrees among hornblende crystals signifies that a textural equilibrium in the cumulate rock has been reached (e.g., Hunter 1987, Holness 2005, Holness *et al.* 2007b). Rare olivine occurs as small grains, interstitial and anhedral in shape.

Anhedral to subhedral olivine is present as small and large grains and as interstitially grown crystals in sample DCL222009B from drill core SIM83002 at 38.73–38.79 m (figs. 245E–F). Subhedral to euhedral hornblende mostly occurs as large grains. Subhedral to anhedral clinopyroxene appears as large grains to interstitial crystals, some lamellae and exsolution of opaque minerals are present, and a few oikocrysts with chadacrysts of plagioclase, amphibole, and opaque minerals are also observed. Plagioclase occurs as large subhedral grains with spots of sericite-saussurite alteration and as occasional crystals that were bent or kinked while at igneous conditions. Minor biotite occurs and has brownish red to tan pleochroism.

Olivine is intergrown with clinopyroxene, and minor hornblende occurs in sample DCL222010B from drill core SIM83003 at 64.21–64.25 m (figs. 246A–B). Large anhedral to subhedral olivine grains extend into interstitially grown parts. Subhedral to anhedral clinopyroxene occurs as grains and interstitially. Anhedral hornblende is interstitial. Large subhedral plagioclase grains with minor sericite-saussurite alteration are observed.

Sample DCL230009A from drill core SIM83001 at 64.01–64.07 m is well-preserved but for major alteration along fractures with secondary green amphibole and sericite-saussurite. Anhedral, large grains of olivine is intergrown with subhedral to anhedral clinopyroxene that have some lamellae and exsolution of opaque minerals. Hornblende and biotite dominate in areas with intergrown olivine and clinopyroxene (figs. 246C–D). Rare large plagioclase crystals have bends or kinks, deformation twins, and undulose extinction formed while hot in a cumulate rock and considered the result of compaction of the crystal pile or mush (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). Two generations of biotite are observed, the first has brownish red pleochroism and the second dark tan to light tan.

Large hornblende grains with interstitial extensions and intergrown olivine and clinopyroxene are present in sample DCL230010A from drill core SIM83001 at 57.46–57.51 m (figs. 246E–F). Anhedral hornblende occurs as large to small grains. Anhedral olivine grains and subhedral to anhedral clinopyroxene grains with a few lamellae and exsolution of opaque minerals are observed. Two generations of biotite occur, the first has brownish red pleochroism and the second dark tan to red to light tan. Subhedral to anhedral plagioclase grains are observed with minor sericite-saussurite alteration.

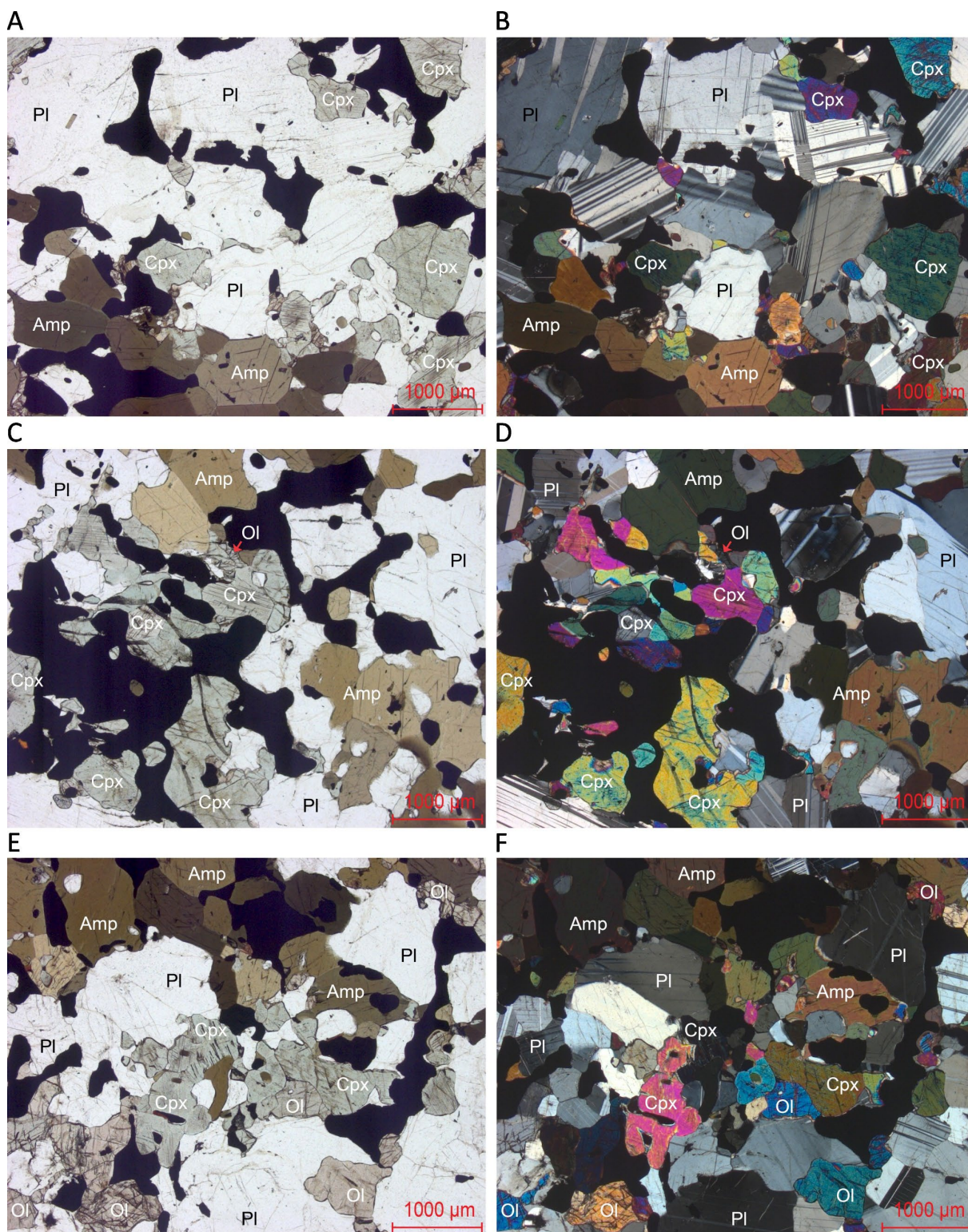


Figure 245. A. and B. Subhedral clinopyroxene and subhedral to euhedral hornblende as main mafic minerals in gabbroic cumulate. Plagioclase is subhedral to anhedral with opaque minerals occurring interstitially. Note granoblastic texture with grain triple junction at 120 degrees among hornblende crystals. C. and D. Anhedral to subhedral plagioclase, clinopyroxene, and hornblende. Note granoblastic texture with grain triple junction at 120 degrees among hornblende and clinopyroxene crystals. Sample DCL222005B from drill core SIM82006 at 27.76–27.80 m. E. and F. Anhedral to subhedral olivine, clinopyroxene, hornblende, and plagioclase. Sample DCL222009B from drill core SIM83002 at 38.73–38.79 m. Left in ppl and right in xpl. Photo: Dick Claeson.

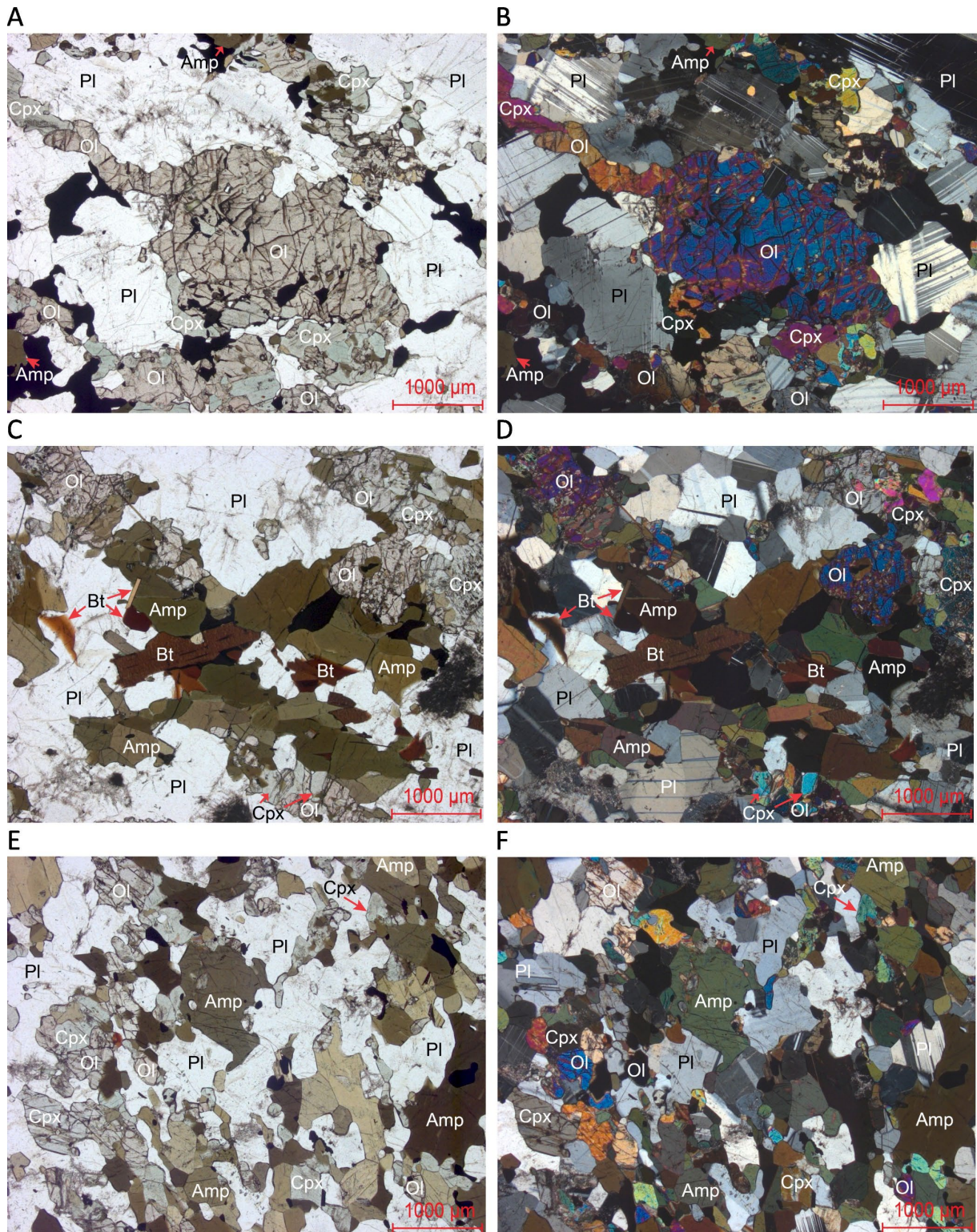


Figure 246. A. and B. A large olivine grain extending to interstitial grown part. Olivine is intergrown with clinopyroxene and minor hornblende. Sample DCL222010B from drill core SIM83003 at 64.21–64.25 m. C. and D. Hornblende and biotite dominated area with intergrown olivine and clinopyroxene. Note large plagioclase crystal at the bottom of image with bend or kink in vertical position. Sample DCL230009A from drill core SIM83001 at 64.01–64.07 m. E. and F. Large hornblende grains with interstitial extensions with intergrown olivine and clinopyroxene. Sample DCL230010A from drill core SIM83001 at 57.46–57.51 m. Left in ppl and right in xpl. Photo: Dick Claeson.

Svedåsen, Bergvallåsen, and Spännarslåtten

Ground-based geophysical data

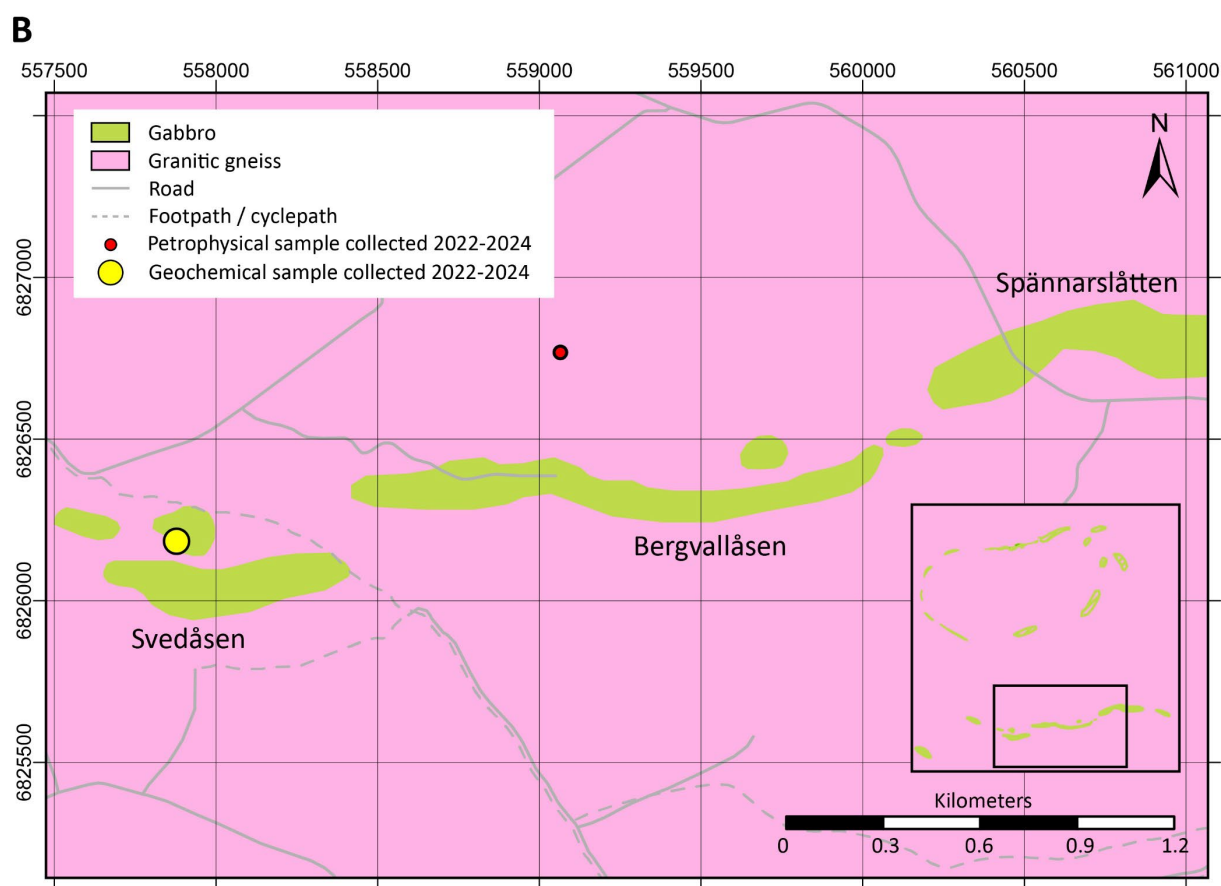
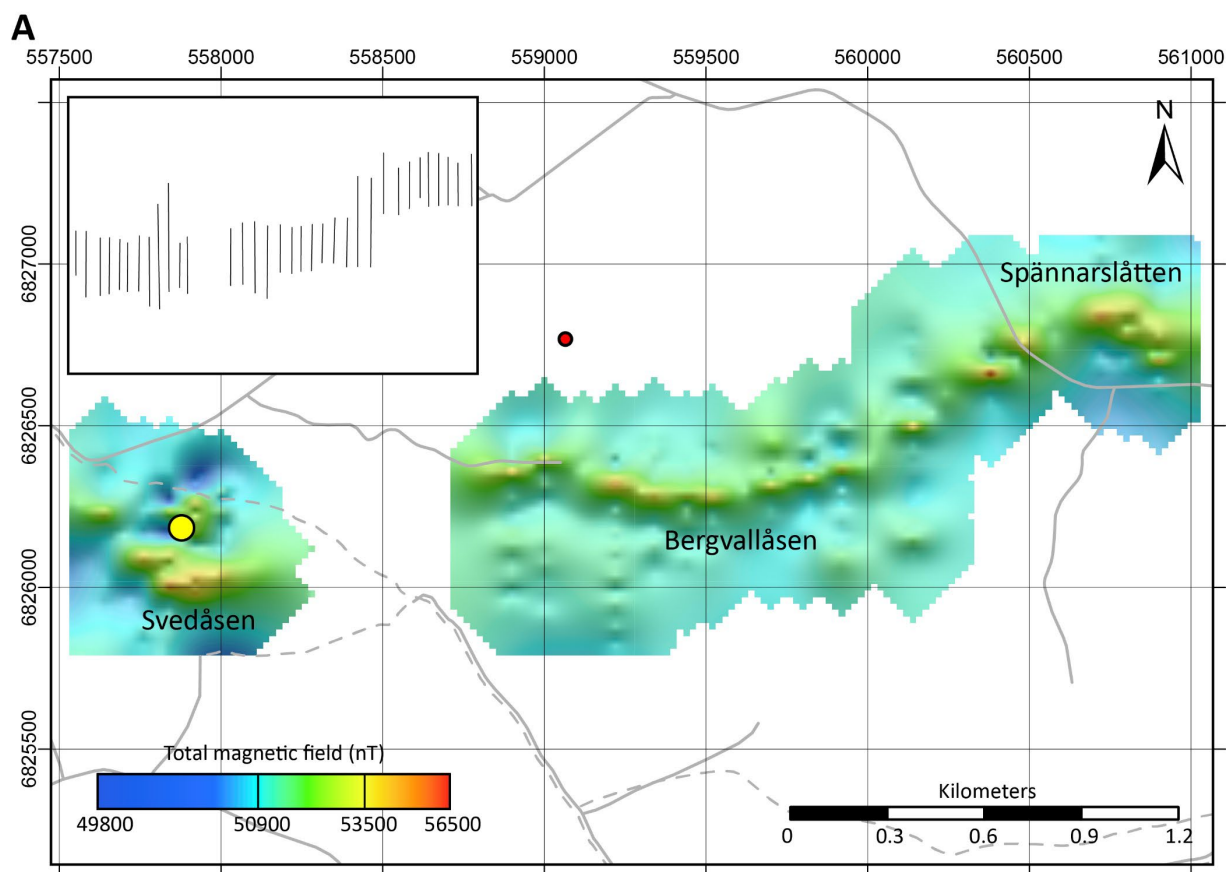
Figure 247 shows the ground magnetic data around the Svedåsen, Bergvallåsen, and Spännarslåtten intrusions together with an updated bedrock geology map. Here a relatively continuous magnetic anomaly, with a single peak can be seen to lie through the Bergvallåsen and Spännarslåtten intrusions. The character of this anomaly is similar to that of the Simesvallen intrusion to the north, and hence it can be interpreted that the mineralisation within these intrusions also has a somewhat planar or sheet like geometry (Persson 1983). The anomaly through both the Bergvallåsen and Spännarslåtten intrusions is some 2 400 m long and about 150 m wide. The highest magnetic field values occur in the eastern part of the anomaly (Spännarslåtten), where the magnetic field reaches up to about 4 400 nT above the background level. Previous modelling work suggested that the mineralised zone in this area is some 100 m wide and dips at about 60° to the north (Persson 1983). The highest magnetic field values in the Bergvallåsen area reach only up to about 3 500 nT above the background level. In the west, there are several distinct anomalies for the Svedåsen intrusion, which implies that it consists of several smaller intrusions. The highest magnetic field values in this area reach up to about 3 500 nT above the background value.

It should be noted that there is a general lack of outcrops in this area and hence, there are very few bedrock observations and samples taken from this area. This was also noted by Persson (1983) during their study. Hence, the majority of the interpretation is based on geophysical data.

Figure 248 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained from inversion of the ground magnetic data. Here the high susceptibility values appear to lie along a fairly continuous single zone through the Bergvallåsen and Spännarslåtten intrusions, whilst at the Svedåsen intrusion several individual zones with high susceptibility appear to be present. When investigating the susceptibility model from the inversion in 3D, it appears that the high magnetic susceptibility bodies associated with all three intrusions dip to the north (fig. 248).

A broad positive magnetic anomaly can be identified between Simesvallen and Spännarslåtten based on the airborne magnetic data (see fig. 17A). Persson (1983) proposes a possible interpretation that this could indicate an additional gabbro body located at shallow depth and hence could be the target for further geophysical investigation and modelling. Furthermore, a clear positive gravity anomaly appears to be associated with these intrusions, which appears to be largest in the area around Bergvallåsen (fig. 17B).

► **Figure 247.** **A.** Map of the total magnetic field from ground measurements collected in 1983 over the Svedåsen (western), Bergvallåsen (central) and Spännarslåtten (eastern) intrusions, which were digitised as part of this study. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Simesvallen intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of samples are shown as coloured dots in both A and B.



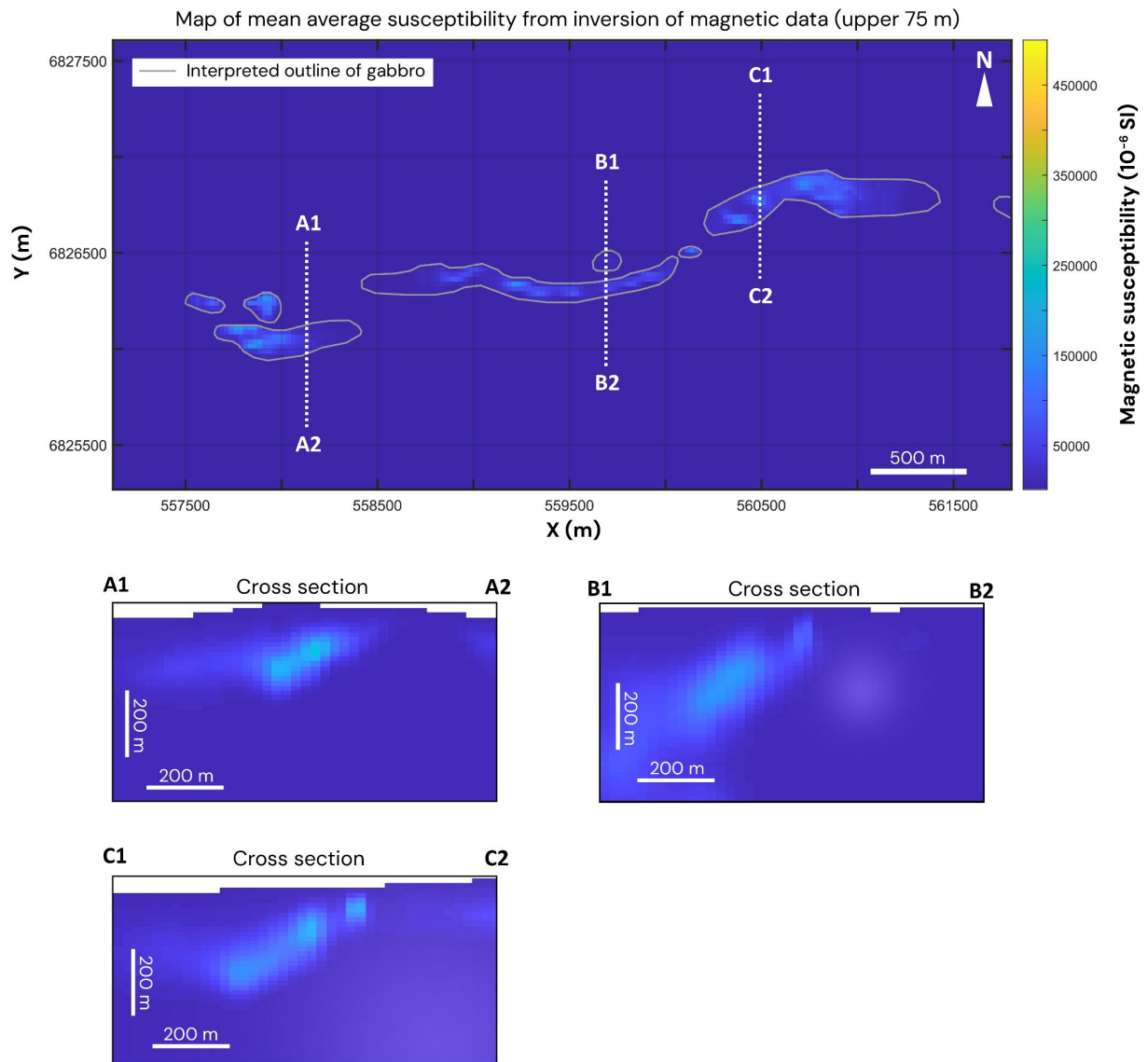


Figure 248. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Svedåsen (western), Bergvallåsen (central) and Spännarslåtten (eastern) intrusions. Cross sections (A1–A2, B1–B2 and C1–C2) through the magnetic susceptibility model obtained from the inversion are shown below to the map. The locations of the cross sections are denoted on the map as dotted white lines. The map and sections are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

At Svedåsen, immediately to the south of Simesvallen, a massive gabbroic rock with weak magmatic layering occurs (fig. 249). Two samples were collected at Svedåsen (fig. 250).



Figure 249. Massive gabbroid from Svedåsen (6826428/556991). Photo: Helge Reginiussen.



Figure 250. Sampled gabbroid from Svedåsen (6826184/557878). Photo: Helge Reginiussen.

Karsjöberget

Ground-based geophysical data

A positive anomaly was observed in both the gravity and airborne magnetic data at this location (see fig. 17), hence this anomaly was investigated in this project as a suspected mafic intrusion. Figure 251 shows the ground magnetic measurements over the Karsjöberget anomaly as well as an updated map of the bedrock geology around the anomaly. The magnetic anomaly at Karsjöberget is about 500 m long, about 100 m wide and general has an east–west strike. The anomaly is relatively weak, where the highest magnetic field values reach up to about 2500 nT above the background level. The highest magnetic field values appear to be concentrated in the west, within a single continuous positive anomaly. In the updated bedrock geology map this anomaly is interpreted to be due to an intrusion. However, no outcrops within the anomaly were identified during field investigations, so it was not possible to confirm that the anomaly at Karsjöberget is linked to a mafic intrusion. Figure 252 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained by inverting the ground magnetic data. Here the highest magnetic susceptibility values appear to occur in the western part of the intrusion. The 3D magnetic susceptibility model from the inversion indicates that the region with higher susceptibilities in the west dips to the north (fig. 252).

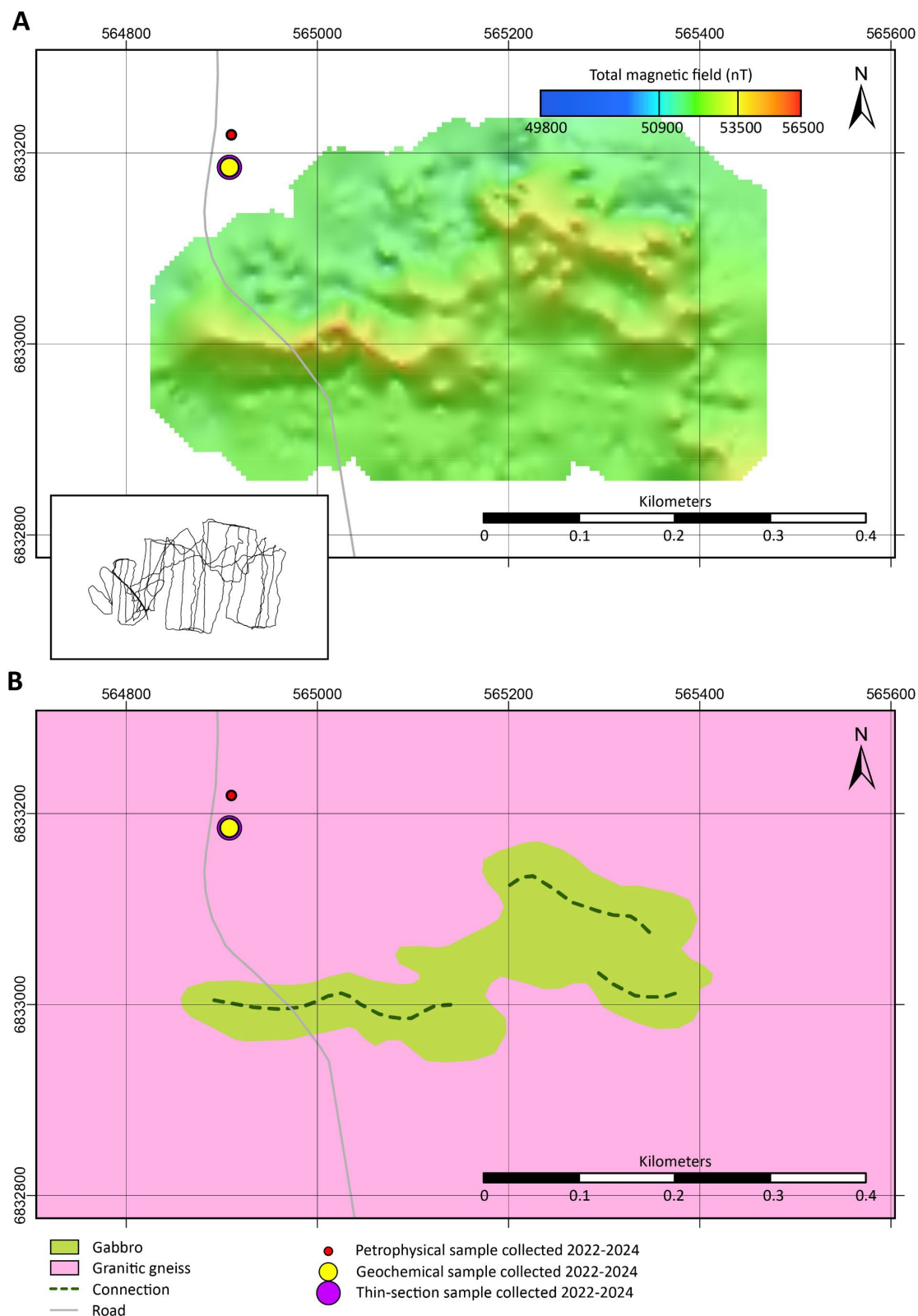


Figure 251. A. Map of the total magnetic field from ground measurements collected as part of this study over the anomaly at Karsjöberget. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Karsjöberget anomaly, which is interpreted here as a mafic intrusion. The locations of samples are shown as coloured dots in both A and B.

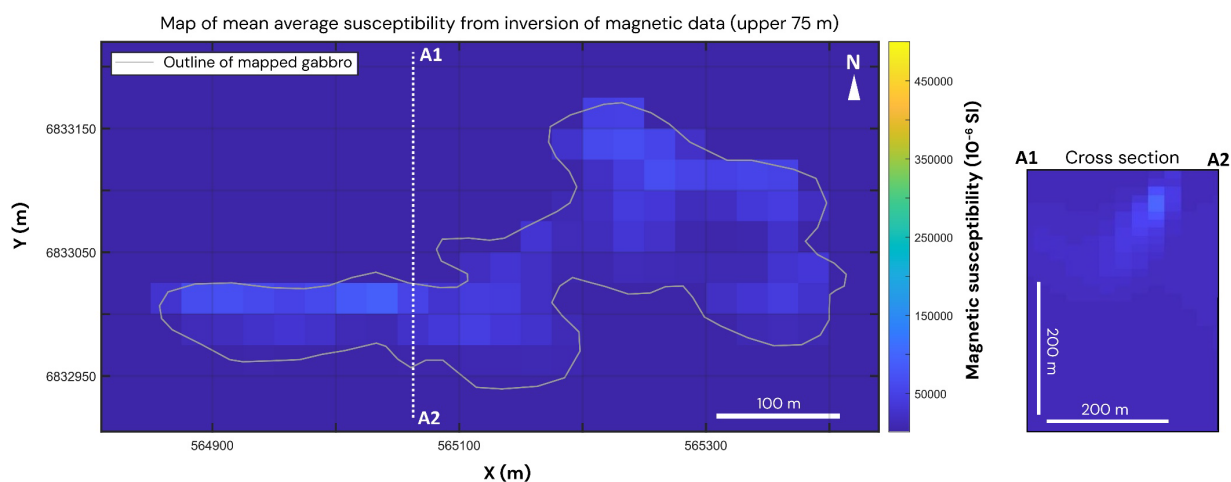


Figure 252. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Karsjöberget intrusion. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The map and section are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geochemical data for Simesvallen and Svedåsen

The drill cores from Simesvallen were analysed for the elements Fe and V at Swedish Mineralprocesses AB (Minpro AB) in 1983. Analogue data ($n = 103$) from 10 of these cores has been digitised in the current project. The linear relationship between Fe and V is good in both historic and new analyses (fig. 253).

Variations in vanadium contents with depth in the drill cores are shown in figure 254. In general, the analyses from 1983 are in good agreement with the new analyses.

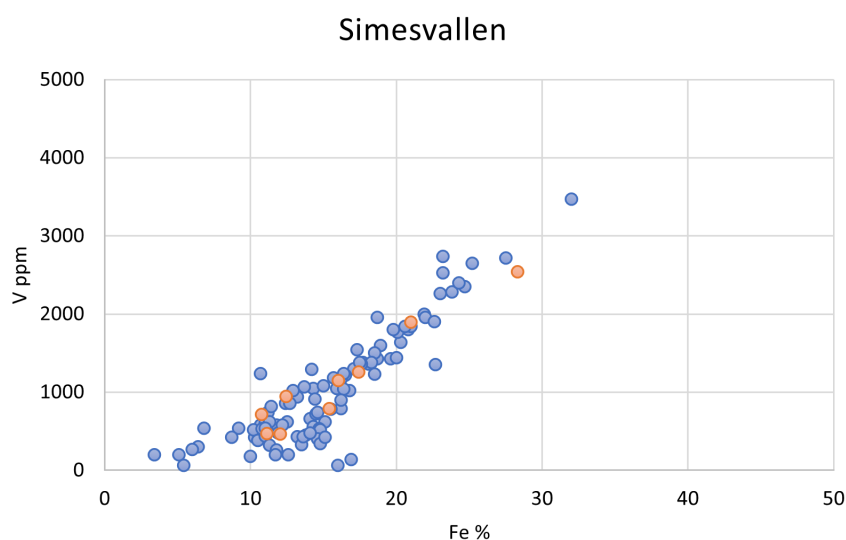


Figure 253. Fe and V contents in gabbroids at Simesvallen. Blue dots are drill core analyses from 1983 ($n = 103$) and the orange are analyses obtained in the current project from drill cores ($n = 8$) and a single field sample ($n = 1$). The Pearson coefficient (r) for the whole dataset is 0.89. The average V:Fe ratio is 0.006.

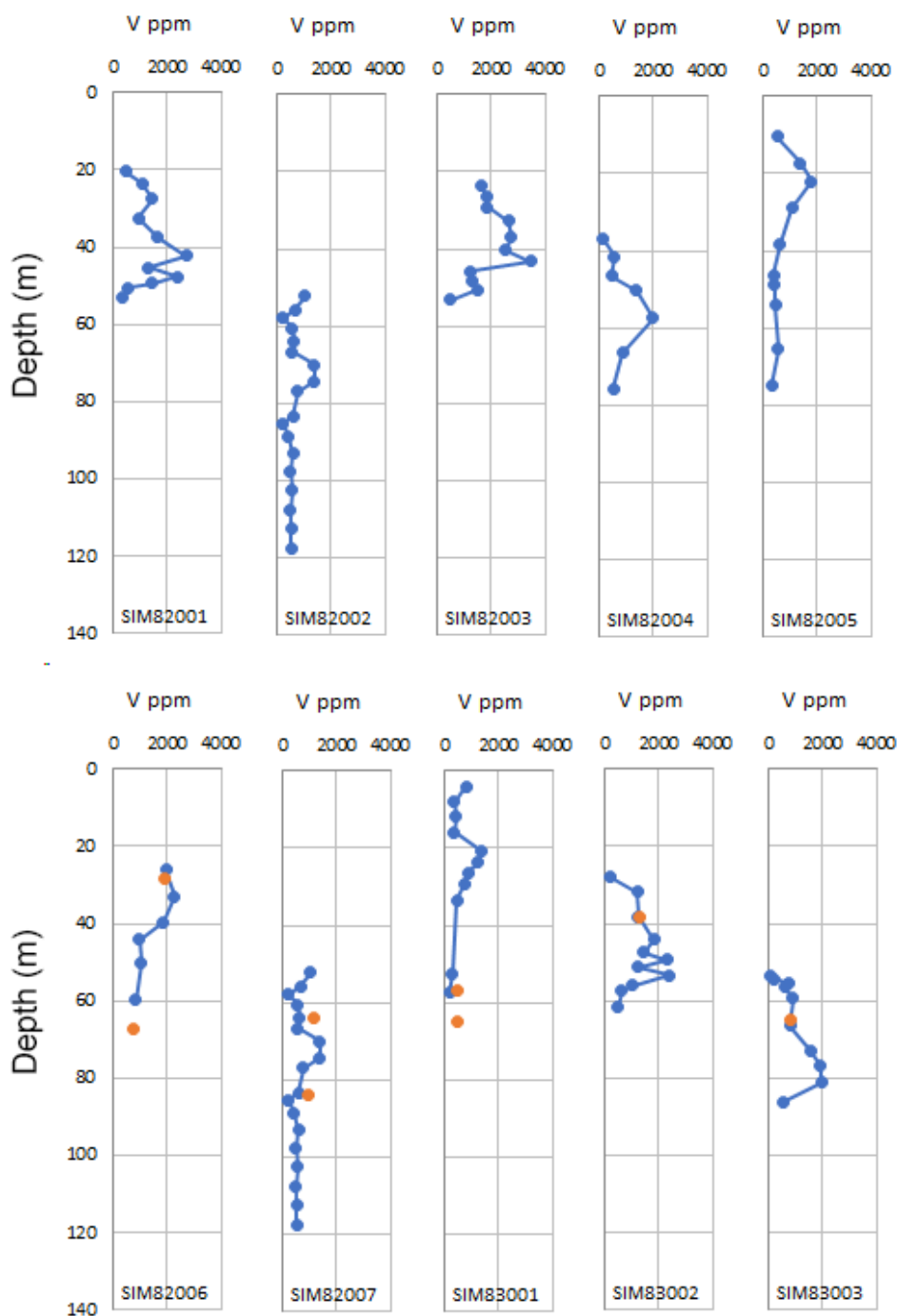


Figure 254. Variations in vanadium content with depth in Simesvallen drill cores. Blue dots are drill core analyses from 1983 and the orange (n = 8) are analyses obtained in the current project.

New analyses of major elements of the nine samples (eight drill core samples and one field sample) from Simesvallen and two field samples from Svedåsen (located to the south of Simesvallen) are plotted against SiO_2 in figure 255. In figure 256 vanadium is plotted against a selected suite of major element oxides and trace elements.

The samples from Simesvallen (n = 9) show large compositional variations with the following ranges (in %): SiO_2 (29.20–48.50), Al_2O_3 (6.75–14.10), Fe_2O_3 (15.40–40.50, average: 22.96), CaO (7.29–10.65), Na_2O (0.96–2.71), MgO (3.90–7.69), MnO (0.19–0.32), K_2O (0.30–0.64), P_2O_5 (0.06–0.35), and TiO_2 (1.68–7.20, average: 3.38).

Vanadium concentrations are in the range 446 to 2 540 ppm with an average of 1 136 ppm. Ni contents are in the range <1-159 ppm, Zn (111–197 ppm), Co (64–112 ppm), Cu (10–295 ppm), Cr (10–290 ppm), Y (20–41 ppm) and Sc (40–59 ppm).

The Σ REE (not including scandium and yttrium) are generally low, varying from 45 to 105 ppm (average 65 ppm).

The Simesvallen samples exhibit strong negative correlations between SiO_2 and Fe_2O_3 ($r = -0.99$) and also TiO_2 ($r = -0.97$). The other oxides have more scattered patterns (fig. 255 and Table 12). Vanadium shows good positive correlations with Fe_2O_3 ($r = 0.97$), TiO_2 ($r = 0.94$), Ge ($r = 0.89$), and Ga ($r = 0.84$); (fig. 256 and Table 12). Good negative correlations are observed between V and SiO_2 ($r = -0.98$).

In the AFM diagram a strong Fe-enrichment and tholeiitic affinity is evident (fig. 257). Primitive mantle normalised trace-element compositions are shown in figure 258. A characteristic feature is the strong negative Nb anomaly, and positive Pb and Ti anomalies.

Chondrite normalised REE patterns are subparallel (fig. 259) interpreted to result from fractional crystallisation. The nine Simesvallen samples (not including the two Svedåsen samples) have low to moderate LREE/HREE ratios with $(\text{La}/\text{Yb})_N$ in the range 1.55-2.28. Low to moderate degree of fractionation among the light REEs are shown by $(\text{La}/\text{Sm})_N$ between 1.26 and 1.64. Similarly, low to moderate fractionation among the heavy REEs is obvious as shown by $(\text{Gd}/\text{Yb})_N$ ranging from 1.11 to 1.52.

The whole suite has negative (Eu/Eu^*) , in the interval 0.81–0.98.

In the Th-Hf-Nb diagram (fig. 260) the samples plot in the field of Island arc calc-alkaline basalt (CAB), Island arc tholeiite (IAT) and N-MORB, except for one sample from Svedåsen that plots in the E-MORB-WPT field. A trend from N-MORB to volcanic arc signature is indicated by the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 261A and 261B).

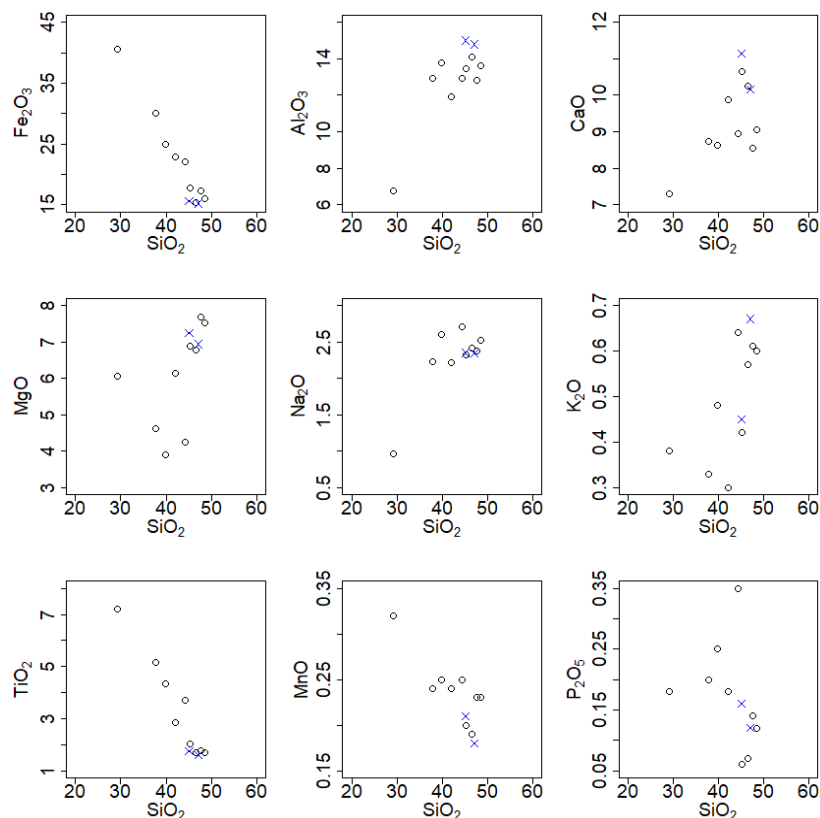


Figure 255. Harker diagrams for major element oxides in Simesvallen samples (black circles) and Svedåsen (blue 'X'). All concentrations are in %.

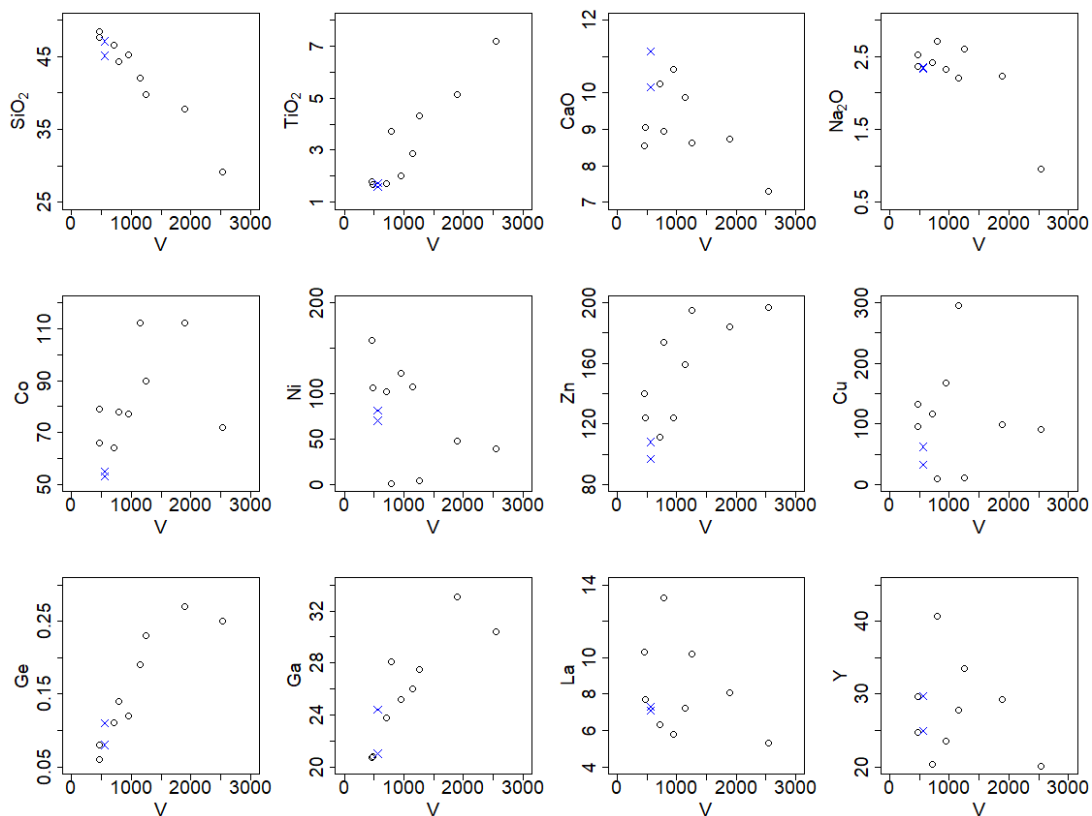


Figure 256. Harker diagrams for vanadium (ppm) vs. selected major and trace elements in samples from Simesvallen (black circles) and Svedåsen (blue 'X'). Major element oxide concentrations are in %. Trace elements are reported as ppm.

Table 12. Pearson correlation matrix for selected elements from Simesvallen samples (n = 9). The two samples from Svedåsen are not included in the calculations.

	V	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	Ce	Co	Cu	Ga	Ge	In	La	Ni	Y	Zn
V	1.00																
SiO₂	-0.98	1.00															
TiO₂	0.94	-0.97	1.00														
Al₂O₃	-0.77	0.82	-0.75	1.00													
Fe₂O₃	0.97	-0.99	0.98	-0.84	1.00												
CaO	-0.57	0.66	-0.75	0.67	-0.73	1.00											
Na₂O	-0.81	0.81	-0.70	0.95	-0.80	0.55	1.00										
Ce	-0.32	0.23	-0.02	0.33	-0.14	-0.22	0.58	1.00									
Co	0.33	-0.28	0.27	0.03	0.30	0.01	0.05	0.22	1.00								
Cu	-0.06	0.13	-0.32	-0.08	-0.16	0.48	-0.17	-0.47	0.38	1.00							
Ga	0.84	-0.80	0.85	-0.42	0.80	-0.37	-0.40	0.06	0.53	-0.23	1.00						
Ge	0.89	-0.88	0.87	-0.48	0.86	-0.45	-0.48	-0.04	0.63	-0.10	0.92	1.00					
In	0.93	-0.96	0.95	-0.66	0.94	-0.64	-0.64	-0.06	0.44	-0.19	0.84	0.95	1.00				
La	-0.39	0.29	-0.08	0.36	-0.20	-0.21	0.61	0.99	0.11	-0.53	-0.03	-0.12	-0.12	1.00			
Ni	-0.49	0.56	-0.70	0.20	-0.57	0.45	0.06	-0.41	-0.16	0.68	-0.72	-0.64	-0.63	-0.39	1.00		
Y	-0.24	0.16	0.04	0.33	-0.09	-0.14	0.58	0.97	0.33	-0.43	0.18	0.08	0.03	0.95	-0.51	1.00	
Zn	0.74	-0.81	0.89	-0.52	0.84	-0.73	-0.39	0.34	0.48	-0.37	0.78	0.86	0.91	0.28	-0.78	0.42	1.00

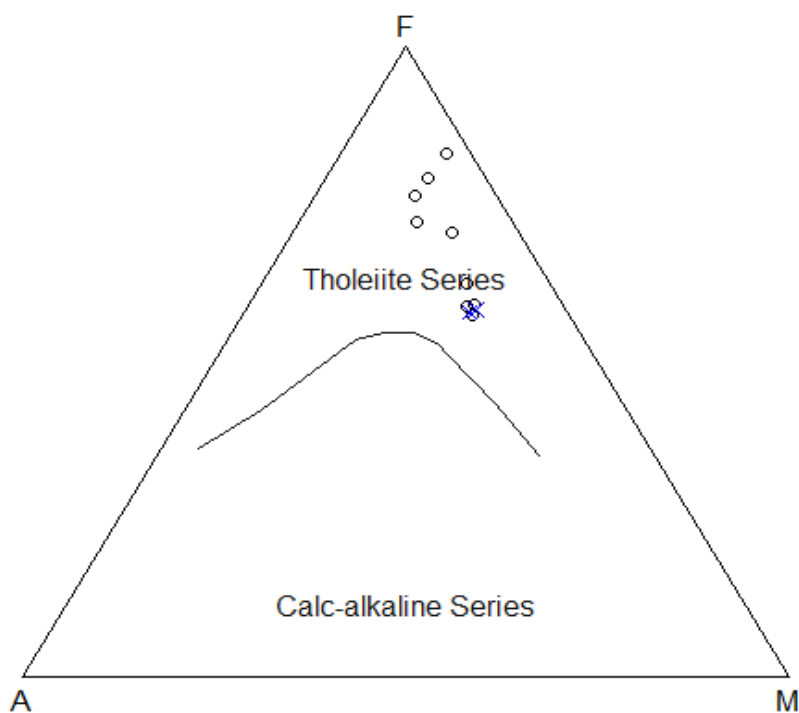


Figure 257. The samples from Simesvallen (black circles) and Svedåsen (blue 'X') plotted in an AFM-diagram (Irvine & Baragar 1971).

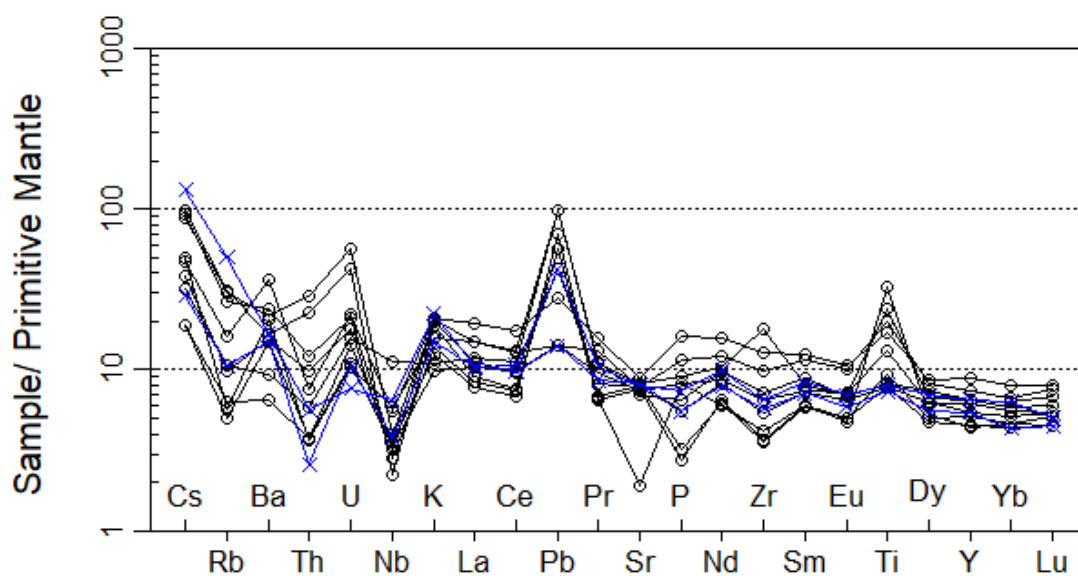


Figure 258. Primitive mantle normalised diagram for Simesvallen samples (black circles) and Svedåsen samples (blue 'X'). Normalising values from Sun & McDonough (1989).

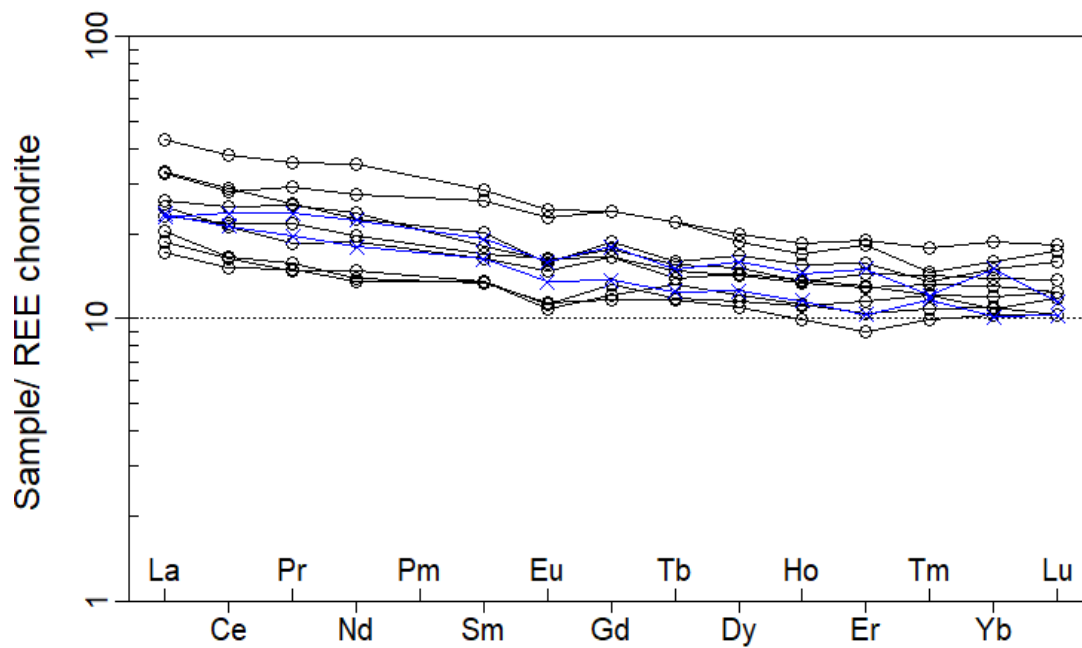


Figure 259. Chondrite normalised REE diagram for samples from Simesvallen (black circles) and Svedåsen samples (blue 'X'). The samples are characterised by patterns with moderate $(La/Yb)_N$ ratios (1.52–2.32). Chondrite values are from Boynton (1984).

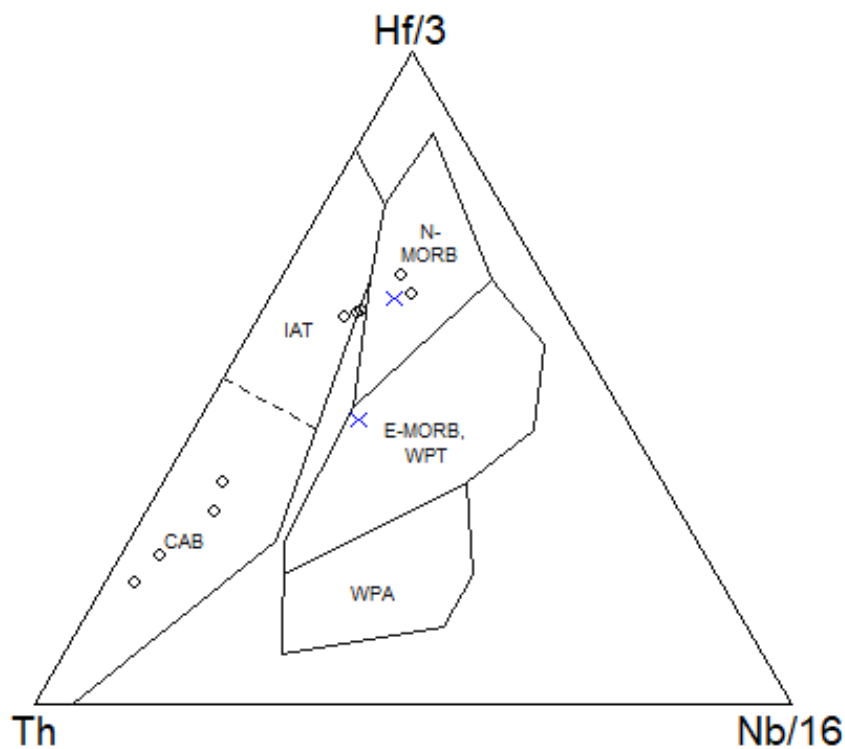


Figure 260. Simesvallen samples (black circles) and Svedåsen (blue 'X') plotted in a triangular diagram for geotectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB, WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

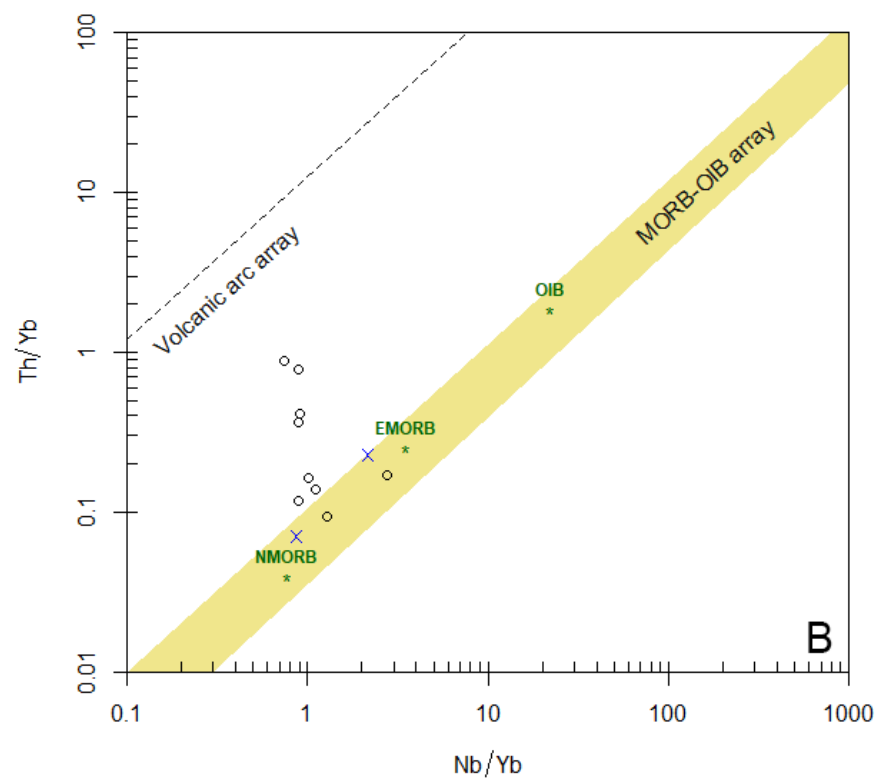
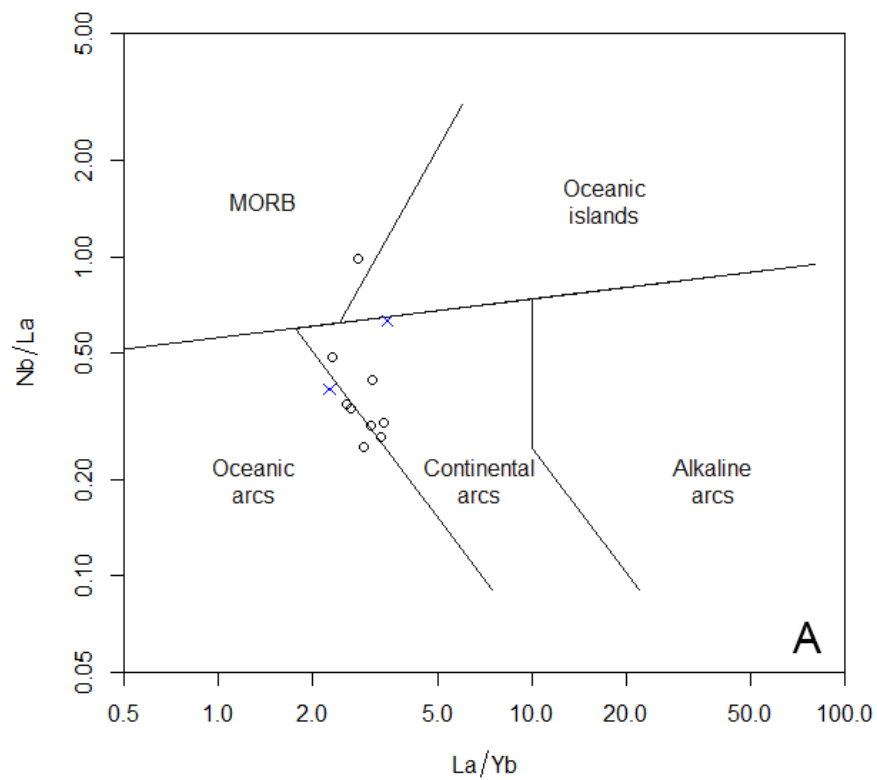


Figure 261. Simesvallen samples (black circles) and Svedåsen (blue 'X') plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

The area south of Simesvallen

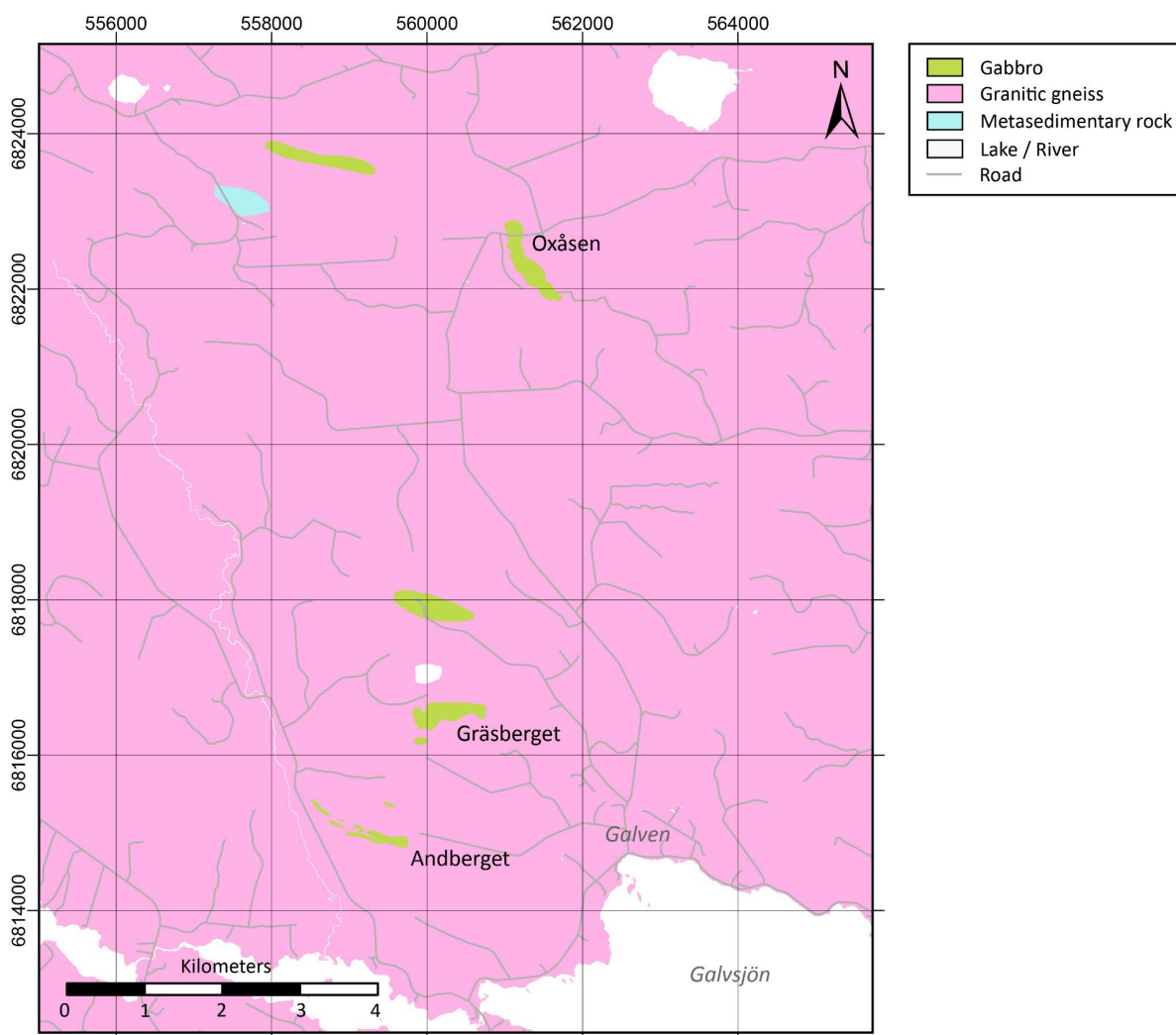


Figure 262. Bedrock geology map showing the area south of the Simesvallen intrusion. The names of the mafic intrusions referred to in the report are shown as black text. Names of some lakes are shown as grey italic text.

Based on airborne magnetic data a number of anomalies south of Simesvallen can be identified (see figs. 262 and 17A), which previously have been interpreted to be small mafic intrusions. Due to the relative size and strength of their anomalies, the Oxåsen, Gräsberget, and Andberget intrusions were chosen as targets for further investigation. Andberget and Gräsberget are located northwest of lake Galvsjön approximately 20 km northwest of Bollnäs (fig. 262). Oxåsen lies approximately 15 km north of Gräsberget.

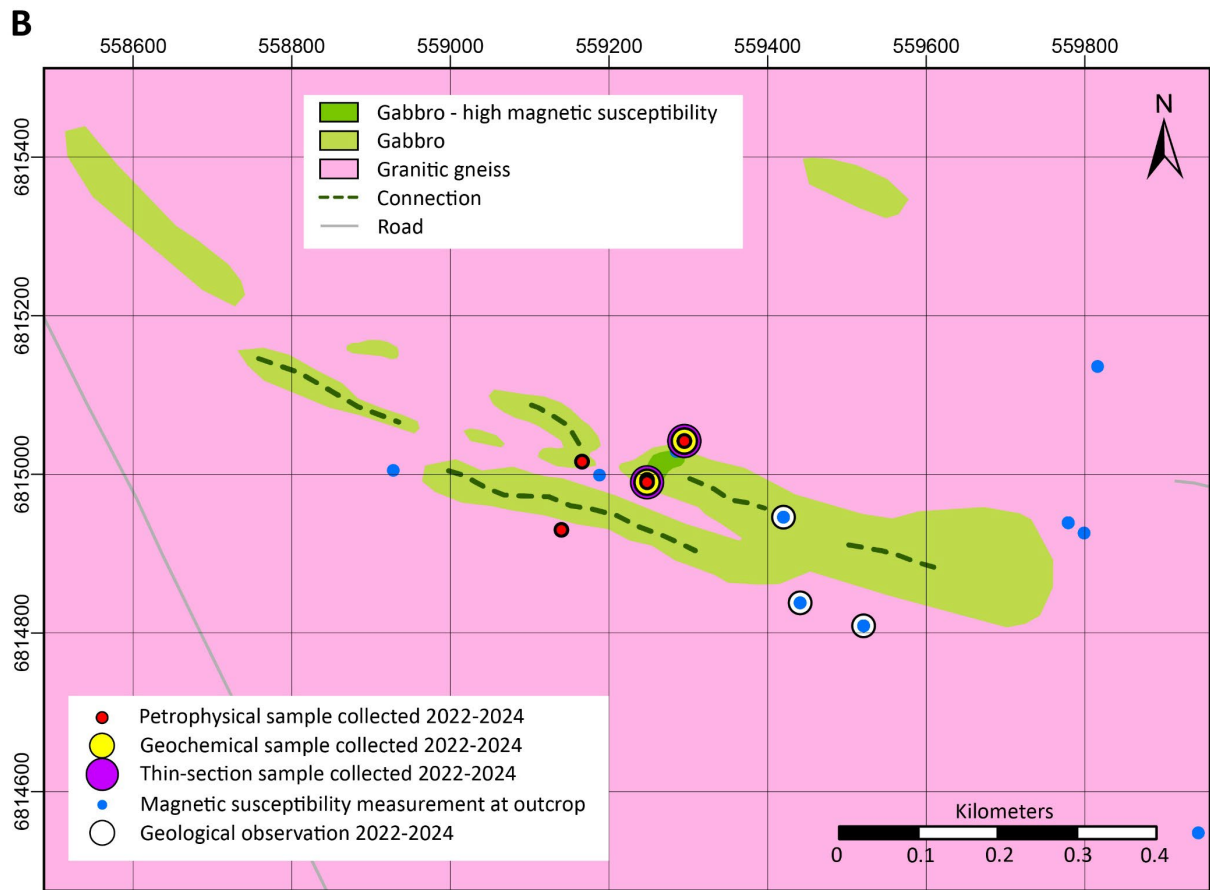
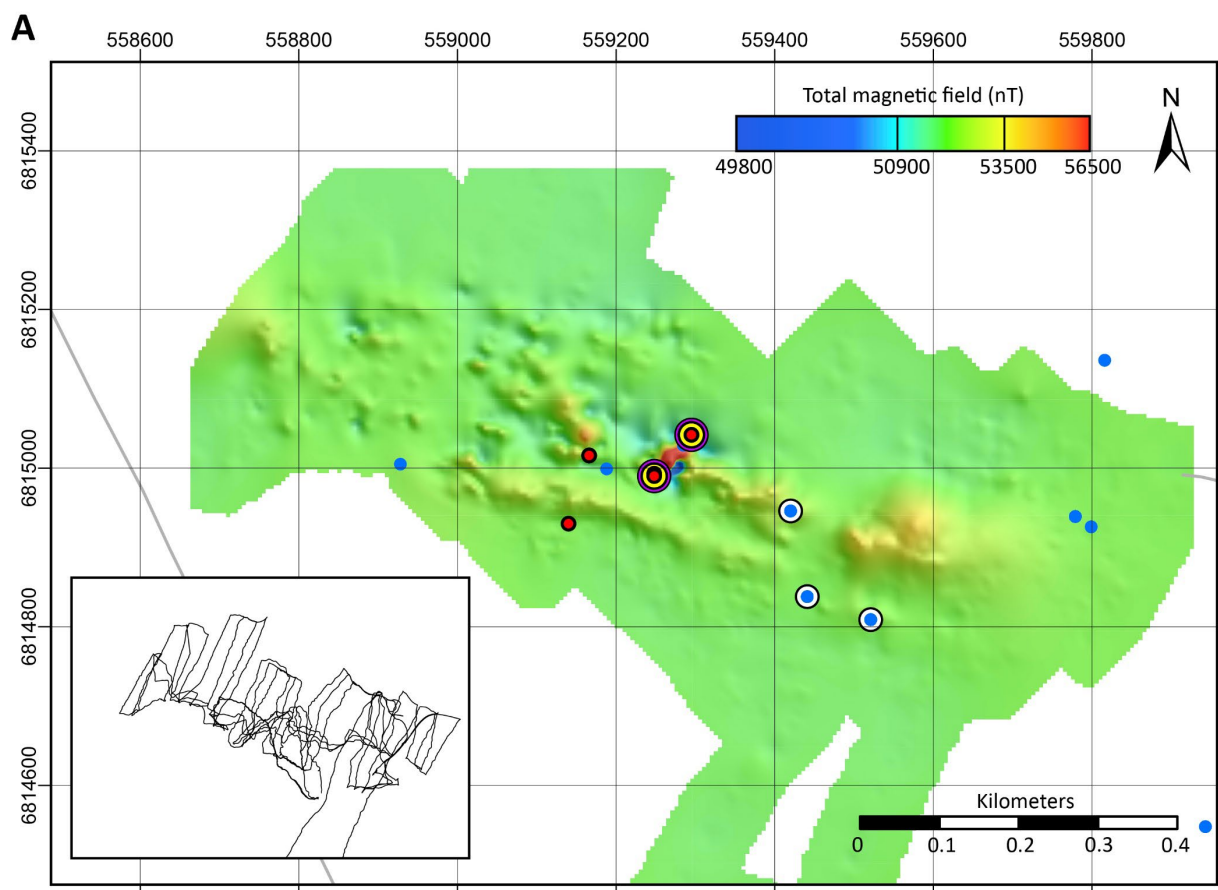
As part of this study about 0.5 km², 0.45 km², and 0.56 km² of ground based magnetic field measurements were collected over the Oxåsen, Gräsberget, and Andberget intrusions, respectively. For the Oxåsen and Andberget surveys the nominal line spacing was 40 m, while for the Gräsberget survey the nominal line spacing was about 60 m.

Andberget

Ground-based geophysical data

Figure 263 shows the ground magnetic measurements over the Andberget intrusion as well as an updated bedrock geology map. Here the anomaly associated with the intrusion appears to be about 700 m long, 150 m wide and has a strike of approximately 110°. The intrusion appears to have a very small area in the centre with relatively high magnetic field values, in this area the maximum value reaches about 17 000 nT above the background value. However, apart from this small area (of about 200 m²) the magnetic field value does not exceed 3 000 nT above the background value over the rest of the intrusion. Within the intrusion there appears to be two linear anomalies which are relatively continuous throughout the area. These can be interpreted to be lenses or layers with higher degrees of mineralisation. However, due to the relatively low magnetic field values and geological observations in the area we interpret the intrusion to have a somewhat discontinuous geometry, consisting of a number of small mafic bodies within the surrounding granitic rocks. Figure 264 shows the average magnetic susceptibility in the upper 75 m of the model obtained by inverting the ground magnetic data. Here the highest magnetic susceptibilities can be observed to be located in the central and eastern parts of the intrusion. In the 3D magnetic susceptibility model, the high susceptibility feature coupled to the intrusion does not appear to have a consistent dip direction, appearing rather diffuse in the inversion result. However, in the eastern part of the intrusion the inversion gives an indication that the intrusion dips to the north (fig. 264).

► **Figure 263.** **A.** Map of the total magnetic field from ground measurements collected as part of this study over the Andberget intrusion. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Andberget intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of geological observations, samples, and magnetic susceptibility measurements at outcrop are shown as coloured dots in both A and B.



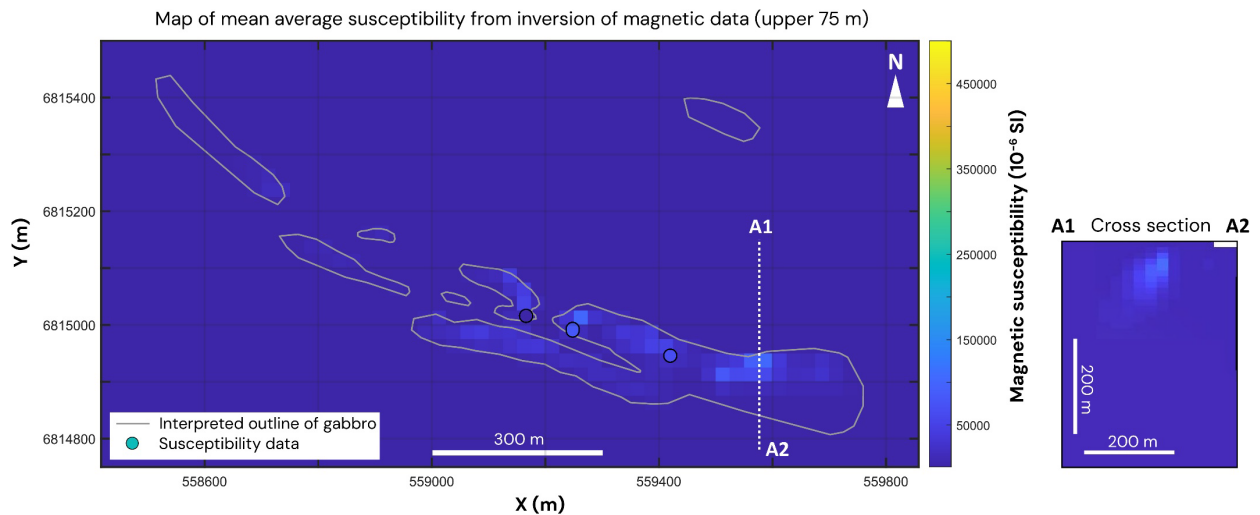


Figure 264. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Andberget intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geological observations

In general, good outcrops of gabbro are scarce at Andberget, but a few gabbroic outcrops and an older abandoned shallow mining pit with a small waste-rock heap was visited and sampled. In the observed outcrops the gabbro is medium- to coarse-grained, massive and apparently undeformed (fig. 265) compared to the surrounding granitic gneiss (fig. 268). Strongly mineralised samples from the waste-rock heap are fine- to medium-grained and massive (figs. 266 and 267).



Figure 265. Massive gabbroid in outcrop at Andberget (6814946/559420). Photo: Helge Reginiussen.



Figure 266. Weakly mineralised gabbroid from a small waste-rock heap at Andberget (6815042/559295). Analysis gave the following: 23.20% Fe_2O_3 , 4.52% TiO_2 , and 896 ppm V. Photo: Helge Reginiussen.



Figure 267. Strongly magnetite-mineralised rocks (from the same waste-rock heap as the sample in fig. 266). Analysis gave the following: 41.7% Fe_2O_3 , 9.37% TiO_2 , and 2 410 ppm V. Photo: Helge Reginiussen.



Figure 268. Granitic gneiss at Andberget (6814809/559521). Photo: Helge Reginiussen.

Description of thin sections – ore minerals

The ore minerals magnetite, ilmenite, and small grains of pyrrhotite were identified in mineralised sample HRE220024A (fig. 269, see fig. C34 for panorama). The texture of the larger grains of magnetite and ilmenite suggests that both were crystallising together at the magmatic stage and that ilmenite is not only an exsolved mineral in this rock (fig. 269). There is plenty of exsolved ilmenite as laths and trellis in the magnetite (figs. 269B–C). Ilmenite has exsolved hematite but there are other minerals that look like darker exsolution trellis, which are feasibly magnetite or ulvöspinel (figs. 269B–C, cf. Haggerty 1991, Tan *et al.* 2016a). There is a high probability that both ulvöspinel and pleonaste are present among the tiny trellis-type exsolution in the magnetite (e.g., Haggerty 1991, Tan *et al.* 2016b), but no SEM-work has been done to identify the smallest exsolved minerals and the optical microscopy was deemed inadequate for proper identification.

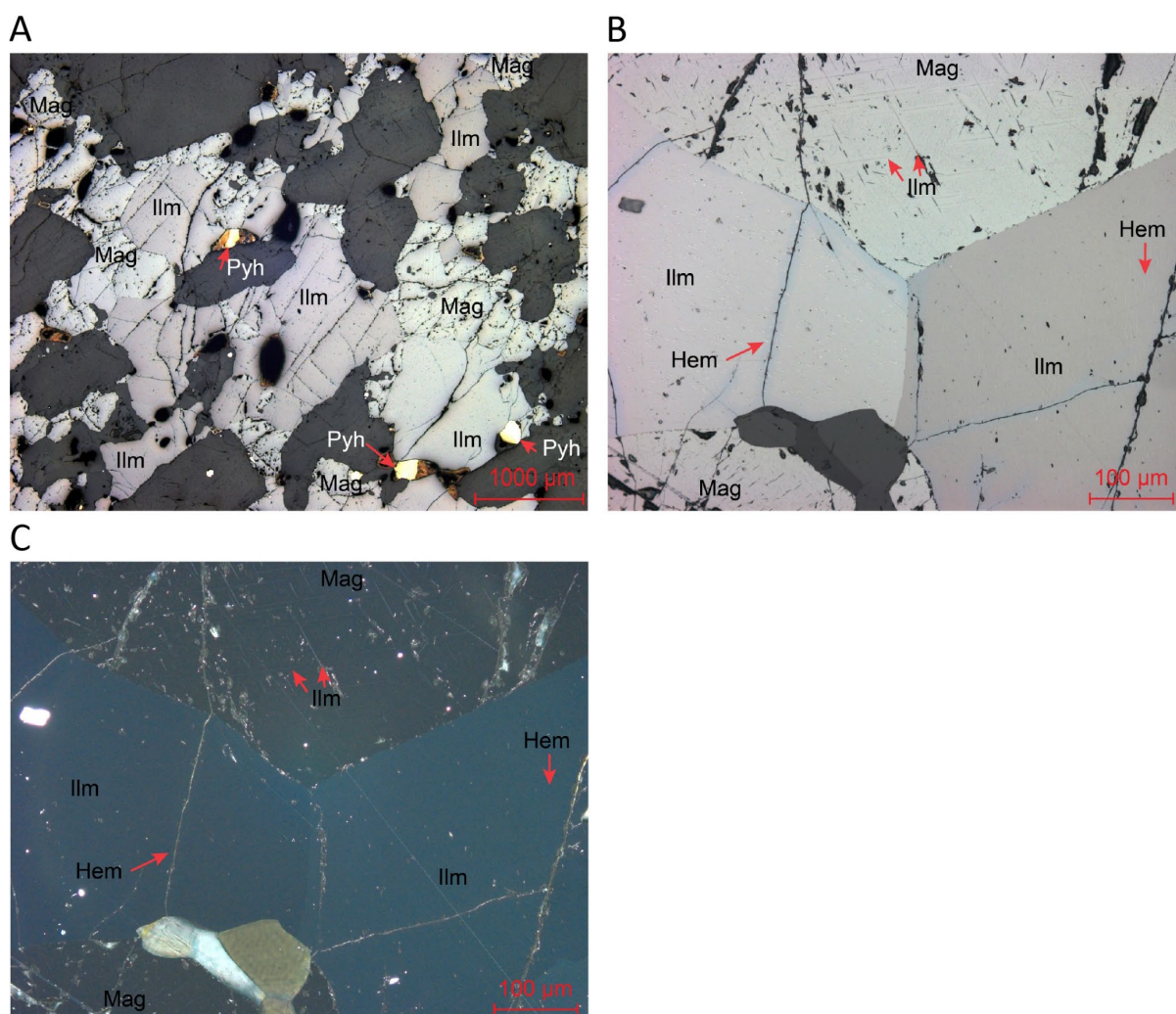


Figure 269. Ore minerals from the Andberget intrusion, mineralised sample HRE220024A (see fig. C34 for panorama). **A.** Overview of relations between magnetite, ilmenite, and small pyrrhotite grains in opaque framework. Close-up images of relations between magnetite and ilmenite, ilmenite as trellis exsolutions along crystallographic planes within magnetite, and tiny hematite exsolution lamellae in ilmenite, **B.** plain reflected light and **C.** using a differential interference contrast (DIC) objective. All images in reflected light, unmarked darker grey grains are silicate minerals. Photo: Dick Claeson.

Description of thin sections – silicate minerals

The mineralised sample HRE220024A (panorama fig. C34) has roughly equal amounts of hornblende and clinopyroxene. Euhedral to anhedral hornblende occurs as small to large grains, interstitially grown crystals, and aggregates with Fe-Ti oxides (figs. 270A–D). Subhedral to anhedral clinopyroxene has lamellae and opaque exsolutions, few crystals altered to secondary green amphibole. Plagioclase has strong pigmentation in central portions of crystals compared with rims. Bends or kinks, deformation twins, and undulose extinction are present across several of the large plagioclase crystals (figs. 270C–D).

In the lesser mineralised sample HRE230017A (panorama fig. C35), clinopyroxene is the main mafic silicate mineral, subhedral to anhedral grains and interstitially grown crystals with lamellae and opaque minerals exsolution, minor green amphibole alteration (figs. 270E–F). Subhedral to anhedral hornblende occurs as small to large grains, interstitially grown crystals, and aggregates with Fe-Ti oxides. Olivine occurs as small to large anhedral grains. Plagioclase has strong pigmentation in central portions of crystals compared with rims. Some plagioclase has distinct bends or kinks, deformations twins, and undulose extinction due to deformation while hot during compaction (e.g., Hunter 1996, Holness *et al.* 2007b, Toplis *et al.* 2008, Namur *et al.* 2011, Holness *et al.* 2017). There is minor patchy sericite-saussurite alteration of plagioclase.

The sample HRE220024B is well-preserved with relatively large crystals, apart from the interstitial grains and some intergrowths. Roughly equal amounts of subhedral-anhedral hornblende and clinopyroxene. Fe-Ti oxides and hornblende forms aggregates. Clinopyroxene has exsolutions as lamellae and opaque minerals. Occasionally anhedral small to large grains of olivine can be observed. Fine-grained hornblende and plagioclase can be observed to grow between coarser-grained clinopyroxene and olivine on one side and Fe-Ti-oxide and hornblende on the other (figs. 271A–B). The fine-grained portions are interpreted as late-forming intergrowths. Interstitially grown plagioclase as rims lacks the dark grey pigmentation present in early formed parts of the crystal, which also applies to entirely interstitially grown plagioclase crystals (figs. 271C–D). Euhedral to subhedral, large crystals of apatite are present, which in the studied thin sections are very rare (figs. 271E–F).

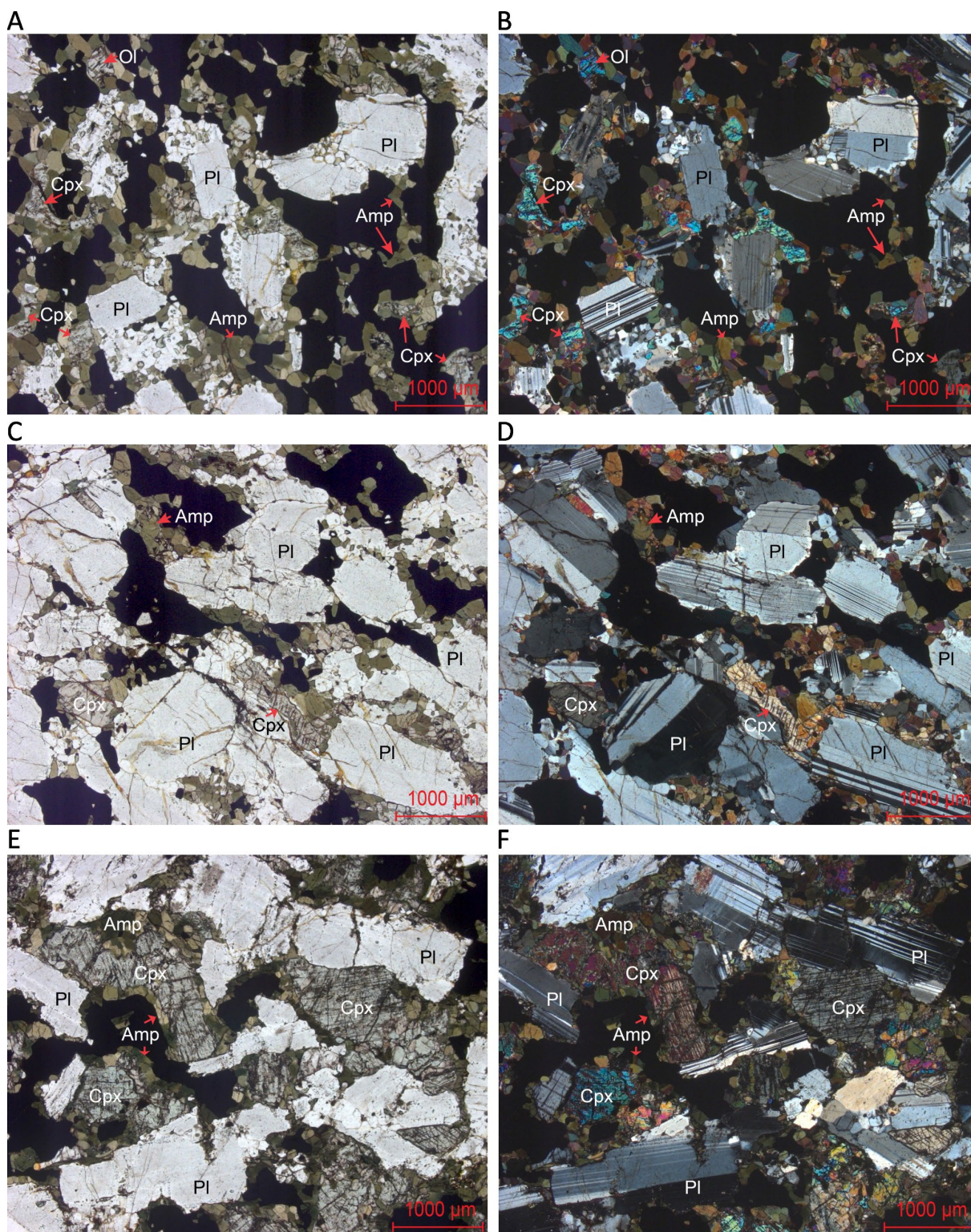


Figure 270. A. and B. Fine-grained parts of hornblende and clinopyroxene between large-grained plagioclase and Fe-Ti-oxide, with smaller areas of intergrown hornblende and plagioclase with minor clinopyroxene. Note strong pigmentation in central portions of plagioclase compared with the rim. C. and D. Bends or kinks are present across several of the large plagioclase crystals, note the one in centre of image, as well as deformation twins and undulose extinction. Sample HRE220024A (6815042/559295). E. and F. Plagioclase in centre of image has distinct bends or kinks, deformation twins, and undulose extinction. Sample HRE230017A (6814990/559248). Left in ppl and right in xpl. Photo: Dick Claeson.



Figure 271. A. and B. Intergrown fine-grained hornblende and plagioclase between clinopyroxene-olivine and Fe-Ti-oxide-hornblende. C. and D. Interstitially grown plagioclase as rims lacks the dark grey pigmentation present in early formed parts of the crystal, which also applies to entirely interstitially grown plagioclase crystals. E. and F. Euhedral to subhedral, large crystals of apatite at red arrows. Fe-Ti oxides and hornblende in aggregates. All images sample HRE220024B (6815042/559295). Left in ppl and right in xpl. Photo: Dick Claeson.

Gräsberget

Ground-based geophysical data

Figure 272 shows the ground magnetic data collected over the Gräsberget intrusion as well as an updated bedrock geology map of the area. The anomaly at Gräsberget appears to be about 850 m long, 200 m wide and has an approximately east–west strike. The highest magnetic field values occur in the central part of the intrusion where they reach values of about 3 200 nT above the background value. Due to the relatively sparse line spacing it is not possible to clearly image some of the smaller local magnetic anomalies which can give an idea of the zonation of the mineralisation within the intrusion. Figure 273 shows a map of the average magnetic susceptibility from the model obtained from inverting the ground magnetic data. Here the highest magnetic susceptibility values appear to be located on the northern boundary of the intrusion. In the 3D susceptibility model, the high magnetic susceptibility feature in the model appears to dip to the south (fig. 273).

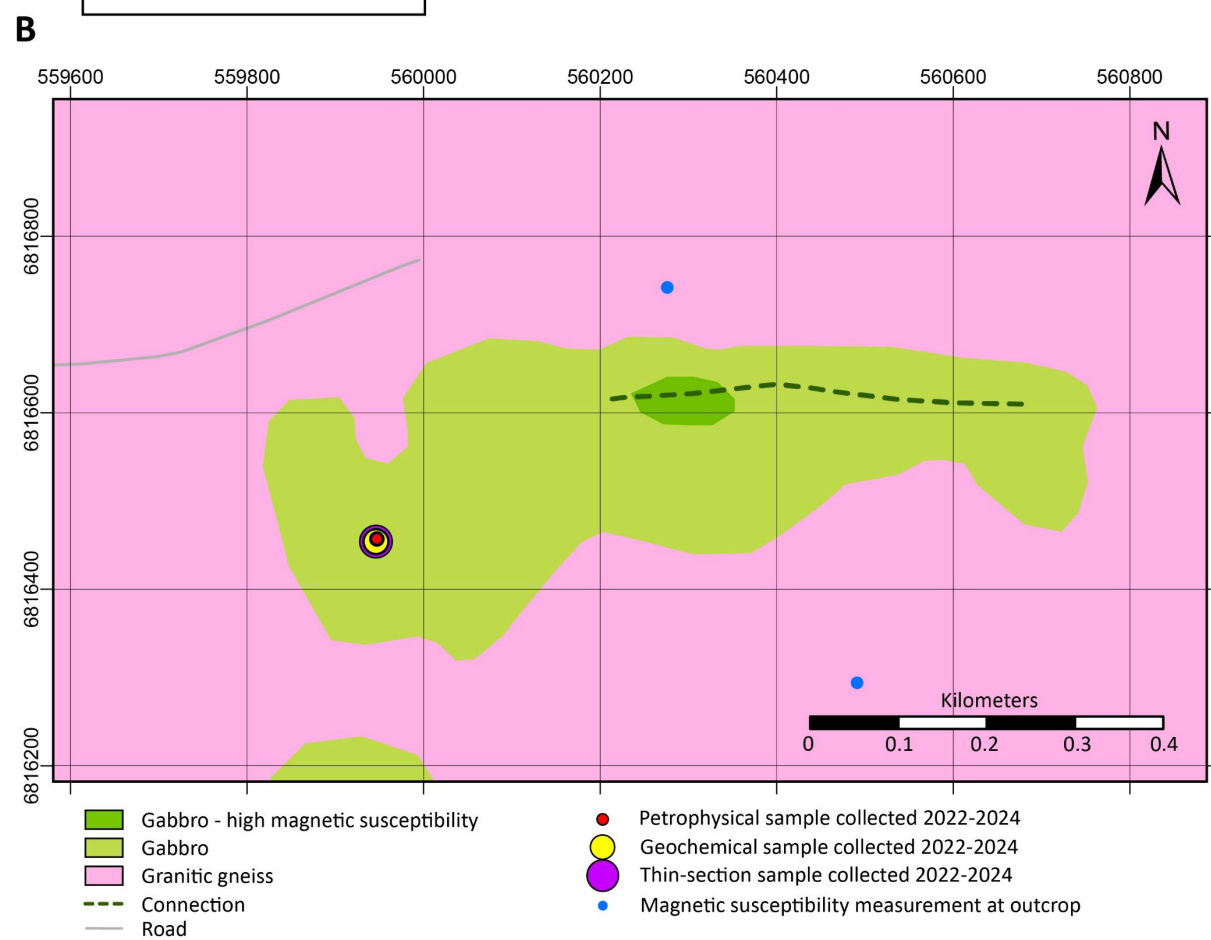
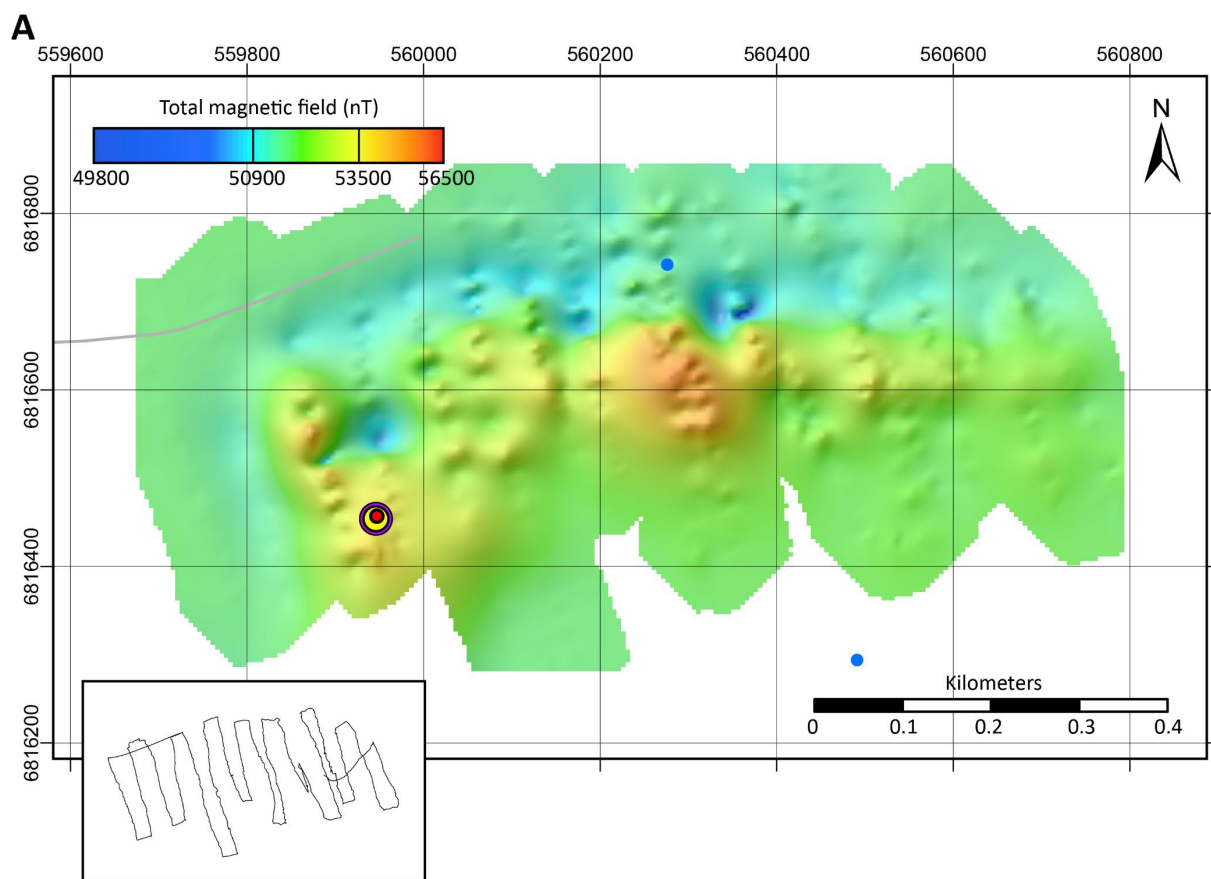
Geological observations

At Gräsberget outcrops are extremely rare due to an extensive till cover, and only one gabbroic outcrop was found. This gabbroid is predominantly medium- to coarse-grained and massive, but a weak modal layering (c. 10 cm thick) was observed.

Description of thin sections – silicate minerals

The main silicate minerals in the cumulate rock sample HRE220050A are clinopyroxene, hornblende, olivine, biotite, and plagioclase (fig. 274). The rock is mostly well-preserved with minor alteration of clinopyroxene to secondary green amphibole. There are roughly equal amounts of clinopyroxene and hornblende. Aggregates of Fe-Ti oxide, biotite, and hornblende with outboard parts of intergrown fine-grained hornblende and plagioclase are present. Most clinopyroxene is subhedral to anhedral with lamellae and opaque exsolutions. Anhedral small to large olivine crystals occur. Subhedral-anhedral plagioclase with minor sericite-saussurite alteration, bent-kinked crystals while hot are present. Biotite is relatively abundant and has brownish red to light tan pleochroism. One large biotite crystal has a texture that implies that dynamic deformation has occurred, possibly while hot like that seen in plagioclase. Apatite occurs as rare small grains. There are small to large quartz grains and interstitially grown crystals with weak undulose extinction.

► **Figure 272. A.** Map of the total magnetic field from ground measurements collected as part of this study over the Gräsberget intrusion. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Gräsberget intrusion, interpreted from the ground magnetic field data and the available geological observations and samples. The locations of samples and magnetic susceptibility measurements at outcrop are shown as coloured dots in both A and B.



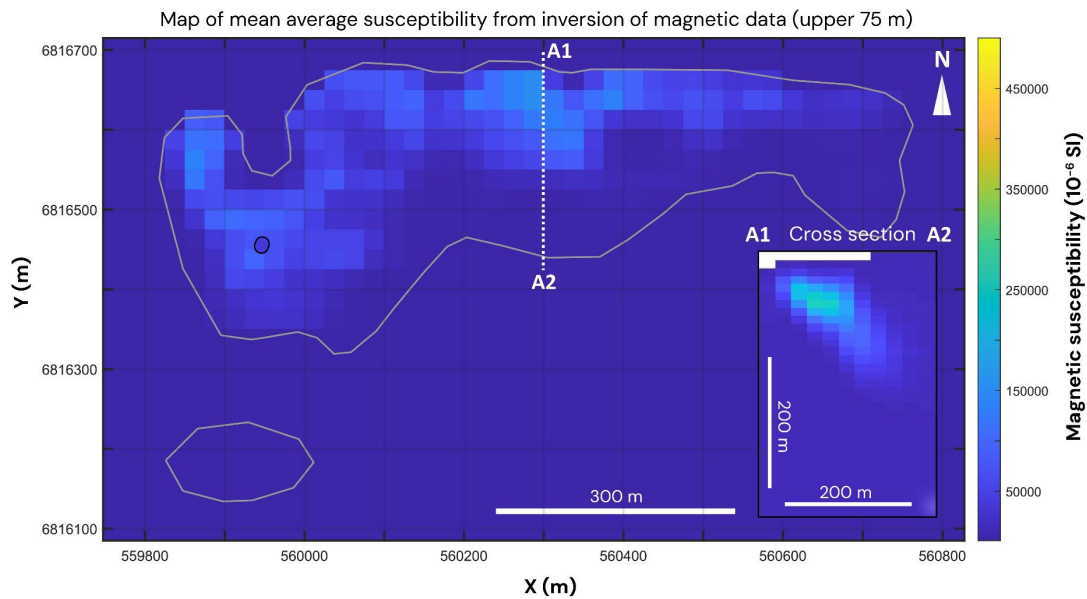


Figure 273. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Gräsberget intrusion. All magnetic susceptibility measurements collected at the surface are shown as dots. A cross section (A1–A2) through the magnetic susceptibility model obtained from the inversion is shown. The location of the cross section is denoted on the map as a dotted white line. The dots, map and section are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface, represented by the white line.

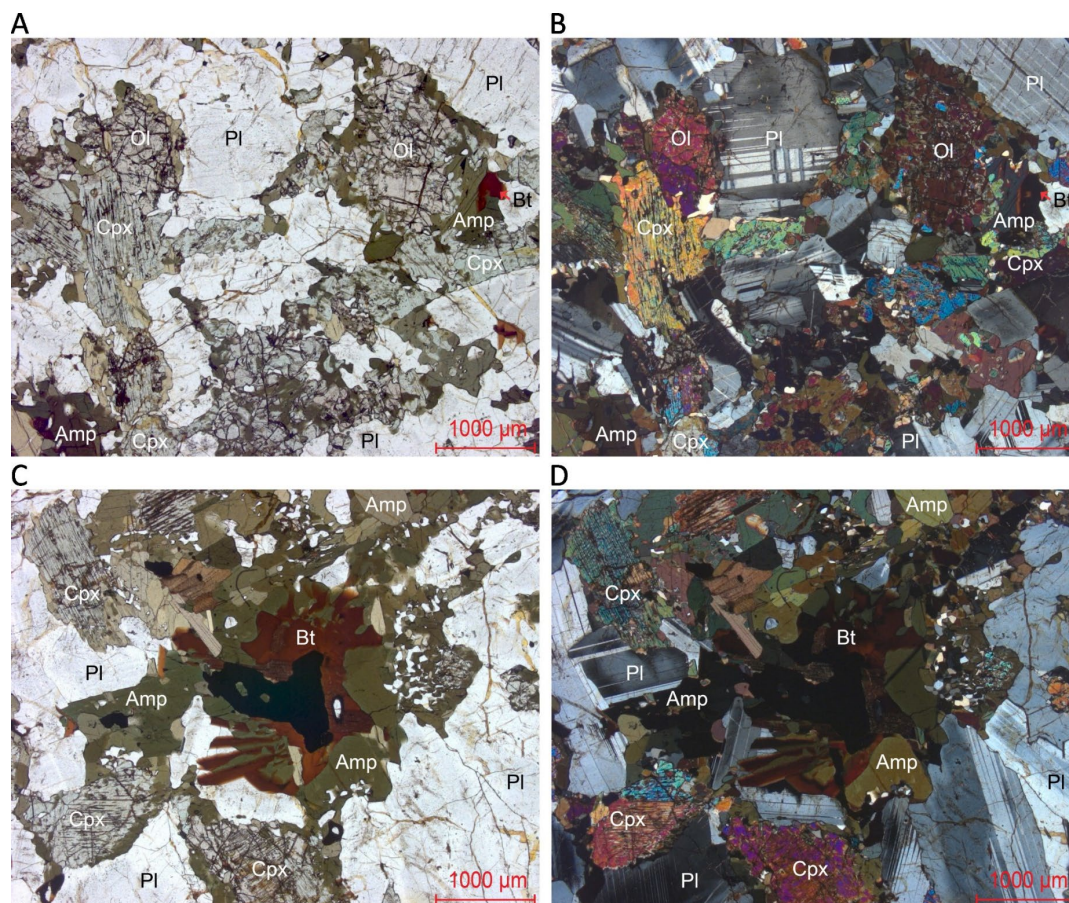


Figure 274. A. and B. Olivine, clinopyroxene, hornblende, biotite, and plagioclase in a cumulate rock. C. and D. Aggregate of Fe–Ti oxide, biotite, and hornblende with outboard parts of intergrown fine-grained hornblende and plagioclase. Subhedral to anhedral clinopyroxene and plagioclase. All images sample HRE220050A (6816454/559946). Left in ppl and right in xpl. Photo: Dick Claeson.

Oxåsen

Ground-based geophysical data

Figure 275 shows the ground magnetic data collected over the Oxåsen anomaly as well as the updated bedrock geology map. It should be noted that no outcrops were found in the vicinity of the anomaly at Oxåsen, so it was not possible to confirm with geological observations that this anomaly is associated with a mafic intrusion. However, due to the strength and size of the anomaly and given the broader geological environment, this anomaly is interpreted to be associated with a mafic intrusion. The anomaly at Oxåsen is about 1 000 m long and 200 m wide with an approximate strike of about 145° . The highest magnetic field values lie in the southeastern and central parts of the anomaly, where values of about 7 000 nT above the background value occur in some places. Within the anomaly lie a series of local positive magnetic field anomalies which can be correlated up to about 100 m. These do not typically lie parallel to the interpreted edge of the intrusion, as in many of the other intrusions in this study. Instead, several of these have a strike of about 110° . In this study they are interpreted to represent layers or lenses of the intrusion with greater levels of mineralisation.

Figure 276 shows a map of the average magnetic susceptibility in the upper 75 m of the model obtained from inversion of the ground magnetic data. Here the highest magnetic susceptibilities appear to be located in the southern and central parts of the intrusion. In the 3D susceptibility model from the inversion, the high susceptibility layer associated with the intrusion appears to dip consistently to the northeast (fig. 276).

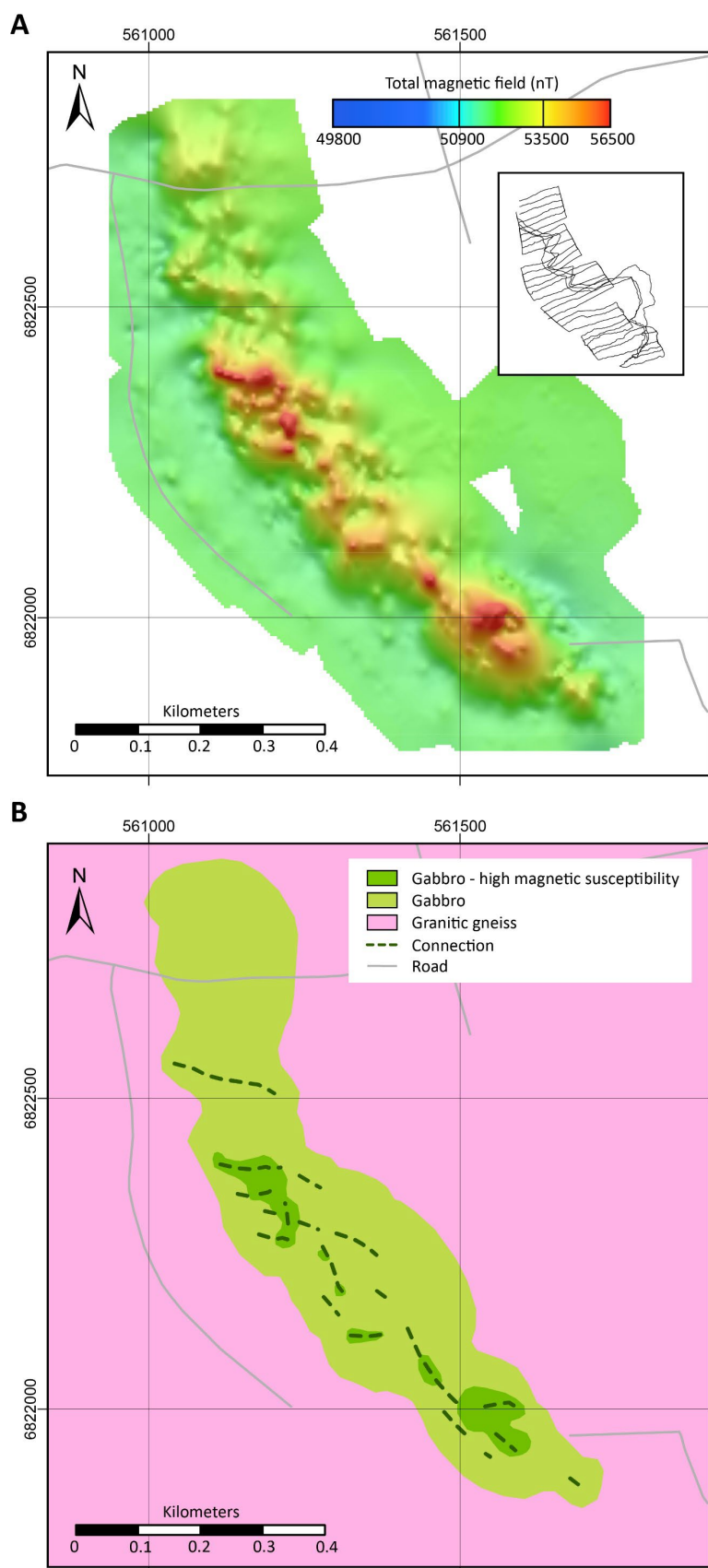


Figure 275. A. Map of the total magnetic field from ground measurements collected as part of this study over the Oxåsen intrusion. The inset map shows a smaller version of the map area, where the locations of the measurement profiles are shown as black lines. **B.** Updated map of the bedrock geology around the Oxåsen intrusion, interpreted from the ground magnetic field data.

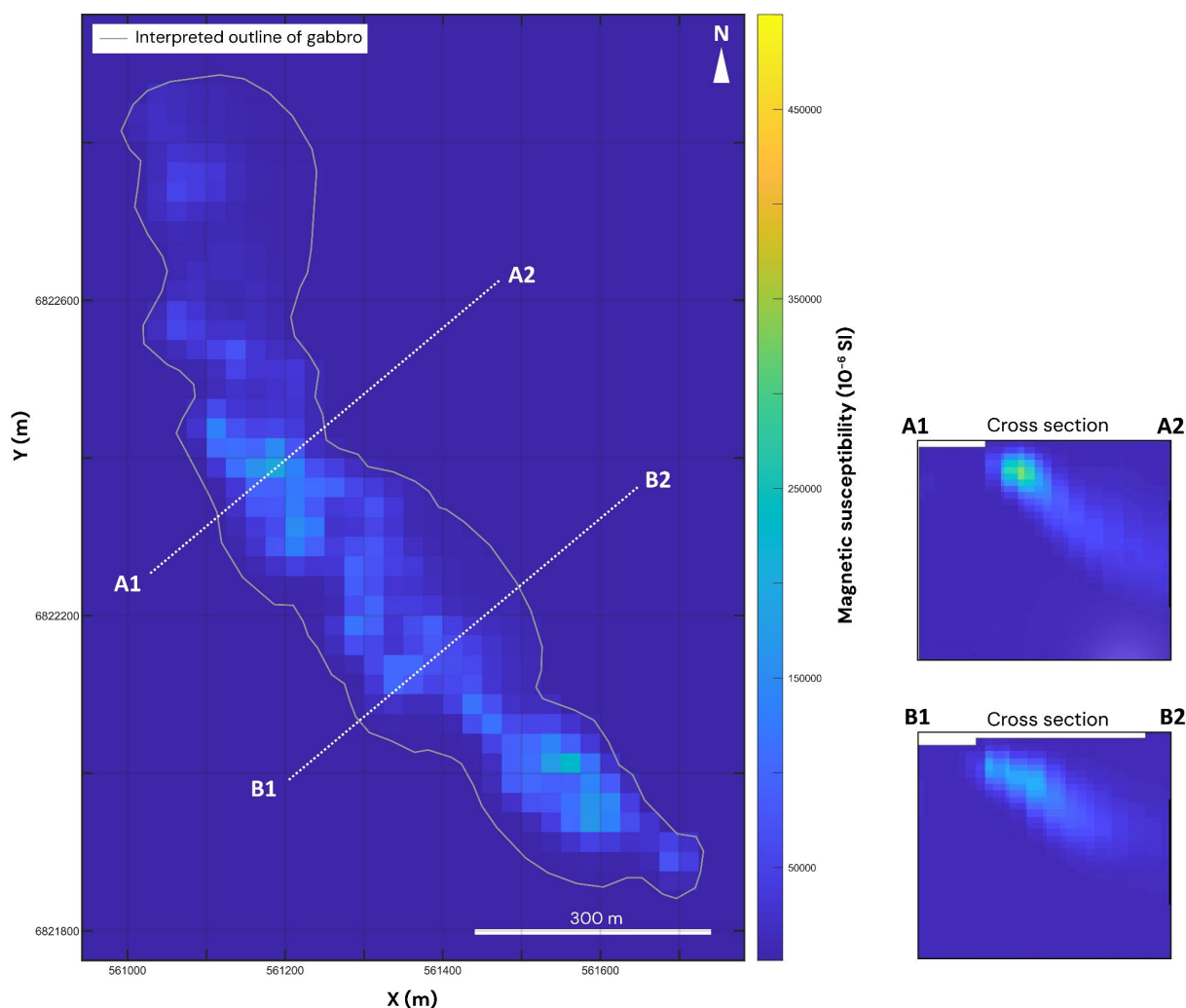


Figure 276. Map of the mean average magnetic susceptibility in the upper 75 m of the unconstrained inversion model, calculated from the ground magnetic data from the Oxåsen intrusion. Cross sections (A1–A2 and B1–B2) through the magnetic susceptibility model obtained from the inversion are shown beside the map. The locations of the cross sections are denoted on the map as dotted white lines. The map and sections are shown with the same magnetic susceptibility colour scale. Note that this map is constrained to the area where the intrusion is interpreted to be present at the top bedrock surface.

Geochemical data from the area south of Simesvallen

Major element compositions from three samples from Andberget and one sample from Gräsberget are shown in figure 277. Vanadium is plotted against a selection of oxides and trace elements in figure 278.

The number of samples analysed are too few to allow for statistical analysis, but it is noted that the vanadium concentrations in the sample from Gräsberget is 633 ppm, while the three samples from Andberget contain 896, 986, and 2 410 ppm V, respectively. One sample from Andberget contains 9.37% TiO_2 .

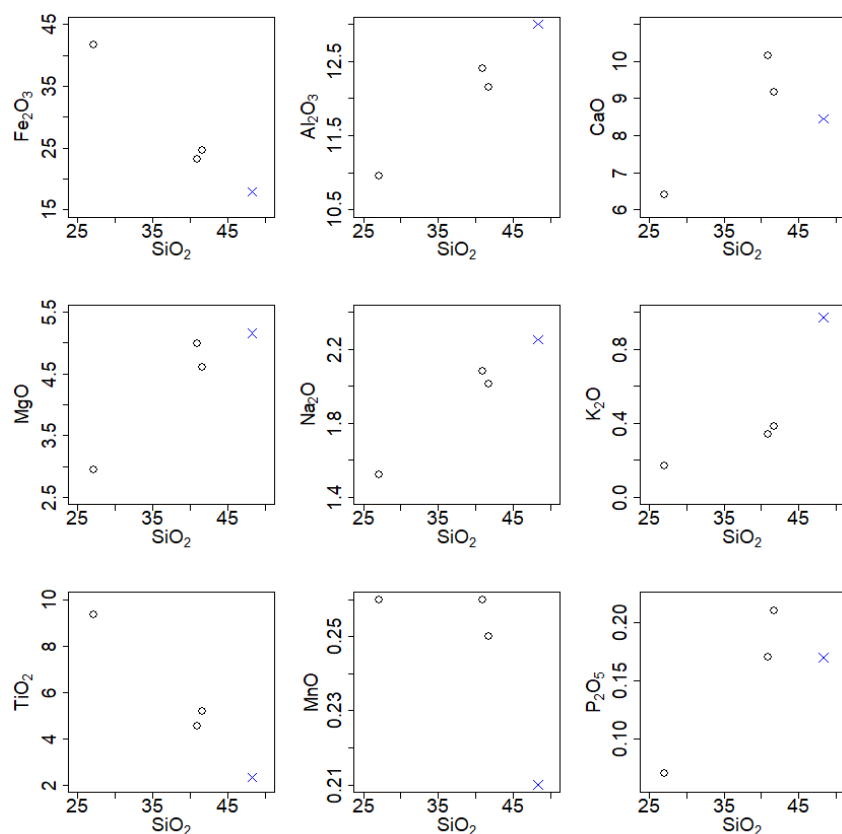


Figure 277. Harker diagrams for major element oxides in Andberget (black circles) and Gräsberget (blue 'X'). All concentrations are in %.

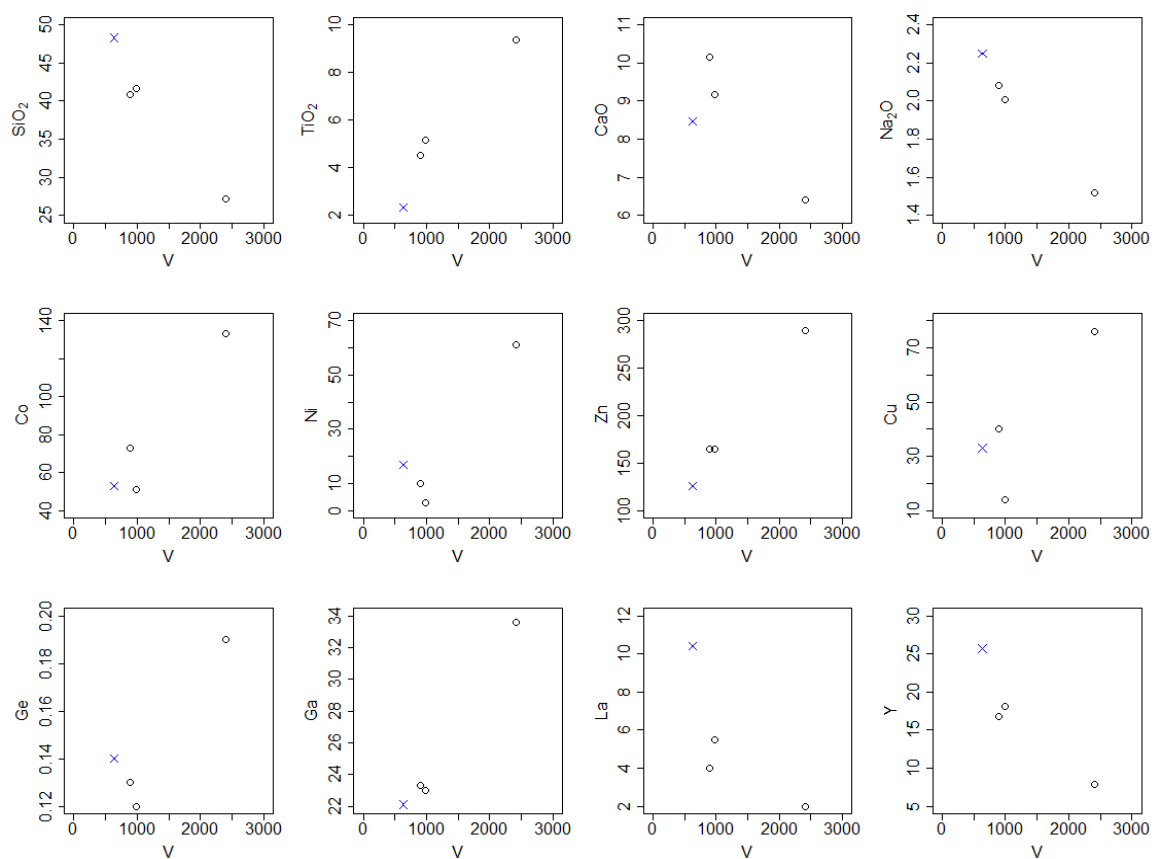


Figure 278. Vanadium (ppm) vs. selected major element oxides (%) and trace elements (ppm) in Andberget (black circles) and Gräsberget (blue 'X').

In the AFM diagram a strong Fe-enrichment and tholeiitic affinity is evident (fig. 279). Primitive mantle normalised trace-element compositions are shown in figure 280. A characteristic feature is the strong negative Nb anomaly, and positive Pb and Ti anomalies. Chondrite normalised REE patterns are relatively flat (fig. 281) with $(La/Yb)_N$ in the range 1.29–2.60.

In the Th-Hf-Nb diagram (fig. 282) the samples plot in the field of Island arc calc-alkaline basalt (CAB). In the La/Yb vs. Nb/La and the Nb/Yb vs. Th/Yb diagrams (figs. 283A–B) the samples plot predominantly in the volcanic arc fields.

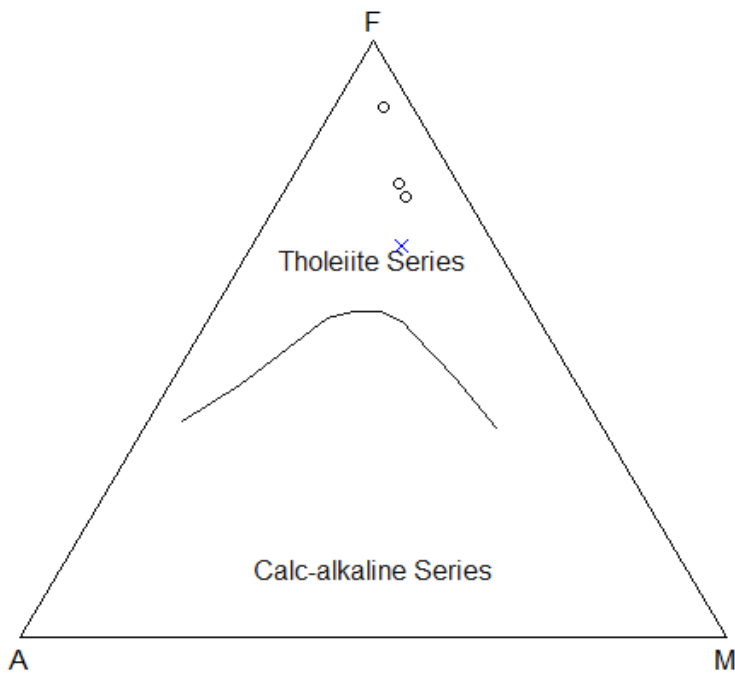


Figure 279. AFM diagram (Irvine & Baragar 1971) for Andberget samples (black circles) and Gräsberget sample (blue 'X').

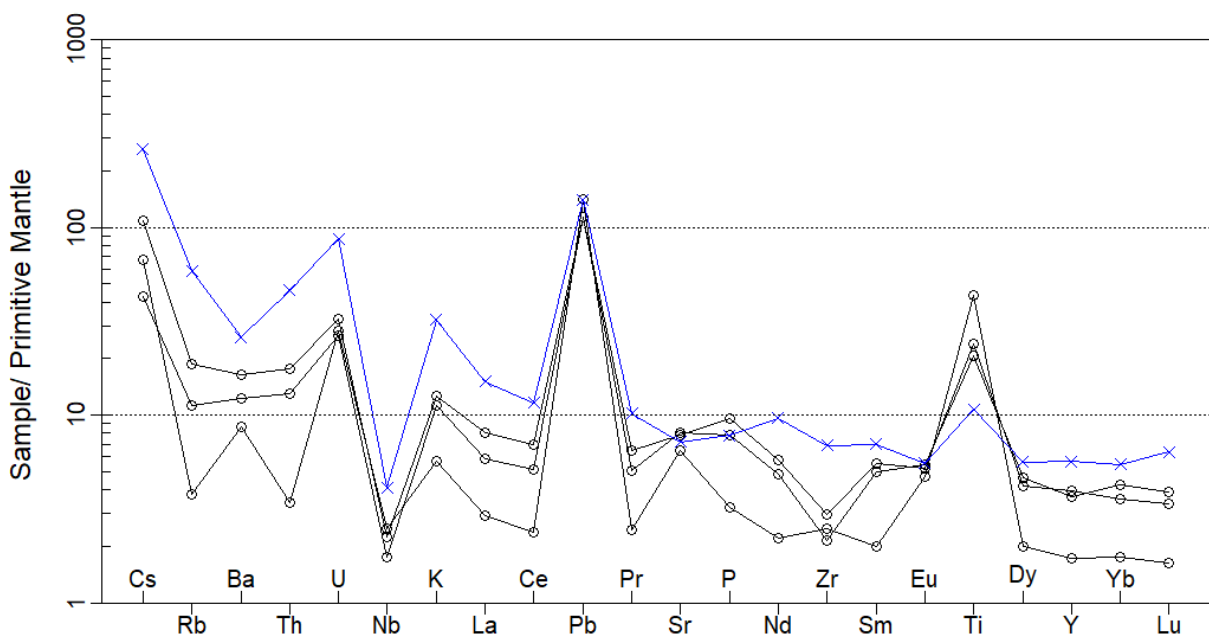


Figure 280. Primitive mantle normalised diagram for Andberget (black circles) and Gräsberget (blue 'X'). Normalising values from Sun & McDonough (1989).

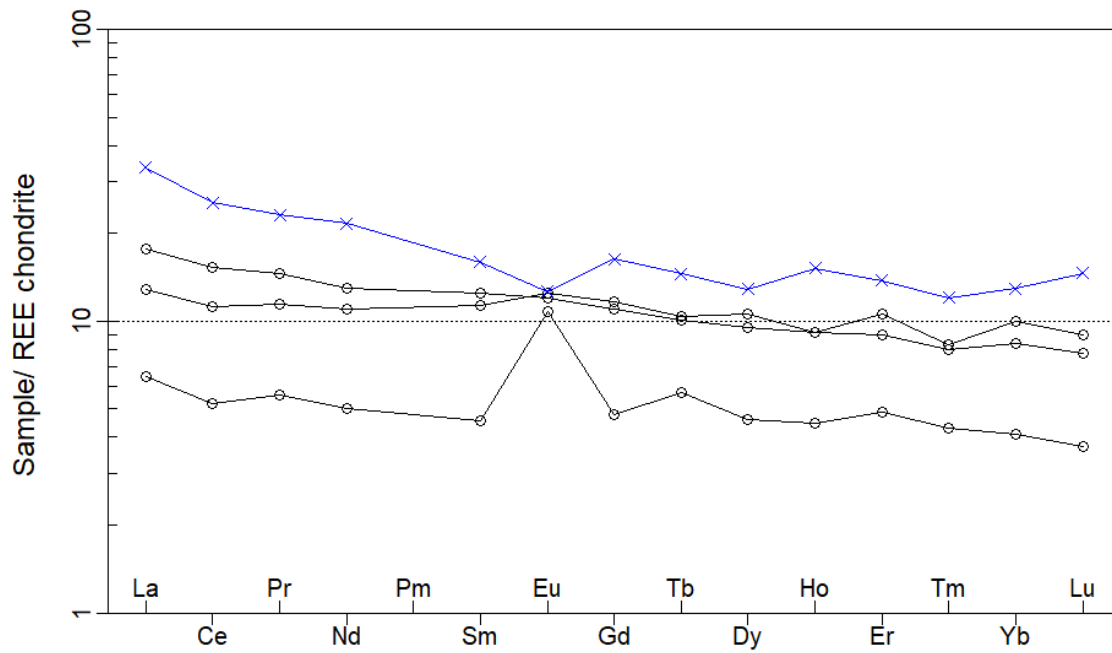


Figure 281. Chondrite normalised REE diagram for samples from Andberget (black circles) and Gräsberget (blue 'X'). The samples are characterised by patterns with moderate $(La/Yb)_N$ ratios (1.57–2.60). Chondrite values are from Boynton (1984).

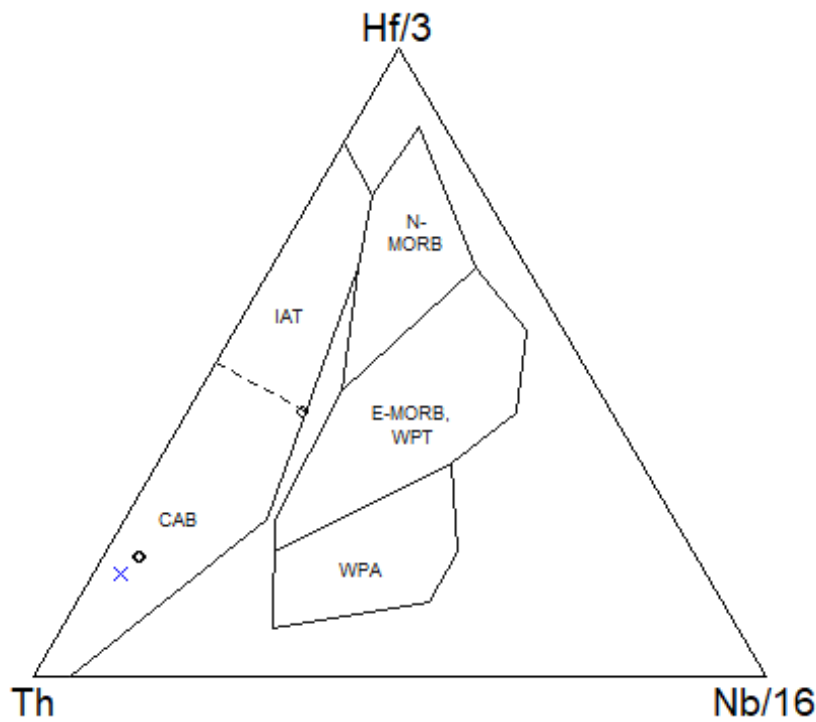


Figure 282. Andberget (black circles) and Gräsberget (blue 'X') samples plotted in a triangular diagram for tectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB-WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

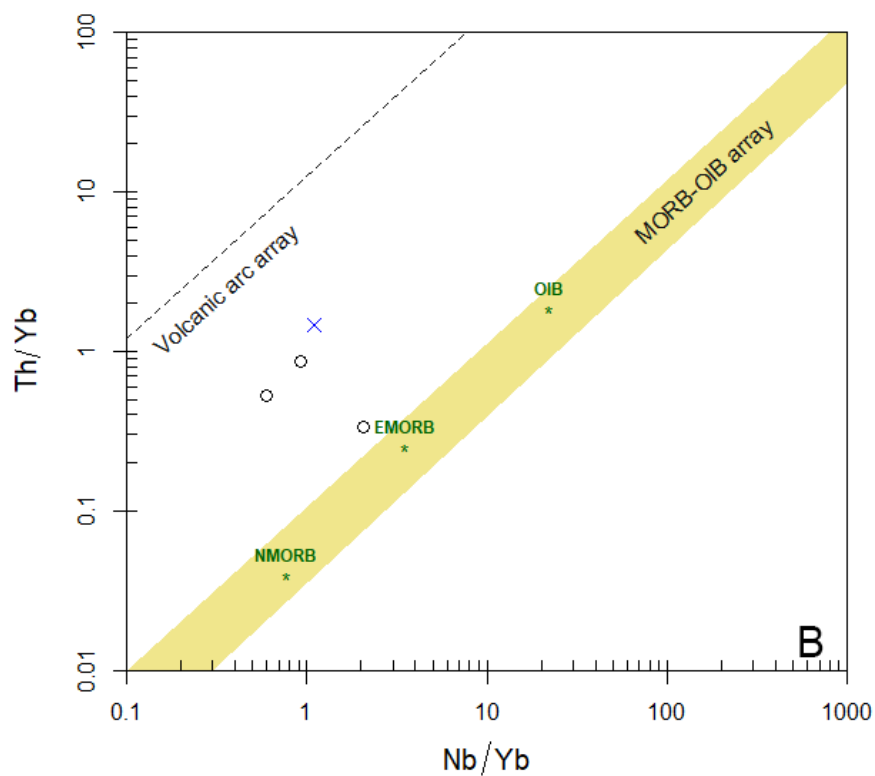
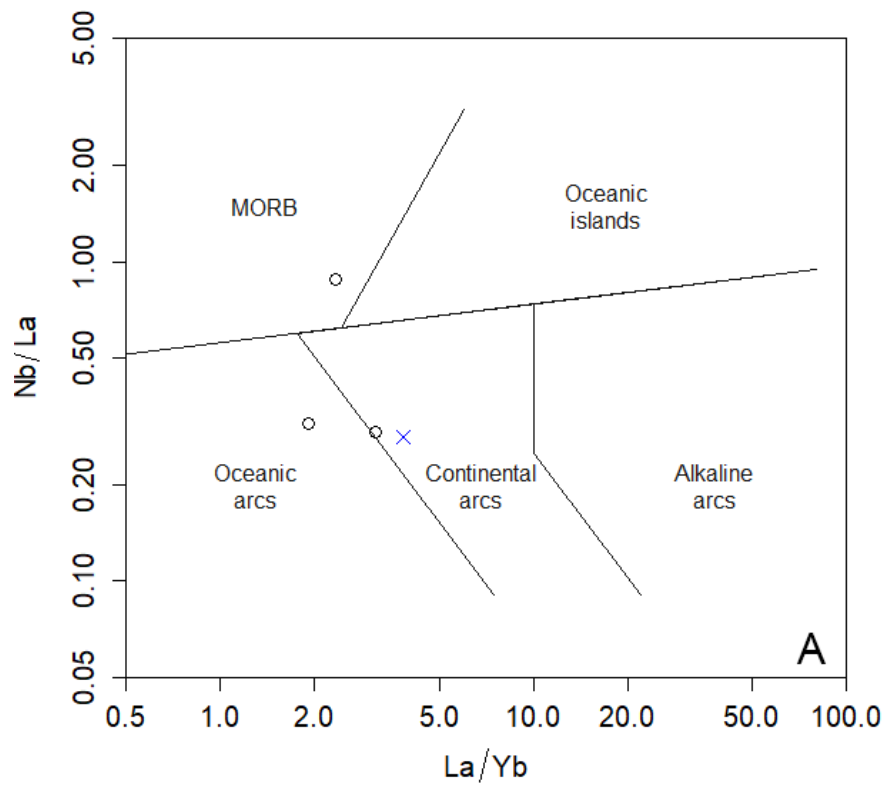


Figure 283. Andberget (black circles) and Gräsberget (blue 'X') plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

The area between Bollnäs and Ockelbo

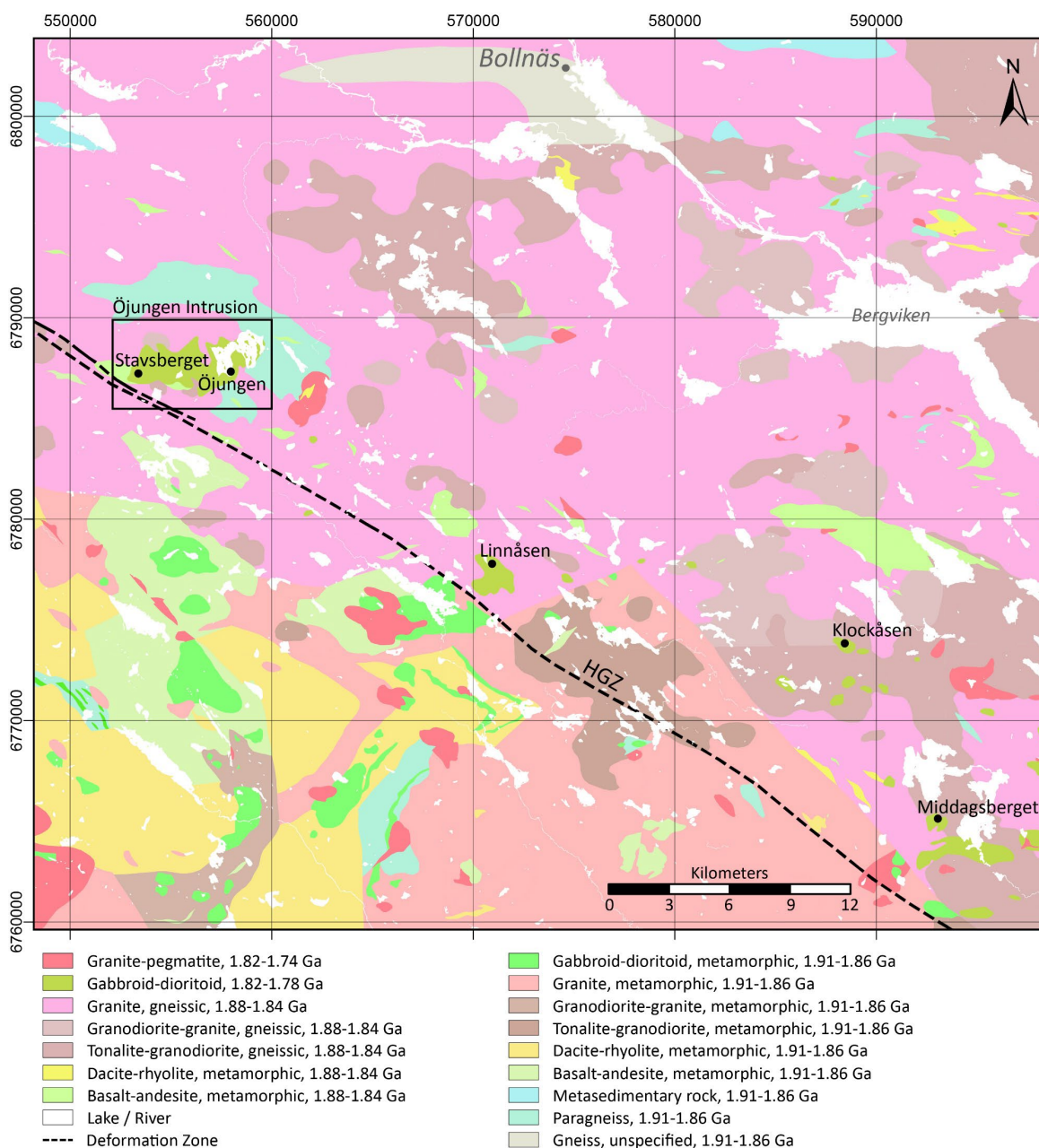


Figure 284. Bedrock geology map showing the area between Bollnäs and Ockelbo. The names of the locations referred to in the text are labelled in black. Note that Öjungen and Stavsberget are both localities on the Öjungen intrusion. HGZ: Hagsta gneiss zone.

Several mafic intrusions, visible as anomalies on the aeromagnetic map occur in the area between Bollnäs and Ockelbo in the southern part of the Ljusdal lithotectonic unit (fig. 284). Prior to this project very little data regarding the mineralogical and geochemical characteristics of these intrusions were available in the SGU databases. Although these intrusions occur outside of the main defined project area, their magnetic signature warranted a closer look. Therefore, a selection of the intrusions was visited, sampled and analysed in the current project to compare with the gabbroids further to the north in the Dellen-Ljusdal-Järvsö area.

Geological observations

A large gabbroic intrusion occurs in the area around lake Stora Öjungen (Öjungen intrusion) c. 25 km southwest of Bollnäs. The aeromagnetic anomaly indicates a body covering an area of approximately 8×3.5 km. In outcrop at Öjungen a massive, light greyish gabbroid with a diffuse modal layering defined by centimetre thick dark layers alternating with dm-thick light-coloured layers was observed (figs. 285 and 286). Another outcrop approximately 5 km to the west at Stavsberget, presumably in the same intrusion, comprising massive gabbroid was also sampled (fig. 287).

At Middagsberget (c. 15 km north of Ockelbo) a medium-grained, greyish, gabbroic rock with altered appearance is exposed in several outcrops (fig. 288). The altered character is very different from the vanadiniferous gabbroids in the Dellen–Ljusdal–Järvsö area. Magnetic susceptibility shows large variations across the visited outcrops.

Klockåsen (c. 20 km north of Ockelbo) comprises several outcrops of well-exposed predominantly massive gabbroic rocks. In places a weak modal layering is visible (fig. 289A). At one locality a medium-grained gabbroid occurs as enclaves or inclusions with knife sharp contacts to a more fine-grained gabbroic rock (fig. 290). Megacrysts of clinopyroxene (fig. 291) occur in both types, although these are more abundant in the coarse variant.

At Linnåsen (c. 25 km south of Bollnäs) an outcrop comprising fine- to medium-grained, massive gabbroid was sampled (fig. 292). This locality is located at the southwestern edge of the Ljusdal lithotectonic unit, approximately 1 km from the inferred regional Hagsta gneiss zone (fig. 284), but no visible tectonic overprint was noted at this outcrop.



Figure 285. Gabbroid at Öjungen has a weak modal layering, parallel to the scale, (6787647/558408). Photo: Helge Reginiussen.



Figure 286. Close-up of gabbroid from Öjungen (6787647/558408). Photo: Helge Reginiussen.



Figure 287. Massive gabbroid at Stavsberget (6786946/553161). Photo: Daniel Sopher.

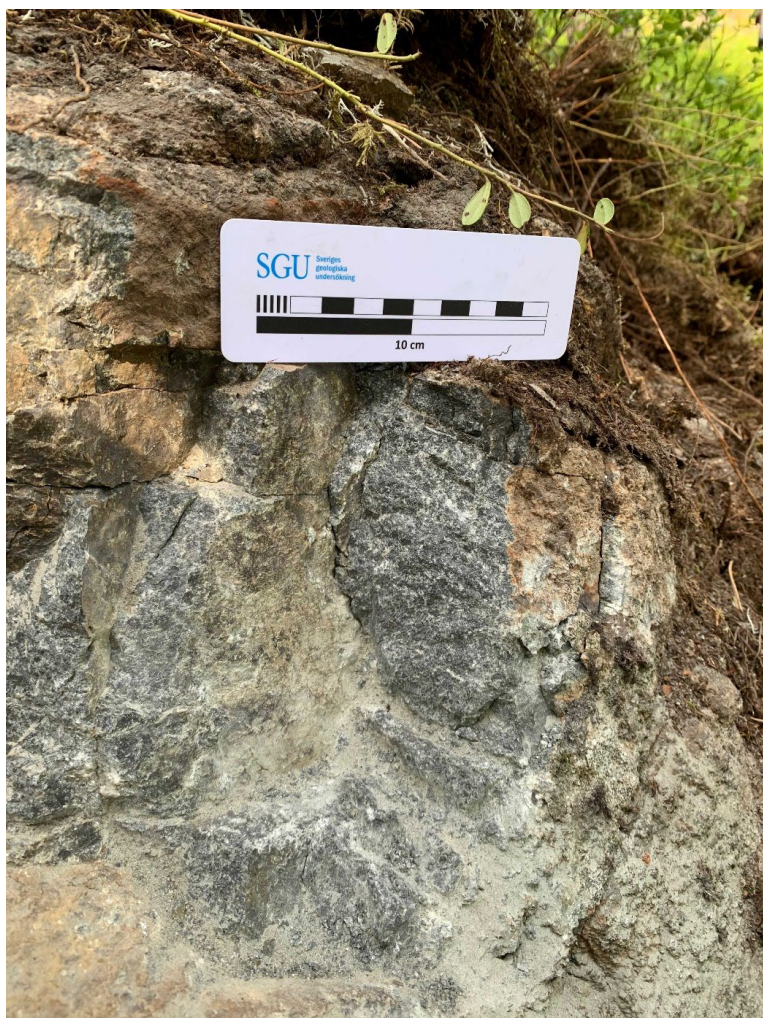


Figure 288. Altered gabbroid at Middagsberget (6765088/592681). Photo: Helge Reginiussen.

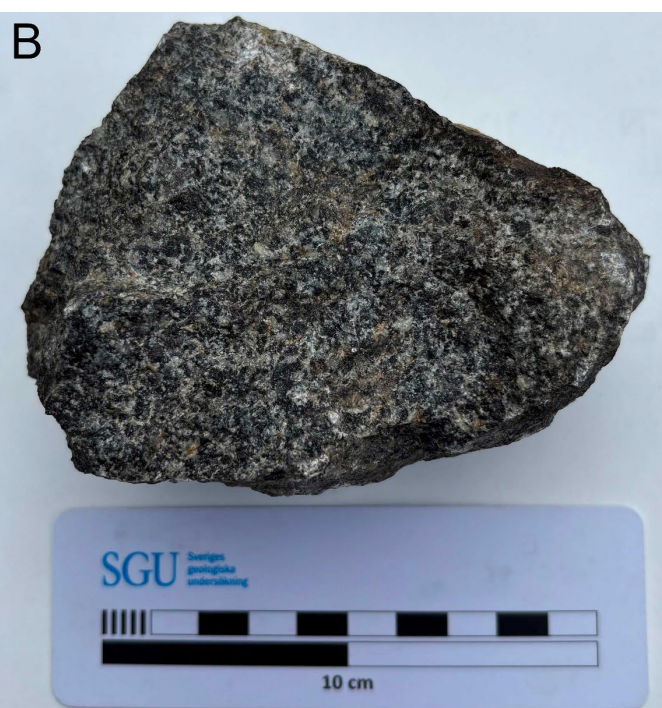


Figure 289. A. Outcrop at Klockåsen showing a predominantly massive gabbroid with a weak modal layering. B. Close-up of sampled gabbroid (6773765/588303). Photo: Helge Reginiussen.



Figure 290. Fine- to medium-grained gabbroid at Klockåsen with enclaves of coarser gabbroid. (6773754/588406).
Photo: Helge Reginiussen.



Figure 291. Sample from gabbroid at Klockåsen (6773754/588406).
Photo: Helge Reginiussen.



Figure 292. Massive, fine- to medium-grained gabbroid at the western slope of Linnåsen (6777721/571029). Photo: Helge Reginiussen.

Description of thin sections – silicate minerals – Öjungen intrusion

A sample from the Öjungen intrusion is mostly well-preserved, relatively coarse-grained, and looks different compared to most thin sections in this study (fig. 293). Hornblende is the main mafic silicate mineral with subhedral to anhedral, small to large grains. Some hornblende oikocrysts with chadacrysts of plagioclase, clinopyroxene, and opaque minerals occur, whereas intricately intergrown hornblende with clinopyroxene is present. Clinopyroxene occurs mostly within hornblende or intergrown with hornblende, and minor alteration is observable.

Plagioclase is subhedral to anhedral with small and large grains. Plagioclase has in several large, subhedral crystals recorded a complex growth history, with well-preserved distinct rims and zonation, and possible resorption (figs. 293C–E). These rims and zonation patterns are interpreted to indicate that the crystals grew for the most part with access to a supernatant liquid, but that the conditions changed during their growth (Deer *et al.* 2001). The patterns may occur due to e.g., changes in chemical composition of the supernatant liquid and changes in crystallisation temperature, inferring a rather turbulent life in a magma chamber or conduit where transport within or replenishment of the magma chamber may have occurred, instead of a more stable location like a crystal mush (Deer *et al.* 2001 and references therein). The zonation patterns of plagioclase in the Öjungen sample have not been observed in any of the other samples studied in this project, with the exception of outer growth of an interstitial nature that is different compared to the cores of the grains, which is observed in most samples studied.

Biotite occurs as two groups, the first formed has brown pleochroism and the second brownish red to light tan. Biotite is relatively abundant in this sample. Large and small interstitial crystals of quartz have undulose extinction (fig. 293F). Grains of magnetite with small ilmenite parts occur and sulphide minerals as small grains to droplets.

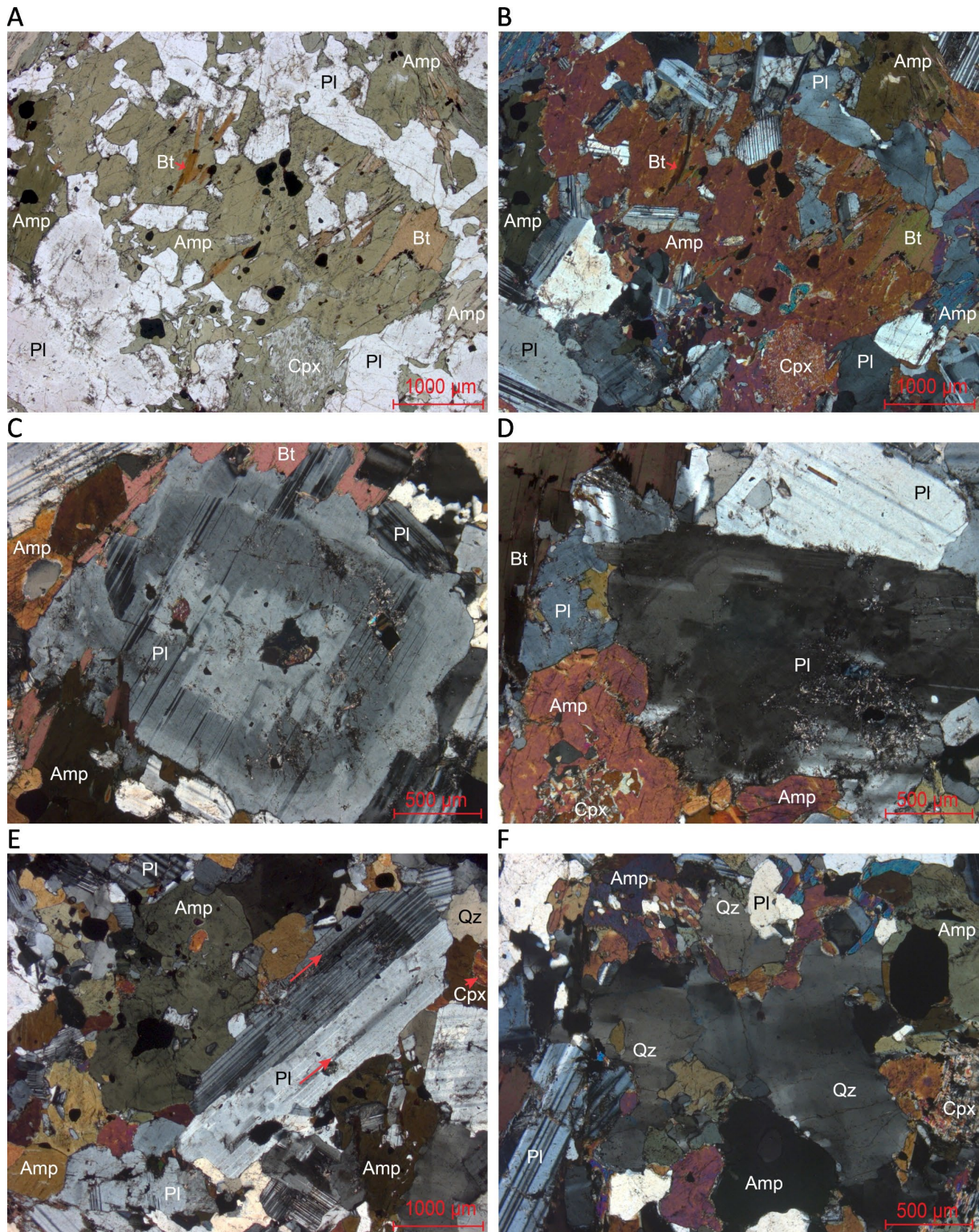


Figure 293. Gabbroid cumulate with hornblende as main mafic mineral. **A.** and **B.** Hornblende oikocryst with chadacrysts of plagioclase + clinopyroxene + opaque minerals. **C.** Subhedral, large plagioclase with complex growth zoning, recording at least three different episodes of growth. **D.** Subhedral, large plagioclase with several episodes of growth as rims outboard of the original crystal. **E.** Subhedral, large plagioclase with original crystals along strike perimeter marked with red arrows, major additional growth is seen at both ends as well. **F.** Large crystals of undulose quartz. Sample HRE230019A (6787647/558408). A. in ppl and the rest of images in xpl. Photo: Dick Claeson.

Geochemical data for the area between Bollnäs and Ockelbo

In detail the geochemical signatures of these intrusions differ from the vanadiniferous gabbroids in the Ljusdal-Dellen-Järvsö area e.g., in the AFM diagram (fig. 294) the samples from Klockåsen stand out by plotting in the calc-alkaline field. The samples analysed generally have low vanadium contents; Stora Öjungen (391–517 ppm), Middagsberget (295 ppm), Klockåsen (208–237 ppm), and Linnåsen (572 ppm). The trace-element patterns do, however, resemble Island arc basalts, with negative Nb and Ti anomalies and positive Pb anomalies in a primitive mantle normalised diagram (fig. 295), but they generally have higher $(La/Yb)_N$ ratios than most of the other gabbroids analysed in this project (fig. 296). The Klockåsen samples stand out with $(La/Yb)_N$ ratios in the range 10.91–14.90. Many of these samples also show fractionation among the HREE. For example, Klockåsen has elevated $(Gd/Yb)_N$ ratios (2.62–2.78) and $(Dy/Yb)_N$ ratios (1.51–1.54).

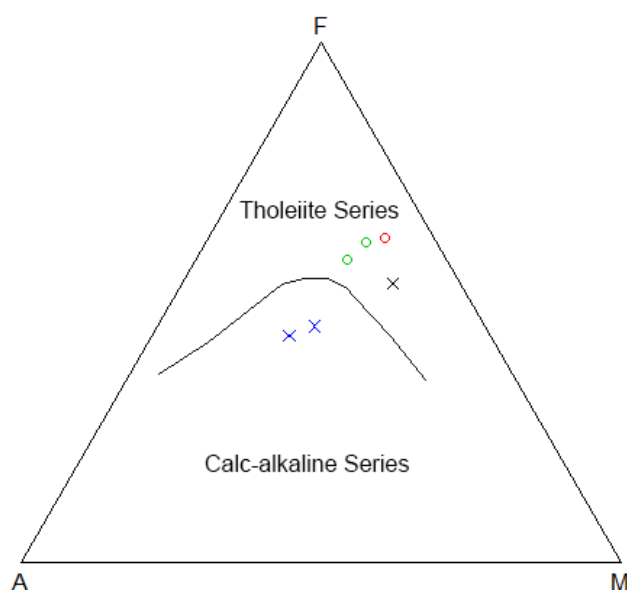


Figure 294. AFM diagram (Irvine & Baragar 1971) for Klockåsen (blue 'X'), Öjungen and Stavsberget (green circles), Linnåsen (red circle), and Middagsberget (black 'X').

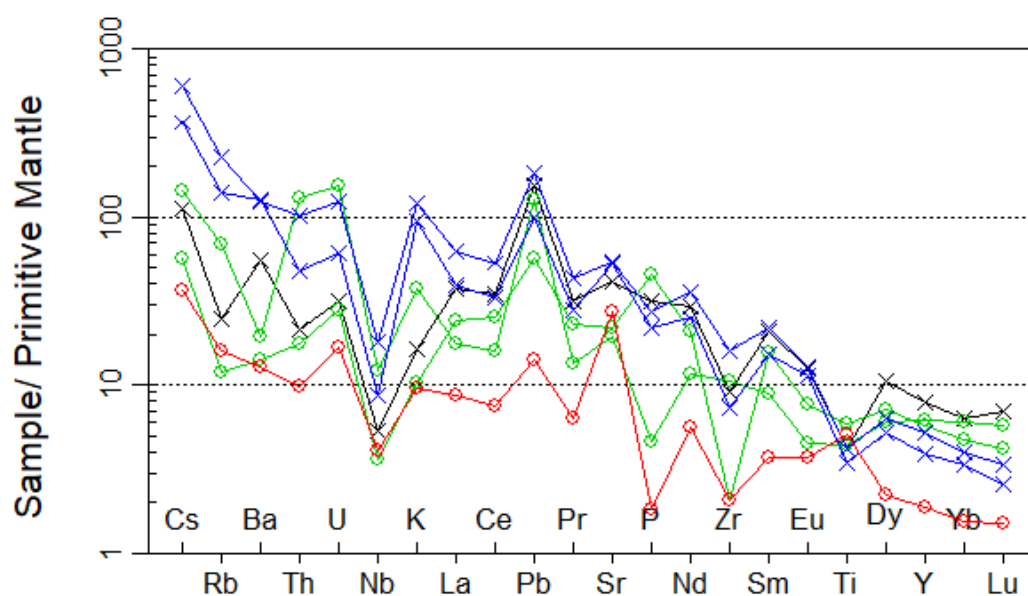


Figure 295. Primitive mantle normalised diagram for Klockåsen (blue 'X'), Öjungen and Stavsberget (green circles), Linnåsen (red circle), and Middagsberget (black 'X'). Normalising values from Sun & McDonough (1989).

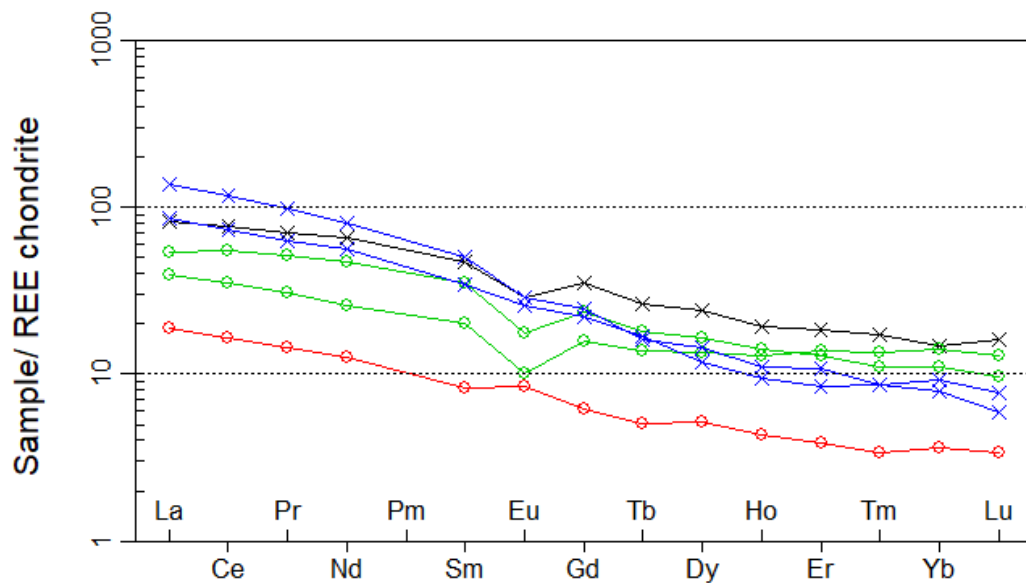


Figure 296. Chondrite normalised diagram for Klockåsen (blue 'X'), Öjungen and Stavsberget (green circles), Linnåsen (red circle), and Middagsberget (black 'X'). Most of the samples have elevated $(La/Yb)_N$ ratios (2.77–14.90, average 7.37) compared to other gabbroids studied in this project. Chondrite values are from Boynton (1984).

In the Th-Hf-Nb diagram (fig. 297) the samples plot in the field of Island arc calc-alkaline basalt (CAB). Due to the high La/Yb these samples plot in the field of alkaline arcs in figure 298A.

The geochemical and petrographical characteristics suggest that these intrusions belong to a younger generation of mafic intrusives than the vanadiniferous gabbros further north in Ljusdals lithotectonic unit. A possibility is that these belong to the Transscandinavian Igneous Belt (TIB).

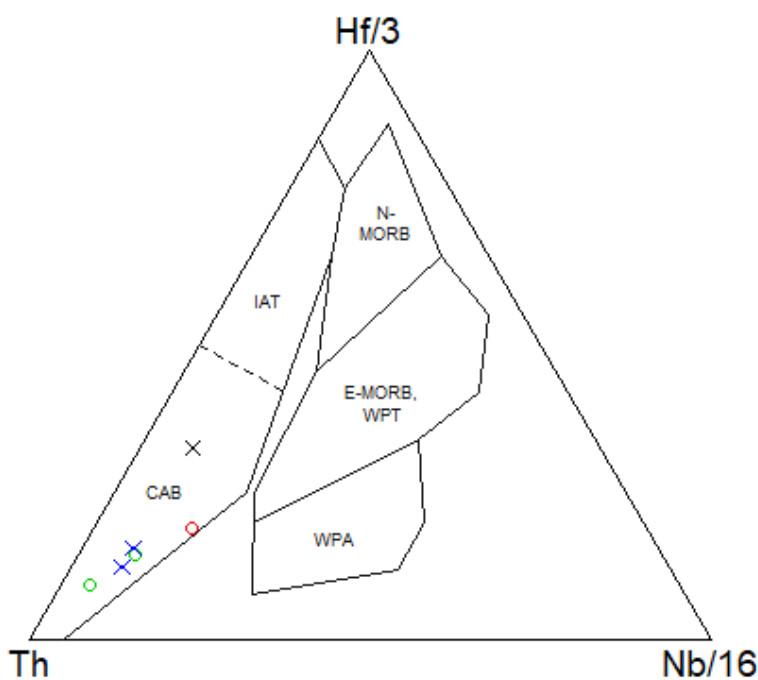


Figure 297. Klockåsen (blue 'X'), Öjungen and Stavsberget (green circles), Linnåsen (red circle), and Middagsberget (black 'X') plotted in triangular diagram for tectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB, WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

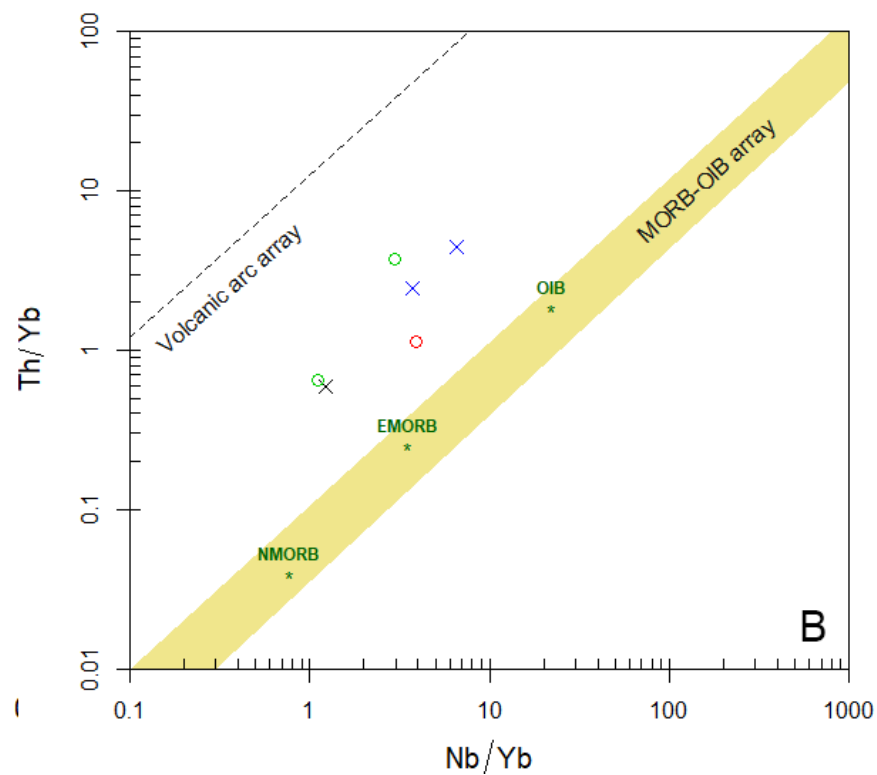
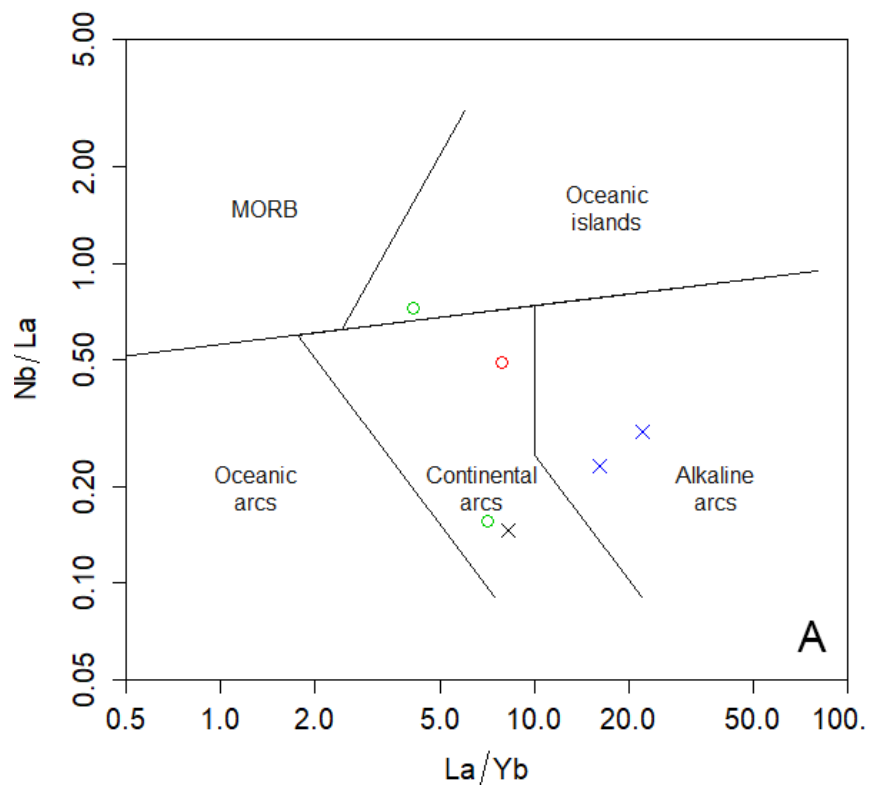


Figure 298. Klockåsen (blue 'X'), Öjungen and Stavsberget (green circles), Linnåsen (red circle), and Middagsberget (black 'X'). plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Lördagsberget

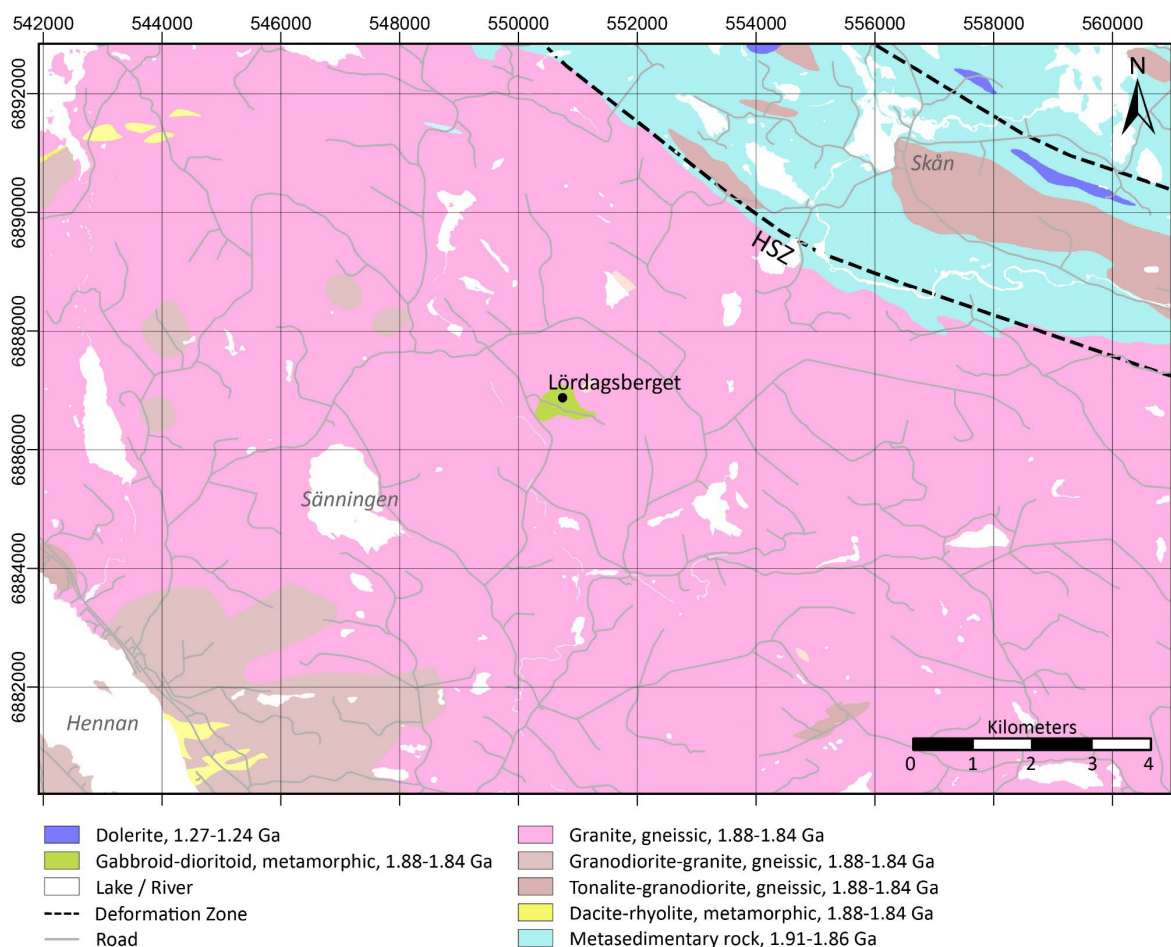


Figure 299. Bedrock geology map showing the area around Lördagsberget. The location of Lördagsberget is labelled in black. Names of some lakes and towns are shown as grey italic text. HSZ: Hassela shear zone.

A metagabbroic rock is exposed close to a forest road at the southwestern slope of Lördagsberget in the northern part of the Ljusdal lithotectonic unit less than 5 km south of the Hassela shear zone some 30 km north northwest of Ljusdal (fig. 299).

In outcrop, the gabbroid is predominantly massive, but exhibits an altered appearance with a high proportion of secondary amphibole concentrated in aggregates (figs. 300 and 302). Thin shear zones (1-2 mm thick) crosscut the rock (fig. 301). Magnetic susceptibility is relatively low (<0.007 SI units).

Only reconnaissance sampling and no detailed work on this rock has been undertaken, but the initial field impression, including the occurrence of abundant thin shear zones, suggests that this gabbroid differs in terms of mineralogy and deformation history from the vanadiniferous gabbroids in the Ljusdal–Dellen–Järvsö area. The metagabbro at Lördagsberget is thus suggested to be of a generation older than the vanadiniferous gabbroids.

Lithogeochemical analysis (one sample only) shows low contents of Fe, Ti, and V. $\text{Fe}_2\text{O}_3 = 14.0\%$, $\text{TiO}_2 = 1.17\%$, and V = 218 ppm.



Figure 300. Outcrop with gabbroid at Lördagsberget (6886672/550761). Photo: Helge Reginiussen.

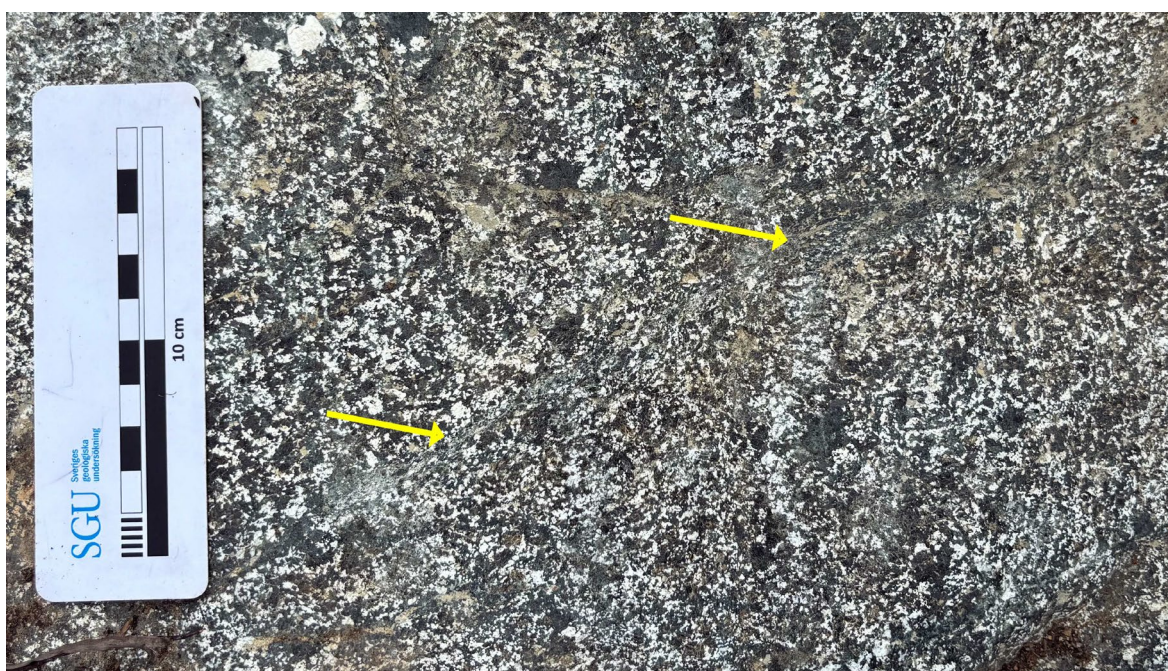


Figure 301. Gabbroid from Lördagsberget. Note thin shear zone in the middle of the image (indicated by arrows) trending from the lower left corner to the upper right corner (6886672/550761). Photo: Helge Reginiussen.



Figure 302. Sample of gabbroid from Lördagsberget (6886672/550761). Photo: Helge Reginiussen.

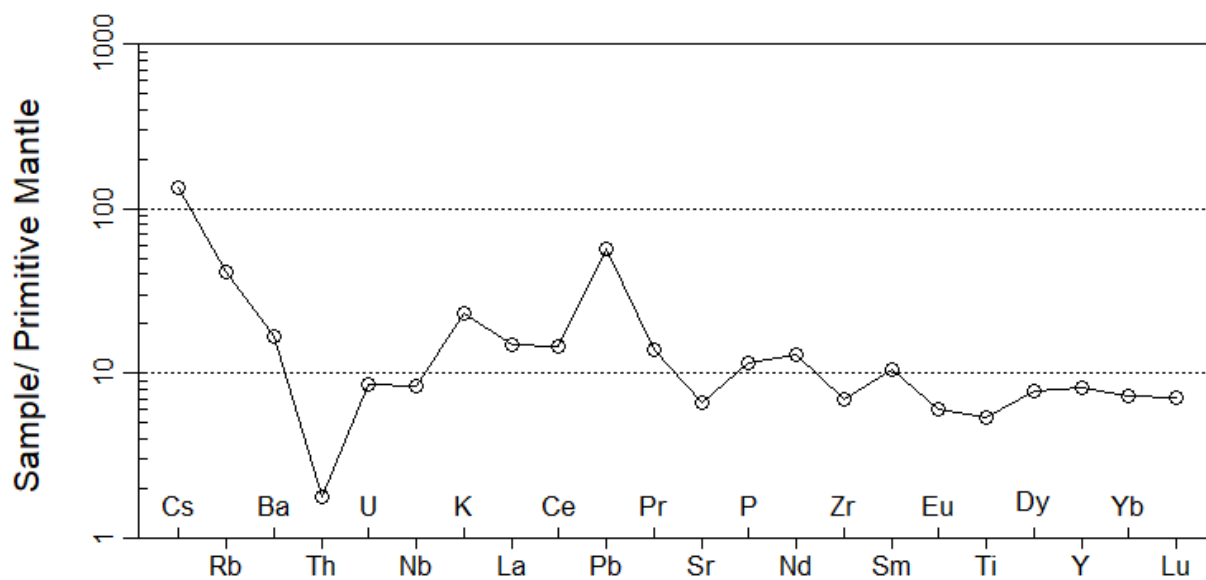


Figure 303. Primitive mantle normalised diagram for one sample from Lördagsberget. Note absence of negative Nb-anomaly. Normalising values from Sun & McDonough (1989).

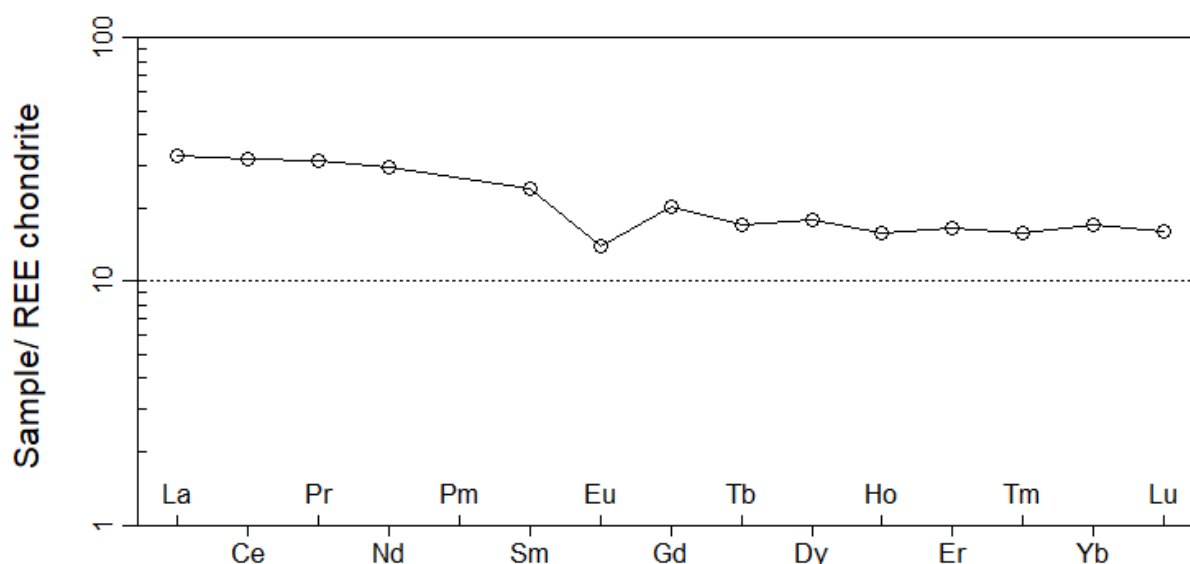


Figure 304. Chondrite normalised diagram for the sample from Lördagsberget. The sample has low LREE/HREE ratio $(La/Yb)_N = 1.93$. Chondrite values are from Boynton (1984).

It is not possible to draw definite conclusions from one sample only, but it should be noted that the analysed sample does not have the negative Nb-anomaly which is common in samples from the other analysed mafic rocks in this project (fig. 303). A weak negative Ti-anomaly is present. The LREE/HREE ratio is low (fig. 304). The very low content of Th gives a very distinctive negative Th-anomaly, and a positive Pb-anomaly is evident. In the Th-Hf-Nb diagram (fig. 305) the sample plots in the field of E-MORB, WPT. The low Th/Yb coupled with a high Nb/Yb results in that the sample plots outside of both the volcanic array and the “Mantle Array” (fig. 306).

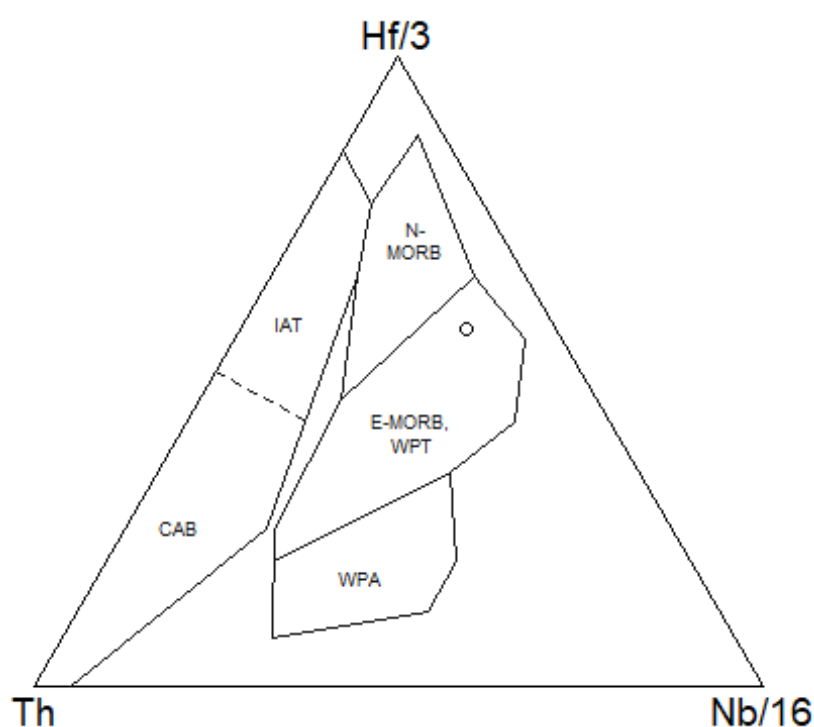


Figure 305. Sample from Lördagsberget plotted in a triangular diagram for tectonic discrimination (Wood 1980). Abbreviations: CAB (Island arc calc-alkaline basalt), IAT (Island arc tholeiite), N-MORB (Normal mid-ocean ridge basalt), E-MORB, WPT (Enriched mid-ocean ridge basalt/intraplate tholeiitic basalt), WPA (Intraplate alkaline basalt).

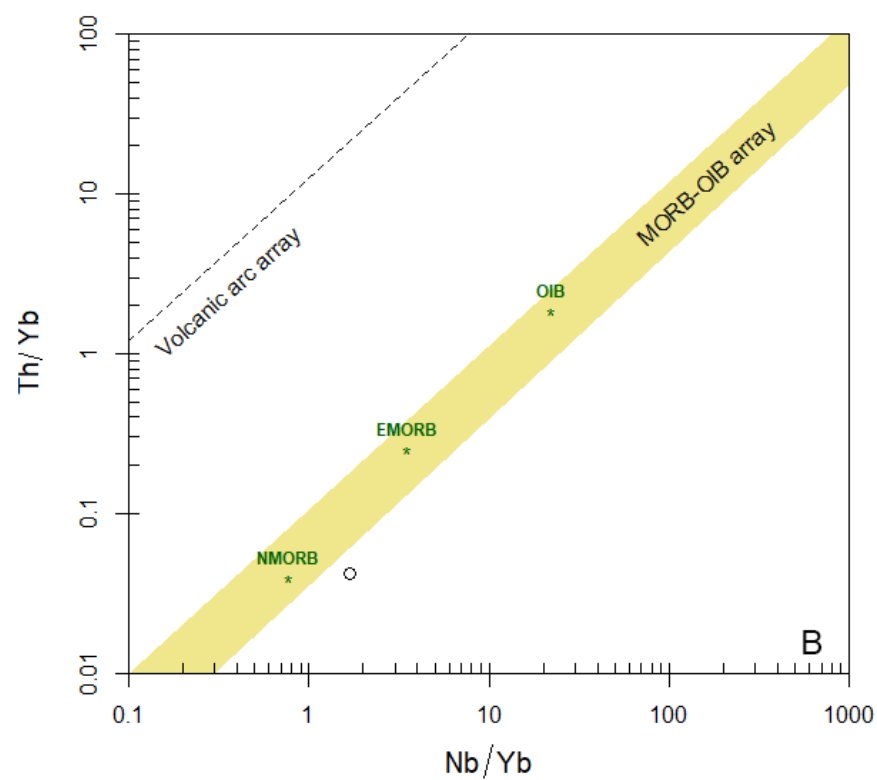
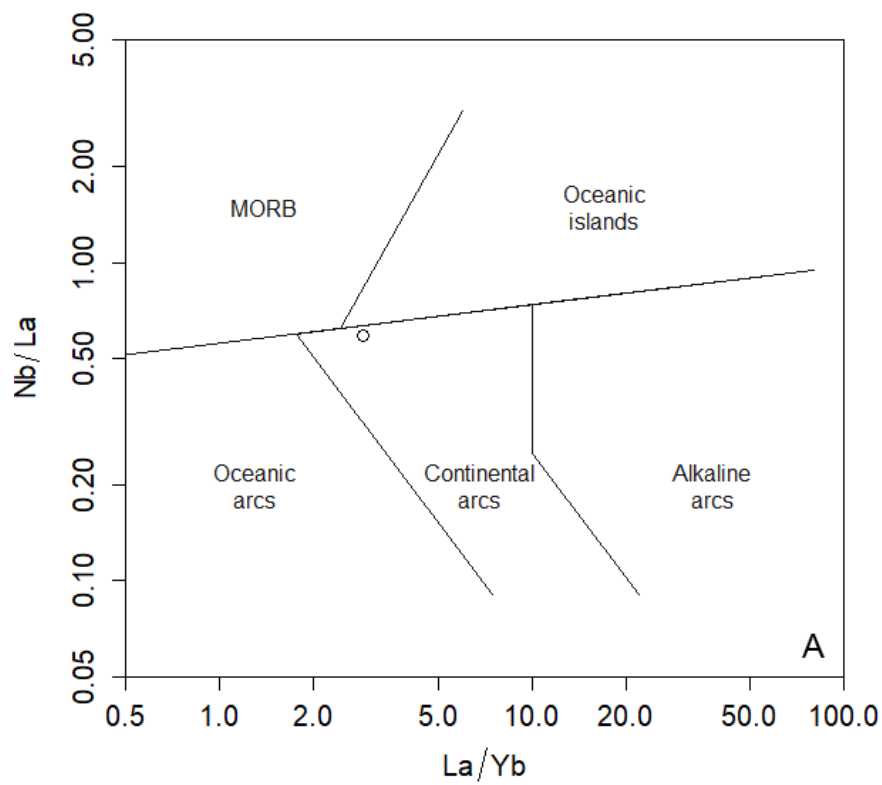


Figure 306. Sample from Lördagsberget plotted in diagrams for geotectonic discrimination. **A.** La/Yb vs. Nb/La diagram (Hollocher *et al.* 2012). **B.** Nb/Yb vs. Th/Yb diagram (Pearce 2008).

Poikilitic texture with oikocrysts and chadacrysts within mafic intrusions of the Ljusdal batholith

Poikilitic texture is produced when smaller crystals are enclosed within a larger crystal in an igneous rock. The enveloping crystal is called an oikocryst and the enclosed crystals chadacrysts. During the formation of the oikocryst, some earlier formed chadacrysts may become partly or completely resorbed when interacting with the later-formed liquid, due to them no longer being stable. For the most part chadacrysts do survive and have well-developed crystal faces, euhedral or subhedral.

The first relevant question to be addressed concerning how oikocrysts grow is: where do they grow? In cumulates, oikocrysts are nominally interpreted as having grown after initial accumulation of cumulus grains (chadacrysts). However, chemical and/or textural evidence has led to interpretations that some oikocrysts started to grow prior to accumulation, i.e., within the supernatant liquid, and the included minerals in those parts of the oikocryst are thought of as primocrysts (e.g., Tegner & Wilson, 1995, Latypov *et al.* 2024). To include abundant chadacrysts, an oikocryst should grow in a crystal-rich portion of the magma chamber. The simplest way is to grow in the crystal pile at the floor or in an inward growing boundary layer at the roof or walls. An oikocryst that grows in equilibrium with the main magma reservoir will show little or no compositional zoning because its growth will not substantially modify the liquid composition from which it is growing. If the liquid composition evolves progressively during oikocryst growth, for example in a solidifying mush where pore space becomes limited and thus is no longer in continuous contact with the main magma reservoir, different domains from the same oikocryst will have compositional zoning (e.g., Meurer & Claeson 2002, Claeson *et al.* 2007).

There are several examples of different minerals making up oikocrysts as well as chadacrysts in the intrusions included in this project. Clinopyroxene and hornblende are the most common oikocrysts. In some rare cases biotite can also form oikocrysts. Minerals occurring as chadacrysts are clinopyroxene, hornblende, olivine, plagioclase, and opaque minerals. Oikocrysts can be used to interpret how interstitial liquids evolve and the order of crystallisation, infer other processes like different degrees of contamination in layered ultramafic rocks, structural order as well as replenishment events in layered intrusions, and several other petrogenetic issues (e.g., Meurer & Claeson 2002, Claeson *et al.* 2007, Namur *et al.* 2010, Barnes *et al.* 2016, Latypov *et al.* 2024).

The large clinopyroxene oikocryst from Simesvallen with lots of small olivine chadacrysts showing no resorption texture in figure 307 may be interpreted as an oikocryst that started growing prior to accumulation in a crystal mush (e.g., Tegner & Wilson 1995; Holness *et al.* 2007a,b, Latypov *et al.* 2024). This oikocryst grew in equilibrium with the main magma reservoir and shows little or no compositional zoning because its growth was not substantially modified by the liquid composition. Most of these small olivine crystals (primocrysts) were included at this stage because the clinopyroxene growth rate was much faster than that for olivine. At a later stage when olivine primocrysts stopped forming, the olivine chadacrysts were preserved within the clinopyroxene oikocryst, which at this time was located in the crystal pile or mush (fig. 307). This oikocryst also shows that both olivine and clinopyroxene were on the liquidus of the supernatant liquid at the stage of olivine inclusion.

In some oikocrysts, earlier formed chadacrysts are partly or completely resorbed due to interacting with a later-formed liquid. The large oikocryst of dark brown hornblende with chadacrysts of plagioclase and clinopyroxene from the Kramsta intrusion is a good example of this resorption texture (figs. 308A, B). Both clinopyroxene and plagioclase chadacrysts are for the most part just remnants left from the dissolution-resorption process. Other oikocrysts lack textural indication of resorption. An example of a clinopyroxene oikocryst from the Kramsta intrusion with a large chadacryst of plagioclase and no resorption texture is shown in figures 308C and D.

To establish compositional zoning it has to be measured, however, in this study, the colour change in both plane-polarized and cross-polarized microscope images of several clinopyroxene oikocrysts (fig. 309) is a good indication that zoning is present and growth of the clinopyroxene oikocrysts took place in a place where the liquid composition evolved progressively. For example, in a solidifying mush where pore space becomes progressively more limited (e.g., Meurer & Claeson 2002, Claeson *et al.* 2007).

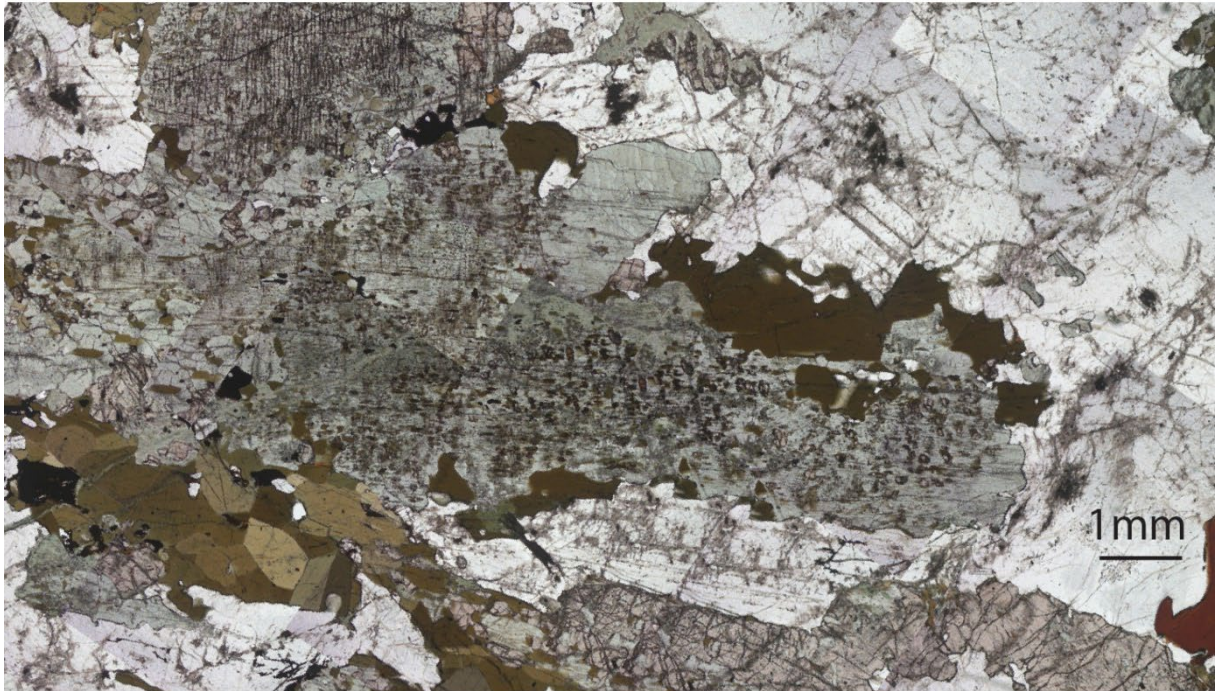
In some large hornblende oikocrysts, e.g., at Storåsen, green poikilitic hornblende have chadacrysts of clinopyroxene, hornblende, plagioclase, and opaque minerals (figs. 310A, B). Most of the chadacrysts show minor resorption features, with the exception of the hornblende chadacrysts with tan to brownish colour, which are subhedral and in part have well-developed crystal faces. An interpretation of this feature is that the hornblende chadacrysts formed from the supernatant liquid and thus were on the liquidus along with the rest of the chadacrystic minerals, the oikocryst would thus form later and most probably within a mush of crystals.

There are also sparsely occurring oikocrysts of biotite with chadacrysts of plagioclase and opaque minerals in the Bläckmyran intrusion. Here it is common to observe infilling of opaque minerals within the biotite, in some cases radiating from a larger opaque crystal or rounded plagioclase chadacryst (figs. 310C–E).

The wealth of oikocrysts of different minerals in the Fe-Ti-V intrusions is in line with our interpretation of these rocks as mostly composed of cumulates.

The suggested Transscandinavian Igneous Belt (TIB) intrusions in the southern part of the study area also have oikocrysts with chadacrysts, e.g., a sample from the Öjungen intrusion displays several hornblende oikocrysts with chadacrysts of clinopyroxene, plagioclase, and opaque minerals and some biotite oikocrysts with small plagioclase chadacrysts (fig. 311). However, the appearance of these oikocrysts does not resemble any of the ones found in thin-sections from the vanadiniferous gabbroic intrusions of the Ljusdal lithotectonic unit.

A



B

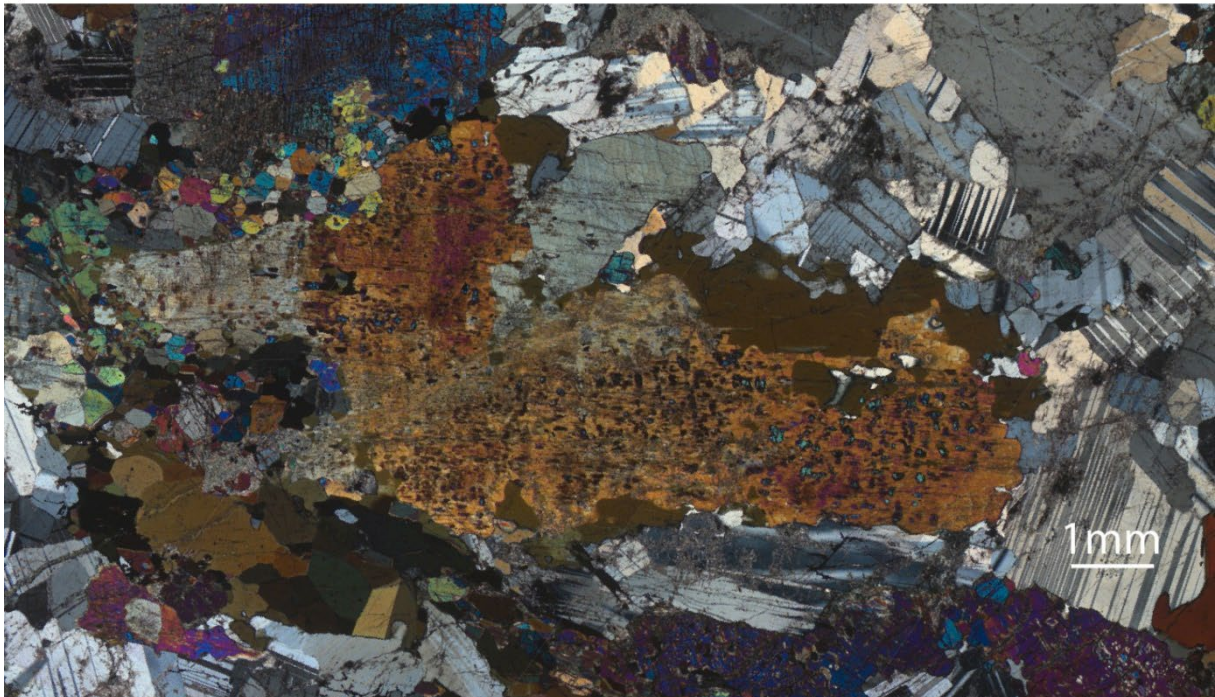


Figure 307. Oikocryst of clinopyroxene with lots of chadacrysts (primocrysts) of olivine with different orientation, some blue and others dark in the xpl-image, **A.** ppl and **B.** xpl. All olivine without resorption texture. Sample DCL222006B from drill core SIM82006 at 66.66–66.75 m from the Simesvallen intrusion. Photo: Dick Claeson.

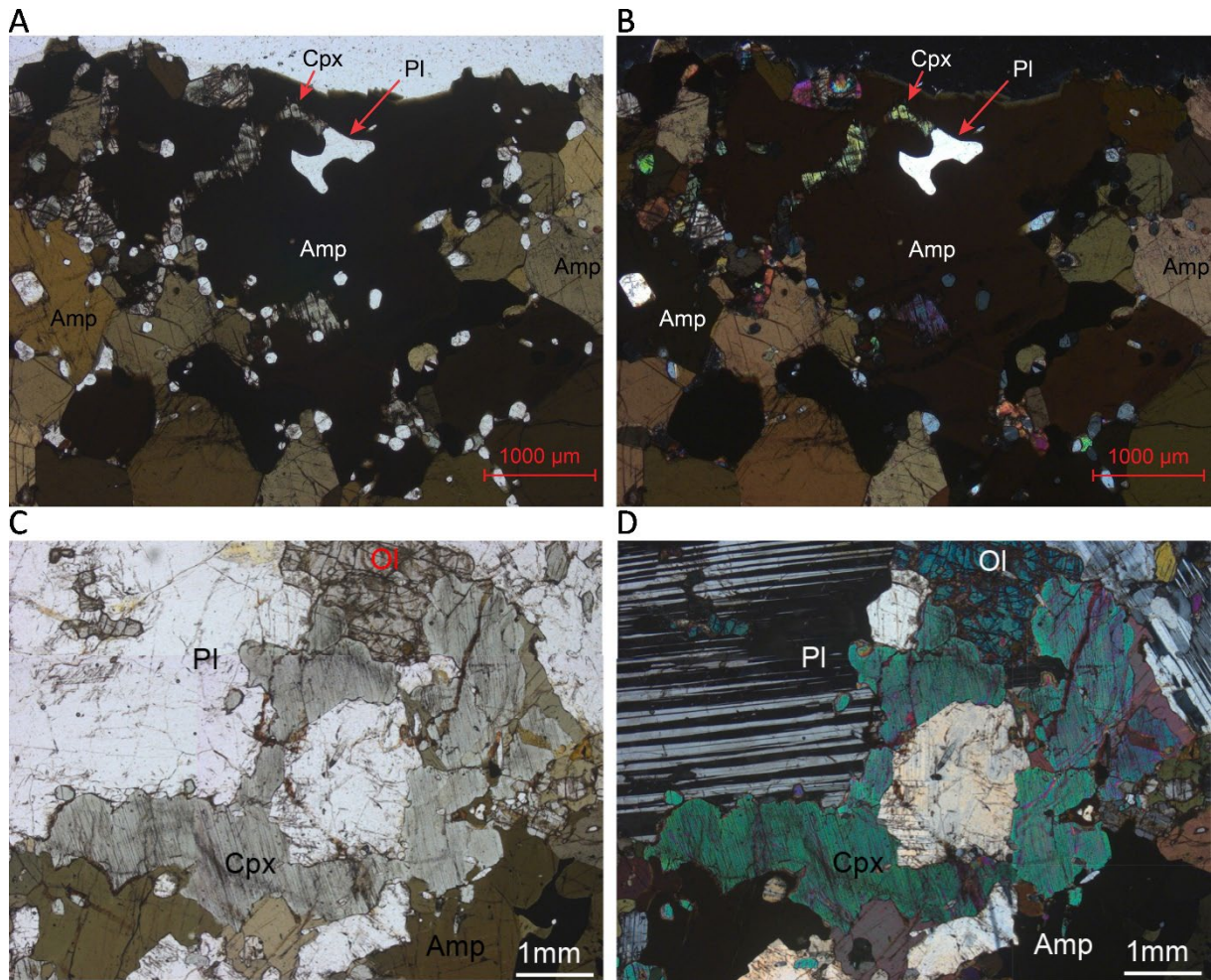


Figure 308. In the centre of the image is a large oikocryst of dark brown hornblende with chadacrysts of plagioclase and clinopyroxene, **A.** ppl and **B.** xpl. Both chadacryst minerals display resorption texture. Sample HRE220043A from the Kramsta intrusion. Oikocryst of clinopyroxene with a large chadacryst of plagioclase without resorption texture, **C.** ppl and **D.** xpl. Sample HRE220017A from the Kramsta intrusion. Photo: Dick Claeson.

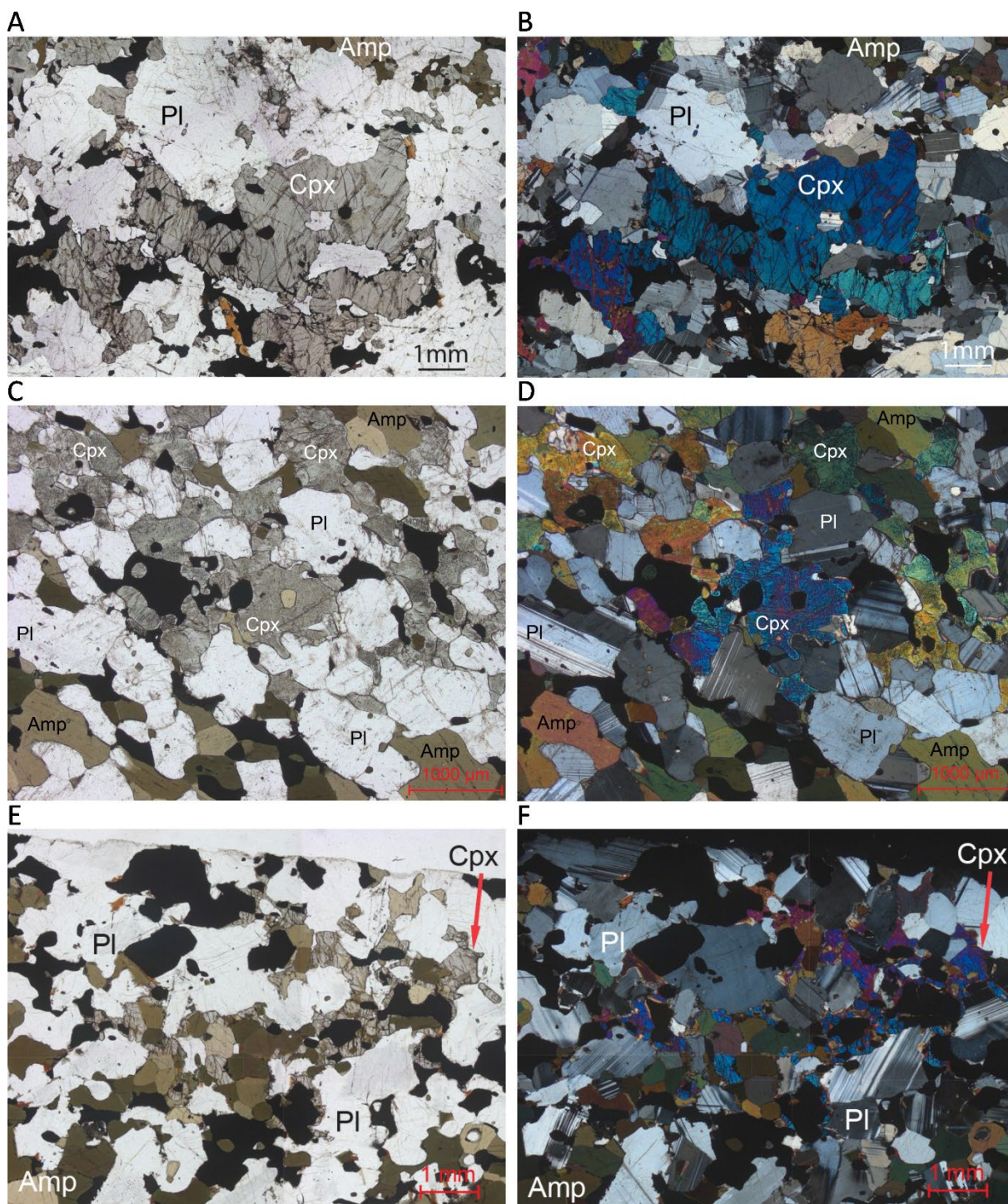


Figure 309. Oikocryst of clinopyroxene with chadacrysts of plagioclase and opaque minerals, **A.** ppl and **B.** xpl. Note the change in blue colour in clinopyroxene, sample DCL222009B from drill core SIM83002 at 38.73–38.79 m from the Simesvallen intrusion. Oikocryst of clinopyroxene with chadacrysts of hornblende, plagioclase, and opaque minerals in the centre of the images, **C.** ppl and **D.** xpl. Note the change in the blue colour of the oikocryst, sample DCL230002A from drill core BLA82004 at 61.33–61.37 m from the Bläckmyran intrusion. Oikocryst of clinopyroxene with chadacrysts of plagioclase and opaque minerals, **E.** ppl and **F.** xpl. Note the change in blue colour of the oikocryst and that the oikocryst occurs across almost the entire thin-section, sample DCL234000A from drill core BLA82006 at 13.54–13.60 m from the Bläckmyran intrusion. Photo: Dick Claeson.

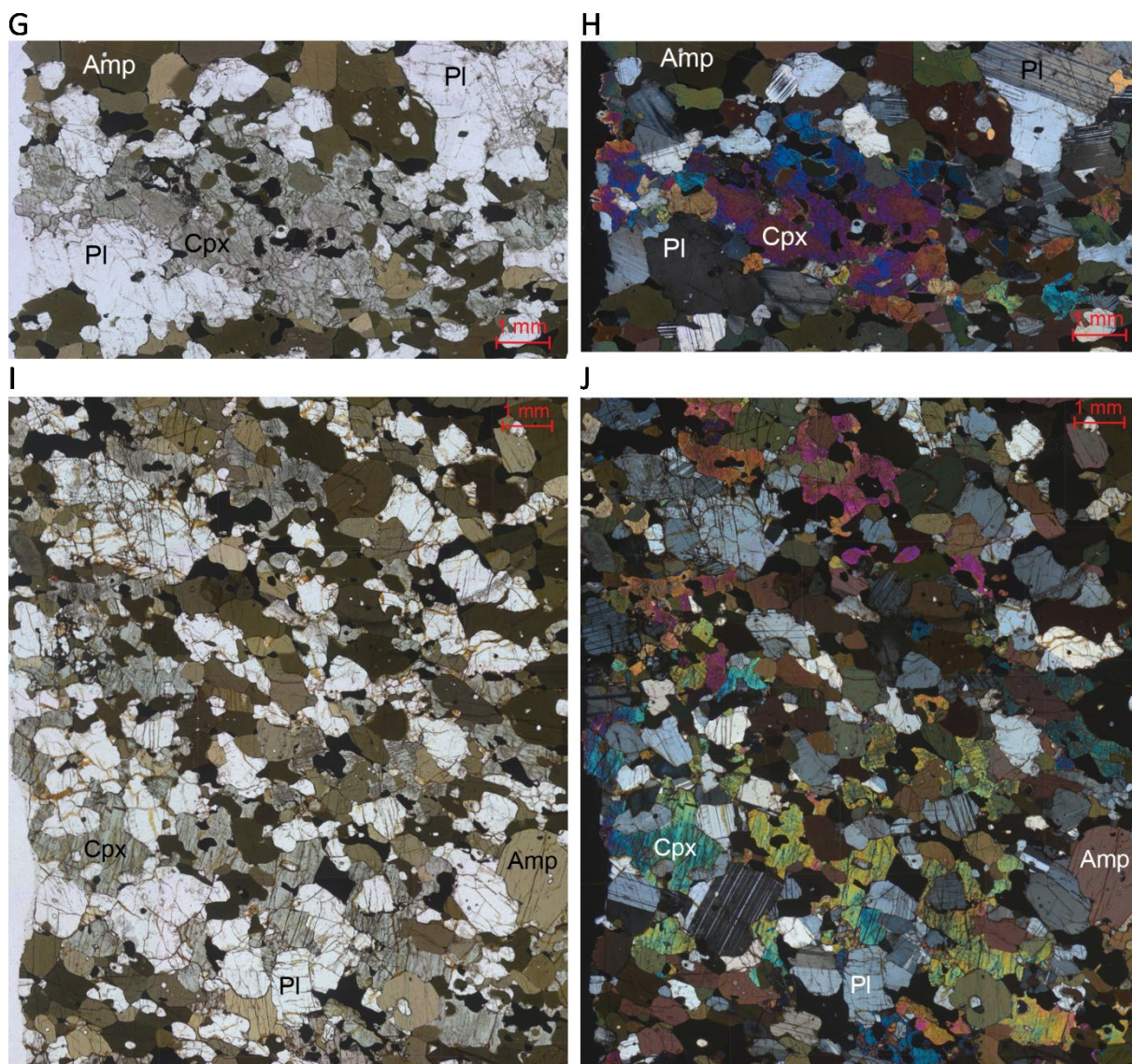


Figure 309. continued. Oikocryst of clinopyroxene with chadacrysts of hornblende, plagioclase, and opaque minerals, **G.** ppl and **H.** xpl. Note the change in blue colour of the oikocryst, sample DCL223043A from drill core BLA82008 at 89.29–89.33 m from the Bläckmyran intrusion. Several oikocrysts of clinopyroxene with chadacrysts of hornblende, plagioclase, and opaque minerals, **I.** ppl and **J.** xpl. Note the change in colour of yellowish green of the large oikocryst in the centre and towards the bottom right-hand side of the image, sample HRE230027A from the Gråsjön intrusion. Photo: Dick Claeson.

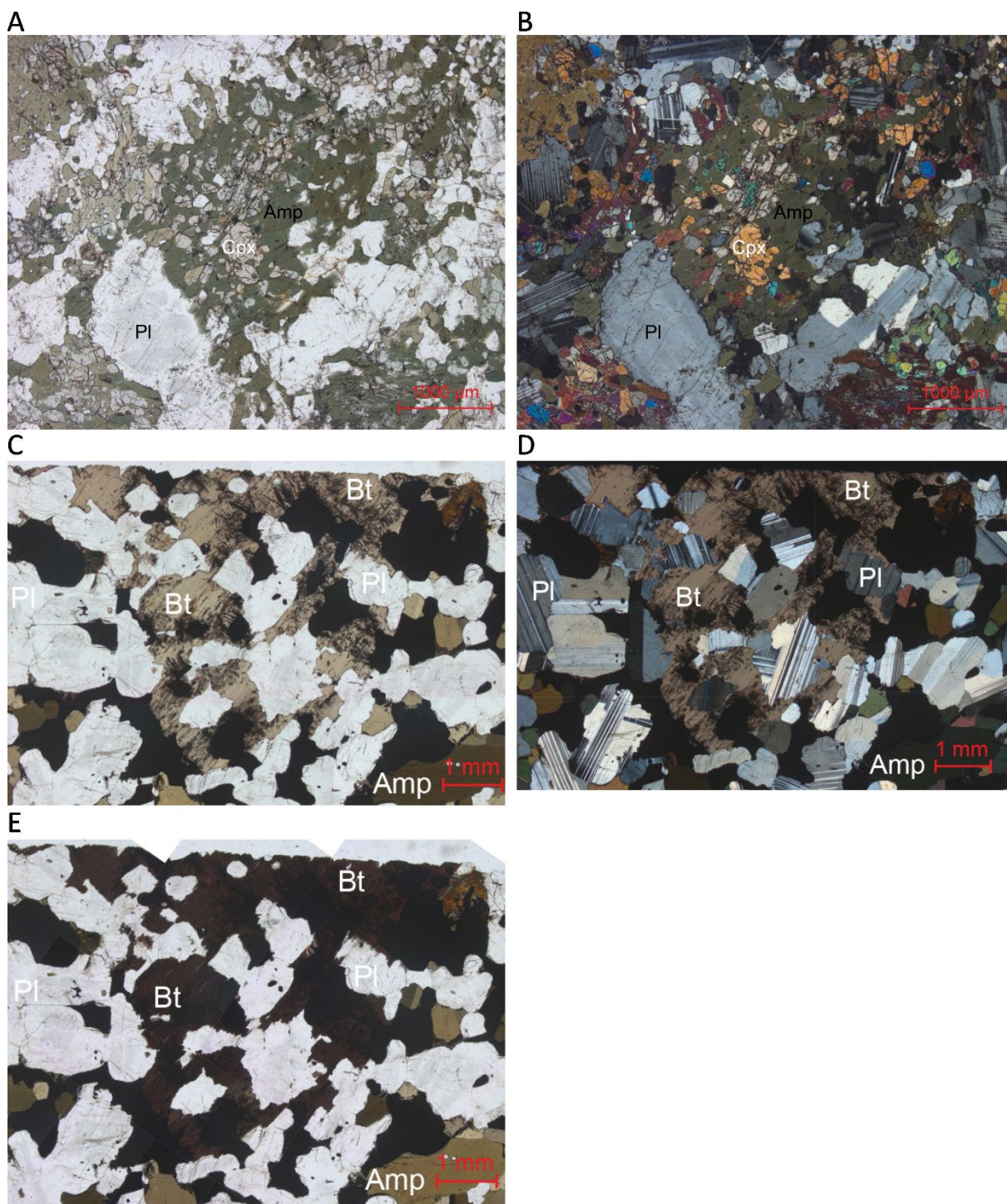


Figure 310. Oikocryst of green hornblende with chadacrysts of clinopyroxene, hornblende, plagioclase, and opaque minerals, **A.** ppl and **B.** xpl. Sample HRE220032A from the Storåsen intrusion. Oikocryst of biotite with chadacrysts of plagioclase and opaque minerals, **C.** ppl and **D.** xpl. Pleochroism in the oikocryst biotite ranges from tan in **C.** to reddish brown in **E.**, both in ppl but different orientation. Note the common infilling of opaque minerals within the biotite, some radiating from a larger opaque crystal. Sample DCL223036A from drill core BLA81001 at 179.77–179.81 m from the Bläckmyran intrusion. Photo: Dick Claeson.

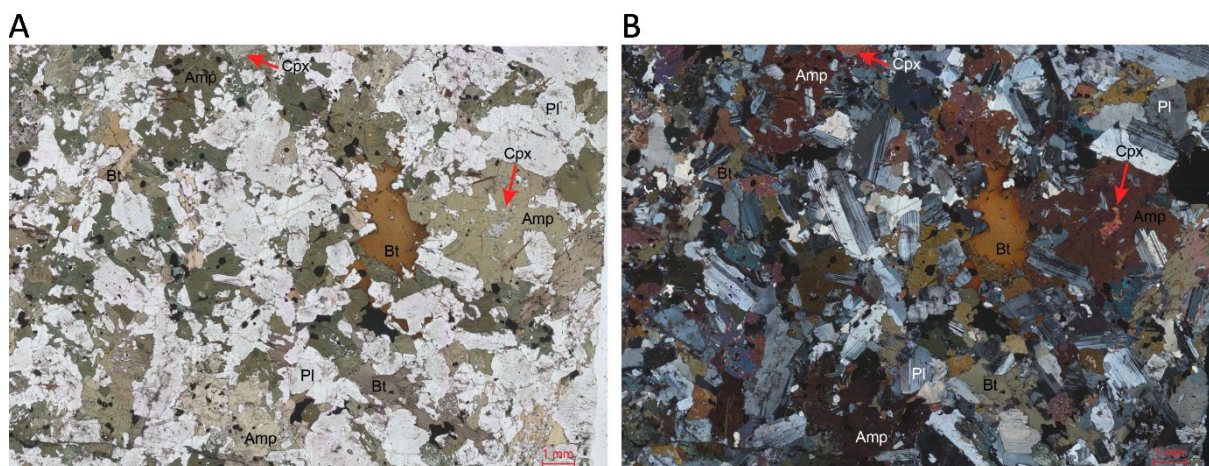


Figure 311. Several oikocrysts of hornblende with chadacrysts of clinopyroxene, plagioclase, and opaque minerals, **A.** in ppl and **B.** in xpl. Biotite oikocryst with small plagioclase chadacrysts. The Öjungen intrusion is suggested to belong to TIB and thus not related to the Fe-Ti-V intrusions. Sample HRE230019A from the Öjungen intrusion. Photo: Dick Claeson.

Immiscibility of Fe-rich melt in the mafic intrusions of the Ljusdal batholith, an example from the Kramsta intrusion

Segregation of immiscible melts occur at high temperature in slowly cooling magma chambers, where suitable conditions for formation of two melts are met, one Fe-rich and the other Si-rich (Charlier *et al.* 2013). At high temperature, immiscible melts have small compositional contrasts, so that very low interfacial tension promotes easy nucleation of immiscible liquid droplets and very slow coarsening, requiring extensive periods of time to enable the segregation of two liquids (Charlier *et al.* 2013). Elevated content of titanium in the supernatant melt promotes immiscibility (Charlier & Grove 2012).

The anomalous contents of the high field strength elements (HFSE) Zr, Hf, Nb, and Ta, elevated Zn and Mo, high U and Th, seen in the sample HRE220042A from Kramsta, is consistent with and postulated as geochemical hallmarks of the Fe-rich immiscible liquids of a basaltic magma (Veksler *et al.* 2006). This is the most convincing example of Fe-rich immiscible liquids playing a part in formation of the most mineralised portions of the studied Fe-Ti-V intrusions in our dataset. However, several other samples plot in the two-liquid field of Charlier & Grove (2012) diagram seen in figure 312. The reader is reminded that all the studied intrusions are plutonic rocks with layering features evident, which means that the whole-rock samples plotted in figure 312 most probably differ from ferrobasaltic liquid compositions and a liquid line of descent is difficult to reliably deduce.

The anomalous contents in sample HRE220042A from Kramsta mentioned above is easily seen in the extended N-MORB normalised diagram, where it is compared with the other samples from the Järvsö area, including the other sample used for dating the intrusion (fig. 313A). The sample HRE220042A also displays a very different REE pattern compared to the rest of the Järvsö Field samples (fig. 313B). Specifically, a distinct negative slope, an enrichment in HREE (which is even more pronounced in the heavier REE) and a deep negative Eu-anomaly in comparison to the other samples. This suggests that even the REE are fractionated during the segregation of immiscible melts in the Kramsta intrusion. The HREE of sample HRE220042A is most certainly

within the zircon crystals in the Fe-Ti-V mineralised rock (Zr 1 980 ppm, $\text{REE}_{\text{tot}} = 67.0$ ppm). Igneous unaltered zircon is LREE depleted, HREE enriched, has a negative Eu-anomaly and a positive Ce-anomaly (Hoskin & Schaltegger 2003). The generally low content of REE and specifically HREE in the Järvsö Field rocks provides a setting where the zircon-rich rock stands out (fig. 313B). Had the rocks generally been richer in REE and HREE, such an enrichment of HREE from the crystallisation of zircon might have been disguised and not that apparent. The two samples that have the highest content of REE from the Fe-Ti-V rocks from the Järvsö Field (both above the blue pattern in figure 313B) are DCL234030A $\text{REE}_{\text{tot}} = 215$ ppm and HRE220043A $\text{REE}_{\text{tot}} = 176$ ppm. These samples have much lower Zr content at 112 ppm and 116 ppm, respectively compared with HRE220042A. It should also be noticed that both have much higher P_2O_5 than sample HRE220042A (0.06%), at 1.27 and 1.44%, respectively. The two samples with LREE-enriched patterns (DCL234030A and HRE220043A) are consistent with apatite being the main REE-bearing mineral, which is also suggested by higher P_2O_5 than the other samples of the Järvsö Field (fig. 313B). It is probable that fractionation of apatite occurred prior to the formation of the rocks at the Pojken ore pit (HRE220042A), which would explain the low P_2O_5 and relatively low LREE content.

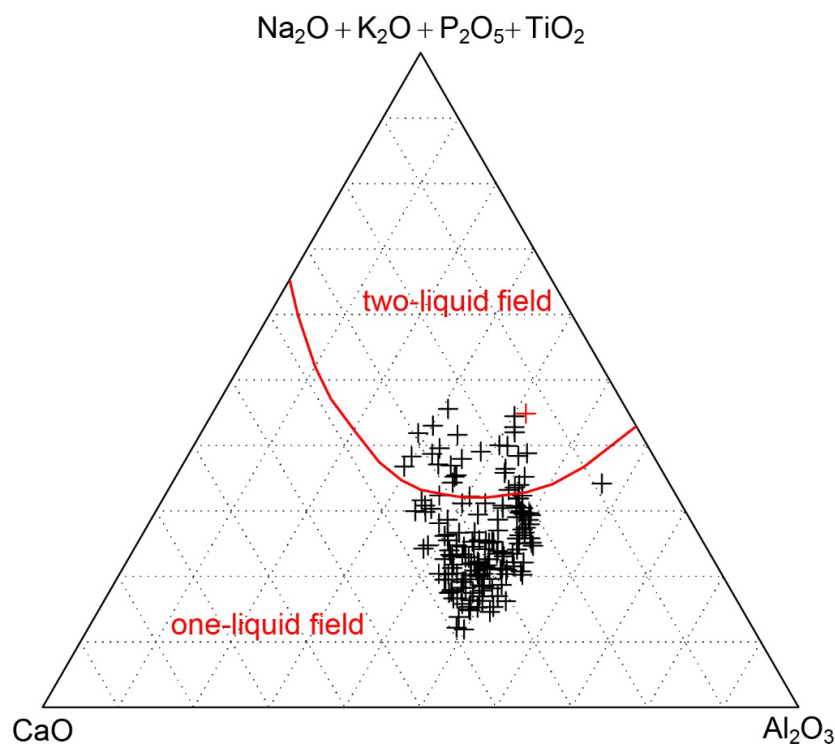


Figure 312. Ternary diagram of CaO , Al_2O_3 , and $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{P}_2\text{O}_5 + \text{TiO}_2$ with all Fe-Ti-V related samples from this study, modified after Charlier & Grove (2012). Red cross sample HRE220042A from the Pojken ore pit, Kramsta.

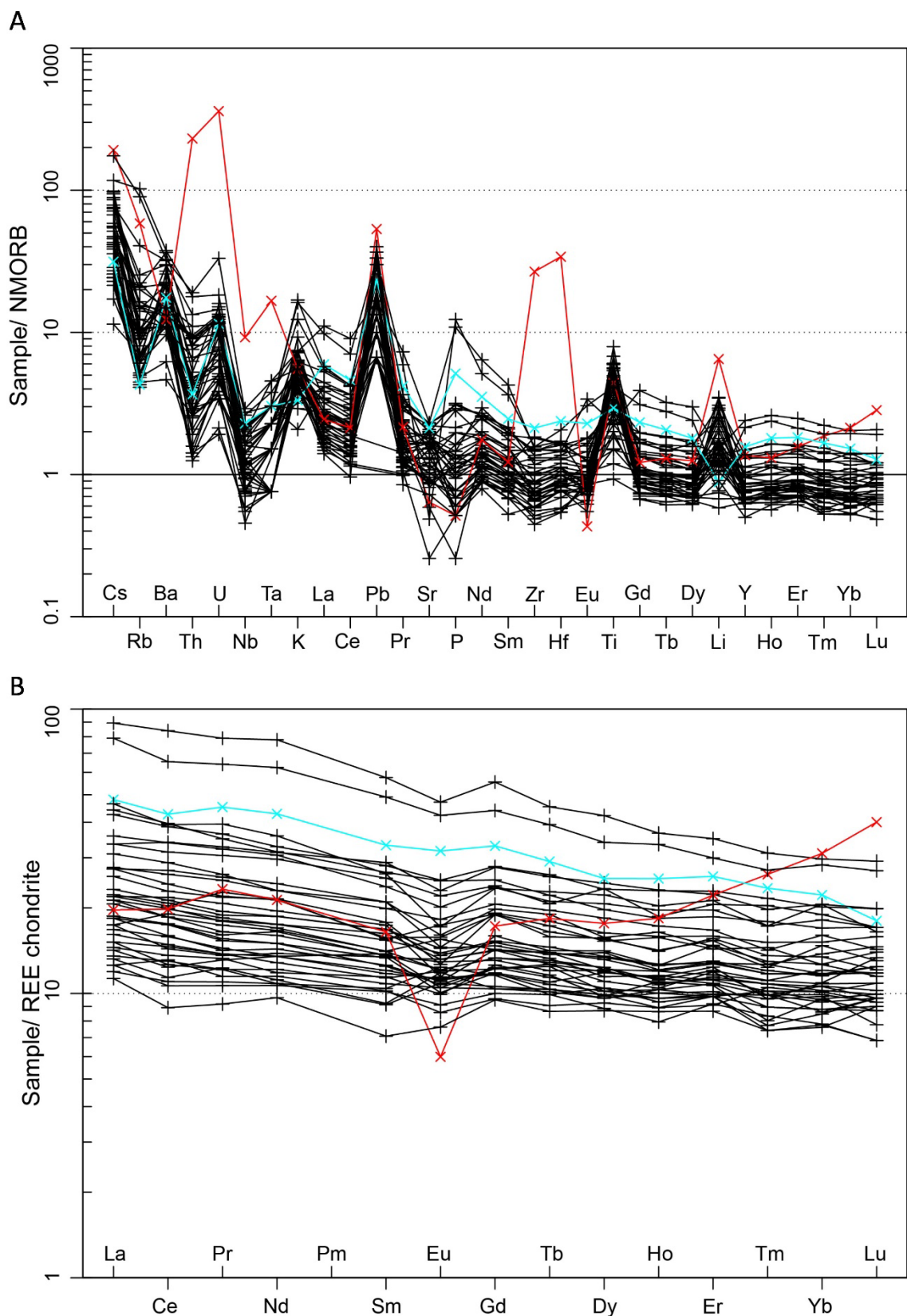


Figure 313. A. Extended N-MORB diagram of rocks from the Järvsö Field with HRE220042A in red and the other age determined sample HRE220044A in blue. Normalisation after Sun and McDonough (1989). **B.** REE diagram of rocks from the Järvsö Field, with same colours as in A. Normalisation after Boynton (1984).

Interstitial igneous garnet from a hydrous mafic magma in the Storåsen intrusion

The outcrop at Storåsen where interstitial igneous garnet occurs consists of a massive gabbro with a pegmatite dyke (without chilled margins in either rock). The rocks are interpreted to be comagmatic (fig. 314).

The studied garnet from Storåsen has mostly anhedral crystals, with only a few subhedral crystals. No euhedral crystals are observed (fig. 315). The garnet occurs interstitially between earlier formed crystals or among aggregates of plagioclase, clinopyroxene, hornblende, opaque minerals, and possibly minor alkali feldspar. No signs of deformation are observed in the full thin-section image or in the outcrop (figs. 314, 315).

The textural relations show that garnet occasionally occurs between clinopyroxene and plagioclase, but in the same thin section, clinopyroxene and plagioclase can be observed without any garnet (or signs of any other reaction) at the mineral contacts (fig. 316). At places the contacts between plagioclase and garnet, as well as clinopyroxene and garnet, are winding with embayments and cusps (fig. 316). The same type of contact shape is also seen between clinopyroxene and plagioclase grains, as well as amphibole and plagioclase (fig. 316). A few contacts between garnet and plagioclase are straight (fig. 316). Also observed are contacts between garnet and plagioclase that have the appearance of small pockets, where buoyant melt might have flown before complete solidification (fig. 316). In detail, plagioclase, clinopyroxene, amphibole, and opaque minerals occur as inclusions within garnet. (fig. 317). A close-up shows that the interstitial garnet lacks symplectite reaction products, such as quartz, which would be expected in a subsolidus reaction between clinopyroxene and plagioclase and that most minerals seen in the thin section are present adjacent to and within the garnet (fig. 317). Crystal boundaries between clinopyroxene and plagioclase that lack garnet should have been dry from melt and fluids during the garnet-forming process, which is consistent with percolating late-stage evolved melt-liquid within the cumulate rock as the means for the formation of interstitial garnet at the Storåsen. Thus, the garnet is interpreted as late-magmatic and formed within the final stages of porous flow within the cumulate rock from an evolved liquid. This evolved liquid was reactive with earlier formed plagioclase and clinopyroxene. The brown hornblende and garnet are in textural equilibrium and have grown at the same time (figs. 316, 317). The brown hornblende often exhibits 120-degree triple junctions, but no uniform grain size, where small crystals appear adjacent to much larger ones. No absorption due to recrystallisation in solid state is observed which suggests that these are primary features of the gabbro and not due to a later metamorphic overprinting (figs. 316, 317).

Coronitic metamorphic garnet in garnet-clinopyroxene gabbro should develop some reaction between pre-existing minerals (e.g., George *et al.* 2022). A simple metamorphic reaction could be that clinopyroxene and plagioclase combine to give garnet and quartz. However, quartz was not identified anywhere in the sample from Storåsen. The interstitial garnet of the Storåsen shows no resemblance to that of garnet grown during deformation and pervasive flux by externally originated hydrous melt (cf. Munnikhuus *et al.* 2023). Nor does the garnet of the Storåsen resemble metamorphic granulite-facies garnet that occurs with clinopyroxene- and plagioclase-bearing metagabbro (e.g., Flowerdew & Daly 2005).

Garnet was an igneous phase in experimental studies of typical hydrous, arc-tholeiitic to calc-alkaline derivative liquids of basaltic and andesitic composition (e.g., Müntener & Ulmer 2006, Alonzo-Perez *et al.* 2009). This suggests a magma reservoir located in the lower crust or at the crust-mantle boundary in a convergent-plate margin setting (25–40 km, at pressure of 7–11 kbar using 3.7 km/kbar). Igneous garnet has been reported in deep-seated arc cumulates (e.g., George

et al. 2022) and inferred in subduction-related andesitic rocks as entrained enclaves from closely related deep-seated cumulates that formed at pressures of 8–10 kbar (e.g., Bach *et al.* 2012).

The partial melting and melt products of the surrounding augen gneiss and strongly deformed metagranitoids (which led to mingling/mixing), seen at several contact locations in our studies of drill cores from other mafic intrusions in the Ljusdal lithotectonic unit (e.g. Kramsta, Bläckmyran), suggest that the ambient temperature had to be high for an elevated period of time. At a few locations at Storåsen back-veining of the newly formed granitic melt was noted (fig. 218). The above-mentioned intrusion depth suggests ambient granulite facies conditions and estimated PT conditions of 7–11 kilobars and 650–900°C during emplacement of the Storåsen intrusion.



Figure 314. A. Outcrop of massive gabbro with a pegmatite dyke, B. close-up of the gabbro, C. the contact without chilled margins in either rock, D. close-up of contact relations. Photo: Helge Regniussen.

A



B

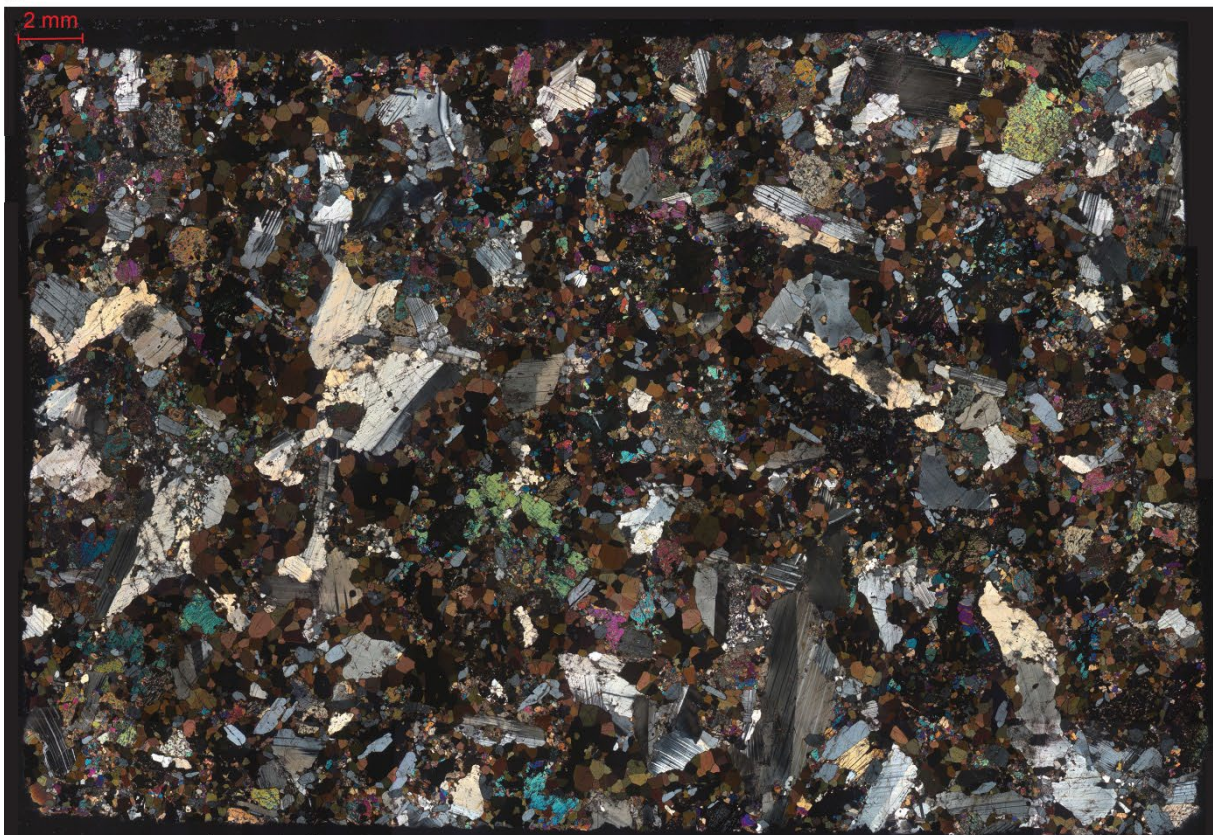


Figure 315. Full thin-section with plagioclase, clinopyroxene, hornblende, Fe-Ti-oxide, and garnet. **A.** plane-polarized light and **B.** cross-polarized light. Garnet, being isotropic, is seen as black in cross-polarized light. Photo: Dick Claeson.

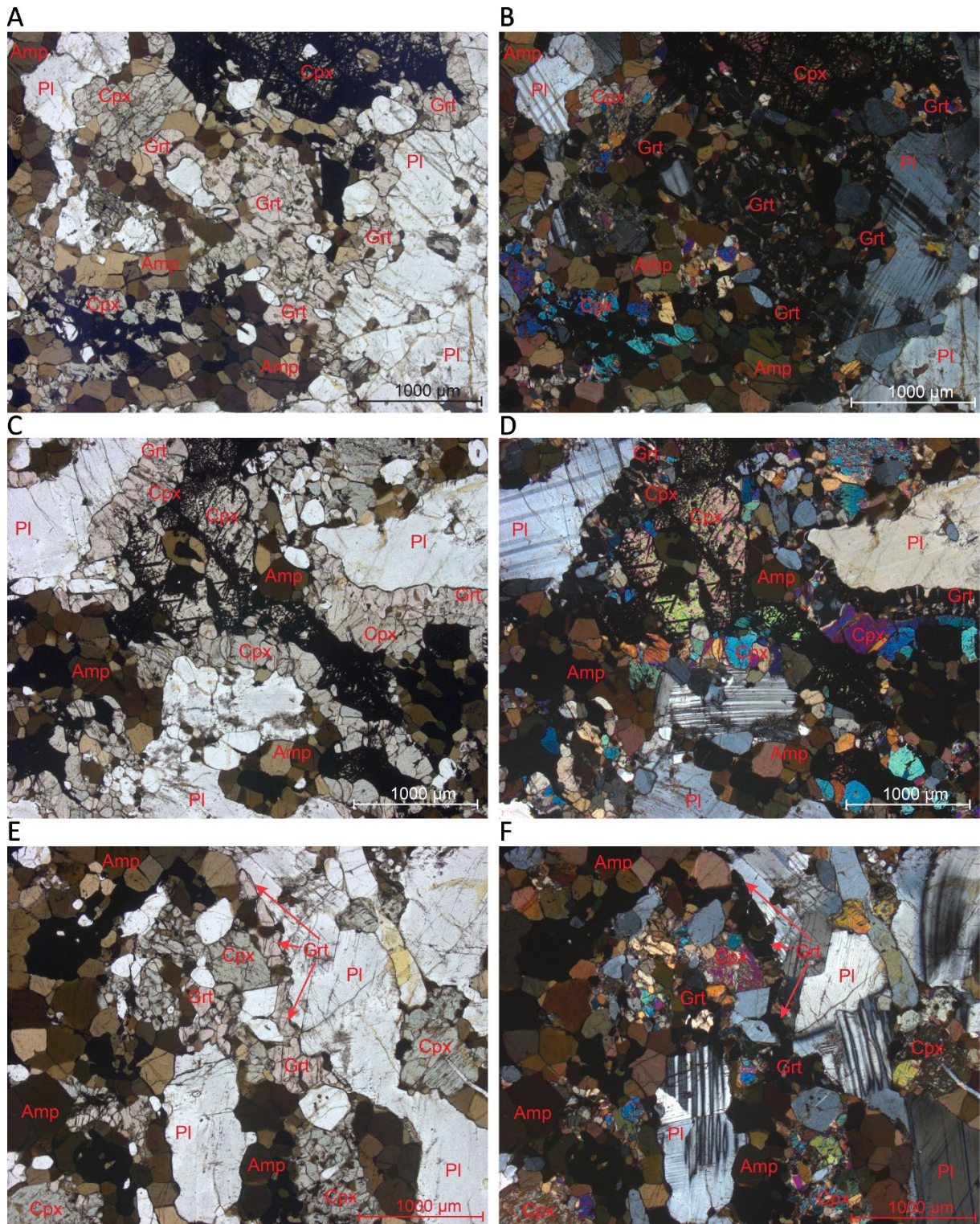
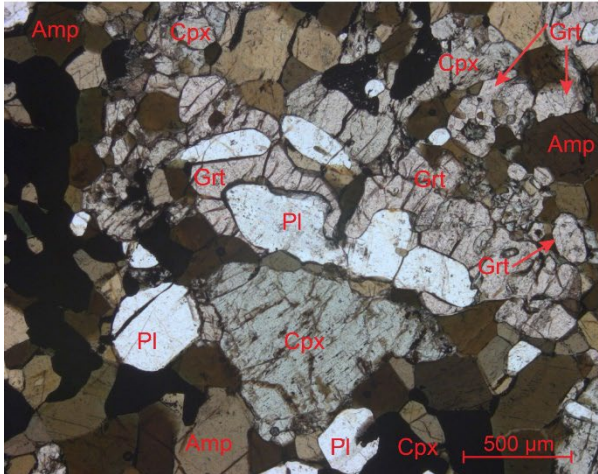


Figure 316. Set of images, A. to H., showing different relations among the minerals in contact with garnet, mostly plagioclase, clinopyroxene, hornblende, and Fe-Ti-oxide. Note the range of interaction-reactions at some grain contacts and lack of reactions at other contacts between plagioclase and clinopyroxene. Note also some grain contacts with and without garnet. The garnet and hornblende are in textural equilibrium. Left images in plane-polarized light and right cross-polarized light. Garnet, being isotropic, is seen as black in cross-polarized light. Photo: Dick Claeson.

G



H

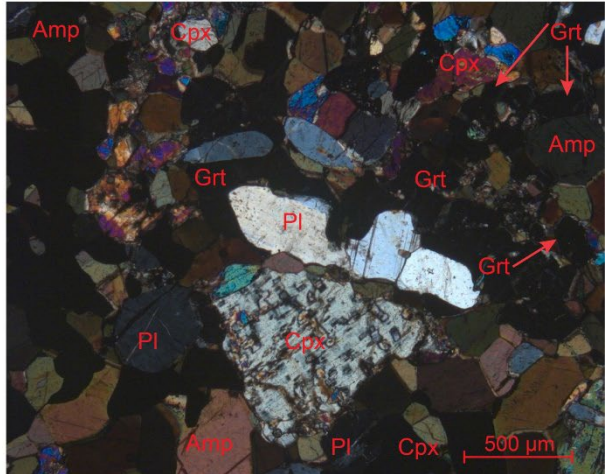
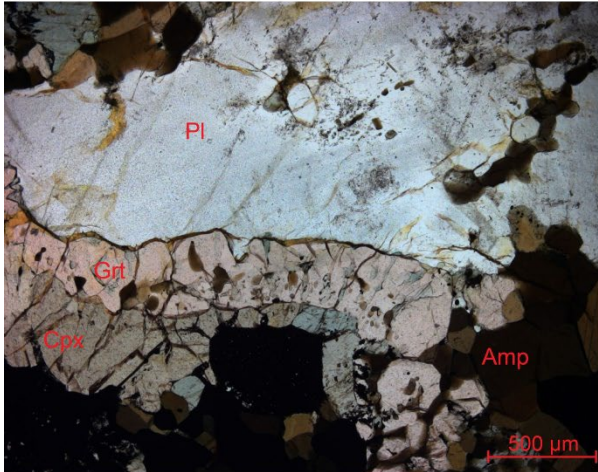
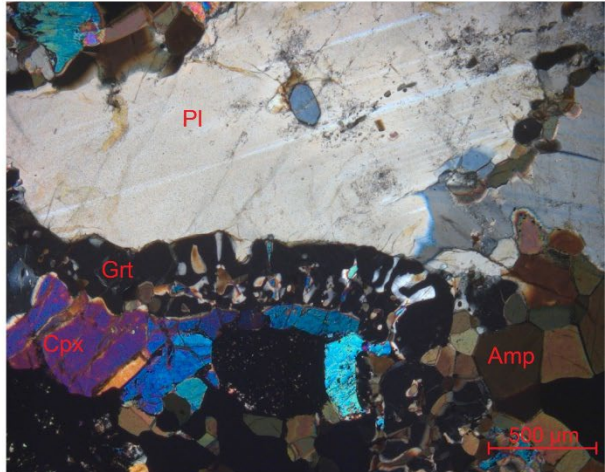


Figure 316. Continued. Relations among garnet, plagioclase, clinopyroxene, and opaque minerals, with embayments and cusps. Note the interstitial texture of garnet. **G.** in plane-polarized light and **H.** cross-polarized light. Garnet, being isotropic, is seen as black in cross-polarized light. Photo: Dick Claeson.

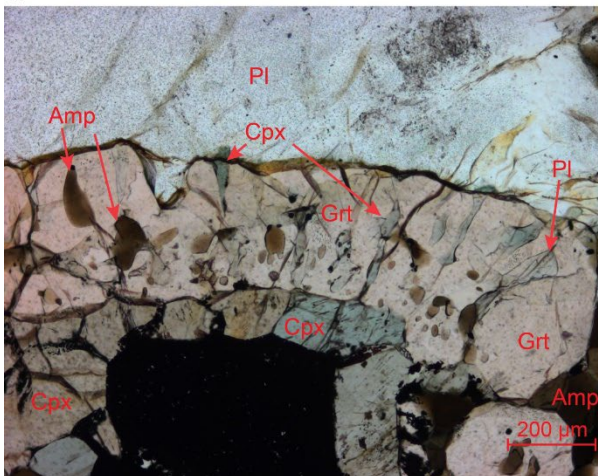
A



B



C



D

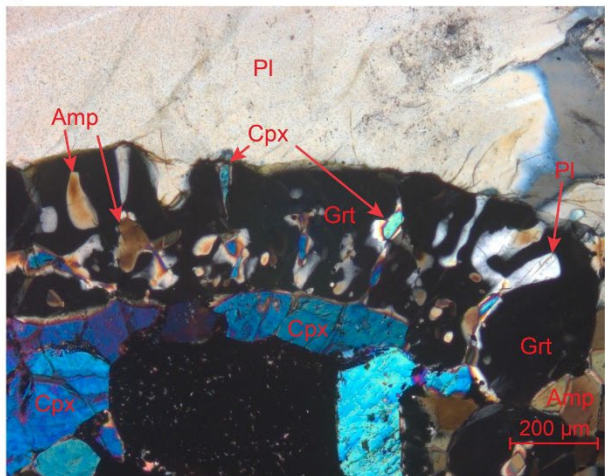


Figure 317. Interstitial garnet grown along plagioclase, clinopyroxene, and amphibole, **A.** in ppl and **B.** in xpl. Close-up of the garnet shows co-crystallisation of plagioclase, clinopyroxene, and amphibole within the interstitial garnet, **C.** in ppl and **D.** in xpl. Note the winding interface of plagioclase and garnet, as well as clinopyroxene and garnet, with embayments and cusps. Photo: Dick Claeson.

Intergrown clinopyroxene and plagioclase are present in the garnet-bearing rock from Storåsen and are interpreted as late-stage crystallisation between the larger crystals formed previously (fig. 318). The large plagioclase crystals in contact with these pockets of smaller crystals have embayment texture, where later-formed plagioclase seems to have dissolved some of the pre-existing crystals (fig. 318). A similar replacement feature is seen for some clinopyroxene crystals (fig. 318). The coprecipitation indicates that the late-stage fluids might not have crystallised the same assemblage of minerals everywhere, where even on the scale of a thin section there may be substantial variation. The presence of larger grains crystallised at one end of this pocket (between the large pre-existing crystals), suggests that these had more time to develop and higher rates of liquid percolation (compare left and right side of pocket in fig. 318). Several of these pockets are present in the full thin section figure 315. The close-up in figure 318 is the largest and is positioned in the lower right-hand part of figure 315, where the position of this pocket within the cumulate can be observed.

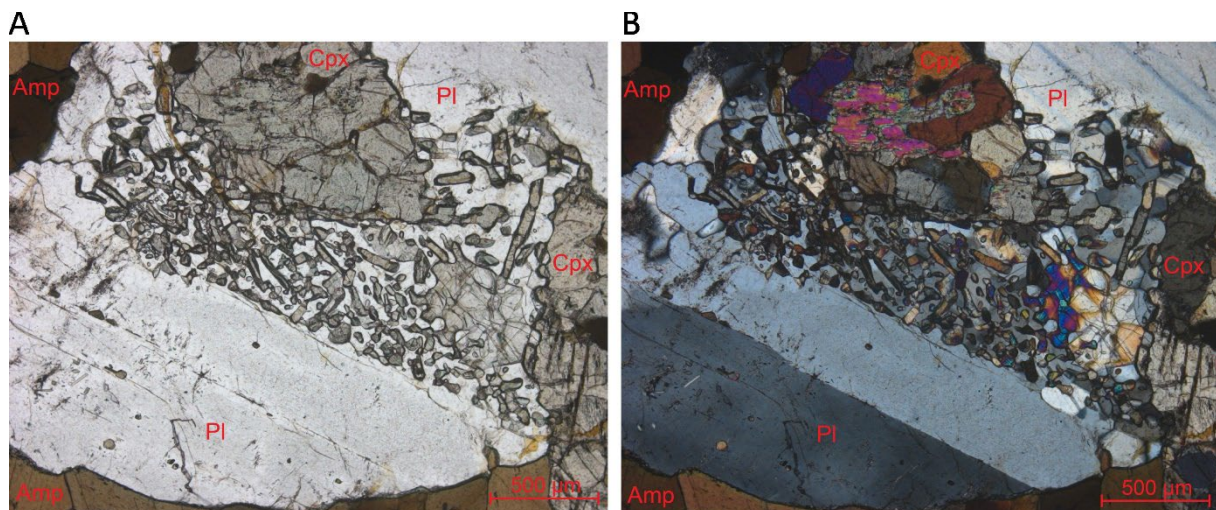


Figure 318. Intergrown clinopyroxene and plagioclase in centre of image, surrounded by earlier formed, much larger crystals of clinopyroxene and plagioclase along with brown hornblende, **A.** in ppl and **B.** in xpl. Note the much larger late-forming clinopyroxene and plagioclase to the right-hand side of the pocket. Photo: Dick Claeson.

Age determination of mafic mineralised rocks in the Järvsö Field

Sample description of age determined rocks

Two samples from the Kramsta gabbroic intrusion were selected for age determination. The samples were taken from Fe-Ti-V mineralised parts of the intrusion, at two old mining pits, located approximately 625 metres apart. Two prior efforts with sampled pegmatitic gabbro proved to be barren of zircon and baddeleyite.

Sample HRE220042A was collected at Öjefältet-Pojken (6842952/559946) and consists mostly of ore-bearing gabbroid (fig. 319). The mining pit is roughly 20×5 metres and approximately two metres deep. The sample is a mineralised gabbroid, with highly variable magnetite content. Lithogeochemical analysis shows that the sample is rich in Fe, Ti, Ga, and Zr, and has anomalous concentrations of Hf, Nb, Th, U, and V (Table 13).

Sample HRE220044A (fig. 320) was collected at Gillermyrgruvan 2 (6842699/559374), which is a mostly overgrown historic mining pit, measuring c. 10 by 3 metres. The sample consist of magnetite mineralised gabbroid and minor ore. Lithogeochemical analysis shows that the sampled magnetite mineralised gabbroid is rich in Ti and anomalous in Fe (Table 13).

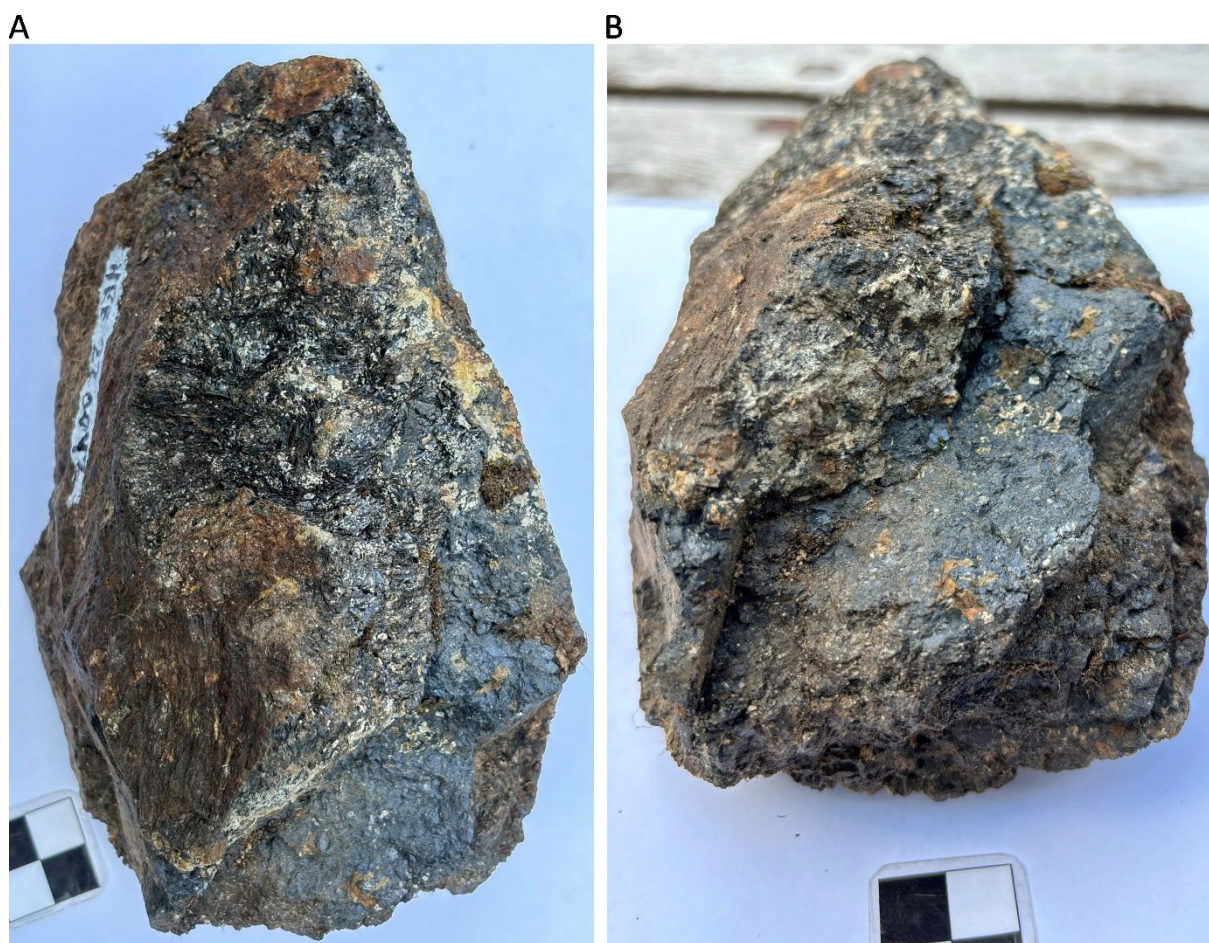


Figure 319. Hand-specimen of sample HRE220042A from Öjefältet-Pojken (6842952/559946). Photo: Dick Claeson.

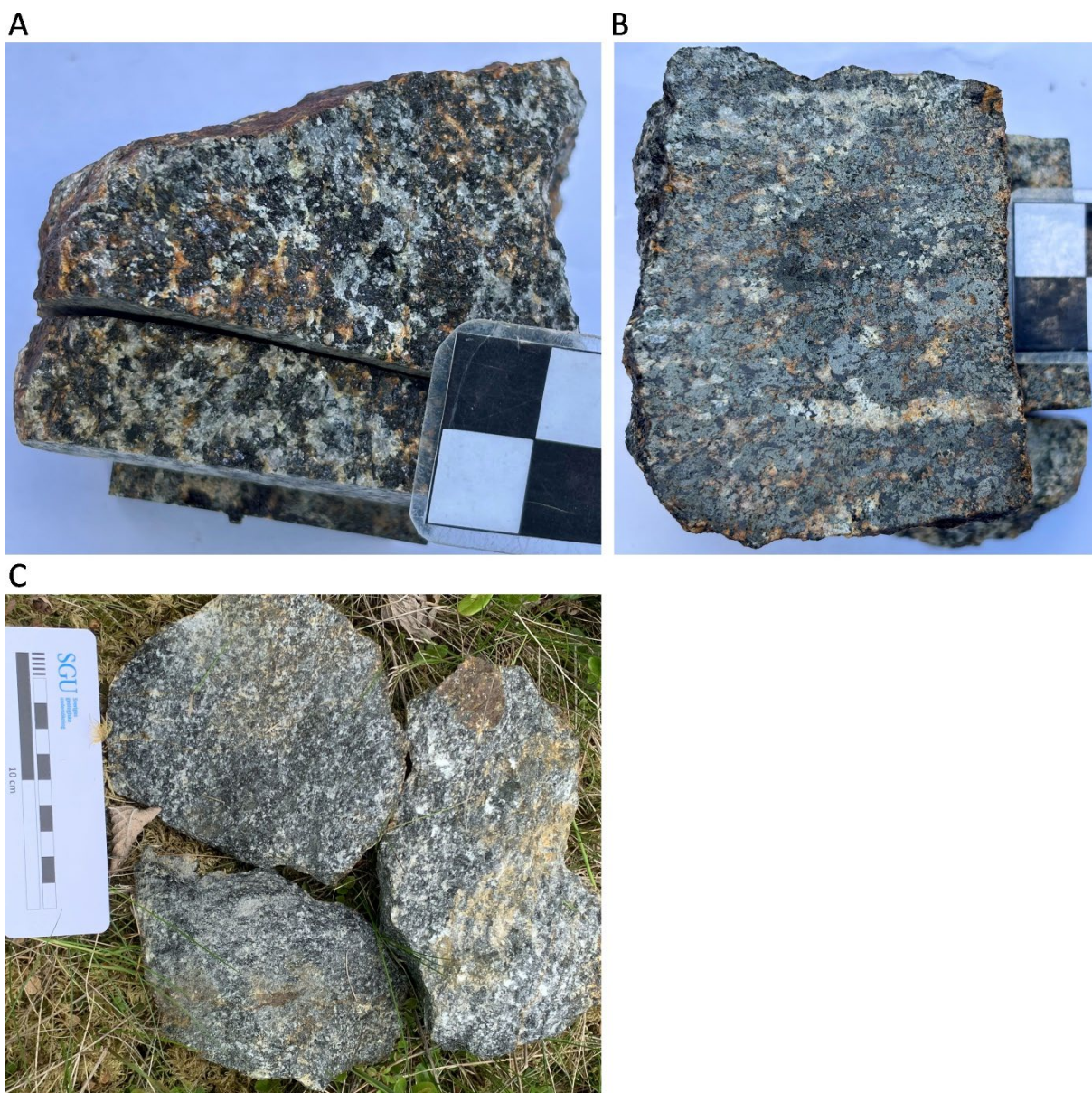


Figure 320. Hand-specimens of sample HRE220044A Gillermyrgruvan 2. Close-ups of **A.** fresh surface, **B.** sawed surface, where dull steel grey areas consist of Fe-Ti oxides. **C.** Variable grain sizes and plagioclase content, (6842699/559374). Photo: A. and B. Dick Claeson, C. Helge Reginiussen.

Table 13. Selection of oxides and elements from the lithogeochemical analyses of the samples used for age determination.

Element	Unit	HRE220042A	HRE220044A
SiO ₂	%	20.1	45.4
Al ₂ O ₃	%	6.63	12.75
Fe ₂ O ₃	%	60.5	21.3
CaO	%	2.18	8.74
MgO	%	2.85	3.74
Na ₂ O	%	1.13	2.43
K ₂ O	%	0.4	0.24
TiO ₂	%	5.58	3.72
MnO	%	0.37	0.27
P ₂ O ₅	%	0.06	0.6
V	ppm	1 765	247
Zr	ppm	1 980	157
Ga	ppm	72.2	26.8
Hf	ppm	69.8	4.87
Nb	ppm	21.5	5.33
Th	ppm	27.7	0.44
U	ppm	16.9	0.54

The minerals in thin section HRE220042A from Öjefältet-Pojken are in parts severely altered while in other parts well-preserved. Half of the section consists of opaque minerals, occurring as framework and interstitial grains. The main silicate minerals are

1. hornblende, which appears as large and interstitial grains which are subhedral to anhedral,
2. olivine, which appears as large grains which are subhedral to anhedral,
3. clinopyroxene, which appears as large subhedral grains, some of which are severely altered but mostly unaltered,
4. plagioclase, which appears as large and interstitial grains, with mostly minor alteration,
5. interstitial biotite, which shows growth in two generations, the first generation has a brownish red pleochroism and the later generation has pale reddish to tan pleochroism (fig. 321).

The opaque framework consists mainly of magnetite and ilmenite, both of which have small inclusions of portions of ilmenite and magnetite, respectively. Exsolution is common for the opaque minerals in the section (fig. 321G).

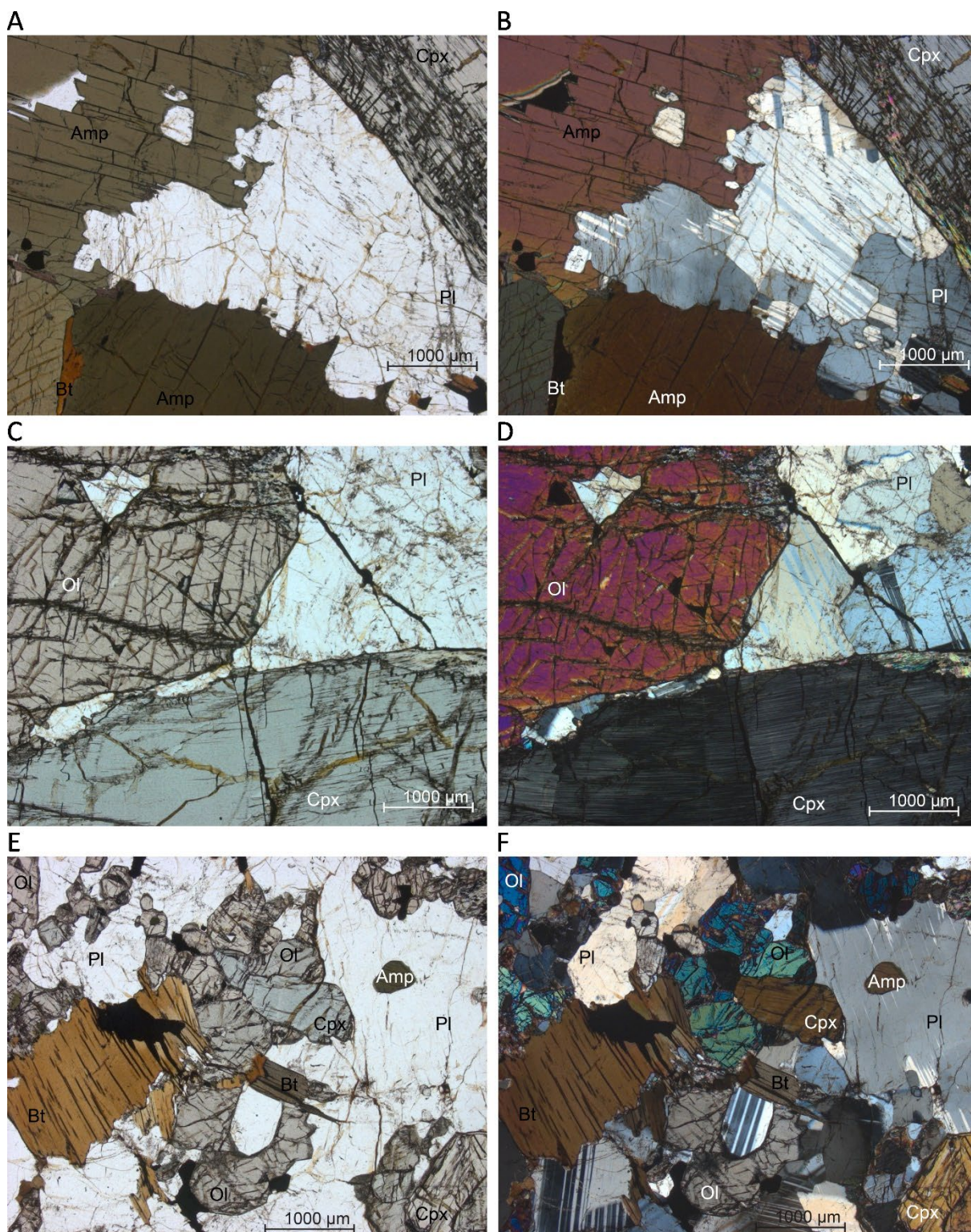


Figure 321. Thin-section images of sample HRE220042A from Öjefältet-Pojken (6842952/559946). Large grains of hornblende, clinopyroxene, plagioclase, and a small, interstitially grown biotite, **A.** in ppl and **B.** xpl. Large grains of olivine, clinopyroxene, and smaller plagioclase grains, where some are interstitial, **C.** and **D.** in ppl and xpl, respectively. Olivine, clinopyroxene, hornblende, plagioclase, and biotite are all well-preserved, **E.** and **F.** in ppl and xpl, respectively. The biotite shows two generations of growth, the first has brownish red pleochroism and the later has pale reddish to tan pleochroism. Second generation biotite seen in the middle of the images **E.** and **F.** continuing growth at the end of a crystal of the first generation.

G

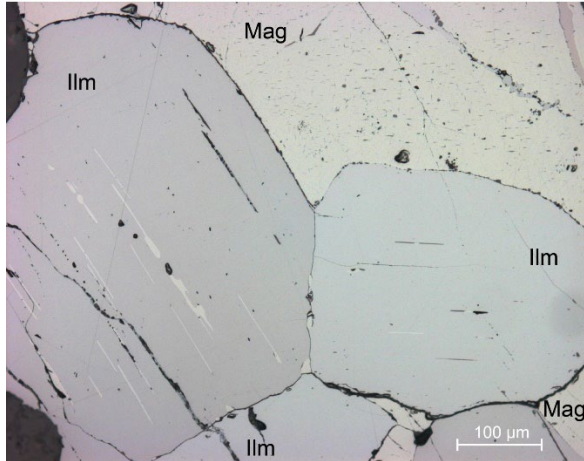


Figure 321. continued. G. Large magnetite and ilmenite grains with smaller inclusions and exsolved portions of ilmenite and magnetite, respectively, in reflected light. Photo: Dick Claeson.

The minerals in thin section HRE220044A from Gillermyrgruvan 2 are, in general, well-preserved. The silicate minerals are fractured and are infilled with opaque minerals, most spectacularly within plagioclase (fig. 322). Hornblende occurs as large and interstitial grains, as well as oikocrysts, which are subhedral to anhedral. Olivine occurs as small and large grains and is anhedral. Clinopyroxene occurs as large grains which are anhedral to subhedral and can contain lamellae and portions of opaque minerals from exsolution. Plagioclase occurs as large anhedral grains and also as chadacrysts (fig. 322). The opaque minerals are, for the most part, interstitial magnetite and ilmenite, with rare sulphide minerals which occur as interstitial grains and droplets (figs. 322G-H). Magnetite and ilmenite grains often have smaller inclusions and exsolutions of ilmenite and magnetite, respectively.

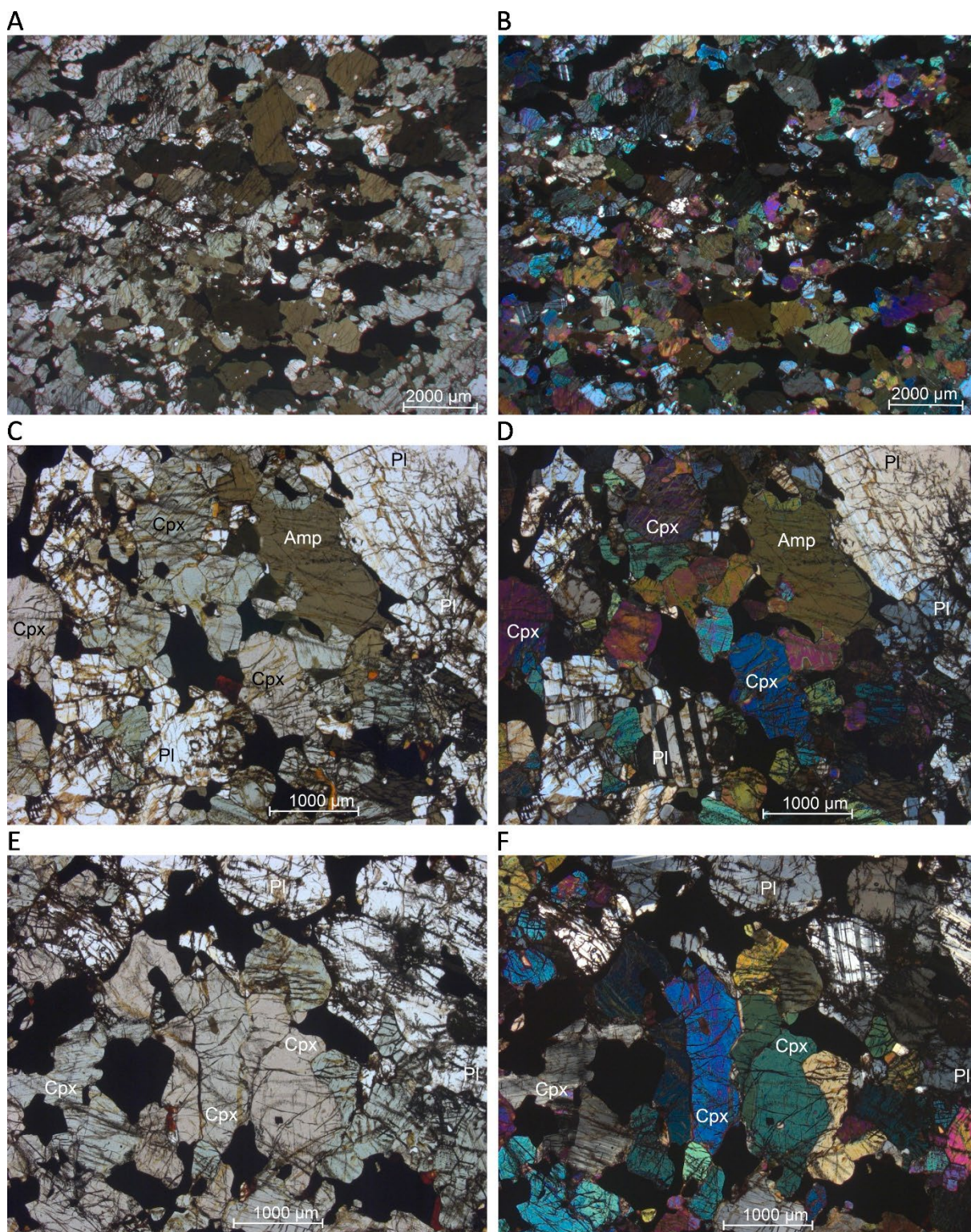


Figure 322. Thin-section images of sample HRE220044A from Gillermyrgruvan 2 (6842699/559374). Overview of thin section with mostly well-preserved minerals, most silicate minerals are fractured and have infillings of opaque minerals, **A.** in ppl and **B.** in xpl. Large grains of clinopyroxene, hornblende, and plagioclase with late interstitial Fe-Ti oxide minerals filling out the pore space, **C.** in ppl and **D.** in xpl. Clinopyroxene and plagioclase with fractures infilled with opaque minerals, most spectacular in plagioclase. Late interstitial Fe-Ti oxide minerals are found between the silicate minerals, **E.** in ppl and **F.** in xpl.

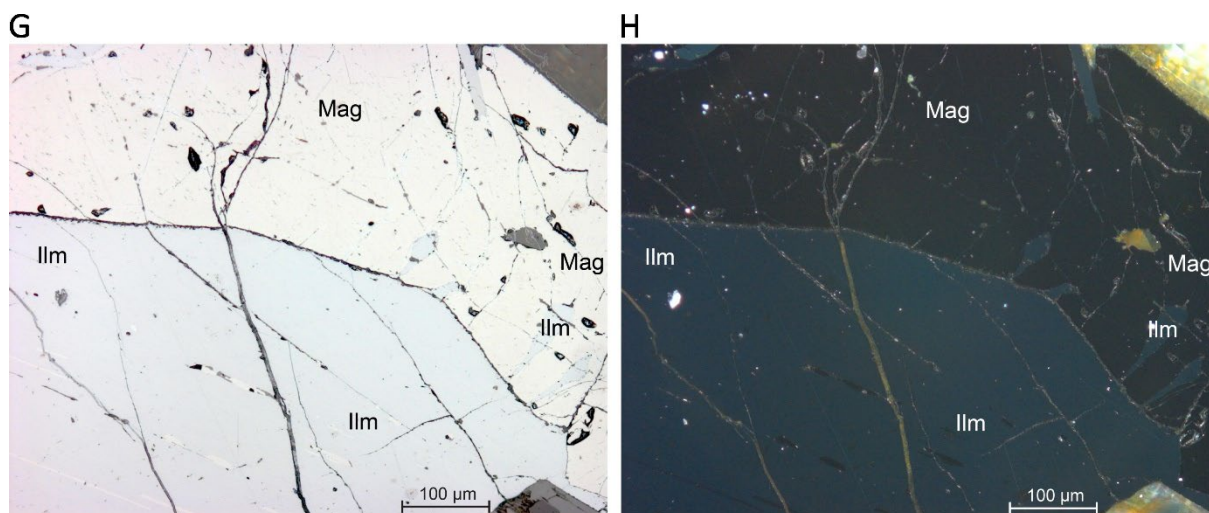


Figure 322. continued. Large magnetite and ilmenite grains with smaller inclusions or exsolved portions of ilmenite and magnetite, respectively. Both **G.** and **H.** in reflected light and in **H.** using a differential interference contrast (DIC) objective. In the latter the magnetite inclusions stand out better as dark regions in the ilmenite grains, which can also be seen in the ordinary reflected light image **G.** as regions which are almost white. Photo: Dick Claeson.

Geochronological methods

U-Pb isotope analyses were done using the Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) laboratory at Lund University. The laboratory includes a Teledyne Photon Machines G2 laser coupled to a Bruker Aurora Elite quadrupole ICP-MS. The laser is equipped with a HelEx 2-volume sample cell with an energy meter in the sample cell. Ablation was done in a He carrier gas (0.8 L/min), which was combined with Ar (0.95 L/min) and N₂ (6.5 mL/min) downstream from the sample chamber.

Instrument tuning, using NIST612, was aimed at obtaining high and stable signal counts on lead isotopes, on low oxide production (below 0.5 % monitoring $^{238}\text{U}/^{238}\text{U}^{16}\text{O}$ and $^{232}\text{Th}/^{232}\text{Th}^{16}\text{O}$) and on Th/U ratios of 1. The following isotopes were measured ^{202}Hg , ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th , and ^{238}U with a total scan time of 200 msec. We used a spot size of $25 \times 25 \mu\text{m}$ and each analysis was done with 300 shots at 10 Hz and a fluence of $3 \text{ J}/\text{cm}^2$. Baseline compositions were measured for 30 seconds before each measurement and subtraction was done with a step-forward approach. Common lead was monitored by measuring ^{202}Hg and mass 204 ($^{204}\text{Hg} + ^{204}\text{Pb}$). The analytical session was setup to run automatically with standard-sample-standard bracketing, using the natural zircon GJ-1 (Jackson *et al.* 2004) for the primary calibration. Zircon BB16 (Santos *et al.* 2017), 91500 (Wiedenbeck *et al.* 1995) and in house 060011 (Næraa *et al.* 2012) were analysed as secondary reference standards. We obtain the following ages from the secondary standards, BB16: $^{206}\text{Pb}/^{238}\text{U}$ age $558 \pm 19 \text{ Ma}$ ($n = 3$, MSWD = 5.3); 91500: Concordia age $1\,054 \pm 7 \text{ Ma}$ ($n = 3$, MSWD = 0.0); 060011: Concordia age $3\,786 \pm 15 \text{ Ma}$ ($n = 3$, MSWD = 0.60). Data reduction was done with Iolite using the X_U_Pb_Geochron4 DSR (Paton *et al.* 2010, 2011) and common-Pb correction was done using the VizualAge DRS by Petrus & Kamber (2012).

Analytical results and interpretation of geochronological data

The zircon had a scruffy appearance where parts appeared semi-metamict, fairly prismatic with fractures, and heavily brown in colour.

A total of 37 crystals were analysed and there was no significant age difference between zircon from the two samples (Table 14). Of the 37 analyses, 11 plotted concordantly (Conc. 99–100% and with their error ellipse touching the Concordia, two of 13 discarded due to the latter) and

gave a $^{207}\text{Pb}/^{206}\text{Pb}$ age of $1\,848 \pm 13$ Ma. There is a certain spread of results with respect to the $^{207}\text{Pb}/^{206}\text{Pb}$ age (MSWD = 15 at 2σ), the reason for which is not entirely obvious.

There are some discordant data that can be excluded (Table 14). In addition, it can be seen that data which is reasonably concordant (99 to 100% Conc.) plots with a spread along the Concordia. The interpretation of this age smear along the Concordia would be either that the sample contains a mix of age populations, or zircon crystals have been variously exposed to lead loss in the past or that a small portion of non-crystalline zircon was analysed. If we accept the Pb-loss scenario, we can select five out of the six analyses that are 100% concordant and calculate a concordant age of $1\,851 \pm 8$ Ma ($n = 5$, MSWD = 0.92 at 2σ , fig. 323).

Inheritance of zircon within the gabbroic magma from surrounding felsic rocks is not considered, since 1) the zircon occur in samples from some of the most evolved compositions of the intrusion (see section *Immiscibility of Fe-rich melt in the mafic intrusions of the Ljusdal batholith, an example from the Kramsta intrusion*), 2) the zircon display characteristics typical of zircon from gabbroic rocks (e.g., Corfu *et al.* 2003, Hoskin & Schaltegger 2003), 3) both samples record overlapping ages while sampling is more than 600 m apart. Specifically, they appear to be the result of fractional crystallisation of the supernatant magma with zircon forming interstitially in the mineralised rocks, note the extreme Zr content, 1 980 ppm of sample HRE220042A and of other incompatible elements (Table 13). Thus, the conclusion of the results from the age determination is that $1\,851 \pm 8$ Ma at 2σ represents the gabbroic Kramsta-Järvsö intrusion igneous crystallisation age. One can find xenocrystic zircon in basic rocks that are inherited from older rocks in the case that the host rock has been completely dissolved. In such cases, the inherited zircon grains become annealed and rounded, usually perfectly crystalline and colourless. These features were not observed in any of the zircon grains within the samples analysed in this study.

Despite the fact that no further age determinations of the Fe-Ti-V-rich gabbroic intrusions in the Ljusdal lithotectonic unit were performed, our interpretation is that the other Fe-Ti-V-rich gabbroic intrusions occurred at the same time as the Kramsta-Järvsö intrusion. We base this on the similarities in petrographic and lithochemical characteristics and lack of metamorphic overprinting or deformation of all of these intrusions. Furthermore, the similarity between intrusions regarding the interaction with the surrounding felsic gneissic rocks, where hybrid rocks are formed at the contacts due to mingling and occasionally mixing (best observed in drill cores) is consistent with one generation of intrusions of more or less the same age. The age determination at $1\,851 \pm 8$ Ma at 2σ of the gabbroic Kramsta-Järvsö intrusion places the Fe-Ti-V-rich magmatism at the very end or after the main deformation phase and high-grade metamorphic event that affected the rocks in the Ljusdal lithotectonic unit in the area where the Fe-Ti-V intrusions occur. The Fe-Ti-V-rich intrusions themselves in this study have none or only minor metamorphic overprinting at low grade, which suggests that no high-grade event reached them after emplacement. However, it is important to note that this interpretation does not stand for all gabbroic intrusions within the Ljusdal lithotectonic unit. For example, in this study other generations of gabbroic intrusions were visited and, in some cases sampled, but they are not regarded as part of the Fe-Ti-V-rich gabbroic intrusions (for example the intrusions from the area between Bollnäs and Ockelbo, and Lördagsberget). Hence, strongly deformed, metamorphosed, older gabbroic intrusions can be found within the Ljusdal lithotectonic unit (e.g., Lördagsberget), as well as possibly younger, TIB-related gabbroic intrusions observed in this study (e.g., the intrusions in the area between Bollnäs and Ockelbo).

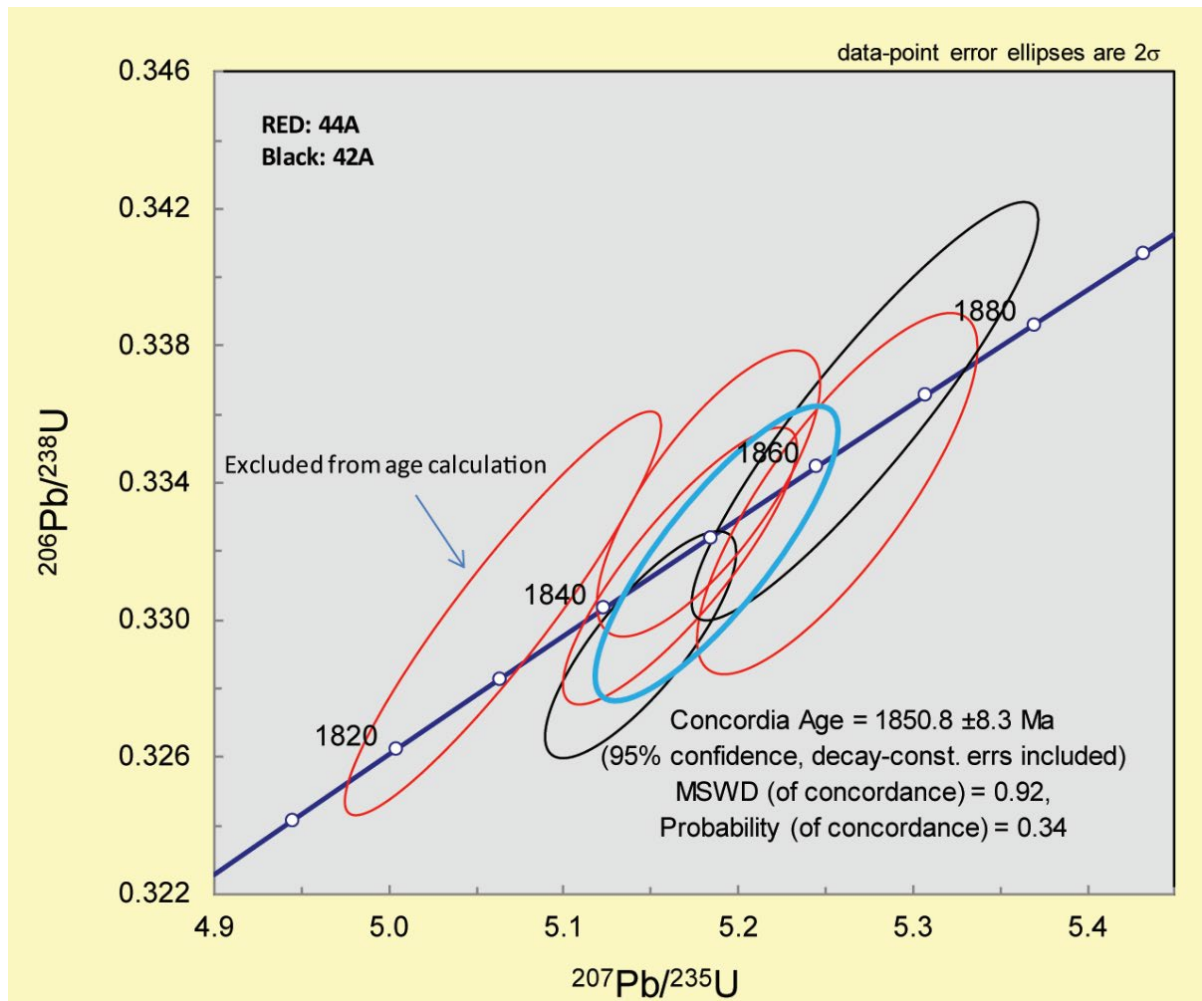


Figure 323. Tera-Wasserburg diagram showing the six 100% concordant U-Pb zircon data of the two Fe-Ti-V mineralised gabbroic samples from the Kramsta-Järvsö intrusion.

Table 14. Isotope data from the two studied samples and standards. LA–Q–ICP–MS zircon U–Pb isotope data from Lund University LA–ICP–MS laboratory.

^{a)} Within-run background–corrected mean ²⁰⁷Pb signal in counts per second [cps].
^{b)} Common Pb estimate based on background–corrected Pb ratios.
^{c)} U and Pb concentrations and Th/U ratios are approximations calculated relative to GJ-1 reference zircon.
^{d)} Corrected for background and within-run U–Pb fractionation and normalised to reference zircon GJ-1; ²⁰⁷Pb/²³⁵U calculated using (²⁰⁷Pb/²⁰⁶Pb)/(²³⁸U/²⁰⁶Pb * 1/137.818).
^{e)} Quadratic addition of within-run errors and and long-term errors of validation material.
^{f)} Rho is the error correlation defined as the quotient of the propagated errors of the ²⁰⁶Pb/²³⁸U and the ²⁰⁷Pb/²³⁵U ratio.

Spot	²⁰⁷ Pb ^a [CPS]	²⁰⁶ Pb/ ²⁰⁴ Pb ^b	Uc [ppm]	Pb ^c [ppm]	Th/U	Isotope ratios, uncorrected for common-Pb							Age data (Ma), uncorrected for common-Pb						
						²⁰⁷ Pb/ ²³⁵ U ^d	2σ [%] ^e	²⁰⁶ Pb/ ²³⁸ U	2σ [%] ^e	rho ^f	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ [%] ^e	²⁰⁷ Pb/ ²³⁵ U	2σ ^e	²⁰⁶ Pb/ ²³⁸ U	2σ ^e	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ ^e	Conc%
HRE220042A 1	1142000	100700000	6340	5090	0,10	4,992	0,57	0,316	0,73	0,83	0,11	0,40	1818	7	1773	11	1870	7	98
HRE220042A 2	694000	61000000	3850	4500	0,09	5,272	1,54	0,336	1,49	0,92	0,11	0,62	1864	20	1868	24	1860	11	100
HRE220042A 5	1113000	550556	6260	4060	0,08	5,034	0,54	0,322	0,65	0,72	0,11	0,46	1825	7	1801	10	1853	8	99
HRE220042A 6	249900	148333	1268	897	0,08	5,144	0,87	0,329	0,82	0,81	0,11	0,52	1843	11	1835	13	1853	9	100
HRE220042A 7	1003000	390870	5751	3946	0,09	5,022	1,25	0,324	1,58	0,95	0,11	0,57	1823	16	1808	25	1841	10	99
HRE220042A 9	413000	181500	2330	1341	0,07	4,714	1,03	0,300	0,90	0,69	0,11	0,76	1770	13	1690	13	1865	14	96
HRE220042A 11	950000	758182	5370	10520	0,24	5,318	0,90	0,335	1,17	0,83	0,12	0,65	1872	12	1861	19	1884	12	99
HRE220042A 12	376000	35200000	2040	2269	0,14	5,133	0,49	0,345	0,67	0,62	0,11	0,53	1842	6	1913	11	1762	10	104
HRE220042A 13	680000	60400000	3607	2330	0,08	5,035	2,07	0,321	2,15	0,98	0,11	0,44	1825	26	1794	34	1861	8	98
HRE220042A 14	613100	355875	3092	2068	0,08	5,419	0,79	0,361	0,72	0,73	0,11	0,56	1888	10	1988	12	1780	10	105
HRE220042A 15	503000	164074	3140	3190	0,17	4,695	1,40	0,299	2,04	0,84	0,11	1,14	1766	18	1685	30	1864	21	95
HRE220042A 16	446000	55824	7810	2540	0,15	1,740	3,24	0,142	2,67	0,95	0,09	1,12	1023	31	858	21	1397	21	84
HRE220042A 19	1300000	870538	7780	4515	0,08	5,051	0,94	0,316	1,49	0,79	0,12	0,95	1828	12	1769	23	1895	17	97
HRE220042A 20	294000	160000	1550	1014	0,11	5,361	0,87	0,357	0,92	0,89	0,11	0,43	1879	11	1970	16	1779	8	105
HRE220042A 21	1159000	505789	6150	4120	0,08	5,208	0,88	0,310	0,81	0,82	0,12	0,51	1854	11	1743	12	1981	9	94
HRE220042A 23	865200	72830000	5123	2437	0,06	5,118	0,95	0,310	1,10	0,61	0,12	0,92	1839	12	1739	17	1955	16	95
HRE220042A 24	1089000	89300000	7680	4010	0,07	4,398	3,23	0,259	2,74	0,91	0,12	1,38	1712	40	1485	36	2002	25	87
HRE220042A 25	1448000	4246667	8230	5770	0,08	5,240	1,12	0,332	1,29	0,89	0,11	0,59	1859	14	1850	21	1870	11	99
HRE220044A 1	107900	43636	577	1920	0,38	5,256	1,25	0,334	1,29	0,81	0,11	0,79	1862	16	1856	21	1868	14	100
HRE220044A 2	238400	1074500	1305	2760	0,26	5,183	1,01	0,334	1,02	0,77	0,11	0,69	1850	13	1856	16	1843	13	100
HRE220044A 3	117200	10450000	595	1720	0,28	5,167	1,06	0,332	1,00	0,86	0,11	0,55	1847	13	1846	16	1848	10	100
HRE220044A 4	728000	64400000	3821	4200	0,13	5,272	0,89	0,333	1,20	0,93	0,11	0,49	1864	11	1854	19	1875	9	99
HRE220044A 5	100300	130571	553	1347	0,30	5,065	1,46	0,330	1,45	0,93	0,11	0,54	1830	19	1839	23	1820	10	100
HRE220044A 8	253000	199167	1630	4100	0,26	4,434	1,51	0,297	1,51	0,87	0,11	0,78	1719	19	1677	22	1769	14	98
HRE220044A 9	734000	386471	4070	17010	0,49	5,027	0,84	0,322	0,90	0,64	0,11	0,74	1824	11	1801	14	1850	13	99
HRE220044A 10	293000	26500000	1594	5040	0,37	5,202	0,93	0,339	1,00	0,79	0,11	0,63	1853	12	1881	16	1821	11	102
HRE220044A 11	1645000	2285000	8090	9440	0,11	5,442	1,08	0,327	1,01	0,92	0,12	0,42	1891	14	1824	16	1966	8	96
HRE220044A 12	92500	8390000	502	1469	0,36	5,138	1,22	0,335	1,31	0,89	0,11	0,60	1842	15	1865	21	1817	11	101
HRE220044A 14	215900	178909	1181	4780	0,50	5,073	0,97	0,333	1,02	0,88	0,11	0,48	1832	12	1853	16	1807	9	101
HRE220044A 15	1024000	2245000	5430	5130	0,11	5,202	1,01	0,328	1,01	0,81	0,11	0,63	1853	13	1830	16	1879	11	99
HRE220044A 16	283000	211667	1520	1820	0,11	5,220	1,10	0,338	1,04	0,86	0,11	0,56	1856	14	1877	17	1832	10	101
BB16 1	5740	16683	219	129	0,25	0,713	1,35	0,089	1,12	0,55	0,06	1,19	546	9	551	6	527	26	101
BB16 2	5670	4156	224	132	0,25	0,717	2,22	0,091	1,65	0,65	0,06	1,71	549	14	560	9	503	38	102
BB16 3	5450	902000	199	123	0,25	0,743	2,17	0,088	1,59	0,74	0,06	1,47	564	14	544	8	647	32	96
BB16 4	5300	13114	202	125	0,26	0,733	1,42	0,092	1,20	0,61	0,06	1,17	559	9	565	6	532	26	101
GJ1-2	9070	1535000	303	27	0,03	0,809	1,15	0,097	0,93	0,69	0,06	0,85	602	8	599	5	613	18	100
GJ1-3	8110	1376000	270	24	0,03	0,809	1,19	0,098	1,02	0,61	0,06	0,99	602	8	602	6	601	21	100
GJ1-4	8750	1472000	291	27	0,03	0,810	1,22	0,098	1,13	0,63	0,06	1,01	603	8	600	6	611	22	100
GJ1-5	8200	9153	277	24	0,03	0,812	1,21	0,098	1,02	0,57	0,06	1,05	603	8	601	6	613	23	100
GJ1-6	8180	1375000	279	25	0,03	0,811	1,03	0,098	0,94	0,62	0,06	0,87	603	7	602	5	605	19	100
GJ1-7	8470	1416000	293	26	0,03	0,804	1,06	0,097	0,87	0,55	0,06	0,93	599	7	596	5	610	20	100
GJ1-8	8390	1418000	292	26	0,03	0,806	1,09	0,098	1,02	0,53	0,06	1,02	600	7	602	6	596	22	100
GJ1-9	8120	1351000	276	24	0,03	0,818	1,27	0,098	0,96	0,59	0,06	1,04	607	9	603	6	623	22	99
91500-SM-G7-1	5000	2355	75	142	0,41	1,810	1,63	0,177	1,47	0,62	0,07	1,35	1049	16	1052	14	1044	27	100
91500-SM-G7-2	4900	2220	75	142	0,41	1,818	1,78	0,178	1,63	0,73	0,07	1,27	1052	17	1054	16	1048	26	100
91500-SM-G7-3	4930	16625	76	141	0,40	1,847	1,80	0,179	1,62	0,75	0,08	1,21	1062	18	1059	16	1069	24	100
O60011-1	427000	28317	299	3609	0,71	40,769	1,25	0,794	1,51	0,90	0,37	0,67	3790	19	3768	43	3801	10	99
O60011-2	249000	13857	168	1870	0,58	40,280	1,34	0,793	1,39	0,94	0,37	0,49	3778	20	3764	40	3785	7	100
O60011-3	299800	10623	194	1985	0,53	42,957	1,06	0,841	1,09	0,95	0,37	0,35	3841	16	3934	32	3793	5	102
O60011-4	309000	5159	223	3540	0,86	40,523	1,26	0,798	1,38	0,94	0,37	0,46	3784	19	3782	39	3784	7	100

Table 14 continued. Isotope data from the two studied samples and standards. LA–Q–ICP–MS zircon U–Pb isotope data from Lund University LA–ICP–MS laboratory.

^{a)} Within-run background–corrected mean ²⁰⁷Pb signal in counts per second [cps].
^{b)} Common Pb estimate based on background–corrected Pb ratios.
^{c)} U and Pb concentrations and Th/U ratios are approximations calculated relative to GJ-1 reference zircon.
^{d)} Corrected for background and within-run U–Pb fractionation and normalised to reference zircon GJ-1; ²⁰⁷Pb/²³⁵U calculated using (²⁰⁷Pb/²⁰⁶Pb)/(²³⁸U/²⁰⁶Pb * 1/137.818).
^{e)} Quadratic addition of within-run errors and and long-term errors of validation material.
^{f)} Rho is the error correlation defined as the quotient of the propagated errors of the ²⁰⁶Pb/²³⁸U and the ²⁰⁷Pb/²³⁵U ratio.

Spot	Isotope ratios, corrected for common–Pb							Age data (Ma), corrected for common–Pb						
	²⁰⁷ Pb/ ²³⁵ U ^d	2σ ^e	²⁰⁶ Pb/ ²³⁸ U	2σ ^e	rho ^f	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ ^e	²⁰⁷ Pb/ ²³⁵ U	2σ ^e	²⁰⁶ Pb/ ²³⁸ U	2σ ^e	²⁰⁷ Pb/ ²⁰⁶ Pb	2σ ^e	Conc%
HRE220042A 1	4,987	0,041	0,316	0,002	0,875	0,114	0,000	1817	7	1771	11	1871	7	97
HRE220042A 2	5,263	0,088	0,335	0,005	0,923	0,114	0,001	1863	14	1865	25	1861	12	100
HRE220042A 5	5,030	0,040	0,322	0,002	0,814	0,113	0,001	1824	7	1800	10	1853	8	99
HRE220042A 6	5,131	0,049	0,329	0,003	0,826	0,113	0,001	1841	8	1832	13	1851	10	100
HRE220042A 7	5,002	0,087	0,322	0,005	0,945	0,113	0,001	1820	15	1802	26	1840	10	99
HRE220042A 9	4,714	0,059	0,300	0,003	0,748	0,114	0,001	1770	10	1691	14	1865	15	96
HRE220042A 11	5,311	0,074	0,334	0,004	0,885	0,115	0,001	1871	12	1859	20	1884	12	99
HRE220042A 12	5,142	0,045	0,345	0,002	0,789	0,108	0,001	1843	7	1913	11	1765	10	104
HRE220042A 13	5,010	0,111	0,319	0,007	0,981	0,114	0,000	1821	19	1785	34	1862	8	98
HRE220042A 14	5,422	0,047	0,362	0,002	0,785	0,109	0,001	1888	8	1989	12	1779	10	105
HRE220042A 15	4,671	0,108	0,297	0,006	0,871	0,114	0,001	1762	20	1679	30	1863	21	95
HRE220042A 16	1,722	0,048	0,141	0,004	0,914	0,088	0,001	1017	18	852	20	1391	22	84
HRE220042A 19	5,042	0,088	0,315	0,005	0,869	0,116	0,001	1826	15	1767	23	1895	16	97
HRE220042A 20	5,354	0,055	0,357	0,003	0,900	0,109	0,000	1877	9	1969	16	1778	8	105
HRE220042A 21	5,203	0,049	0,310	0,003	0,849	0,122	0,001	1853	8	1742	12	1980	9	94
HRE220042A 23	5,112	0,074	0,309	0,003	0,772	0,120	0,001	1838	12	1737	17	1955	16	94
HRE220042A 24	4,378	0,138	0,258	0,007	0,899	0,123	0,002	1708	26	1478	37	2003	25	87
HRE220042A 25	5,229	0,077	0,332	0,005	0,918	0,114	0,001	1857	13	1846	22	1870	11	99
HRE220044A 1	5,234	0,089	0,333	0,004	0,785	0,114	0,001	1858	15	1853	21	1864	19	100
HRE220044A 2	5,175	0,065	0,333	0,003	0,824	0,113	0,001	1848	11	1854	17	1842	13	100
HRE220044A 3	5,160	0,058	0,331	0,003	0,858	0,113	0,001	1846	10	1843	15	1849	10	100
HRE220044A 4	5,262	0,070	0,333	0,004	0,927	0,115	0,001	1863	11	1851	20	1876	9	99
HRE220044A 5	5,034	0,081	0,329	0,005	0,924	0,111	0,001	1825	14	1832	24	1817	11	100
HRE220044A 8	4,408	0,073	0,296	0,004	0,892	0,108	0,001	1714	14	1672	22	1765	14	98
HRE220044A 9	5,015	0,058	0,322	0,003	0,775	0,113	0,001	1822	10	1799	14	1848	13	99
HRE220044A 10	5,192	0,062	0,338	0,003	0,847	0,111	0,001	1851	10	1878	17	1821	12	101
HRE220044A 11	5,442	0,057	0,327	0,003	0,913	0,121	0,001	1891	9	1824	15	1966	8	96
HRE220044A 12	5,118	0,080	0,334	0,004	0,855	0,111	0,001	1839	13	1859	22	1817	15	101
HRE220044A 14	5,067	0,055	0,333	0,003	0,892	0,110	0,001	1831	9	1852	16	1806	9	101
HRE220044A 15	5,195	0,062	0,328	0,003	0,851	0,115	0,001	1852	10	1828	16	1879	11	99
HRE220044A 16	5,205	0,062	0,337	0,004	0,874	0,112	0,001	1854	10	1874	17	1831	11	101
BB16 1	0,696	0,034	0,089	0,001	0,236	0,057	0,003	536	21	549	6	484	105	102
BB16 2	0,664	0,056	0,090	0,002	0,214	0,054	0,004	517	35	556	10	350	186	107
BB16 3	0,750	0,051	0,088	0,001	0,244	0,062	0,004	568	30	542	9	674	141	95
BB16 4	0,714	0,033	0,091	0,001	0,278	0,057	0,003	547	20	561	7	488	97	103
GJ1-2	0,835	0,023	0,098	0,001	0,345	0,062	0,002	616	13	600	5	678	55	97
GJ1-3	0,812	0,024	0,098	0,001	0,356	0,060	0,002	604	14	600	6	618	61	99
GJ1-4	0,819	0,026	0,097	0,001	0,341	0,061	0,002	607	14	599	6	639	63	99
GJ1-5	0,782	0,027	0,097	0,001	0,337	0,058	0,002	587	16	598	7	541	71	102
GJ1-6	0,835	0,026	0,098	0,001	0,319	0,062	0,002	616	14	602	6	667	62	98
GJ1-7	0,804	0,025	0,097	0,001	0,274	0,060	0,002	599	14	595	5	614	64	99
GJ1-8	0,810	0,024	0,097	0,001	0,355	0,060	0,002	603	14	600	6	614	61	99
GJ1-9	0,822	0,026	0,098	0,001	0,312	0,061	0,002	609	14	602	6	636	64	99
91500-SM-G7-1	1,644	0,102	0,175	0,003	0,240	0,068	0,004	987	40	1038	14	875	124	105
91500-SM-G7-2	1,606	0,102	0,174	0,003	0,271	0,067	0,004	973	41	1036	17	832	128	107
91500-SM-G7-3	1,798	0,088	0,177	0,003	0,330	0,074	0,003	1045	32	1049	16	1036	93	100
060011-1	40,751	0,733	0,794	0,013	0,928	0,372	0,003	3789	18	3769	47	3800	10	99
060011-2	39,889	0,601	0,787	0,011	0,939	0,368	0,002	3768	15	3742	40	3782	8	99
060011-3	42,645	0,488	0,837	0,009	0,952	0,370	0,001	3834	11	3920	32	3790	5	102
060011-4	40,106	0,576	0,794	0,011	0,940	0,367	0,002	3773	14	3766	38	3777	7	100

Discussion and interpretation of results

Geochemistry and geotectonic setting: Summary and interpretation

The geotectonic setting in which the gabbroic rocks of the Ljusdal lithotectonic unit formed can be inferred from the lithogeochemical compositional characteristics and by key incompatible trace element ratios although care must be taken to ensure that the observed characteristics reflect primary features of the tectonic regime and not later fractionation or crustal contamination.

Because the six samples from the area between Bollnäs and Ockelbo have different compositions e.g., much higher LREE/HREE ratios and low Ti and V, than the vanadiniferous gabbroids further north they will be considered separately.

The average compositions of basalts (normalised to primitive mantle) from different tectonic settings including Island arc basalts (IAB), normal MORB (N-MORB) enriched-MORB (E-MORB) and Ocean Island basalt (OIB) are shown in figure 324. Figure 325 shows primitive mantle normalised average compositions of Masugnsberget, Gruvberget–Sumåssjön, Bläckmyran, Simesvallen, and Kramsta. The overall patterns and contents of key elements such as Nb and Pb in the analysed samples show clear similarities to Island arc basalt (fig. 325).

In figure 326 the average chondrite normalised patterns from the main gabbroic intrusions are shown together with Island arc basalt.

A feature shared by most gabbroic samples analysed in this project is an enrichment in the large-ion lithophile elements (LILE), Pb, and LREEs relative to HREEs, but depletion in some of the high field strength elements (HFSE), most notably Nb, relative to HREEs. This overall picture can be explained by dehydration reactions in the down-going slab that release water-soluble incompatible elements relative to water-insoluble incompatible elements. For example, the relative depletion of Nb, which is a prominent feature of magmas produced in subduction zones (e.g., Pearce 1982, Zheng 2019), is a result of the low solubility of Nb in water-rich fluids in the shallow parts of a subduction zone (Baier *et al.* 2008). On the other hand, the positive Pb anomaly that is commonly observed in such environments (fig. 324) is caused by mobilisation of this element by fluids released from the subducting slab which in turn may enrich the overlying mantle wedge.

As shown in the individual object descriptions in earlier chapters, trace-element ratios and various tectonic discrimination diagrams also suggest formation in an arc-related setting (e.g., figs. 75, 76, 127, 159). In order to explore this from a more overarching viewpoint, the average trace-element ratios for the main deposits at Masugnsberget, Gruvberget–Sumåssjön, Bläckmyran, Simesvallen, Kramsta, Skälberget, and Storåsen-Kullberget are plotted in figure 327 together with the basalt “end members” from figure 324.

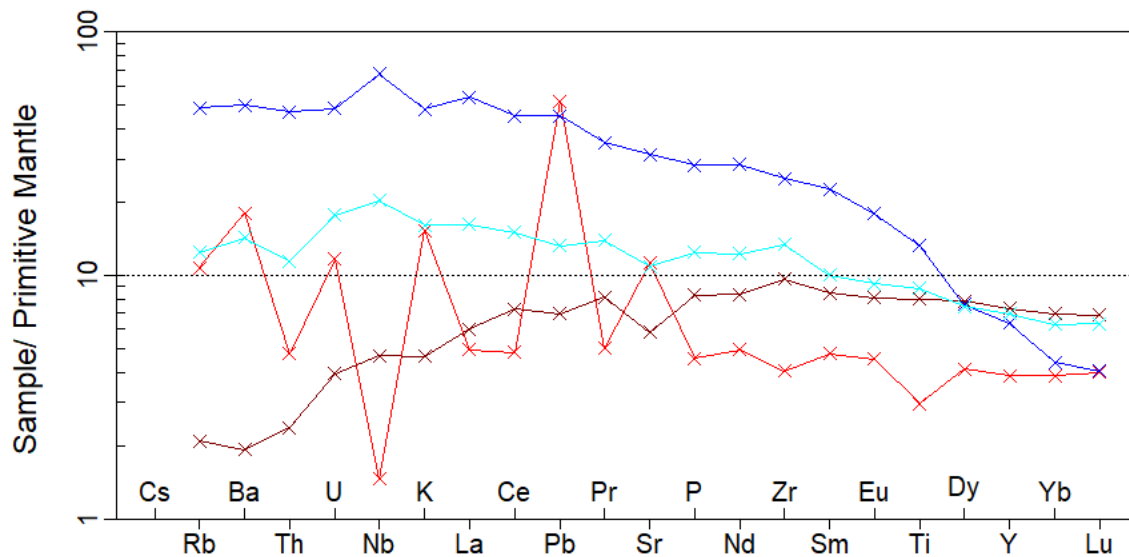


Figure 324. Primitive mantle normalised diagram showing Normal-MORB (N-MORB, brown), Island arc basalt (IAB, red), Enriched-MORB (E-MORB, cyan) and Ocean island basalt (OIB, blue). Data sources for the “end members” are from Niu & O’Hara (2003 and references therein). Normalising values from Sun & McDonough (1989).

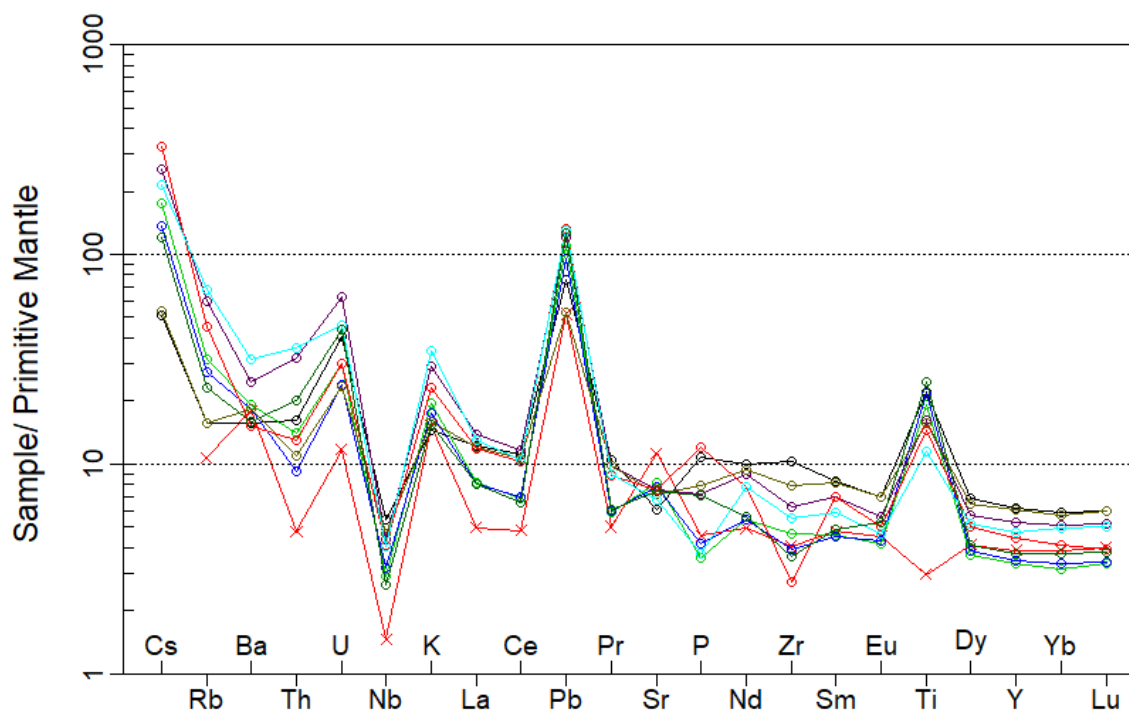


Figure 325. Primitive mantle normalised diagram showing average compositions from Masugnsherget-Blistra (purple circle, average of 26 samples), Gruvberget-Sumåssjön (green circle, average of 28 samples), Bläckmyran-Gråsjön (blue circle, average of 37 samples), Simesvallen (beige circle, average of 9 samples), the Järvsö area (black circle, average of 47 samples), Storåsen-Kullberget-Kattuggelberget (cyan circle, average of 12 samples), Skälberget (red circle, average of 5 samples), and Andberget-Gråsberget (dark green circle, average of 4 samples). Average Island arc basalt (IAB from fig. 324) is shown for comparison (red ‘X’ symbol). The average analyses (comprising 168 samples) from the current project are very similar to IAB, except for the pronounced Ti-anomaly caused by accumulation of titanomagnetite. Normalising values from Sun & McDonough (1989).

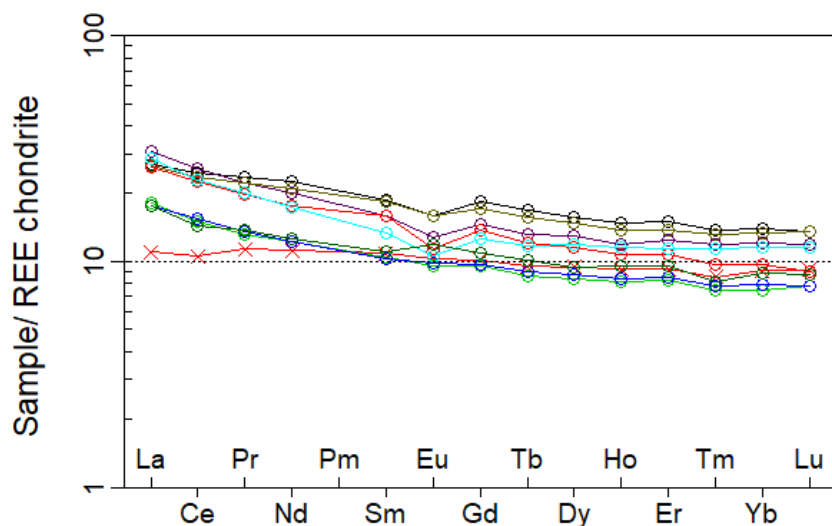


Figure 326. Chondrite normalised diagram showing average compositions Masugnsberget–Blistra (purple circle, average of 26 samples), Gruvberget–Sumåssjön (green circle, average of 28 samples), Bläckmyran–Gråsjön (blue circle, average of 37 samples), Simesvallen (beige circle, average of 9 samples), the Järvsö area (black circle, average of 47 samples), Storåsen–Kullberget–Kattuggelberget (cyan circle, average of 12 samples), Skalberget (red circle, average of 5 samples), and Andberget–Gräsberget (dark green circle, average of 4 samples). Average Island arc basalt (IAB from fig. 324) is shown for comparison (red 'X' symbol). Average Island arc basalt (red 'x' symbol) is shown for comparison.

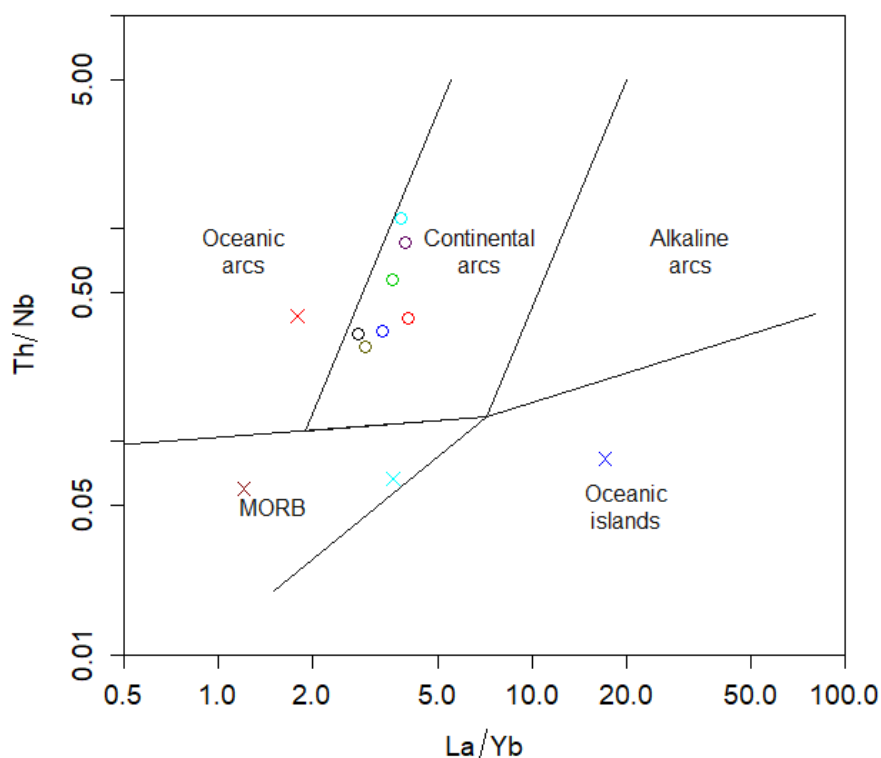


Figure 327. Average compositions of Masugnsberget (purple circle, average of 26 samples), Gruvberget–Sumåssjön (green circle, average of 28 samples), Bläckmyran (blue circle, average of 34 samples), Simesvallen (beige circle, average of 9 samples), Kramsta (black circle, average of 39 samples), Storåsen–Kullberget (cyan circle, average of 12 samples), and Skalberget (red circle, average of 5 samples) plotted in a La/Yb vs. Th/Nb diagram for tectonic discrimination (Hollocher *et al.* 2012). Average compositions of the “end members” Island arc basalt (red 'X'), N-MORB (brown 'X'), E-MORB (cyan 'X'), and OIB (blue 'X') are plotted for reference. The average compositions of “end members” are from Niu & O'Hara (2003 and references therein).

In the diagram in figure 327 the objects from this study all plot in the field of continental arcs. Also note that all the reference “end members” plot correctly in this diagram.

Arc-related magmas typically have a negative Ti-anomaly (fig. 324). The vanadiniferous gabbroids studied in this project, do however show the opposite, namely strong positive Ti-anomalies (fig. 325). This is interpreted as a result of titanomagnetite fractionation.

In summary, the geochemical and mineralogical data indicate that the gabbroids were derived from hydrous tholeiitic mafic magmas with arc-like geochemical signatures probably in a continental volcanic arc during the Svecokarelian orogeny. However, their undeformed appearance (lack of tectonic foliations) and intrusive field relations to surrounding deformed granitoids, suggest emplacement at a late stage in the orogenic evolution.

The proposed scenario is consistent with the radiometric dating in this project of gabbroid from the Kramsta intrusion that suggest an intrusive age of 1851 ± 8 Ma, which is younger than the first phase of ductile deformation (D1) in the Ljusdal unit dated to 1.87–1.86 Ga (Högdahl & Bergman 2020).

Comparison of ground magnetic data and inversion results for the different intrusions

So far throughout this report we have presented and discussed the various ground magnetic datasets and magnetic susceptibility inversion results for a range of intrusions. When presenting these results efforts have been made to display the results from the different datasets with the same colour scale to allow for comparison. However, due to the format of the report and varying distance scales for the maps, it is challenging for the reader to make a direct comparison between the different intrusions. Hence, in this section we provide some simple quantitative comparisons between the size and amplitude of the different magnetic anomalies. We also compare the results from the different magnetic susceptibility models, obtained from inversion of the ground magnetic data.

To compare the magnetic anomalies, a background magnetic field strength was first chosen for each intrusion. This background value was chosen based on an inspection of the values at the edge of each dataset, deemed to be outside the magnetic anomaly. Four threshold values were then specified, which were 2 500 nT, 5 000 nT, 7 500 nT, and 10 000 nT above the background value. The area over which the total magnetic field strength exceeded these various threshold values was then calculated for each dataset. These values hence give an idea of the amplitude of each magnetic anomaly relative to the background value as well as its aerial extent. These values are shown in Table 15 for each intrusion. A graphical representation of some of these values is also shown in figure 328. To compare the results from the magnetic susceptibility inversion, the maps which show the average magnetic susceptibility within the upper 75 m of the inversion model were used. Four magnetic susceptibility threshold values were chosen (0.1, 0.2, 0.3, and 0.4 SI). The area where the average magnetic susceptibility exceeded these different thresholds was then calculated (Table 15).

Table 15. Table comparing total magnetic field data and magnetic susceptibility inversion results for a range of different intrusions in this study. For each intrusion a background magnetic field value was specified. The third to sixth columns show the area in m² of the total magnetic field map which was greater than the threshold specified at the top of the column. In this case the threshold is the field strength in nT above the background value. The final four columns are related to the maps of average magnetic susceptibility in the upper 75 m of the inversion models, which were generated for each intrusion. The four columns describe the area in m² which are above the different thresholds specified at the top of the column.

Intrusion	Background (nT)	Area of total magnetic field map (m ²) above the cut off values stated below, where the cut off values define the value above the background value				Area of the map of average magnetic susceptibility in the upper 75 m of the inversion model (m ²) above the cut off values stated below			
		2500 nT	5000 nT	7500 nT	10000 nT	0.1 SI	0.2 SI	0.3 SI	0.4 SI
Bläckmyran	50000	139900	48700	16500	4600	114375	45000	21250	8750
Gruvberget–Sumåssjön	50000	112900	37300	8300	3000	137500	77500	39375	12500
Kramsta	50900	252600	45900	6500	1700	303750	108125	46250	13750
Skalberget	51700	45725	9150	3025	1375	46875	10625	625	0
Storåsen	51500	244225	49075	9950	1300	185000	38750	6250	625
Kullberget	51600	99050	18650	4425	1100	78750	17500	5625	1250
Storsveden	50900	59400	23900	4500	800	50625	25000	11875	6250
Järvsö–Gruvberget	50900	70600	28200	5700	500	70000	36250	16250	5000
Masugnsberget	50000	66500	8800	1600	400	36250	9375	3750	625
Kramsta–north	51500	137325	22775	1625	375	118750	34375	3125	0
Andberget	52200	1075	525	275	175	1250	0	0	0
Gråsjön	50000	77200	0	0	0	6250	0	0	0
Blistra	50000	42300	200	0	0	19375	625	0	0
Svedåsen–Bergvallåsen–Spännarslätten	50900	31200	0	0	0	38125	0	0	0
Simesvallen	50900	25600	1200	400	0	31250	10000	2500	0
Oxåsen	52100	25400	850	25	0	21875	625	0	0
Lövåsen	51900	24600	50	0	0	23125	625	0	0
Gräsberget	52000	7400	0	0	0	13750	0	0	0
Oktjärnen	52000	4550	0	0	0	10000	0	0	0
Tallåsen	51750	1525	0	0	0	1875	0	0	0
Gartsbo	51950	1150	75	0	0	0	0	0	0
Karsjöberget	52200	50	0	0	0	0	0	0	0

With regards to the total magnetic field maps, Bläckmyran and Gruvberget–Sumåssjön appear to have the largest areas which exceed the highest threshold of 10 000 nT above the background. These are followed by the Kramsta, Skälberget, Storåsen, and Kullberget intrusions which also have more than a 1 000 m² above the highest threshold value. Storsveden, Järvsö–Gruvberget, Masugnsberget, Kramsta-north and Andberget are the only remaining intrusions which have magnetic anomalies which are greater than 10 000 nT above the background level. Given the strong correlation between magnetic susceptibility and iron, titanium and vanadium concentration (see petrophysics section of the report), these intrusions are likely to have relatively high concentrations of these elements. Despite not exceeding 10 000 nT above the background Simesvallen and Oxåsen have relatively high magnetic field values, exceeding 7 500 nT above the background. The intrusions with the weakest magnetic anomalies, not exceeding the threshold value of 5 000 nT are Karsjöberget, Tallåsen, Oktjärnen, Gräsberget, Svedåsen–Bergvallåsen–Spännarslätten, and Gråsjön.

In terms of size, Kramsta and Storåsen appear to be the largest, where the magnetic anomaly exceeds the threshold of 2 500 nT over more than 200 000 m². Bläckmyran, Gruvberget–Sumåssjön, Kullberget, and Kramsta-north are also relatively large, with areas of about 100 000 m² or more where the total magnetic field exceeds the threshold of 2 500 nT. The smallest intrusions appear to be Karsjöberget, Tallåsen, Gartsbo, and Andberget where the area that the magnetic field exceeds the threshold of 2 500 nT is less than 2 000 m².

With regards to the inversion results, Bläckmyran, Gruvberget–Sumåssjön and Kramsta appear to have the highest average magnetic susceptibility values within the upper 75 m of the model, with the largest areas exceeding the highest threshold of 0.4 SI. Storsveden and Järvsö–Gruvberget also appear to have high average magnetic susceptibilities in the upper part of the inversion model, with areas exceeding the threshold of 0.4 SI of more than 5 000 m². The Gartsbo and Karsjöberget intrusions appear to have the lowest average magnetic susceptibilities in the upper 75 m of the inversion models, where no areas exceed the lowest susceptibility threshold of 0.1 SI.

Although there is a strong relationship between magnetic susceptibility and degree of mineralisation in these intrusions, it is important to highlight that these quantitative results only give a very approximate idea of the relative size and concentration of these deposits. For example, the relationship between magnetic susceptibility and vanadium concentration varies between the different deposits (see petrophysics section of the report). Remanent magnetisation has been shown to be significant in these intrusions (see petrophysics section), which also complicates the relationship between amplitude strength and mineralisation. It should also be noted that the coverage of the ground magnetic measurements can vary between intrusions, where the line spacing etc can vary. This can also affect the relationship between the observed amplitudes and inferred mineralisation. It is also important to note that the ground magnetic measurements are most strongly affected by the near surface magnetic properties and are less sensitive to those at depth. Furthermore, it should be emphasised that the results from the magnetic susceptibility inversions are only very approximate, with only a weak correlation with the available well and surface measurements.

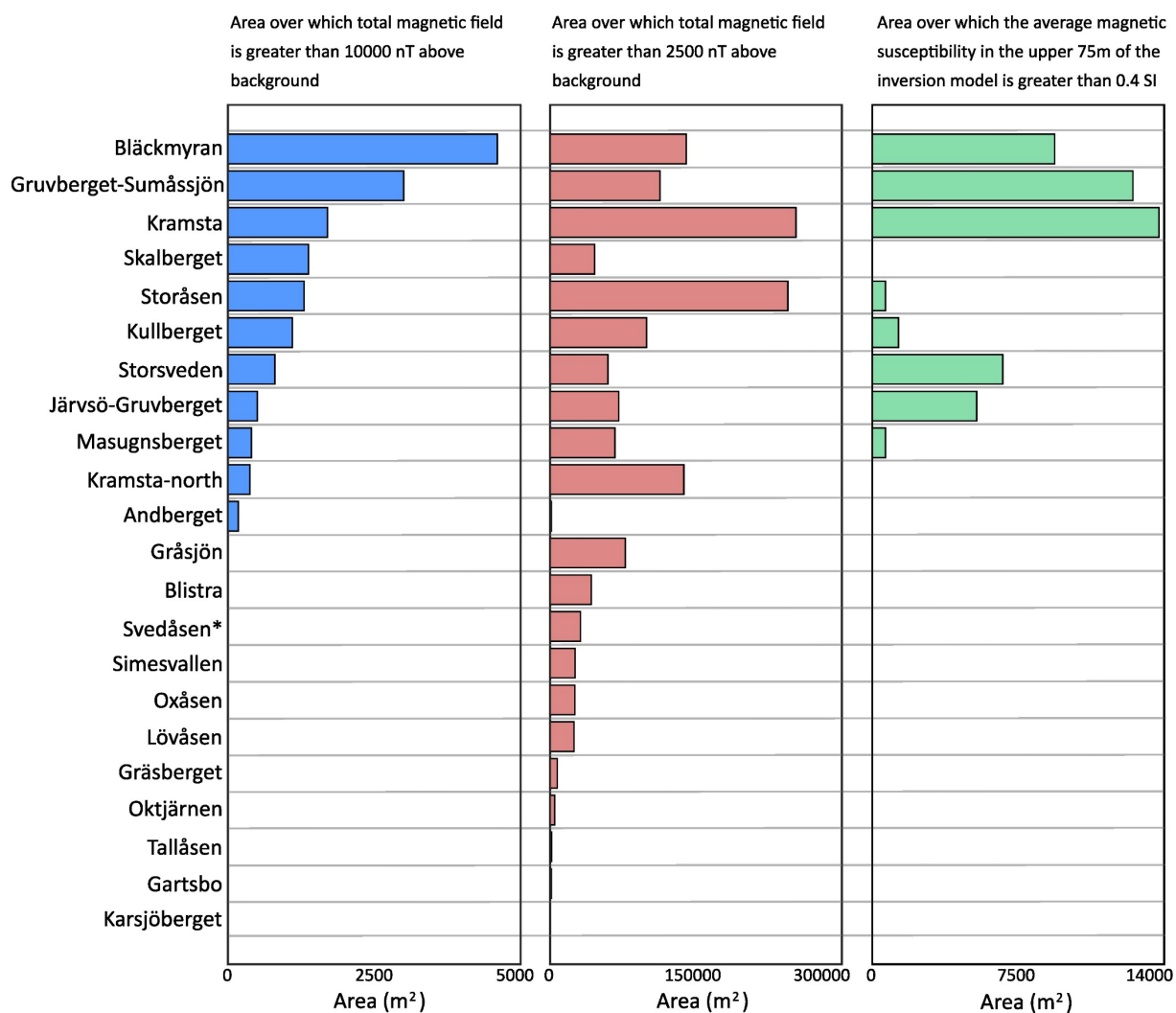


Figure 328. A bar graph comparing the total magnetic field data and magnetic susceptibility inversion results for the different intrusions. The data shown in this graph are shown numerically in Table 15. The left bar graph shows the area for each intrusion where the total magnetic field is above 10 000 nT over the background level. The middle bar graph shows the area for each intrusion where the total magnetic field is above 2500 nT over the background level. The right bar graph shows the area over which the map of the average magnetic susceptibility in the upper 75 m of the inversion model is above 0.4 SI. Note that the row labelled Svedåsen* includes the Svedåsen, Bergvallåsen, and Spännarslätten intrusions.

Geophysical modelling of the regional gravity anomaly beneath the Ljusdal lithotectonic unit

In this section we investigate the main regional gravity anomaly which lies below the Ljusdal lithotectonic unit. The peak of this anomaly lies about 10 km west of Järvsö and the anomaly is about 50 km wide, appearing as a red-orange-yellow area in figure 15. Many of the vanadium-bearing intrusions appear to occur above this anomaly and hence, there is the possibility that this large gravity anomaly reflects a large, dense body that is linked to these intrusions.

One potential interpretation is that this regional gravity anomaly is due to a large mafic intrusion at depth, which acted as the source magma chamber for the vanadium-bearing mafic intrusions presently observed at the surface. In this interpretation the vanadium-bearing mafic intrusions would represent relatively small volumes of mafic material which migrated closer to the surface along conduits and fractures (but still at considerable depth when this occurred). A schematic diagram of this potential interpretation is shown in figure 329B. If a large mafic intrusion exists at depth this could be an interesting target for further investigation as it could potentially contain zones with iron, titanium, and vanadium mineralisation, as observed in the intrusions at the present-day surface. However, depending on the nature and evolution of the large-scale intrusion, there is also the potential that it could contain zones with other types of resources (for example nickel, chromium, copper, and PGE mineralisation).

Hence, in this project we have performed geophysical modelling of the gravity anomaly, in order to investigate different scenarios where a large mafic intrusion is present at depth below the Ljusdal lithotectonic unit. As part of these models, we have tried to gain some insight into the potential depth to this large intrusion as well as its thickness and geometry.

The gravity modelling was performed in the Matlab software. As part of the investigation a series of different models of the subsurface were generated where the intrusion was placed at different depths. All of these models were designed to provide the best possible match between the forward modelled gravity response from the model and the observed data. Hence, we present a range of different possible subsurface scenarios, all of which, to a greater or lesser degree, match the observed gravity data.

As part of the modelling process the subsurface was split up into a regular grid of cells with different densities, corresponding to either granite or gabbro. In the calculation we assumed that the gravity response of each cell could be modelled as a point mass located at the centre of each cell. The gravity response from each of the individual cells could then be calculated and summed to provide the total modelled gravity response for the entire model. Figure 329 shows a schematic of the cell-based model and the modelled gravity response. The modelled gravity response for the layer at the base of the intrusion (layer 1) is shown. The response from an individual cell within that layer, is also shown.

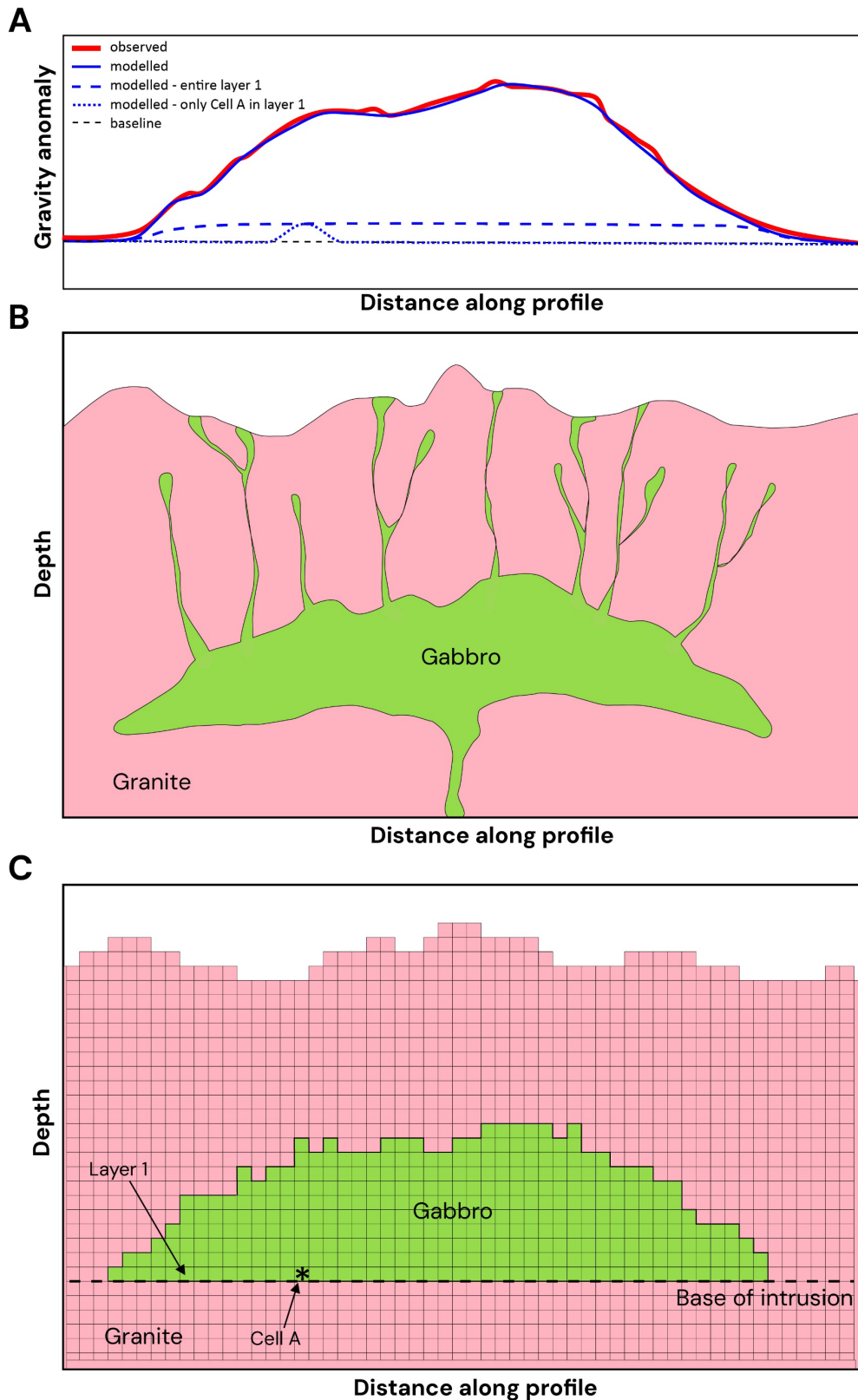


Figure 329. Schematic diagram describing the large-scale gravity modelling performed in this study. **A.** Schematic gravity anomaly collected in a profile over the regional anomaly. The observed data are shown as well as the modelled gravity response of the block model. The modelled response for the bottom layer of the gabbro intrusion (layer 1) and one individual cell from this layer are also shown. **B.** Schematic diagram showing how the vanadium-bearing gabbro intrusions could potentially be linked to a far larger intrusion at depth. **C.** Schematic diagram showing how the regional gravity anomaly was modelled in this study, i.e., the study area was split into a regular grid of cells and some of these were assigned to have an anomalous density (gabbro) relative to the background granite. Cell A and layer 1 are highlighted on the model. The modelled response from layer 1 and the individual cell A can be seen in A. at the top of the figure.

To generate one of these models, where the intrusion sits at a specific depth, we used the following steps:

1. The depth of the base of the intrusion was defined and the cells for the entire layer, corresponding to this depth were then identified. Initially no cells would be assigned to be gabbro within the layer.
2. Each cell from this layer was then tested in turn to see if it should be assigned to be gabbro or not. To test a given cell the gravity response for that cell was calculated (see fig. 329). In the case of the very first cell to be tested, then this gravity response would be compared with the measured gravity anomaly directly. If the modelled response from this one cell did not exceed the observed gravity response, then this cell was assigned to be gabbro. For all subsequent cells the gravity response for that cell would be calculated and then combined with the response for all cells already assigned to be gabbro in the model. If this combined response did not exceed the observed gravity response, then this cell would be assigned to be gabbro. After testing each cell within the layer, the modelled response for all gabbro cells in this layer could be calculated, as shown in figure 329.
3. This process was then repeated for each of the layers above. However, only cells which were located above a cell which was assigned to be gabbro were tested.
4. When no more cells could be assigned to be gabbro (as the modelled response would then exceed the observed response) then the process was stopped.

This procedure therefore provided an automated way to generate a model of a gabbro intrusion located at a given depth, which matched the observed gravity response. Furthermore, the geometry of this model is somewhat similar to the schematic intrusion shown in figure 329B, with a flat base and curved upper surface. Before performing the modelling process a constant background correction of -24 mGal was applied to the observed data. This was chosen as it appeared to be the background value for the large-scale anomaly. The density for the gabbro cells was set to be 600 kg/m^3 while the density of the granite cells was set to be 0 kg/m^3 . The background density is therefore assumed to be that of granite and the density of gabbro is assumed to be 600 kg/m^3 denser than this. This is consistent with the mean average density values discussed in the petrophysics section (see Table 2).

Figure 330 shows a plot summarising some key parameters of the different models which were generated. The x-axis shows the depth of the base of the intrusion in each of the models which were generated, therefore each x-position on the plot shows the results for a different model. The root-mean square (RMS) misfit (i.e., the difference) between the modelled and observed gravity response is shown as a blue curve in figure 330. Where a lower RMS misfit value denotes a better match between the observed and modelled response. Here we can see that the lowest misfit value occurs for an intrusion with a depth of about 1 000 m below mean sea level and gradually increases for models with greater depths. For models where the base of the intrusion is shallower than 1 000 m below mean sea level, there is a rapid increase in the RMS misfit between the observed and modelled response, when moving towards shallower depths. In these cases, the number of cells which are assigned to be gabbro are limited by the top of the model (i.e., the amount of space between the base of the intrusion and the ground surface is not great enough to model an intrusion which matches the observed gravity response).

The minimum depth from the ground surface to the top of the large-scale gabbro intrusion in each of the models as well as the maximum thickness of the intrusion are also shown in figure 330. Here we can see that for modelled intrusions with a base deeper than 1 000 m below mean sea level, the maximum thickness of the intrusion remains somewhat constant at about 1 200 m thick. The minimum depth to the top of the intrusion from the ground surface, as would be expected, is largely negatively correlated with the depth to the base of the intrusion. For the subsequent discussion of the results, we highlight three models which we refer to as 1, 2, and 3,

where the base of the intrusion is placed at -1 000 m, -1 500 m and -2 600 m depth respectively. Models 1, 2, and 3 are also highlighted in figure 330.

Figure 331 shows the observed gravity response as well as the modelled response for models 1, 2, and 3. Here it can be observed that all models provide a relatively good match to the observed gravity response. However, the modelled response from model 3 appears to be very smooth and low frequency, hence, the higher frequency features in the observed data are not adequately captured. This smooth, low frequency character is most likely due to the greater depth of the modelled intrusion and is likely to be the cause of the gradual increase in RMS misfit with greater intrusion depth (fig. 330). Figure 332 shows a series of cross sections through models 1, 2, and 3 as well as the associated observed and modelled gravity responses measured along the cross sections. Here the match between the observed and modelled responses can be observed to be good for all of the models. However, the modelled response is notably smooth and low frequency for model 3.

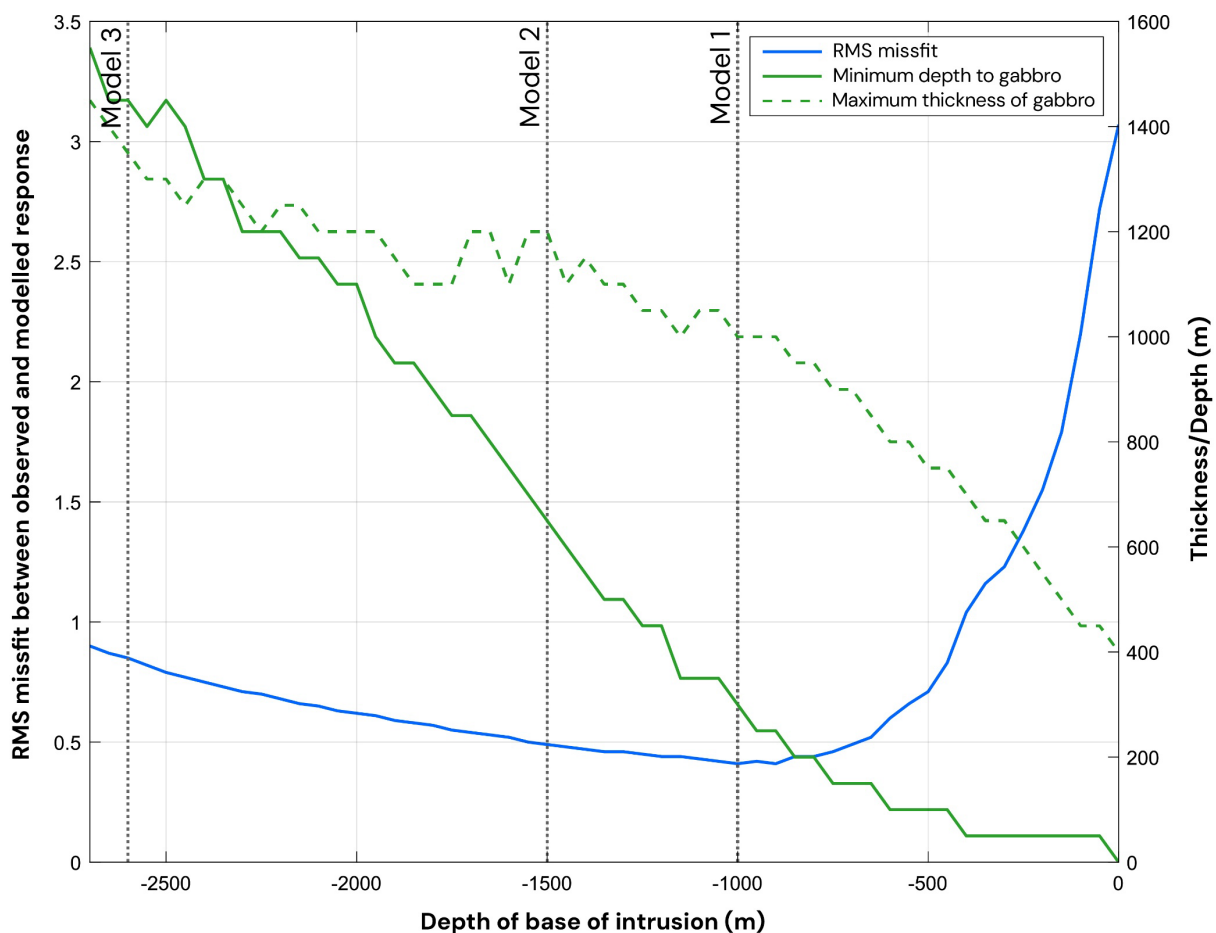


Figure 330. Summary of gravity modelling results. The diagram shows results for a series of different models where the depth of the base of the intrusion is varied. The RMS misfit between the observed and modelled gravity response is shown as a blue line. The minimum depth to the gabbro from the surface as well as the maximum thickness of the gabbro in each model are shown as green solid and dashed lines, respectively. The parameters of the three models described in the text in more detail (models 1, 2, and 3) are shown with grey dashed lines.

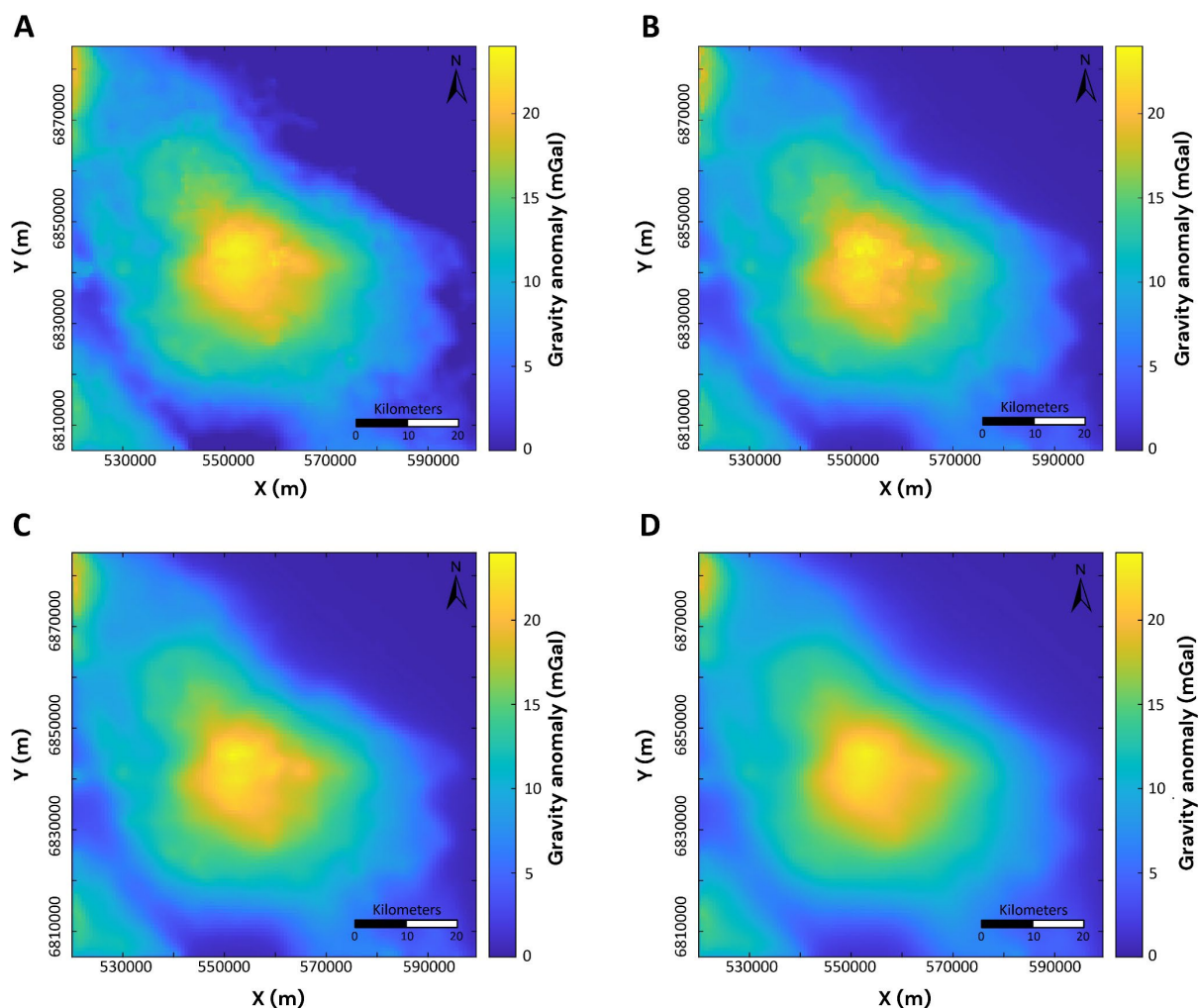


Figure 331. Measured and modelled gravity responses over the main regional gravity anomaly within the Ljusdal lithotectonic unit. **A.** Measured gravity anomaly. **B.** Modelled gravity anomaly from model 1, with base of gabbro intrusion at 1 000 m below mean sea level. **C.** Modelled gravity anomaly from model 2 with base of gabbro intrusion at 1 500 m below mean sea level. **D.** Modelled gravity anomaly from model 3 with base of gabbro intrusion at 2 600 m below mean sea level.

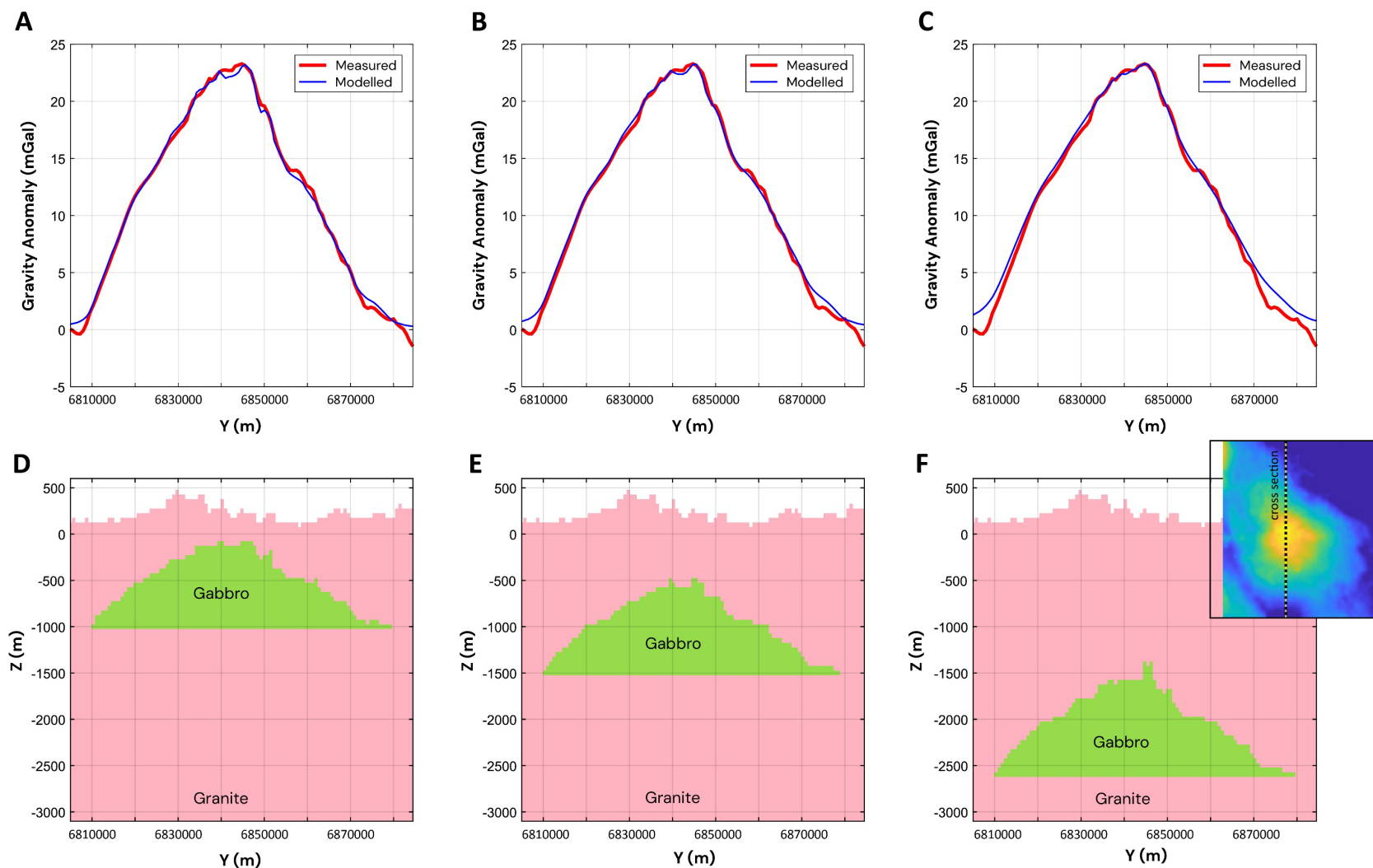


Figure 332. Cross sections and model responses for the regional gabbro intrusion, for different models. **A. B. and C.** show the observed and modelled gravity responses for models 1, 2 and 3, respectively. **D. E. and F.** show cross sections through the 3D density model for models 1, 2 and 3, respectively. The location of the profile used for the cross sections and gravity anomaly results is shown in the small inset map in the top right-hand corner of part F. The data shown in the small inset map is the observed gravity response which is also shown in figure 331A.

Based on these results it is clear that there is a great deal of uncertainty with regards to the depth of the large-scale intrusion. Hence, based on the gravity data alone it is not possible to give a strong indication of the depth to the potential large-scale intrusion. However, in this study we interpret it to be more likely that the base of the intrusion is 1 000 m below mean sea level or deeper. This is due to the relatively poor match between the observed and modelled gravity response for models where the base of the large intrusion is shallower than 1 000 m (fig. 330). We also give a tentative interpretation that the depth to the base of the intrusion is less likely to be deeper than 1 500 m. This is due to the low frequency character of the modelled responses for the deeper intrusions (for example model 3), which does not appear to match the observed response as well as shallower models (for example model 1 and 2). Therefore, we tentatively interpret that models with depth between models 1 and 2 are more likely to be correct than models deeper than model 2.

Figure 333 shows maps of the depth to the top of the intrusion and thickness of the intrusion in models 1 and 2. Here we can observe that the minimum depth to the top of the intrusion is about 300 m in model 1 and about 650 m in model 2. The maximum thickness of the intrusion varies between about 1 000 m in model 1 to about 1 200 m in model 2. The total volume of the large-scale intrusion varies between about 2 000 km³ and 2 200 km³ in models 1 and 2. Figure 334 shows a 3D image of one of the models produced in this study together with the observed gravity response. In this model the base of the intrusion was at 1 400 m depth. Here the curved upper form of the intrusion in the model can clearly be observed.

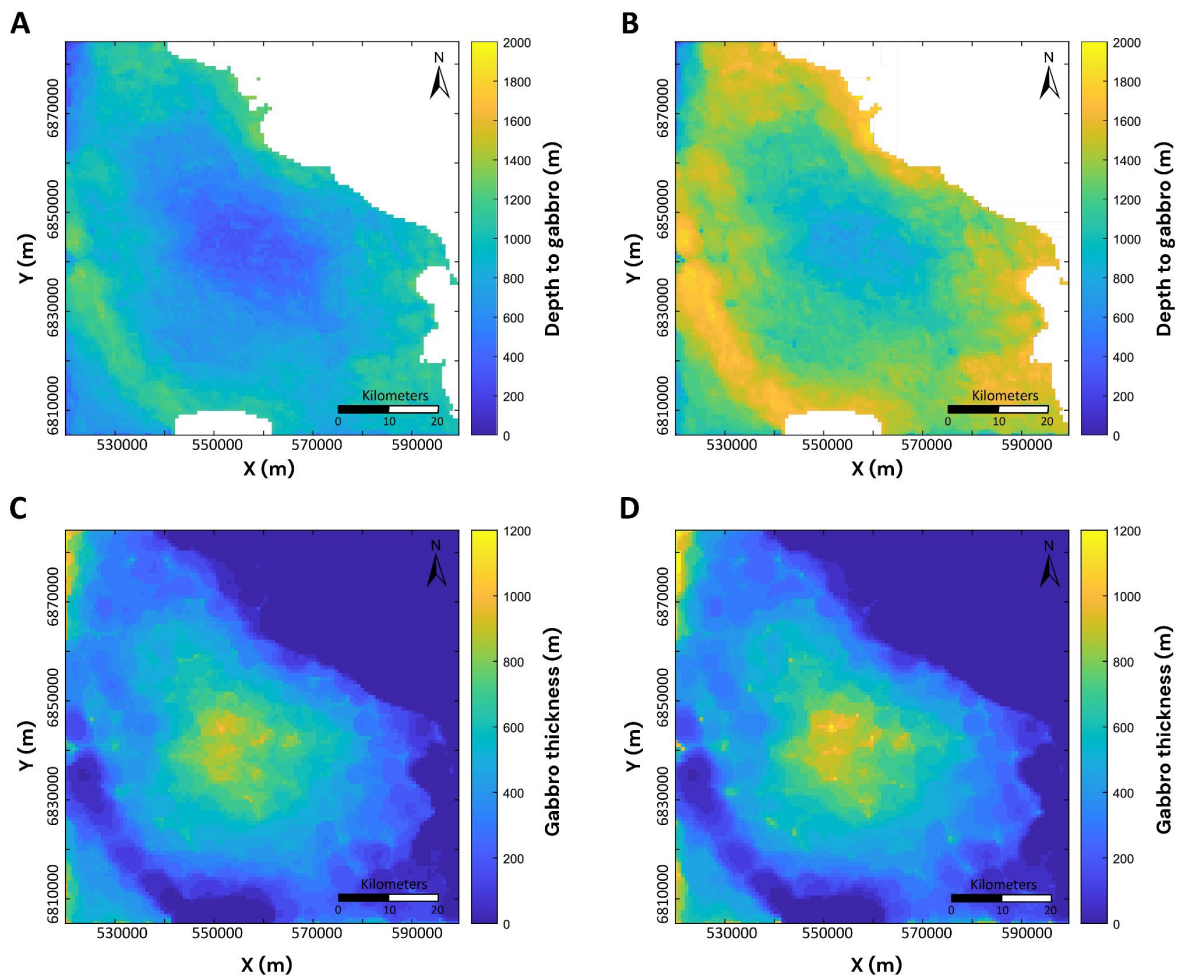


Figure 333. Maps of depth to the regional gabbro intrusion and its thickness for different models. **A.** and **B.** show maps of the depth to the top of the regional gabbro intrusion from the surface for models 1 and 2, respectively. **C.** and **D.** show maps of the thickness of the regional gabbro intrusion for models 1 and 2, respectively.

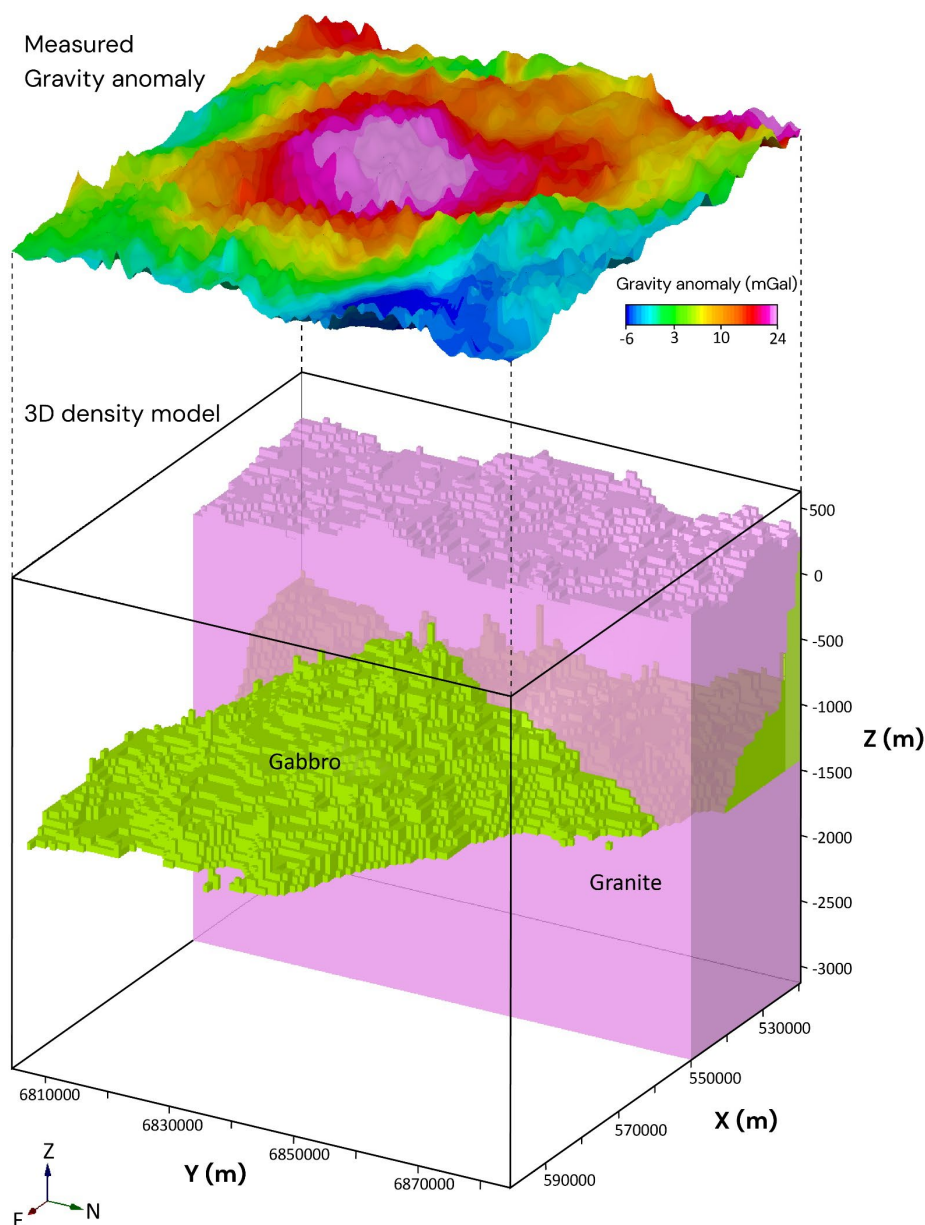


Figure 334. 3D view of the measured gravity anomaly shown together with a regional model generated in this study, where the base of the intrusion was 1 400 m below mean sea level.

When considering these results, it is important to take note of the very large degree of uncertainty, due to the non-uniqueness of the solution i.e., many models can be generated which match the observed gravity response as shown in figure 332. The gravity modelling is also based on a number of assumptions, which, if changed would lead to different subsurface models also. For example, we assume that the gravity anomaly here is due to a single large-scale mafic intrusion at depth. If one was to assume a different geometry, for example a layered sequence of large-scale intrusions, one would obtain a very different model which also matches the observed gravity response. The choice of the gabbro density used in the modelling and the background gravity value also effect the geometry and depth of the modelled intrusion.

In order to provide more constraint on this potential large-scale intrusion at depth additional data collection and analysis would need to be performed. For example, seismic reflection data or data from new boreholes could potentially provide useful constraint on the depth to the top of this large-scale intrusion.

Conclusions

In this study, we have performed a comprehensive investigation of layered mafic intrusions hosting Fe-Ti-V mineralisation in the Ljusdal lithotectonic unit, Sweden. This has included a detailed review of the pre-existing information from these intrusions, where large quantities of data, previously available only in analogue format, were digitised. We have also collected large amounts of new data as part of this study, including 239 new petrophysical samples, 199 new geochemical samples, 133 new thin sections, 12 new ground magnetic surveys, 1 906 new ground gravity measurements, numerous new geological observations (made on both drill core and outcrop), and one new age determination.

Using the available data we have performed a detailed characterisation of over 20 mafic intrusions from the Ljusdal lithotectonic unit. This has included presenting updated bedrock geology maps of the intrusions, description of thin sections, and analysis of the geochemical data.

Based on the data analysis from this study, it is possible to provide a description of the typical features exhibited by these mafic intrusions, which host Fe-Ti-V mineralisation within the Ljusdal lithotectonic unit. Figure 335 shows a schematic diagram which describes the two typical geometries we have observed. The first is a “dyke or sheet like” geometry which is exhibited by the majority of the intrusions, such as Bläckmyran or Simesvallen. The second is a “concentric or bowl like geometry”, which is exhibited only by the Kramsta and Kramsta-north (and perhaps the eastern part of the Storåsen intrusion). Typically, at least in some of the largest layered intrusions in this study, the highest concentrations of Fe-Ti-V can be observed in dark grey fine-medium grained layers with high magnetic susceptibility. Figure 335 also shows that in both geometries the zones with a high degree of mineralisation tend to occur as relatively thin layers or lenses within the intrusion, often parallel to the outer edge of the intrusion. Thin veins with pegmatitic felsic rocks also often occur throughout these intrusions. In some cases xenoliths of the surrounding granitic rock can also be observed. Close to the contact with the surrounding granitic rocks, so called “hybrid” rocks are often observed. These rocks most likely result from mingling and mixing between granitic rocks, melted close to the edge of the intrusion, and mafic rocks from the intrusion in the contact zone. Based on regional-scale map information, some intrusions are elongated in an east–west orientation with a length of between 100 m and 1 000 m and a width of between 50 m and 300 m.

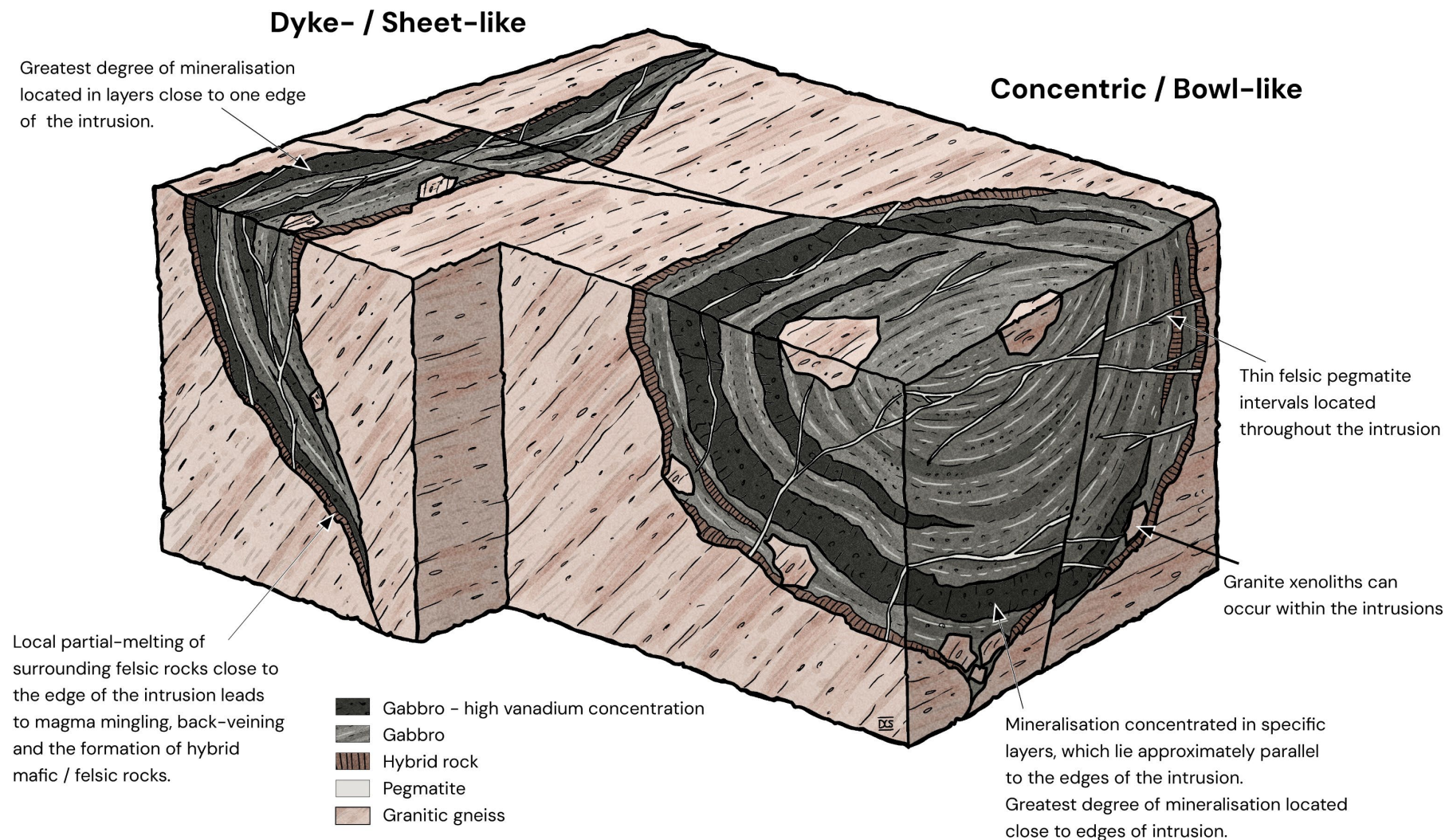


Figure 335. Generalised diagram describing the typical aspects of vanadium-bearing gabbros in the Ljusdal lithotectonic unit.

The Fe-Ti-V intrusions in this study are all layered mafic intrusions, although more or less well-developed. The evidence for this is seen at both macro- and micro-scale, in outcrops and in thin sections under the microscope as well as in the lithochemical analyses, and patterns of magnetic properties of airborne measurements and on outcrops. Layering is exemplified by modal variations of different minerals, observable in outcrops and drill cores. Cryptic layering is also evident, where layering cannot be observed visually, but is inferred by measurements of magnetic properties and geochemical properties. A plethora of textures seen in the images of the thin sections are evidence that the studied rocks are from layered mafic intrusions, for example cumulate textures, igneous granoblastic texture, poikilitic texture with oikocrysts and chadacrysts or primocrysts. Preferred orientation of elongate crystals that are parallel or sub-parallel to the magmatic layering, most common among plagioclase crystals (but also seen in hornblende and biotite) is also indicative of layered mafic intrusions.

The vanadium-bearing mafic intrusions typically have significantly higher density and magnetic susceptibilities than the surrounding foliated granitic rocks. Furthermore, geochemical analyses for these intrusions show a strong correlation between the concentrations of vanadium, titanium, and iron, and there is a clear relationship between the degree of Fe-Ti-V mineralisation and the magnetic susceptibility in the intrusions. This means that magnetic and gravity measurements can provide valuable information for mapping these types of intrusions, as well as characterising any mineralisation present. Results in this project demonstrate, that when correctly calibrated, magnetic susceptibility can be used as a direct indication of the amount of Fe, Ti, and V present when measuring on core samples.

A series of unconstrained magnetic susceptibility inversions were performed for a number of intrusions based on the ground magnetic data. However, the results from these inversions show only a weak correlation between the true magnetic susceptibilities measured at outcrop and on core samples and hence can only be used qualitatively. Therefore, although the potential to utilise magnetic susceptibility inversions to delineate mineralisation remains strong, more detailed work is required to improve the accuracy of the inversion results. Including constraints and taking into account the effect of remanent magnetisation would likely be critical factors to improve the inversion results.

A 3D geological model of the Järvsö Field within this study demonstrates that gravity data can provide valuable constraint on the geometry and thickness of these types of intrusions observed at the surface, as well as help identify potential additional intrusions at depth. The geophysical response of the intrusions investigated within the study have also been compared quantitatively, where the area and strength of the magnetic anomalies have been ranked. Here the largest and strongest anomalies can clearly be identified, which could provide useful input to identify targets for further investigations.

The geochemical and mineralogical data presented in this study indicate that the gabbroids were derived from hydrous tholeiitic mafic magmas with arc-like geochemical signatures probably in a continental volcanic arc during the Svecokarelian orogeny. Their undeformed appearance (lack of tectonic foliations) and intrusive field relations to surrounding deformed granitoids, suggest emplacement at a late stage in the orogenic evolution.

The proposed scenario is consistent with the radiometric dating in this project of gabbroid from the Kramsta intrusion that suggest an intrusive age of 1851 ± 8 Ma, which is younger than the first phase of ductile deformation (D1) in the Ljusdal unit dated to 1.87–1.86 Ga (Högdahl & Bergman 2020). The intrusions were not affected by later deformation during D2 and D3 and associated metamorphism, which is well-documented in other parts of the Ljusdal lithotectonic unit.

Depth of intrusion was deduced from the mineral assemblages formed in the various layered intrusions and maximum depth by the occurrence of igneous interstitial garnet formed at the Storåsen intrusion. These observations show that already at around 1850 Ma ago this portion of the crust was in the lower parts of a volcanic arc, which had previously seen severe metamorphic and deformational overprinting, something the layered Fe-Ti-V intrusions have not. The Fe-Ti-V intrusions, which formed at depth are interpreted to have been uplifted during predominantly extension related uplift of the Ljusdal lithotectonic unit, where they can now be observed at the present-day bedrock surface.

Evidence for immiscibility of an iron-rich liquid from a silica-rich liquid was recorded in one iron mineralised sample from the Kramsta-north intrusion, deduced from lithogeochemical analysis. A denser sampling program focused on finding evidence of immiscibility events in the other intrusions, would probably yield proof of the process being active elsewhere among the other Fe-Ti-V intrusions. If this type of immiscibility occurs but on a much smaller scale, i.e., within portions of layers that are smaller than the typical size of a lithogeochemical sample, then it is possible that the process has been missed in some intrusions within this study (as the samples we utilised were typically quite small, i.e., two to three kilograms).

Reactive or not reactive relation between late-formed iron-H₂O-enriched interstitial liquid and earlier-formed silicate minerals depends on the context in which the iron-H₂O-enriched interstitial liquid ended up crystallising. If the late formed iron-H₂O-enriched interstitial liquid crystallise approximately where it formed, i.e., *in situ*, reactions between it and the surrounding silicate minerals are not seen. However, if the iron-H₂O-enriched interstitial liquid moves from its source area into areas that formed before an iron-H₂O-enriched interstitial liquid had formed (such as in the lower parts of the crystal mush or at even lower portions of the crystal pile) the iron-H₂O-enriched interstitial liquid is very reactive and completely or partially dissolves most silicate minerals it encounters. Even early formed plagioclase is dissolved, completely or partially, and in its place hornblende and Fe-Ti oxides are normally formed as seen in several of the examined thin sections of this study. Theoretically, if the intrusions had been several orders of magnitude larger, this process might have formed larger and massive layers of Fe-Ti oxides as recorded elsewhere (e.g., Dong *et al.* 2021, Wang *et al.* 2021, Chen *et al.* 2023).

It is likely that the majority of the mafic intrusions which host Fe-Ti-V mineralisation within the Ljusdal lithotectonic unit, which are present at the surface of the bedrock, can be identified and have been mapped based on airborne magnetic measurements and geological observations presented in this study. In this study we present new data and analyses of several of the larger intrusions which have previously not been investigated in detail, such as Storåsen, Kullberget, Skälberget, and Kramsta-north. There remains, however, good potential to find additional Fe-Ti-V-bearing intrusions (similar to those observed at the surface) at depth within the Ljusdal lithotectonic unit. Ground gravity data and airborne magnetic data can be valuable tools to locate potential intrusions at depth, where in this study several additional potential intrusions have been identified in the Järvsö Field using these data. Furthermore, the regional-scale gravity anomaly observed within the Ljusdal lithotectonic unit could be indicative of a large mafic intrusion at depth, potentially providing the source for the Fe-Ti-V-bearing intrusions observed at the surface. In this case this large intrusion could be an interesting target for further investigation.

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Appendix A. Petrophysical data

Table A1. Table summarising all of the new petrophysical data collected as part of this study.

Sample ID	Easting (m)	Northing (m)	Description	Density (kg/m ³)	Magnetic Susceptibility (10 ⁻⁶ SI)	J (mA/m)	Declination (degrees)	Inclination (degrees)
DCL222000A	578350	6871445	Gabbro	3138	67159	24494		
DCL222001A	578350	6871445	Gabbro	3288	517553	260455		
DCL222002A	578331	6871407	Gabbro	3257	523728	353185		
DCL222003A	578331	6871407	Gabbro	2996	41667	7756		
DCL222004A	557860	6831044	Granite	2701	71163	1329		
DCL222005A	557860	6831044	Gabbro	3381	440120	59323		
DCL222006A	557860	6831044	Gabbro	3119	87572	29452		
DCL222007A	557723	6831035	Granite	2692	19821	818		
DCL222008A	557723	6831035	Gabbro	3263	215412	66438		
DCL222009A	558171	6831072	Gabbro	3237	202945	9419		
DCL222010A	558180	6831028	Gabbro	3180	141436	38231		
DCL222011A	581996	6869714	Gabbro	3068	9702	2290		
DCL222012A	581996	6869714	Gabbro	3285	498406	16609		
DCL222013A	581996	6869714	Gabbro	3015	40427	2191		
DCL222014A	581996	6869714	Granite	2661	9763	1097		
DCL222015A	581602	6869635	Gabbro	2996	99102	3166		
DCL222016A	581602	6869635	Gabbro	3130	106020	42261		
DCL222017A	581602	6869635	Gabbro	3283	496377	17247		
DCL222018A	581602	6869635	Gabbro	3135	88242	59620		
DCL222019A	581602	6869635	Granite	2660	22099	2854		
DCL222020A	581586	6869702	Gabbro	3524	851882	424678		
DCL222021A	581586	6869702	Gabbro	3088	141009	29843		
DCL222022A	581978	6869789	Gabbro	3593	870526	31447		
DCL222023A	581978	6869789	Gabbro	3773	1200431	4065555		
DCL222024A	581618	6869563	Gabbro	4060	1223405	312216		
DCL222026A	585014	6870606	Gabbro	3250	426866	331329		
DCL222027A	584709	6870221	Gabbro	3330	622001	33989		
DCL222028A	584709	6870221	Granite	2800	78259	42266		
DCL228001A	559587	6841475	Gabbro	3334	196985	48949		
DCL228003A	559918	6841805	Gabbro	3082	50893	24685		
DCL228004A	559980	6841814	Gabbro	3624	838347	306710		
DCL228005A	559442	6841375	Gabbro	3131	67523	5660		
DCL228008A	559745	6841746	Gabbro	3550	473941	61606		
DCL228009A	560193	6841873	Gabbro	3716	768702	105826		
DCL228011A	560193	6841873	Gabbro	3926	1717600	1527347		
DCL223013A	560046	6841857	Gabbro	3890	1122469	79108		
DCL223016A	560046	6841857	Gabbro	4872	6903851	95909		
DCL223017A	560159	6841910	Gabbro	3270	232454	12477		
DCL223019A	559515	6841552	Gabbro	3804	805291	56145		
DCL223020A	559515	6841552	Granite	2664	172	37		
DCL223021A	578403	6871371	Gabbro	3032	115405	4966		
DCL223023A	578403	6871371	Gabbro	2964	38563	21686		
DCL223025A	578403	6871371	Gabbro	3069	89353	5452		
DCL223027A	578421	6871407	Gabbro	3407	599484	212938		
DCL223029A	578421	6871407	Gabbro	3267	207288	26117		
DCL223031A	578421	6871407	Gabbro	3080	34773	22684		
DCL223032A	584678	6870258	Gabbro	3560	711887	168700		
DCL223034A	584678	6870258	Gabbro	3172	171043	74216		
DCL223035A	584678	6870258	Gabbro	3278	465436	18015		

Table A1 continued. Table summarising all of the new petrophysical data collected as part of this study.

Sample ID	Easting (m)	Northing (m)	Description	Density (kg/m ³)	Magnetic Susceptibility (10 ⁻⁶ SI)	J (mA/m)	Declination (degrees)	Inclination (degrees)
DCL223037A	584941	6870507	Gabbro	3289	546978	146290		
DCL223039A	584941	6870507	Gabbro	4128	1784521	594356		
DCL223040A	584941	6870507	Gabbro	3204	209985	55379		
DCL223041A	584856	6870508	Gabbro	3246	214600	10756		
DCL223042A	584856	6870508	Gabbro	3209	156080	6662		
DSR220001A	578211	6871388	Gabbro	3772	1233650	83608		
DSR220002A	578200	6871378	Gabbro	3117	69573	5687		
DSR220003A	578404	6871183	Granite	2589	9371	293		
DSR220004A	577378	6871120	Gabbro	3746	548347	298257		
DSR220005A	577511	6871169	Granite	2669	11603	162		
DSR220006A	582210	6869811	Gabbro	3548	1004810	55292		
DSR220007A	582349	6869816	Gabbro	3017	9810	2929		
DSR220008A	584861	6870538	Gabbro	3268	459230	105297		
DSR220009A	584990	6870532	Gabbro	3149	780675	3869		
DSR220010A	585038	6870597	Gabbro	3657	765584	40684		
DSR220011A	586526	6871786	Gabbro	3116	85743	1536		
DSR220012A	558108	6831094	Gabbro	3627	398918	158903		
DSR220016A	557230	6827231	Granite	2704	167570	1254		
DSR220017A	557258	6827232	Granite	2642	101	22		
DSR220018A	559065	6826768	Granite	2673	1316	99		
DSR220019A	557020	6826795	Granite	2619	151	45		
DSR220020A	556908	6826488	Gabbro	3056	62098	1711		
DSR220021A	559463	6841545	Gabbro	3614	573610	21560		
DSR220023A	559707	6841802	Gabbro	3336	325396	58005		
DSR220024A	559759	6841864	Gabbro	3406	437118	27226		
DSR220025A	560467	6841920	Gabbro	3058	2917	1763		
DSR220025B	560467	6841920	Granite	2614	379	218		
DSR220027A	560442	6842138	Gabbro	3165	126225	4891		
DSR220028A	538658	6865641	Gabbro	3218	370614	13967		
DSR220029A	538774	6865745	Gabbro	3743	1220162	1455019		
DSR220030A	538737	6865521	Gabbro	3173	121468	5650		
DSR220031A	559947	6816457	Gabbro	3039	47748	5411	79	-14
DSR220032A	585569	6882448	Granite	2820	1326	28		
DSR220033A	585614	6882456	Granite	2647	218	67		
DSR220034A	585705	6882339	Gabbro	2879	63435	1689	296	65
DSR220035A	585706	6880131	Granite	2684	290	50		
DSR220037A	576477	6878497	Gabbro	2795	78196	1114		
DSR220038A	576443	6878505	Gabbro	3035	89853	1539	200	44
DSR220040A	576824	6878341	Granite	2707	8038	206		
DSR220041A	566296	6848962	Gabbro	2996	69962	2347		
DSR220042A	566273	6849044	Granite	2648	2256	111		
DSR220043A	566405	6848863	Granite	2618	617	105		
DSR220044A	548253	6833729	Gabbro	2968	61369	2630	136	57
DSR220045A	548165	6833740	Gabbro	3154	189786	4633		
DSR220046A	549789	6834409	Granite	2623	78	57		
DSR220047A	557528	6840633	Gabbro	3425	486748	77060		
DSR220048A	557526	6840615	Gabbro	3465	494883	223320		
DSR220049A	557578	6840368	Gabbro	3448	400573	141139		
DSR220050A	557654	6841076	Gabbro	3042	128979	2709		

Table A1 continued. Table summarising all of the new petrophysical data collected as part of this study.

Sample ID	Easting (m)	Northing (m)	Description	Density (kg/m ³)	Magnetic Susceptibility (10 ⁻⁶ SI)	J (mA/m)	Declination (degrees)	Inclination (degrees)
DSR220051A	557701	6841001	Granite	2662	9007	638		
DSR220052A	564910	6833219	Quartz monzonite	2685	6813	68		
DSR220053A	561171	6817868	Granite	2687	213	24		
DSR220054A	559248	6814993	Gabbro	3091	81875	4057	257	79
DSR220055A	559166	6815016	Gabbro	3218	75489	4092	148	55
DSR220055B	559166	6815016	Granite	2611	11	49		
DSR220056A	559140	6814930	Granite	2624	5652	33		
DSR220057A	542105	6866422	Gabbro	2993	29676	2946	209	33
DSR220058A	542138	6866394	Gabbro	2956	28044	936		
DSR220058B	542138	6866394	Granite	2600	31	122		
DSR220059A	538209	6865248	Gabbro	3072	252858	4503	240	59
DSR220060A	538212	6865246	Gabbro	3023	116231	2706	235	62
DSR220061A	545138	6865100	Gabbro	3251	94944	4110	36	64
DSR220062A	545301	6865122	Gabbro	3064	77586	18334		
DSR220063A	545164	6865090	Gabbro	3163	30586	731	166	30
DSR220064A	553339	6863358	Gabbro	3364	209882	15505		
DSR220065A	560050	6842477	Gabbro	3053	23407	3562	172	47
DSR220066A	559934	6842530	Gabbro	3211	145321	6935	224	54
DSR220067A	559996	6842505	Gabbro	3226	225779	7303		
DSR220068A	560033	6842399	Granite	2646	2056	606		
DSR220069A	560298	6842063	Gabbro	3171	123363	13544	224	41
DSR220070A	560376	6842241	Gabbro	3333	461059	15943	214	24
DSR220071A	560224	6842355	Gabbro	3173	79158	38380	144	-11
DSR220072A	559541	6841683	Gabbro	3294	262558	46227	292	19
DSR220073A	559705	6841806	Gabbro	3302	332489	57001	202	41
DSR220074A	558334	6840636	Granite	2654	8481	883		
DSR220075A	558862	6840726	Granite	2645	8450	641		
DSR220076A	558616	6840590	Granite	2658	12328	6514		
DSR220077A	566096	6848039	Gabbro	3139	92412	3099	142	83
HRE220006A	582028	6869674	Gabbro	3045	64238	1115		
HRE220016A	559817	6841878	Gabbro	3772	1376199	88048		
HRE220021A	538608	6865634	Gabbro	3041	120350	1902		
HRE220024A	559295	6815042	Gabbro	3626	788823	27134		
HRE220024B	559295	6815042	Gabbro	3183	102312	1825		
HRE220032A	542106	6866402	Gabbro	2982	23228	270		
HRE220033A	545117	6865124	Gabbro	3597	1405611	5152		
HRE220033B	545117	6865124	Gabbro	3014	1743	41		
HRE220035A	578499	6869825	Gabbro	3261	295265	15413		
HRE220037A	585440	6870401	Gabbro	3141	153018	10355		
HRE220039A	558955	6843860	Gabbro	3565	573938	36650		
HRE220040A	558777	6843656	Gabbro	3709	895074	34032		
HRE220042A	559946	6842952	Gabbro	4068	2837243	2248820		
HRE220043A	559498	6842610	Gabbro	3499	185056	146164		
HRE220044A	559374	6842699	Gabbro	3101	177663	4381		
HRE220047A	559471	6841544	Gabbro	3631	621974	32725		
HRE220049B	566141	6848053	Gabbro	3872	1780576	158429		
HRE220057A	566379	6849011	Gabbro	3081	32938	3753		
DSR230001A	584827	6870452	Gabbro	3716	942081	1161680		
DSR230002A	584827	6870452	Granite	2652	19029	258		

Table A1 continued. Table summarising all of the new petrophysical data collected as part of this study.

Sample ID	Easting (m)	Northing (m)	Description	Density (kg/m ³)	Magnetic Susceptibility (10 ⁻⁶ SI)	J (mA/m)	Declination (degrees)	Inclination (degrees)
DSR230003A	584827	6870452	Gabbro	3175	146115	5268		
DSR230004A	584855	6870424	Gabbro	3739	1269327	274167		
DSR230005A	584855	6870424	Gabbro	3208	171558	2916		
DSR230006A	584855	6870424	Granite	2653	9460	207		
DSR230007A	584769	6870340	Gabbro	3585	872952	785347		
DSR230008A	584769	6870340	Granite	2649	301	95		
DSR230009A	584741	6870369	Gabbro	3676	944331	253117		
DSR230010A	584600	6870342	Gabbro	3162	60924	10520		
DSR230011A	584600	6870342	Granite	2693	294	338		
DSR230012A	584678	6870258	Gabbro	3067	54067	8101		
DSR230013A	558057	6831072	Gabbro	3116	8189	2700		
DSR230014A	558057	6831072	Gabbro	3071	9015	3618		
DSR230015A	558245	6831100	Granite	2486	103	62		
DSR230016A	558107	6831076	Granite	2668	4175	149		
DSR230017A	559546	6841518	Gabbro	3201	135416	50219		
DSR230018A	559546	6841518	Gabbro	3692	717117	724783		
DSR230019A	559546	6841518	Gabbro	3141	91425	67483		
DSR230020A	559546	6841518	Granite	2650	2928	206		
DSR230021A	559765	6841750	Gabbro	3075	107630	46623		
DSR230022A	559765	6841750	Gabbro	3426	375534	24027		
DSR230023A	559765	6841750	Gabbro	3129	25597	8254		
DSR230024A	559765	6841750	Granite	2649	7733	325		
DSR230025A	559923	6841786	Gabbro	3176	220985	6938		
DSR230026A	560159	6841910	Gabbro	3461	496465	17207		
DSR230027A	560159	6841910	Gabbro	3325	262013	153995		
DSR230028A	560159	6841910	Granite	2617	136	92		
DSR230029A	559985	6841795	Gabbro	3423	465728	38695		
DSR230030A	560046	6841857	Gabbro	3234	195339	9730		
DSR230031A	560046	6841857	Granite	2617	203	31		
DSR230032A	581995	6869713	Gabbro	3297	1805	898		
DSR230033A	581995	6869713	Gabbro	3590	2139318	822020		
DSR230034A	582002	6869686	Gabbro	3120	155239	2429		
DSR230035A	582002	6869686	Granite	2681	24926	530		
DSR230036A	582002	6869686	Gabbro	3004	25826	779		
DSR230037A	581758	6869674	Gabbro	3799	1270357	1071626		
DSR230038A	581758	6869674	Granite	2668	10386	206		
DSR230039A	581758	6869674	Gabbro	3183	175397	74353		
DSR230040A	581524	6869615	Gabbro	3153	283213	9651		
DSR230041A	581524	6869615	Granite	2671	31784	470		
DSR230042A	541491	6840351	Gabbro	3082	181177	1919		
DSR230043A	558409	6787639	Gabbro	2939	66627	2320	98	41
DSR230044A	558552	6787560	Gabbro	2959	140464	6176		
DSR230045A	553161	6786946	Gabbro	2942	3940	286		
DSR230046A	553255	6786949	Gabbro	2979	42201	1910	71	36
DSR230047A	595315	6875228	Green stone	2847	52796	1505	36	58
DSR230048A	586538	6871788	Gabbro	3079	26799	446	211	15
DSR230049A	586478	6871832	Gabbro	3301	129192	4395	226	53
DSR230050A	586572	6871899	Gabbro	2982	118604	4133	246	64
DSR230051A	579006	6869639	Gabbro	2967	70304	1776	152	53

Table A1 continued. Table summarising all of the new petrophysical data collected as part of this study.

Sample ID	Easting (m)	Northing (m)	Description	Density (kg/m ³)	Magnetic Susceptibility (10 ⁻⁶ SI)	J (mA/m)	Declination (degrees)	Inclination (degrees)
DSR230052A	578943	6869620	Gabbro	3023	78472	850	112	57
DSR230053A	578698	6869861	Gabbro	3048	25129	199		
DSR230054A	578700	6869825	Gabbro	3182	208952	1649		
DSR230055A	592692	6765066	Gabbro	2900	80455	3500	193	70
DSR230056A	592624	6765131	Gabbro	2787	31246	785	219	73
DSR230057A	545868	6838125	Gabbro	3002	912	63		
DSR230058A	578052	6871510	Gabbro	3057	82108	2640	219	61
DSR230059A	578187	6871501	Gabbro	3027	169410	8656	12	32
DSR230060A	578205	6871475	Gabbro	2970	39244	1095	215	80
DSR230061A	542430	6866464	Gabbro	3046	40652	2173	268	49
DSR230062A	542513	6866297	Granite	2626	1393	165		
DSR230063A	542565	6866540	Gabbro	2999	13787	569	261	65
DSR230064A	559586	6841474	Granite	2611	2654	18		
DSR230065A	559441	6841374	Gabbro	3234	228983	13284		
DSR230066A	559922	6841786	Gabbro	3271	369221	20534		
DSR230067A	559922	6841786	Granite	2572	92	85		
DSR230068A	559917	6841804	Gabbro	3220	179874	26379		
DSR230069A	559917	6841804	Gabbro	3419	389861	435748		
DSR230070A	584913	6870536	Gabbro	3349	446389	576645		
DSR230071A	584913	6870536	Gabbro	3531	809144	1010994		
DSR230072A	584913	6870536	Gabbro	3170	77785	3125		
DSR230073A	584913	6870536	Granite	2661	18414	369		
DSR230074A	584884	6870480	Gabbro	3318	425394	92655		
DSR230075A	584884	6870480	Gabbro	3227	333963	59888		
DSR230076A	584884	6870480	Gabbro	3165	175379	62957		
DSR230077A	584963	6870556	Gabbro	4019	1534223	906827		
DSR230078A	584963	6870556	Gabbro	3359	588128	115293		
DSR230079A	584963	6870556	Gabbro	3204	215046	5308		
DSR230080A	584963	6870556	Granite	2665	38799	835		
DSR230081A	578279	6871463	Gabbro	3445	684646	25496		
DSR230082A	578279	6871463	Gabbro	3085	104545	3514		
DSR230083A	578311	6871371	Gabbro	3119	267060	157435		
DSR230084A	578311	6871371	Gabbro	3093	224237	39431		
DSR230085A	578488	6871373	Gabbro	3124	101480	61635		
DSR230086A	578488	6871373	Gabbro	3212	190316	151393		
DSR230087A	581966	6869747	Gabbro	3473	546711	548793		
DSR230088A	581966	6869747	Gabbro	3858	1607486	1020049		
DSR230089A	558107	6831076	Gabbro	2959	132086	12774		
DSR230090A	558245	6831100	Gabbro	3046	56948	6096		
HRE230017A	559248	6814990	Gabbro	3144	86150	4719		
HRE230039A	548138	6833767	Gabbro	3612	862598	50200		
HRE230047A	576790	6877021	Gabbro	3042	127293	1935		
HRE230069A	542521	6866532	Gabbro	3246	201055	7576		

Appendix B. Magnetic susceptibility log measurements

In this appendix we present the magnetic susceptibility log measurements on drill core, performed as part of this project. During the project magnetic susceptibility measurements were performed on 19 drill cores. The results of 18 of the cores are presented in this appendix, while the results from one drill core from Bläckmyran (BLA82006) are presented in figure 9 in the main body of the report.

For each plot the magnetic susceptibility log measurements, collected with a hand susceptibility meter (JH-8) are presented on the left-hand side as a black line. The colours to the left of the black line show an interpretation of the lithology. The red circles in the left-hand plot show the magnetic susceptibility measurements performed on samples in SGU's petrophysics lab. Geochemical data is shown in the three columns on the right-hand side of the plot. Here geochemical measurements are shown in red. The black line shows the geochemical concentrations calculated directly from the magnetic susceptibility values, using the trend described in the petrophysics section in the report. If the standard deviation of the error between the trend line and the data is denoted by σ (shown in Table 6), then the dark grey and light grey shaded areas show the calculated geochemical values $\pm \sigma$ and $\pm 2\sigma$, respectively. Refer to the petrophysics section of the report for a full explanation of the methodology for the measurements and calculated geochemical values. The locations of the boreholes are shown in figure B1 for the Gruvberget–Sumåssjön, Bläckmyran, and Masugnsberget intrusions and B2 for the Kramsta and Simesvallen intrusions. Table B1 provides a list of all the boreholes where magnetic susceptibility logging of drill core was performed together with the intrusion in which they are located. The table also lists the figure number for a location map for each borehole and a figure number where the measured data is displayed on a log plot.

Table B1. Table listing all boreholes where magnetic susceptibility measurements were performed on drill core as part of this study. The figure numbers for the basemap showing the location of the borehole as well as the measured data are also listed.

Borehole ID	Intrusion	Year	Depth (m)	Figure number for location map	Figure number for drill core log plot
BLA82004	Bläckmyran	1982	141.65	B1	B3
BLA82006	Bläckmyran	1982	107.15	B1	9
K-D-09	Kramsta	unknown	105.6	B2	B4
K-D-10	Kramsta	unknown	135	B2	B5
K-D-23	Kramsta	unknown	126.58	B2	B6
K-D-25	Kramsta	unknown	115.5	B2	B7
K-D-26	Kramsta	unknown	72.65	B2	B8
K-D-28	Kramsta	unknown	84	B2	B9
K-D-29	Kramsta	unknown	113	B2	B10
K-D-31	Kramsta	unknown	109.27	B2	B11
K-D-34	Kramsta	unknown	105.5	B2	B12
MAB83006	Masugnsberget	1983	82.2	B1	B13
MAB83007	Masugnsberget	1983	51.15	B1	B14
SIM82001	Simesvallen	1982	132	B2	B15
SIM82003	Simesvallen	1982	90.15	B2	B16
SIM83001	Simesvallen	1983	70.95	B2	B17
SUM81001	Gruvberget–Sumåssjön	1981	156.33	B1	B18
SUM81017	Gruvberget–Sumåssjön	1981	98.07	B1	B19
SUM81022	Gruvberget–Sumåssjön	1981	86.5	B1	B20

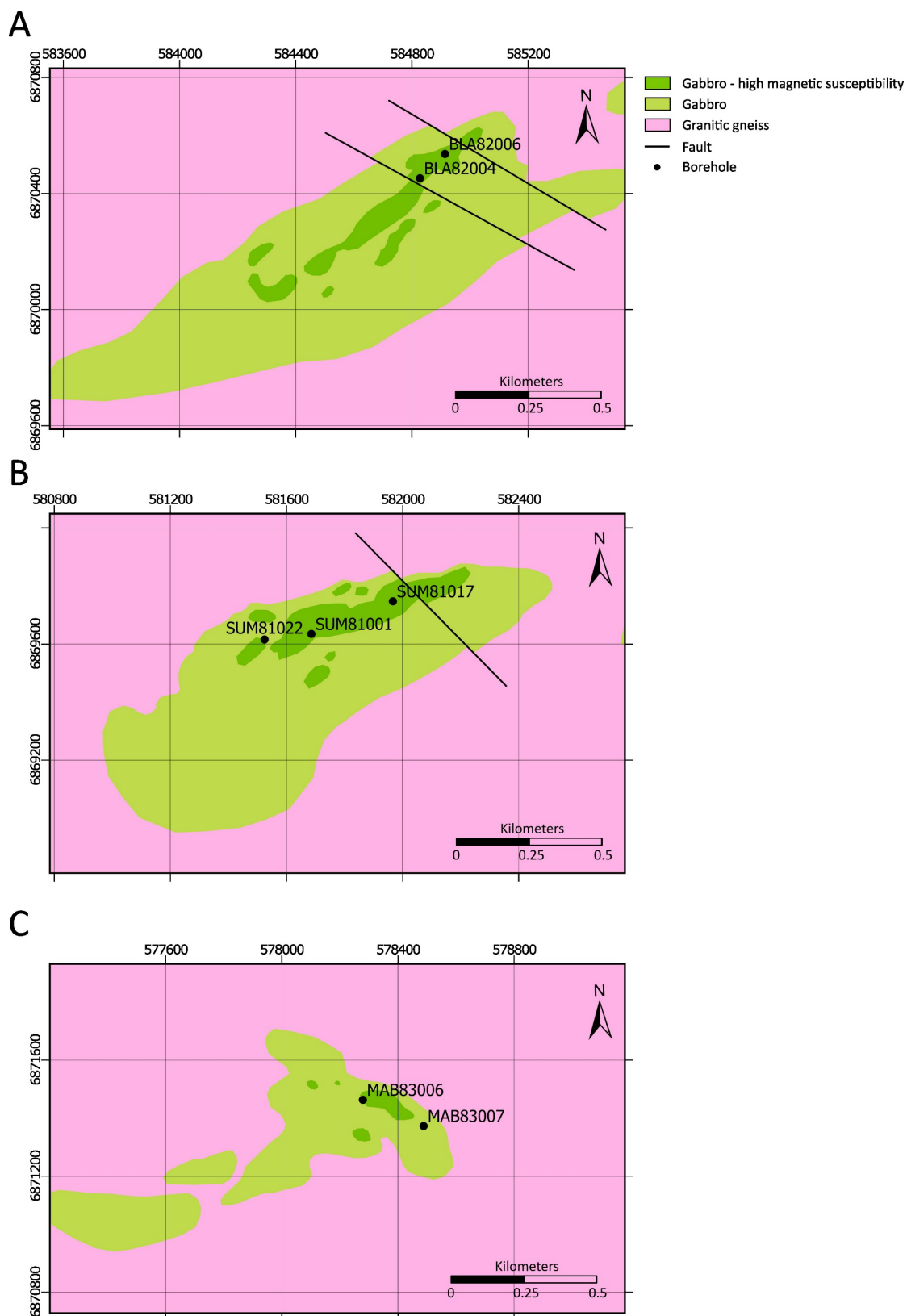


Figure B1. Maps showing the location of boreholes from which drill core was logged for magnetic susceptibility in this study. **A.** Location of boreholes from which drill core was logged in the Bläckmyran intrusion. **B.** Location of boreholes from which drill core was logged in the Gruvberget–Sumåssjön intrusion. **C.** Location of boreholes from which drill core was logged in the Masugnsberget intrusion.

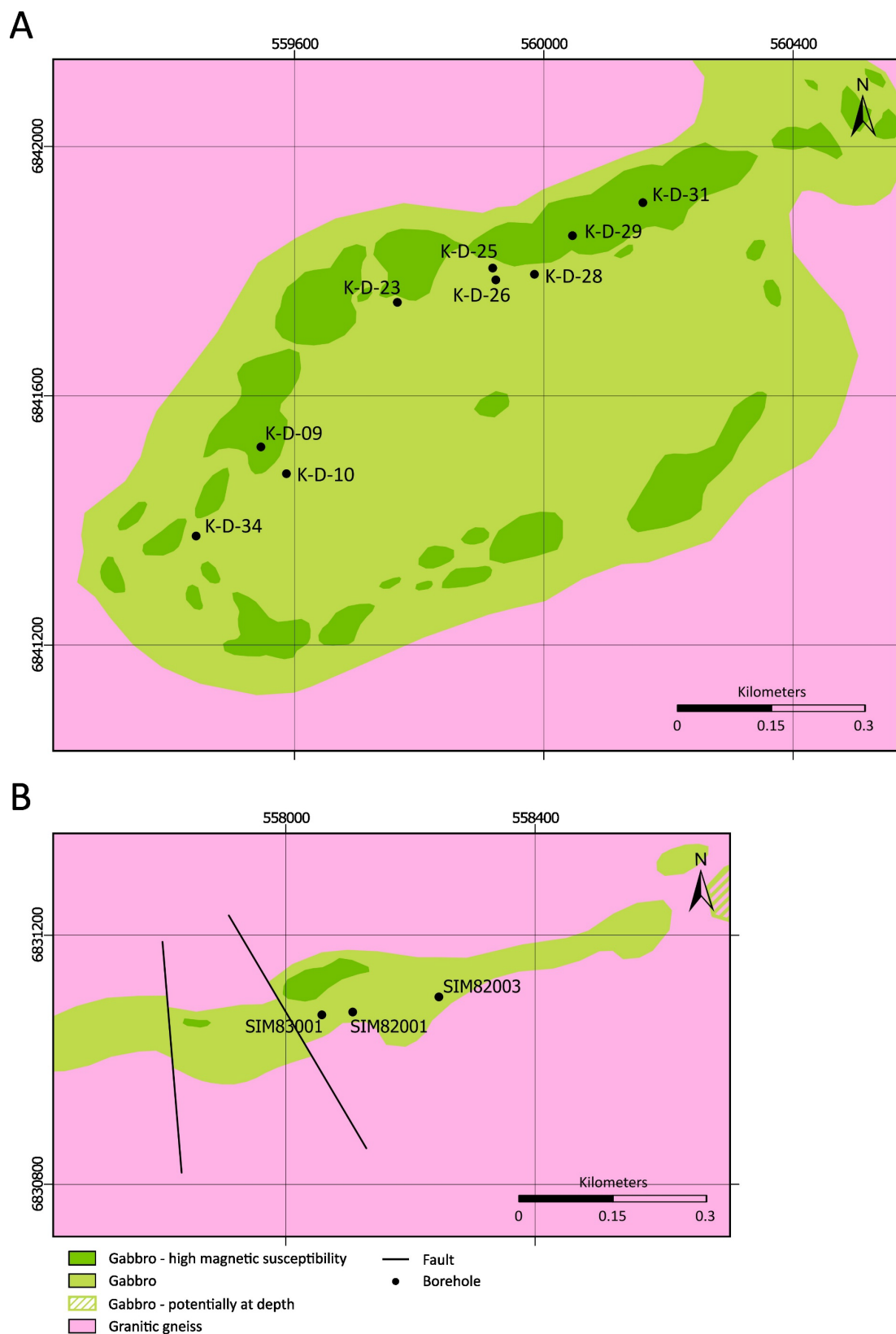


Figure B2. Maps showing the location of boreholes from which drill core was logged for magnetic susceptibility in this study. **A.** Location of boreholes from which drill core was logged in the Kramsta intrusion. **B.** Location of boreholes from which drill core was logged in the Simesvallen intrusion.

BLA82004

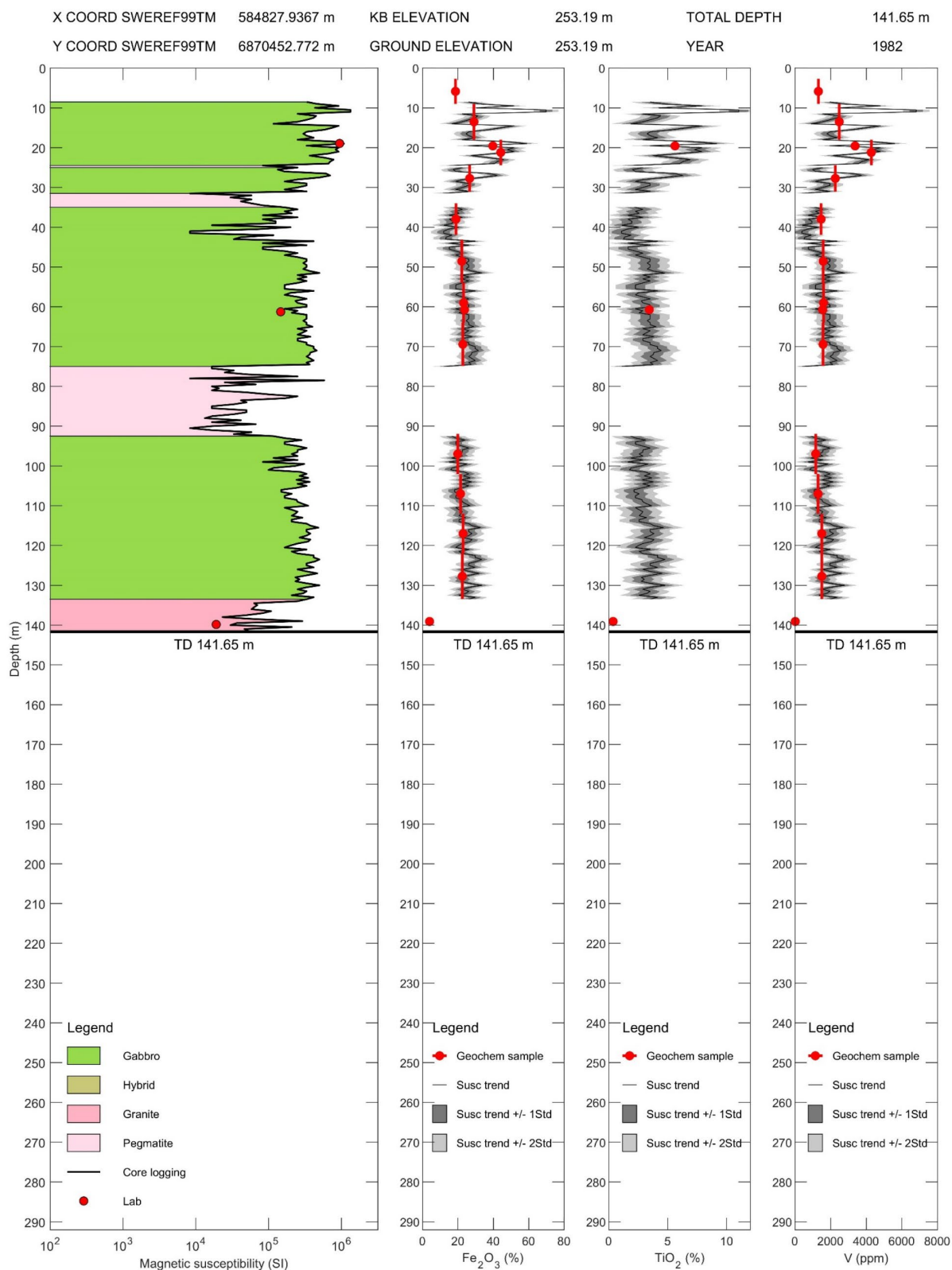


Figure B3. Magnetic susceptibility logging results of drill core from borehole BLA82004 (Bläckmyran intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B1 for the location of the borehole within the intrusion.

K-D-09

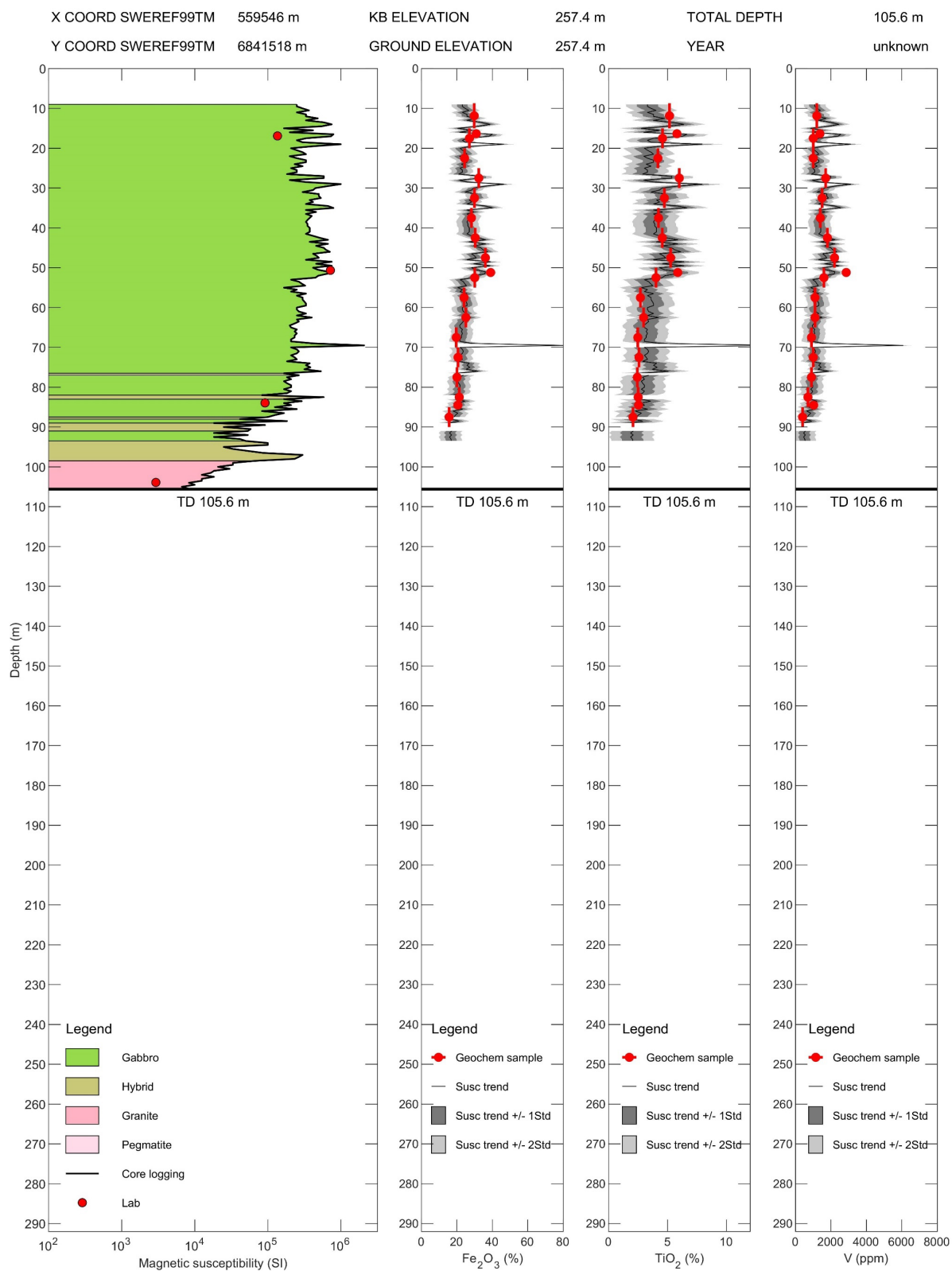


Figure B4. Magnetic susceptibility logging results of drill core from borehole K-D-09 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-10

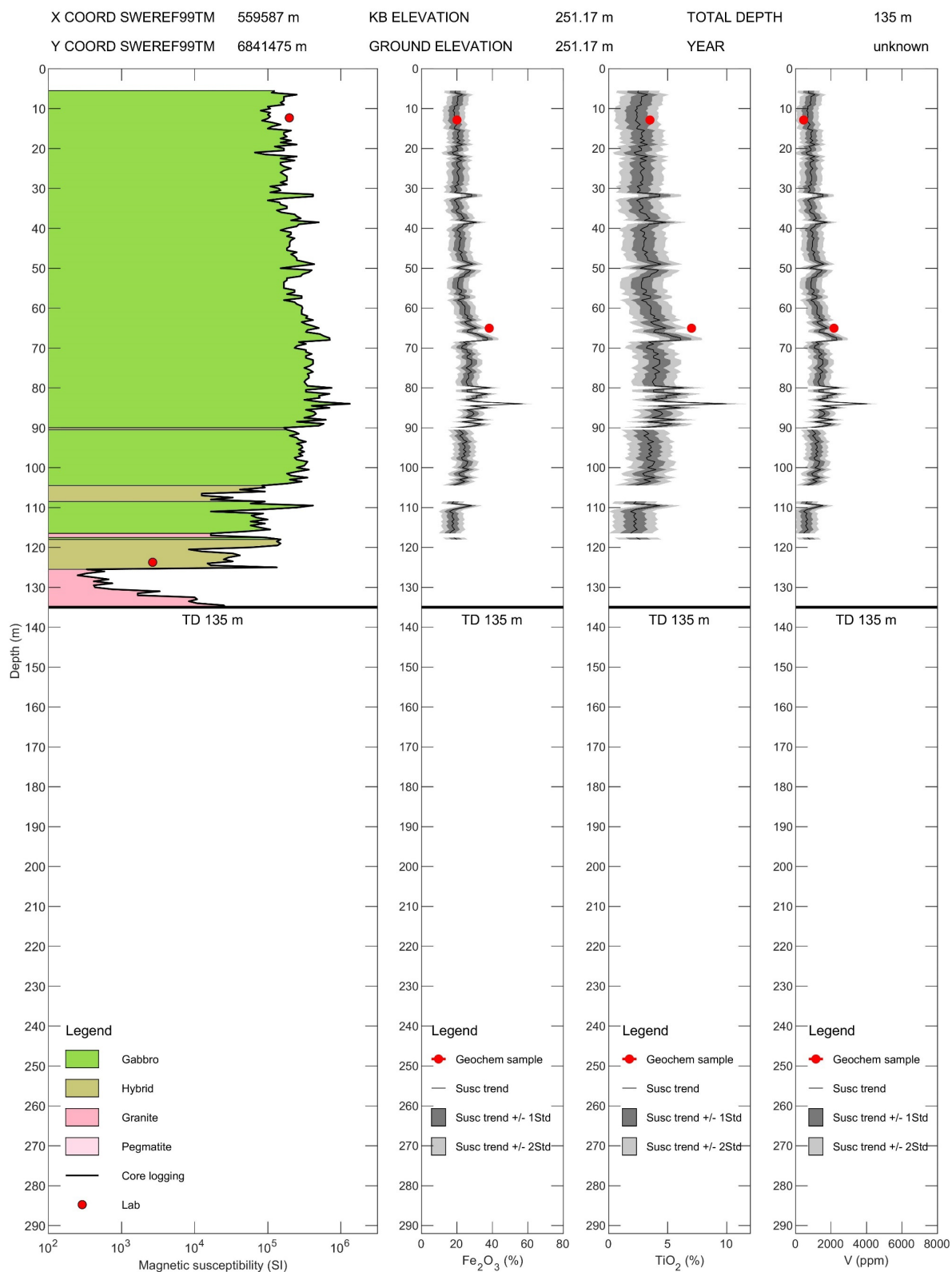


Figure B5. Magnetic susceptibility logging results of drill core from borehole K-D-10 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-23

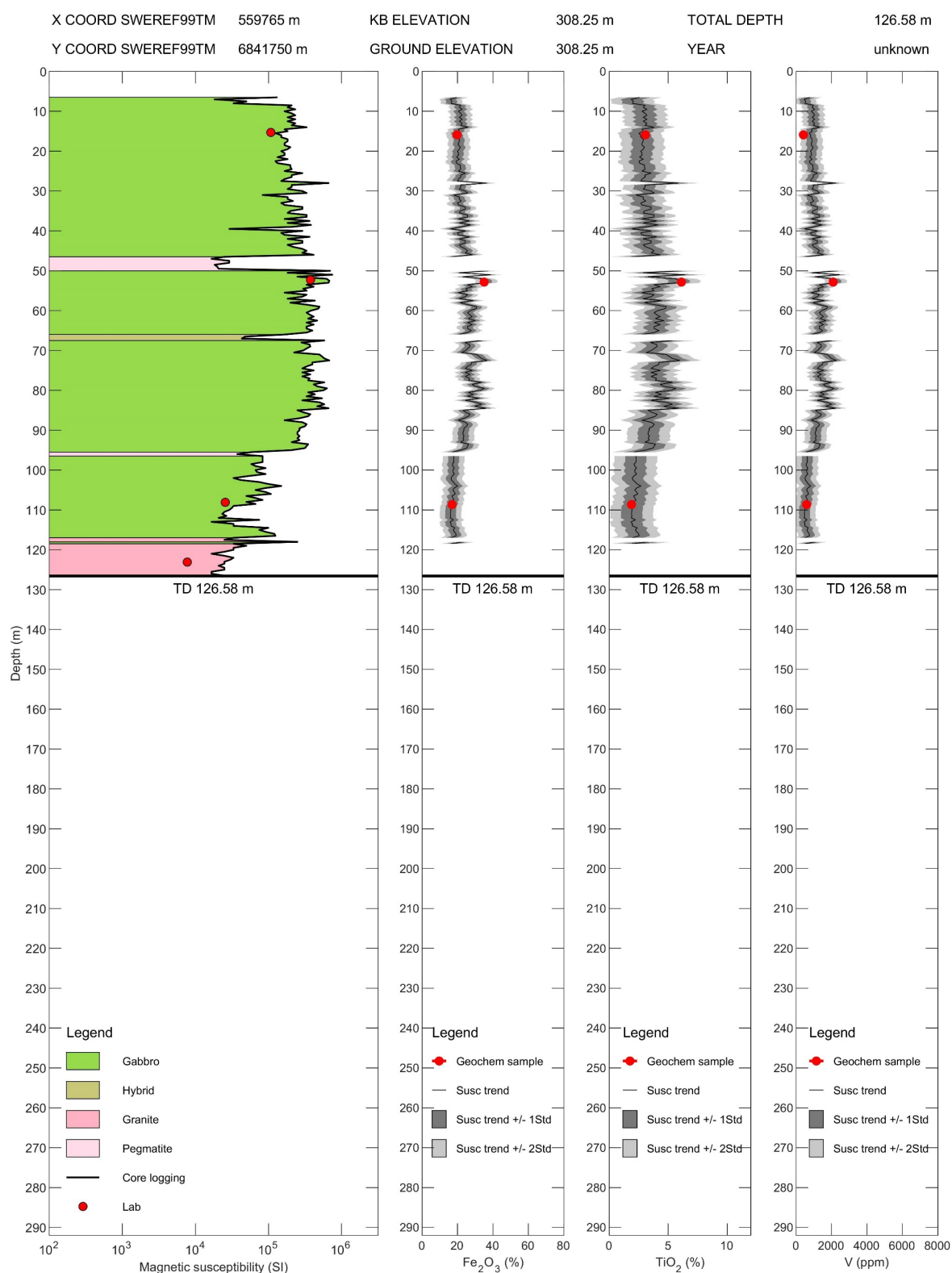


Figure B6. Magnetic susceptibility logging results of drill core from borehole K-D-23 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-25

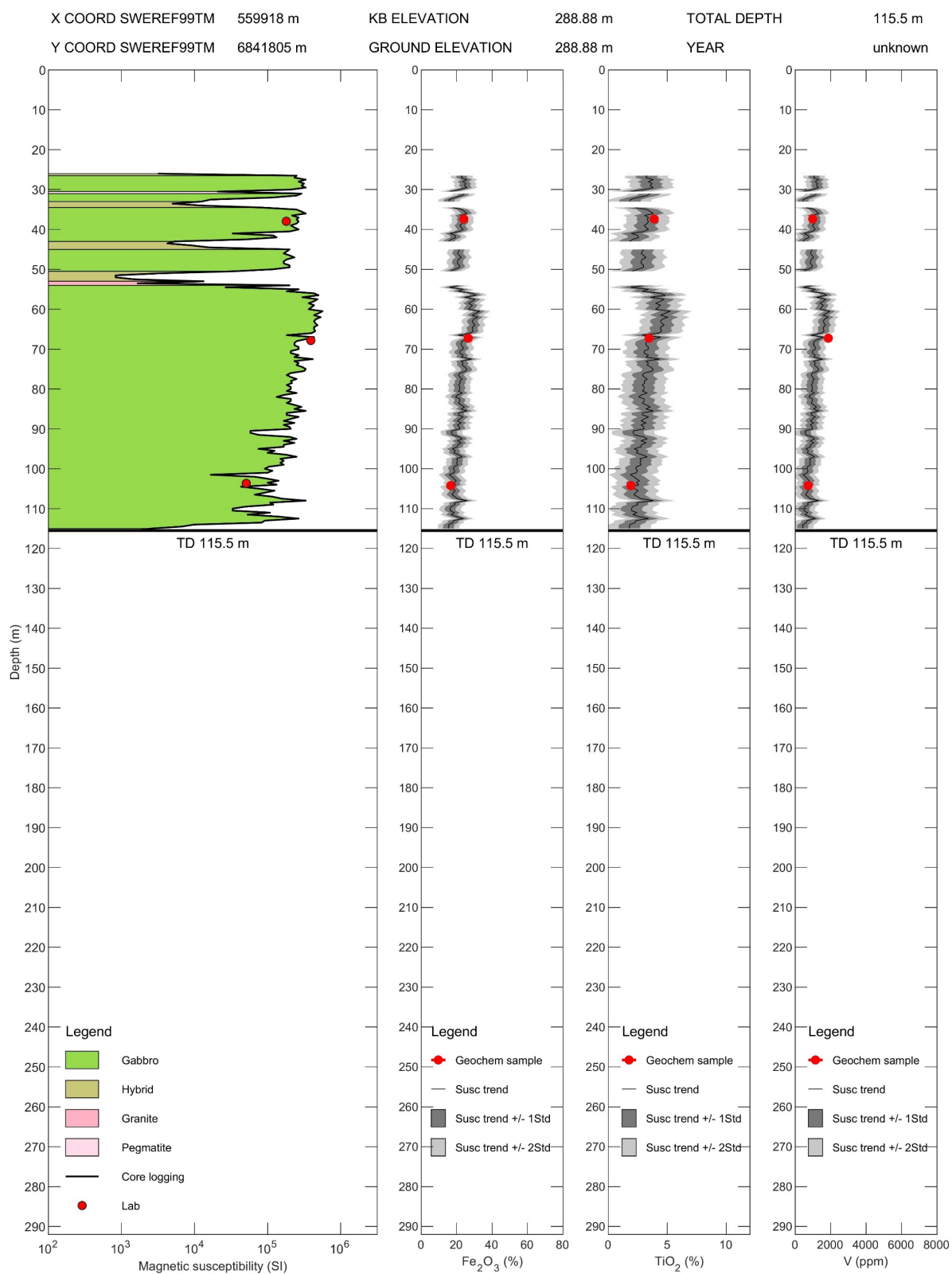


Figure B7. Magnetic susceptibility logging results of drill core from borehole K-D-25 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-26

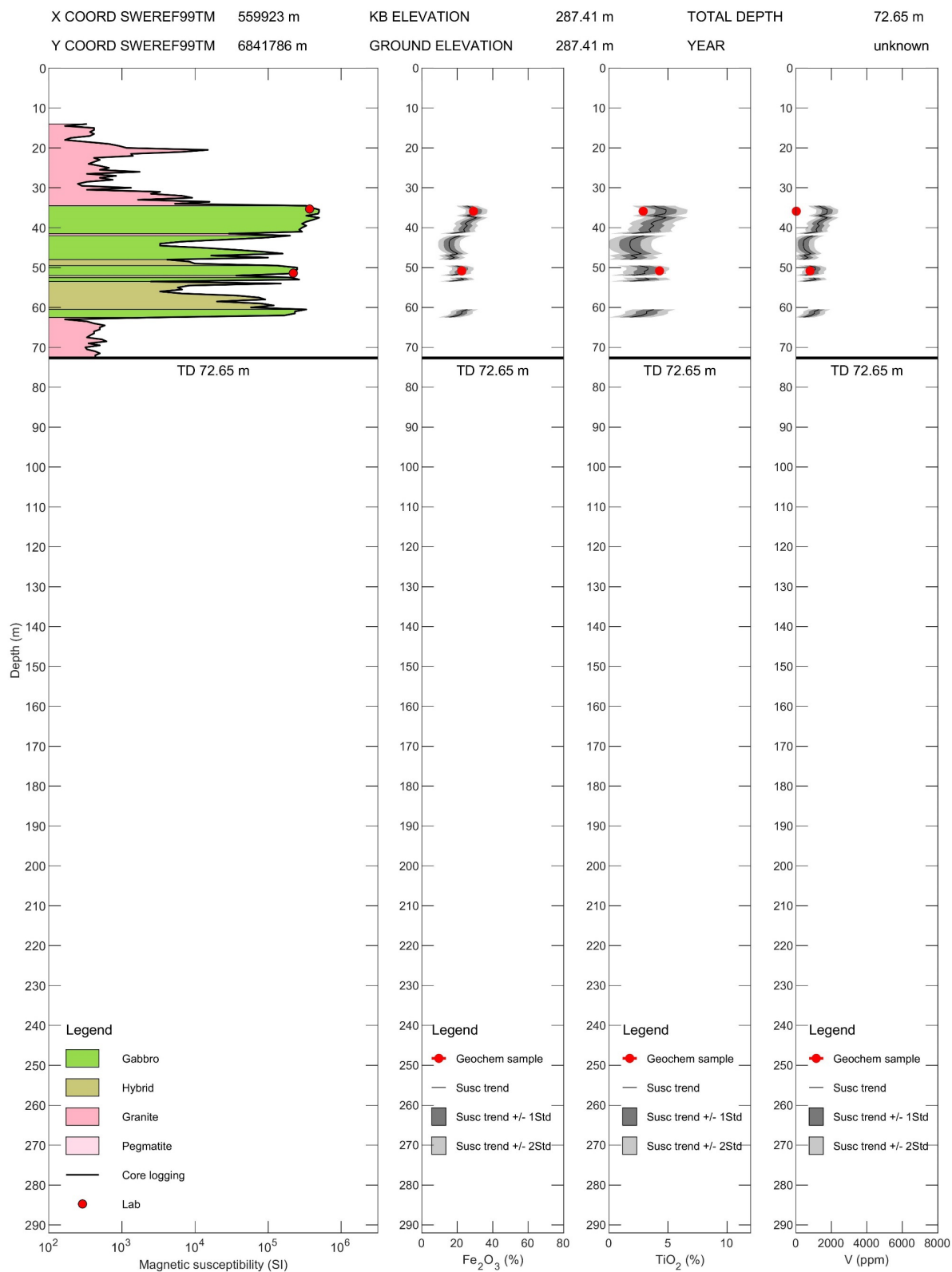


Figure B8. Magnetic susceptibility logging results of drill core from borehole K-D-26 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-28

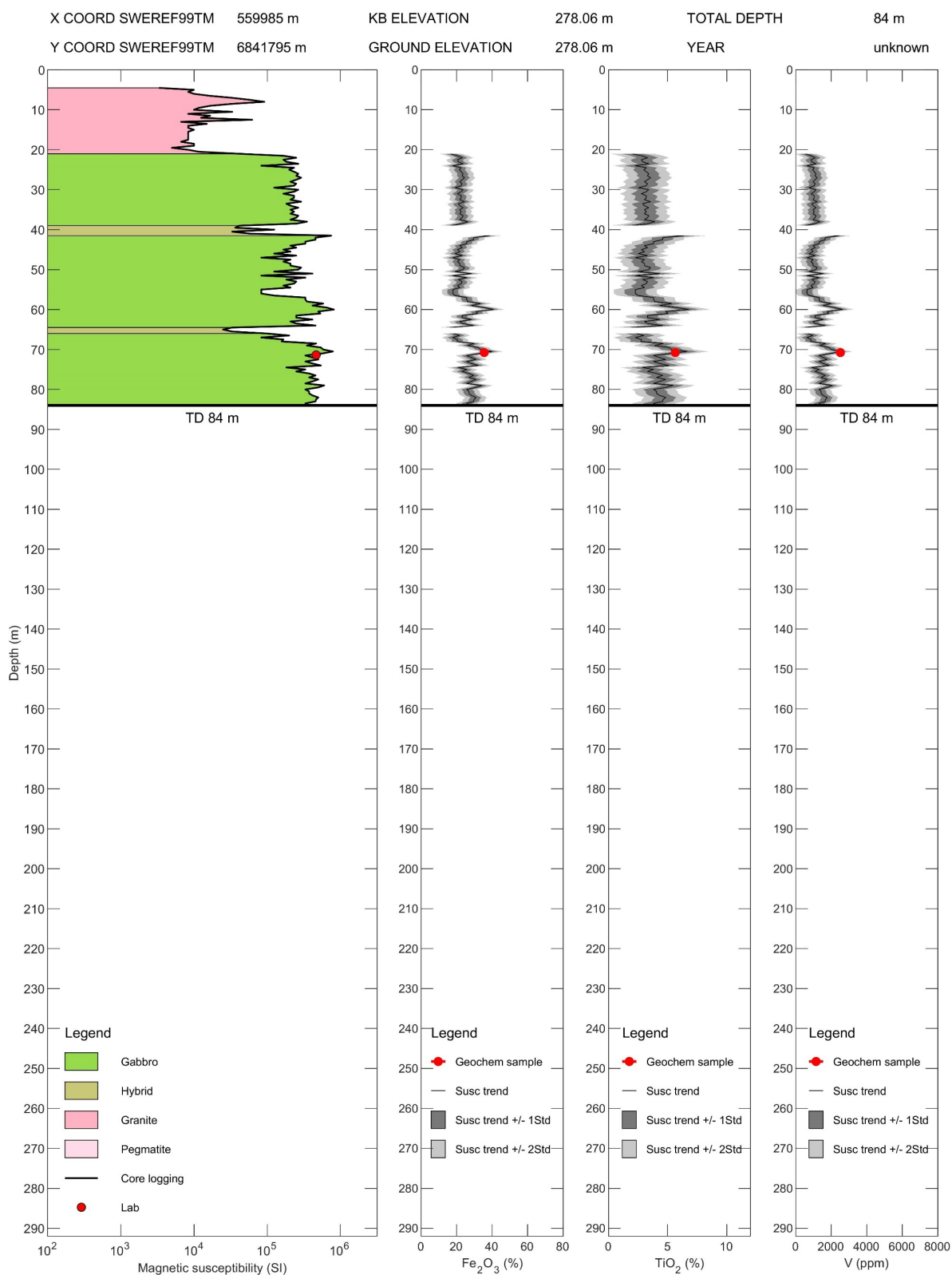


Figure B9. Magnetic susceptibility logging results of drill core from borehole K-D-28 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-29

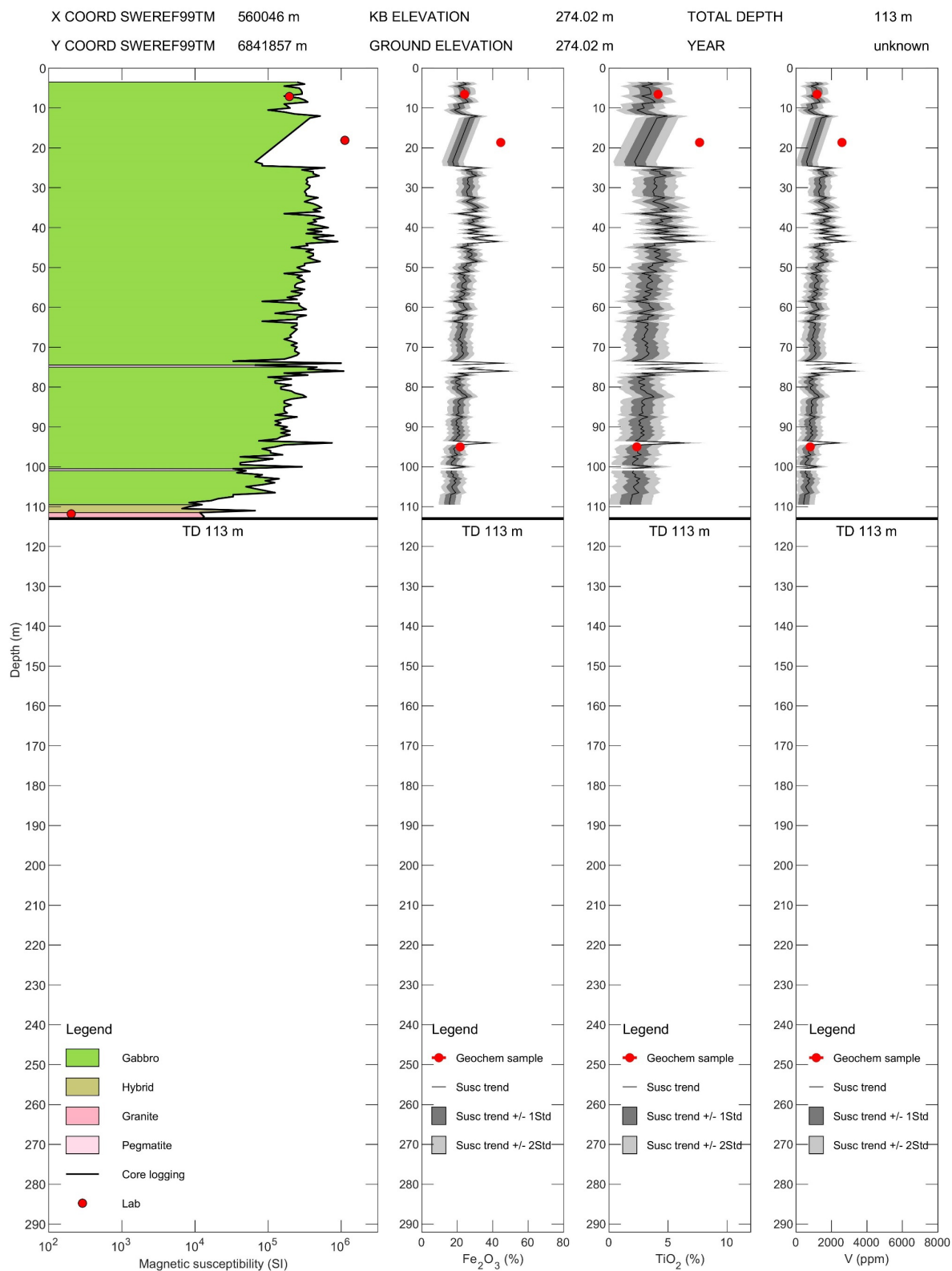


Figure B10. Magnetic susceptibility logging results of drill core from borehole K-D-29 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-31

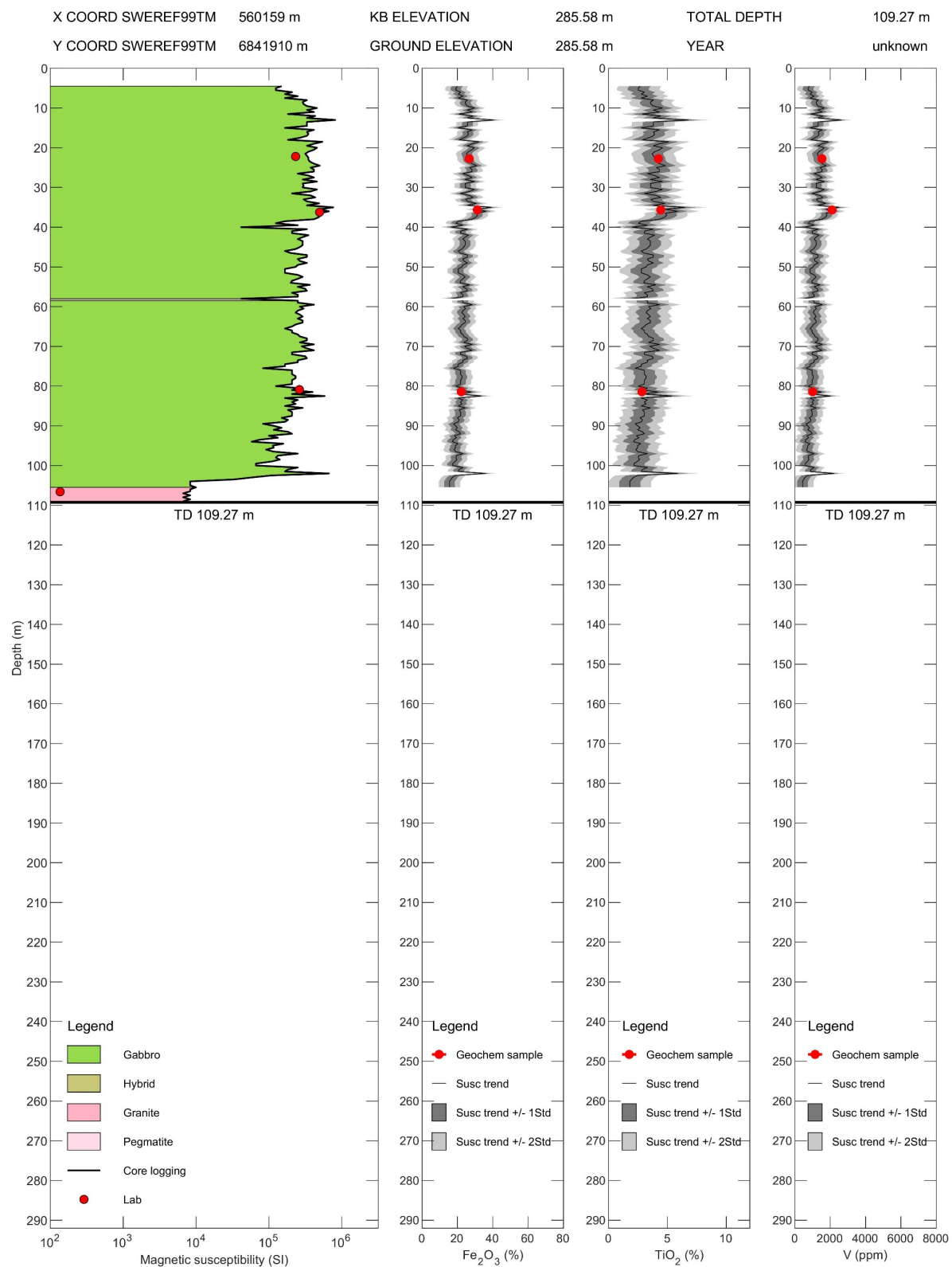


Figure B11. Magnetic susceptibility logging results of drill core from borehole K-D-31 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

K-D-34

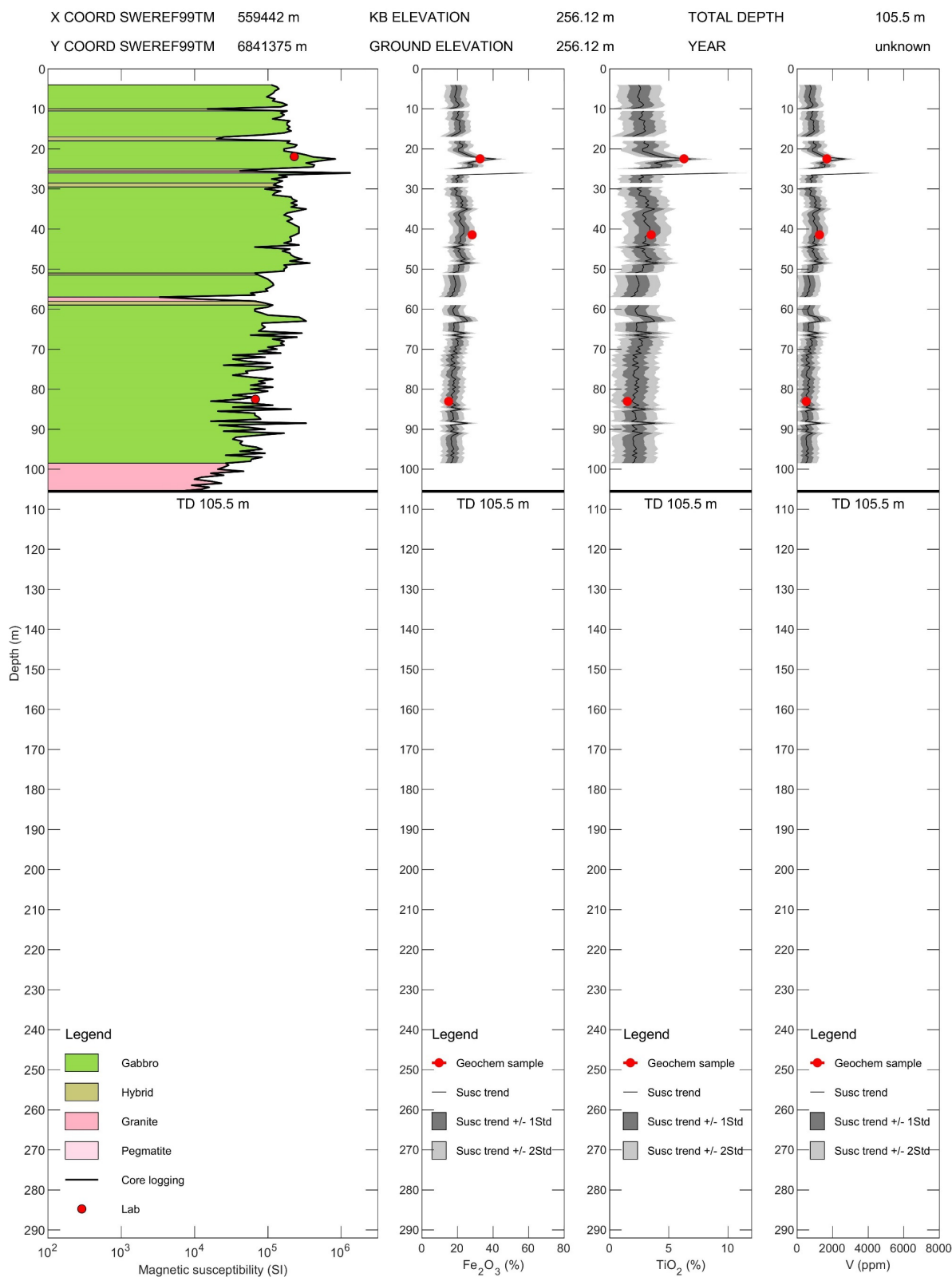


Figure B12. Magnetic susceptibility logging results of drill core from borehole K-D-34 (Kramsta intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

MAB83006

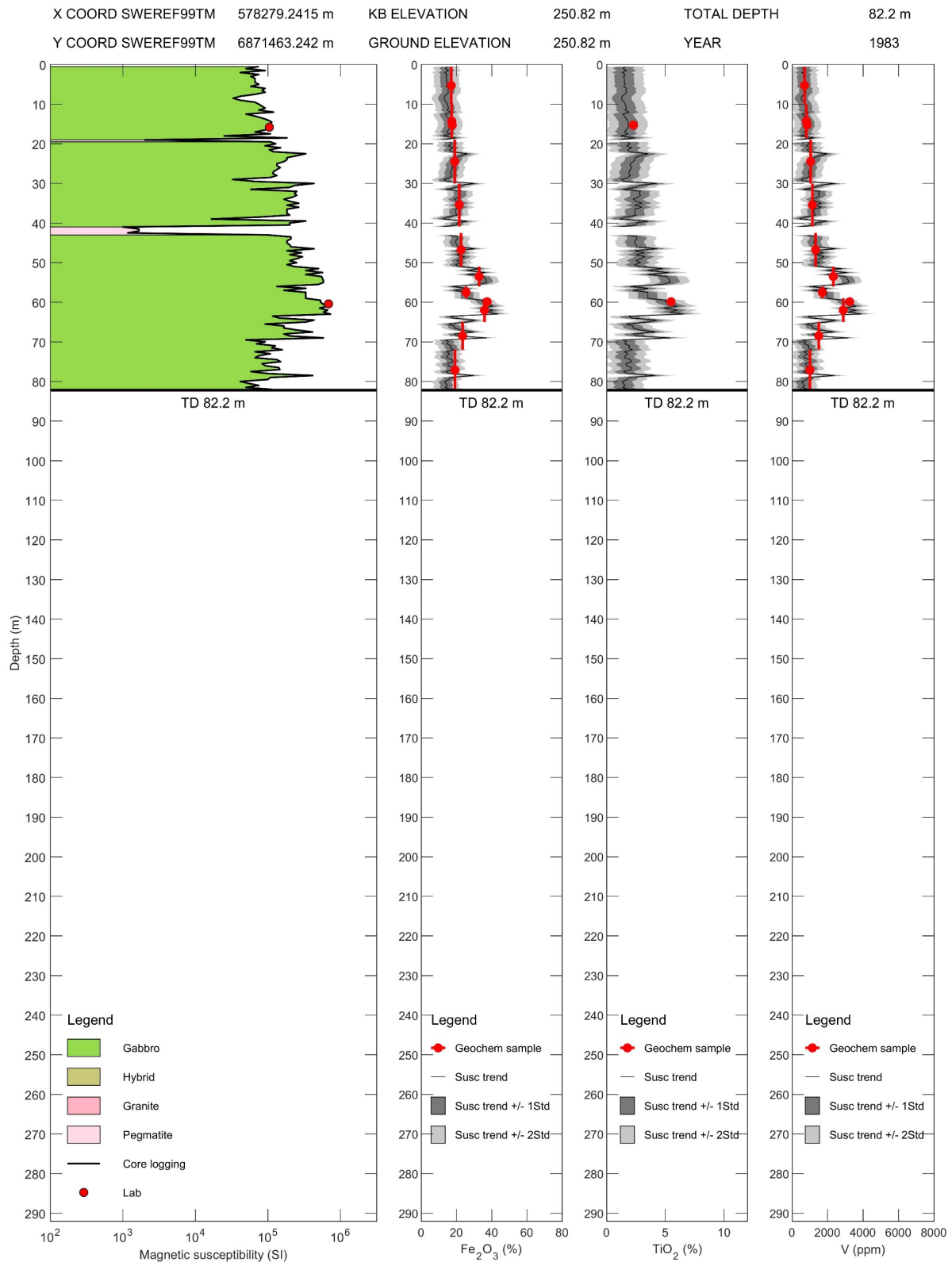


Figure B13. Magnetic susceptibility logging results of drill core from borehole MAB83006 (Masugnsberget intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B1 for the location of the borehole within the intrusion.

MAB83007

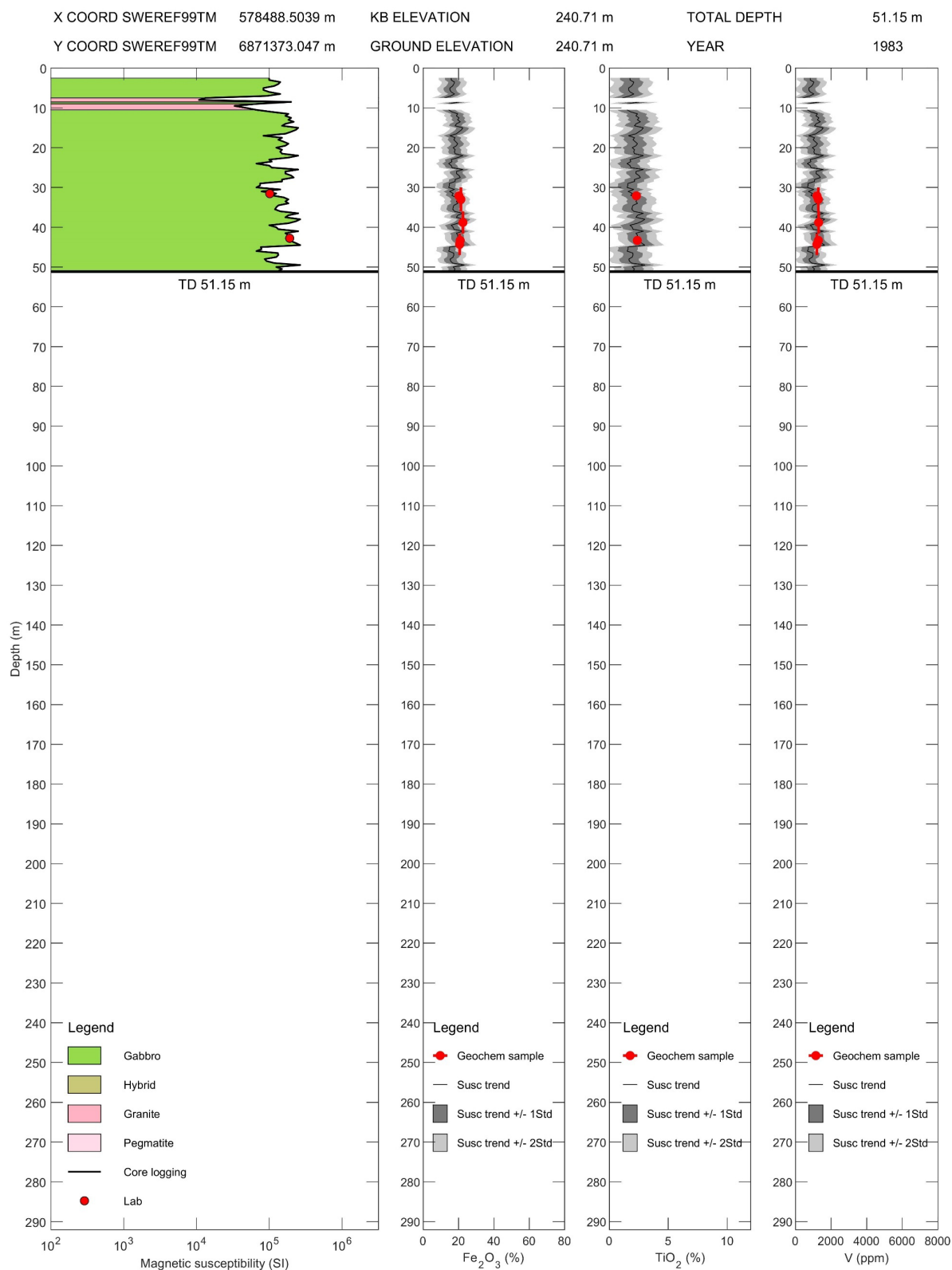


Figure B14. Magnetic susceptibility logging results of drill core from borehole MAB83007 (Masugnsberget intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B1 for the location of the borehole within the intrusion.

SIM82001

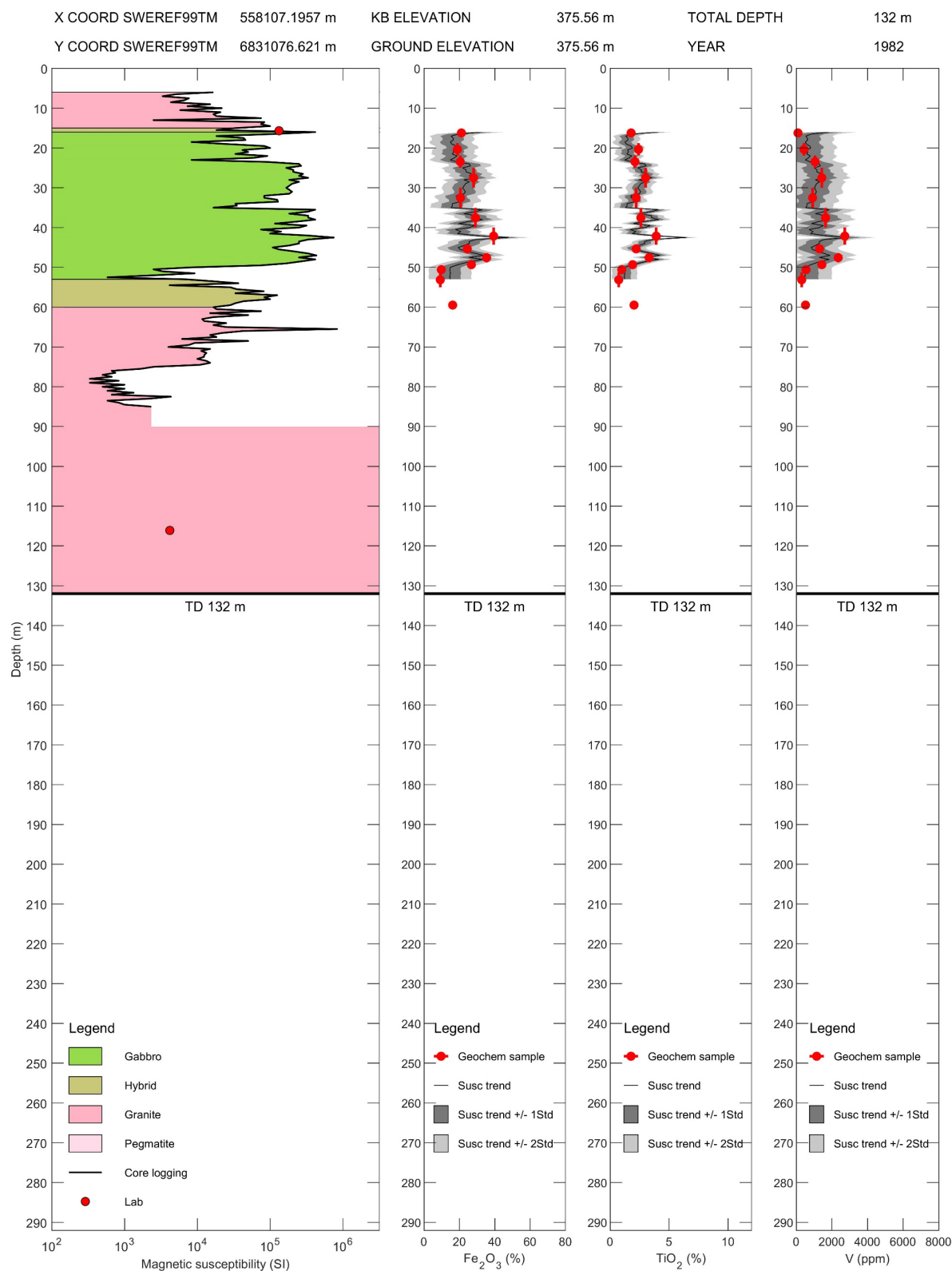


Figure B15. Magnetic susceptibility logging results of drill core from borehole SIM82001 (Simesvallen intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. Note that no susceptibility measurements were performed for the bottom part of the core. See figure B2 for the location of the borehole within the intrusion.

SIM82003

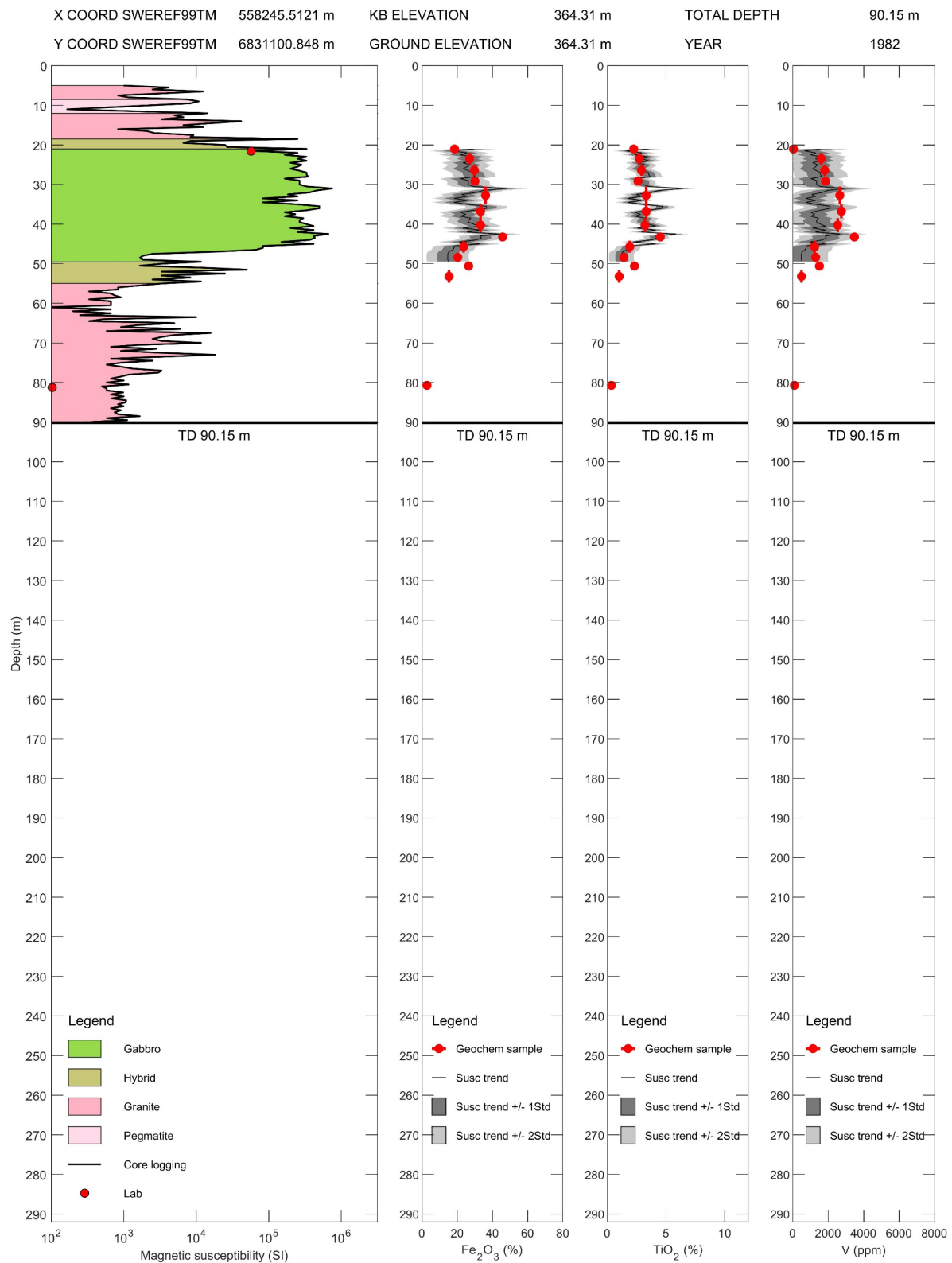


Figure B16. Magnetic susceptibility logging results of drill core from borehole SIM82003 (Simesvallen intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

SIM83001

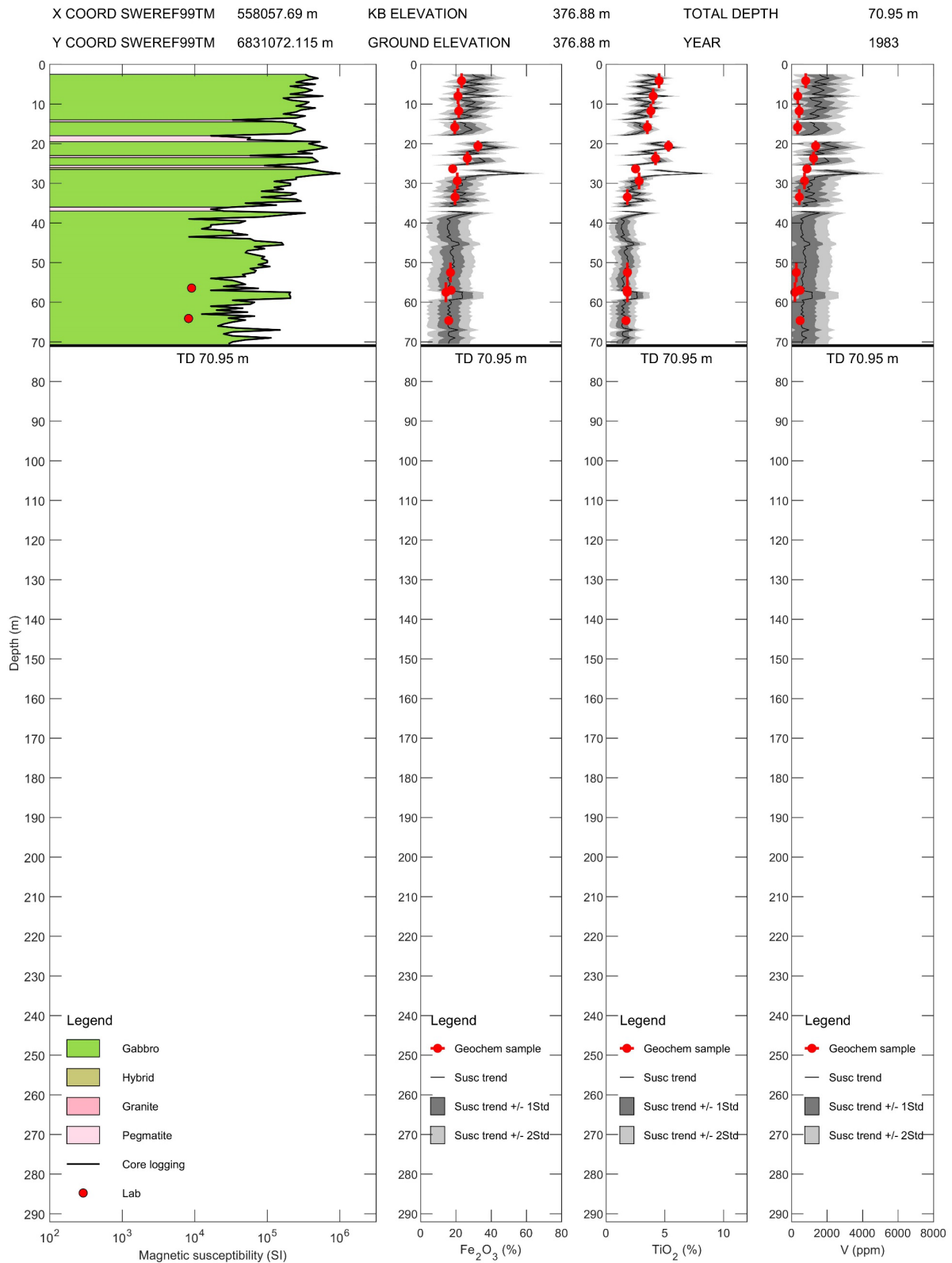


Figure B17. Magnetic susceptibility logging results of drill core from borehole SIM83001 (Simesvallen intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B2 for the location of the borehole within the intrusion.

SUM81001

X COORD SWEREF99TM 581685.7974 m KB ELEVATION 276.37 m TOTAL DEPTH 156.33 m
Y COORD SWEREF99TM 6869635.022 m GROUND ELEVATION 276.37 m YEAR 1981

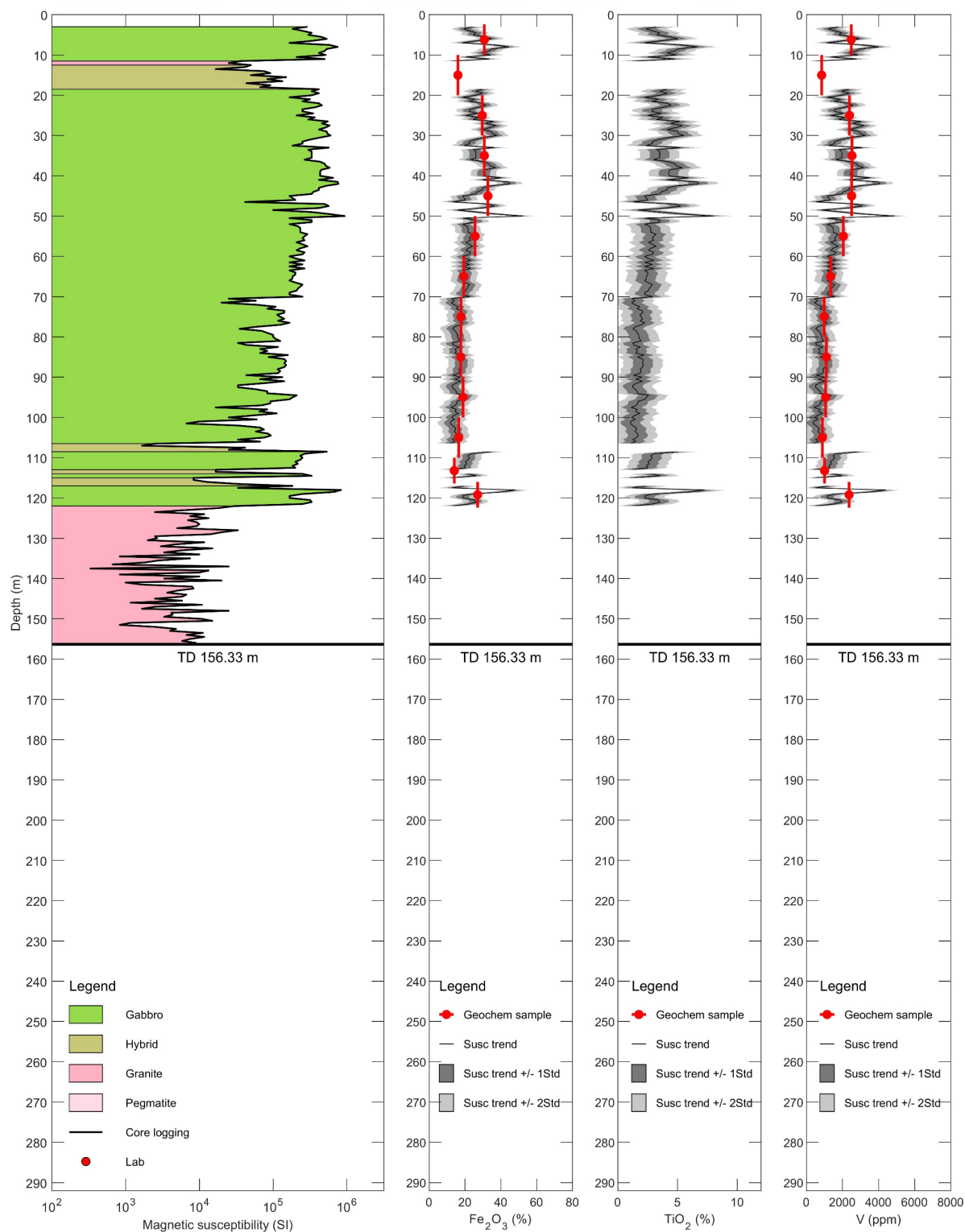


Figure B18. Magnetic susceptibility logging results of drill core from borehole SUM81001 (Gruvberget–Sumåssjön intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B1 for the location of the borehole within the intrusion.

SUM81017

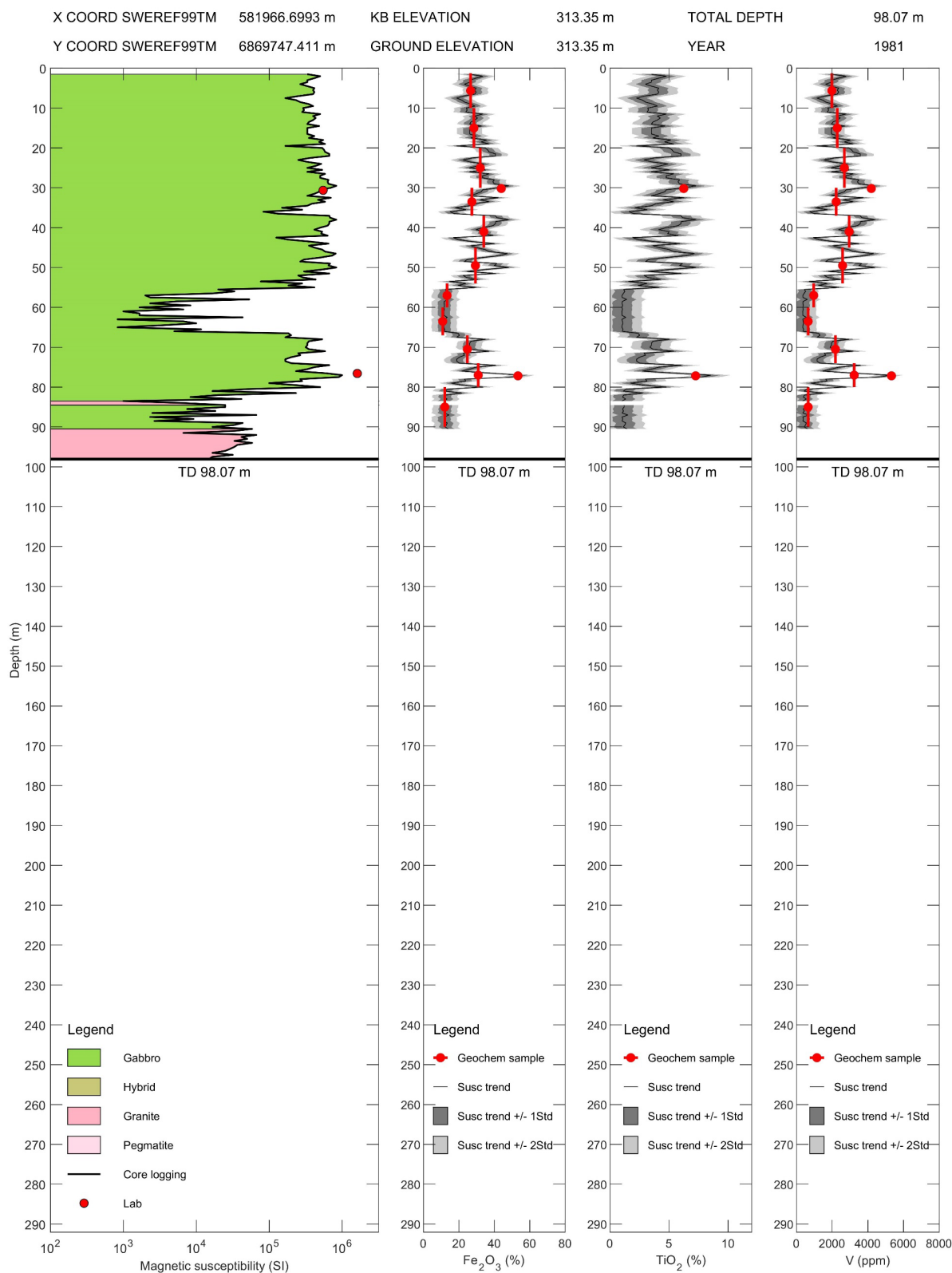


Figure B19. Magnetic susceptibility logging results of drill core from borehole SUM81017 (Gruvberget–Sumåssjön intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B1 for the location of the borehole within the intrusion.

SUM81022

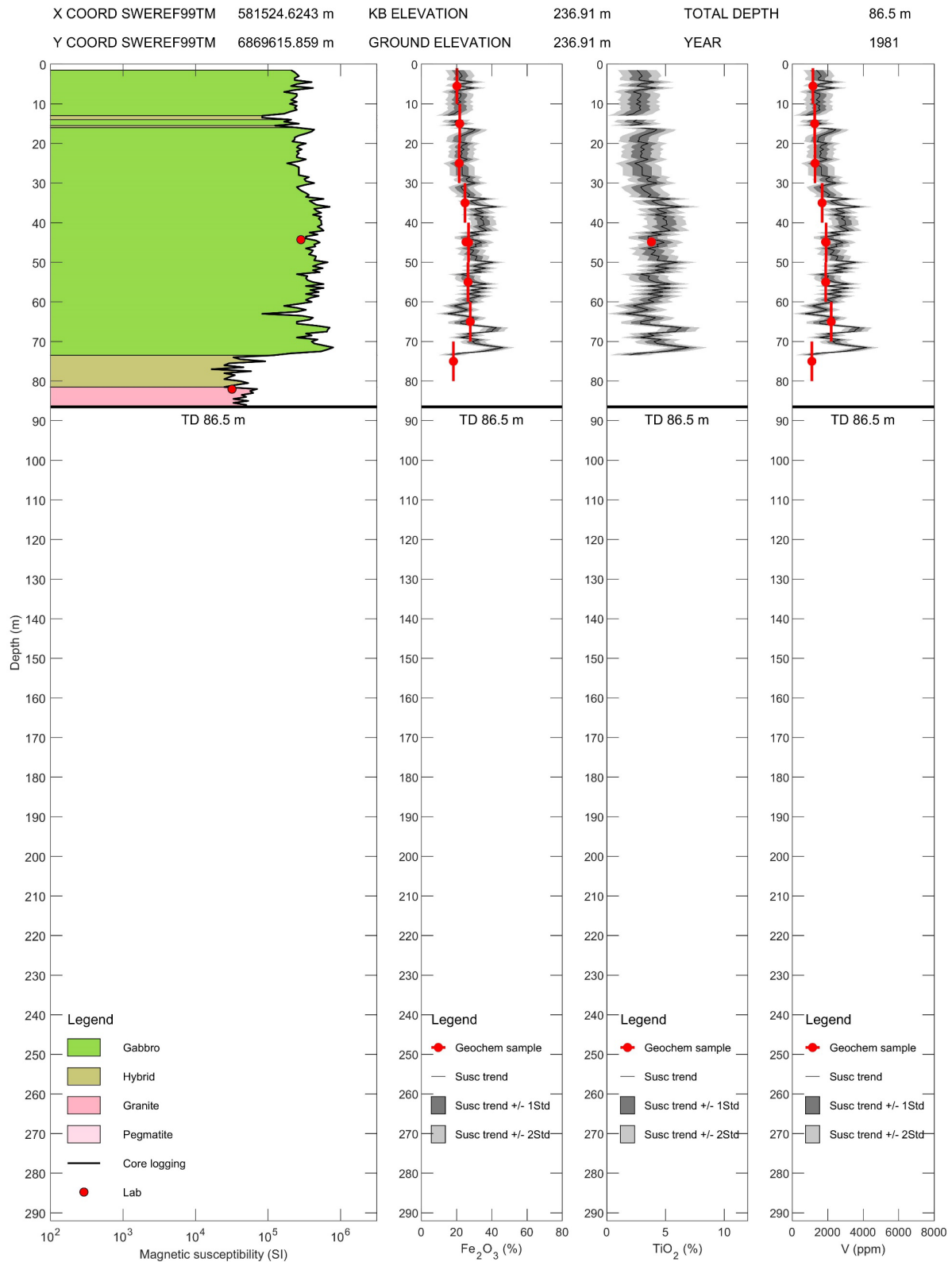


Figure B20. Magnetic susceptibility logging results of drill core from borehole SUM81022 (Gruvberget–Sumåssjön intrusion). Refer to the text at the beginning of the appendix or to figure 9 in the main report for a full explanation of the symbols and lines on the plot. See figure B1 for the location of the borehole within the intrusion.

Appendix C. Thin section panoramas of Fe-Ti-V mineralised samples

In this appendix we present a series of thin-section panoramas of Fe-Ti-V mineralised samples. These panoramas are interpreted and discussed below.

Panoramas of full thin sections are rarely seen in publications because they need lots of space to be legible and display the intricate textures of the rocks. However, in this publication they merit publication because it is an excellent way to show the variation among the intrusions and different mineralised parts of the same intrusion (figs. C1–C35). Hence, these images will allow the reader to study the rocks in a way that only those that have access to the thin sections can. The lack of high-grade metamorphic overprinting of these rocks is generally very easy to recognise when studying the panoramas. The possible future processing of Fe-Ti-V ore in the Ljusdal lithotectonic unit will also benefit from knowing the major mineralogical difference between intrusions and within intrusions recorded in these mineralised rocks. Each panorama is made of 55 to 60 microscope images at high magnification and thus providing good resolution.

Mineralised samples from several of the Fe-Ti-V intrusions of this study have a variety of textures and mineral compositions, shown in the panoramas of the full thin sections below. Layering is evident in some, difficult to discern in others, or, in some sections, lacking altogether. However, it should be noted that no special effort was made to optimise the orientation of the samples for the thin sections, in order to best display potential layering. For the most part, thin sections were chosen for the panoramas if they were representative of the typical mineralised parts of the intrusion. However, in some cases, the panoramas were taken from the most richly mineralised zones of the intrusion, representing an upper end member of the degree of mineralisation in the intrusion.

The opaque minerals are completely dominated by magnetite and ilmenite. Alteration of ilmenite to rutile or hematite is noted in a sampled core from Masungsberget. Sulphide minerals do occur, but only in minor amounts, where pyrite, pyrrhotite, and chalcopyrite are the most common.

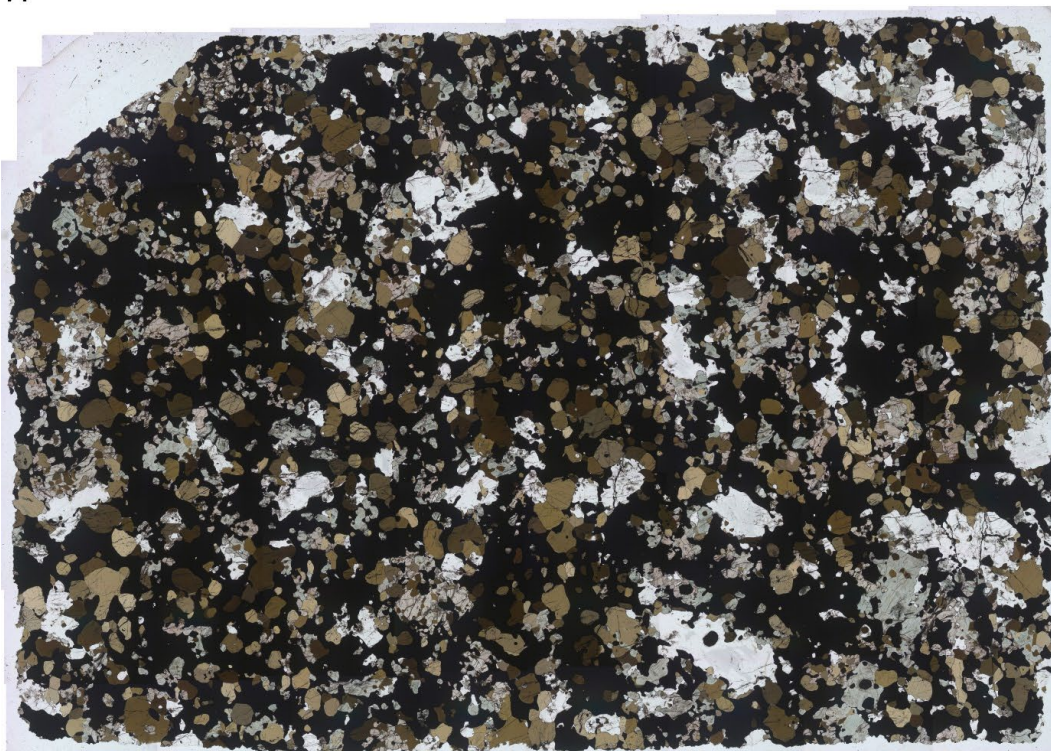
Clinopyroxene and hornblende are the two most common mafic silicate minerals and plagioclase the most common felsic mineral. Some samples have a silicate mineral content that includes only minor amounts of hydrous minerals, other samples (except for the opaque minerals) are completely dominated by hydrous silicate minerals. This indicates a variation in initial content of H₂O in the different intrusions. However, it is apparent that in most of the samples the magma has evolved to a stage where igneous amphibole is stable. Some intrusions most probably even had hornblende on the liquidus, and thus, amphibole was a cumulus mineral and not only a late-crystallising mineral within the crystal mush. In some of the panoramas, plagioclase is interpreted to have been partially dissolved and replaced by opaque minerals. This is especially recognisable in figures C1, C8, C13, C29, and C34. In most other sections the opaque minerals appear to occupy the space between the earlier formed plagioclase crystals, and hence, are more interstitial in nature without dissolution of plagioclase. Experimental studies have shown that plagioclase can dissolve quickly with a very small degree of superheating and also in some cases, when there is an undersaturation of the components of plagioclase within the residual fluid (Donaldson 1985). In our samples, undersaturation of components of plagioclase is probably the most likely mechanism for the partial dissolution of the plagioclase grains. This could occur if the residual fluids that permeate the cumulate mush at a later stage of crystallisation produce enough compositional convection to dissolve plagioclase and crystallise magnetite in its place. Two panoramas have ultramafic characteristics with only very minor plagioclase present (figs. C2, C21). Mineral composition and strong preferred orientation of minerals are seen as layering

features in several of the panoramas (figs. C8, C12, C15, C19, C24, C31). A few panoramas display mineralised rocks that appear more massive in texture across the panorama.

Efforts were made to collect geochemical and petrophysical data from the same sample (when collecting samples at outcrop) or from adjacent samples of drill core. Hence, where available whole rock Fe_2O_3 , TiO_2 , and V contents are given in the figure captions for each of the panoramas. Petrophysical measurements of density (kg/m^3), magnetic susceptibility (SI), and remanent magnetisation intensity (mA/m), where present are also shown. Note that not all data is available for each panorama.

Panoramas of sections are always shown in plane-polarised light. However, in some cases panoramas for cross-polarised light are also shown. In each figure, where both types of panoramas are available for the same section, the plane-polarised light (ppl) is typically shown at the top (part A) and the cross-polarised light (xpl) is typically shown at the bottom of the figures (part B).

A



B

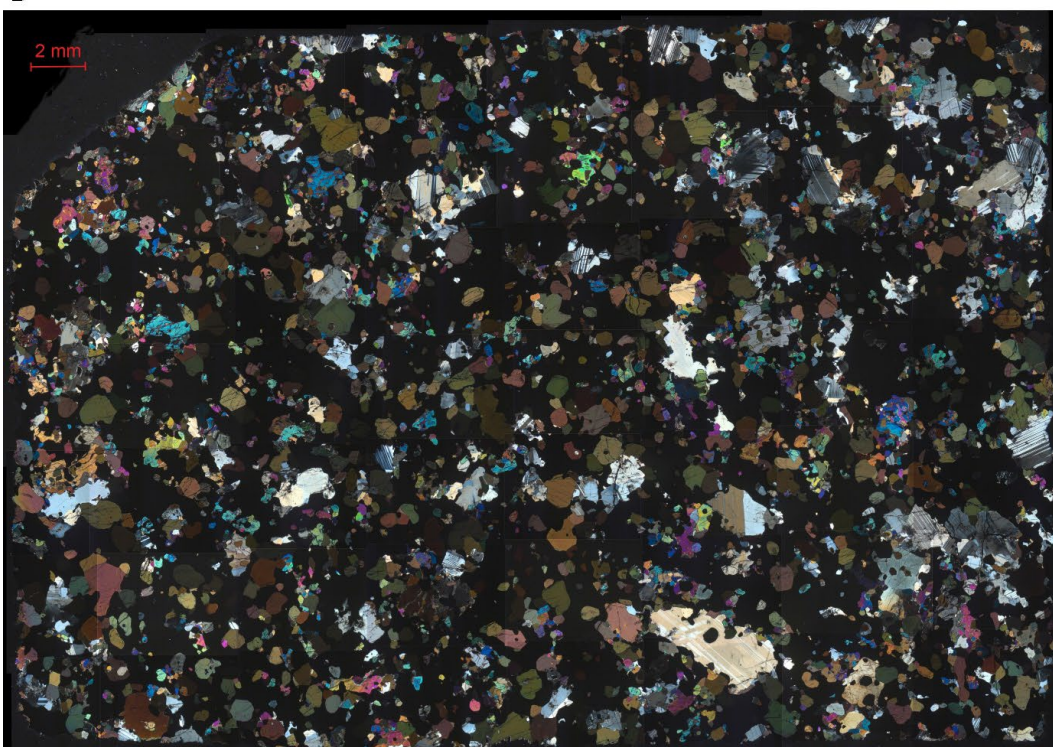


Figure C1. A well-preserved sample, most silicate minerals are anhedral to round in appearance, sitting in a framework rich in opaque minerals. Some plagioclase crystals appear consumed-dissolved in contact with opaque minerals. Hornblende, olivine, clinopyroxene, plagioclase, magnetite, ilmenite, and droplets of sulphides are present. Thin section sample from Kramsta drill core K-D-32, DCL228010A 41.84–41.90 m depth. Geochemical data from DCL223056A, 41.90–42.90 m depth, Fe_2O_3 45.9%, TiO_2 10.1%, V 2 170 ppm. Petrophysical data from DCL223009A 41.08–41.20 m depth, 3 716 kg/m^3 , 0.769 Si, 106 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

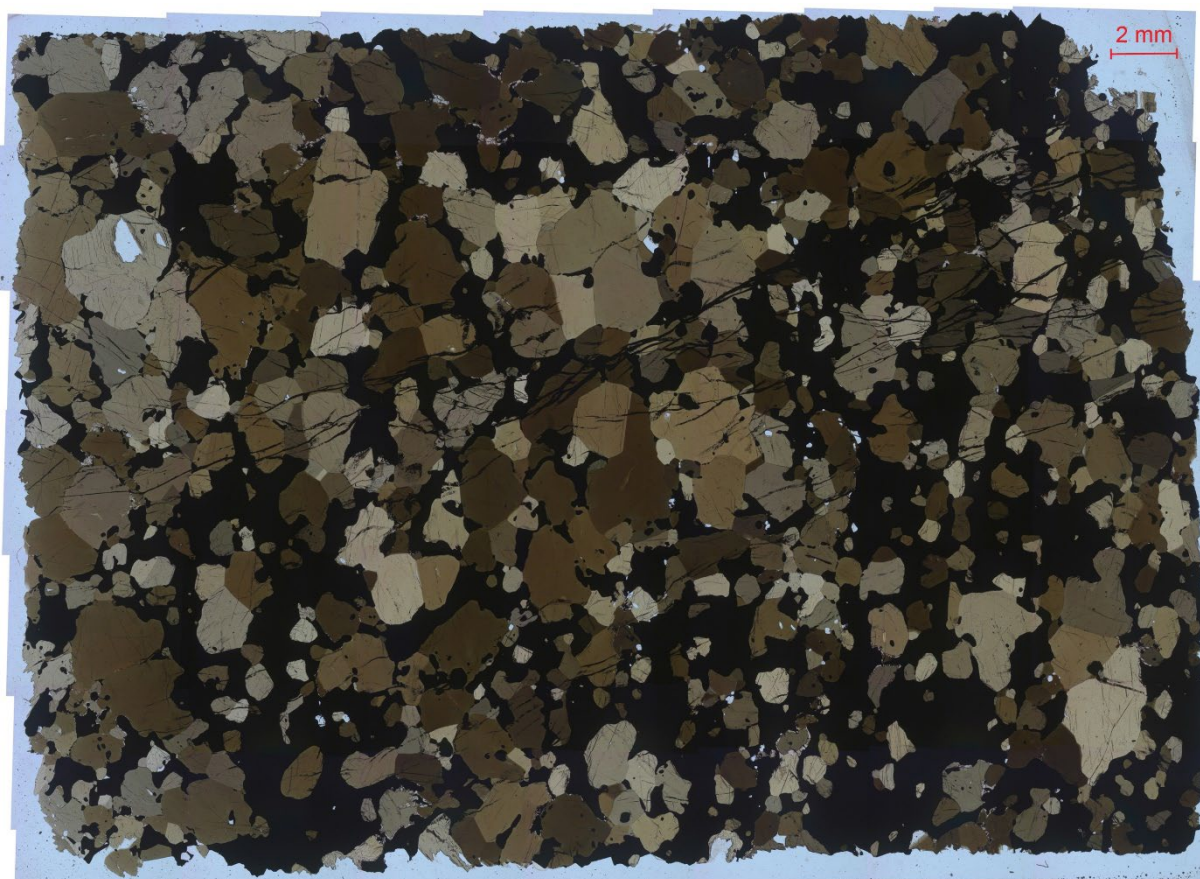


Figure C2. A well-preserved ultramafic sample. Hornblende is the main silicate mineral with large subhedral-anhedral-round grains. A lot of grains are fractured with opaque mineral infilling. Very minor interstitial olivine, clinopyroxene, and plagioclase. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides are present as large grains and droplets. Thin section sampled from Kramsta drill core K-D-08, DCL223018A at 19.00–19.04 m depth. Geochemical data from DCL223046A, 19.04–20.04 m depth, Fe_2O_3 50.4%, TiO_2 7.64%, V 3 620 ppm. Petrophysical data from DCL223019A 18.88–19.00 m depth, 3 804 kg/m^3 , 0.805 SI, 56 100 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

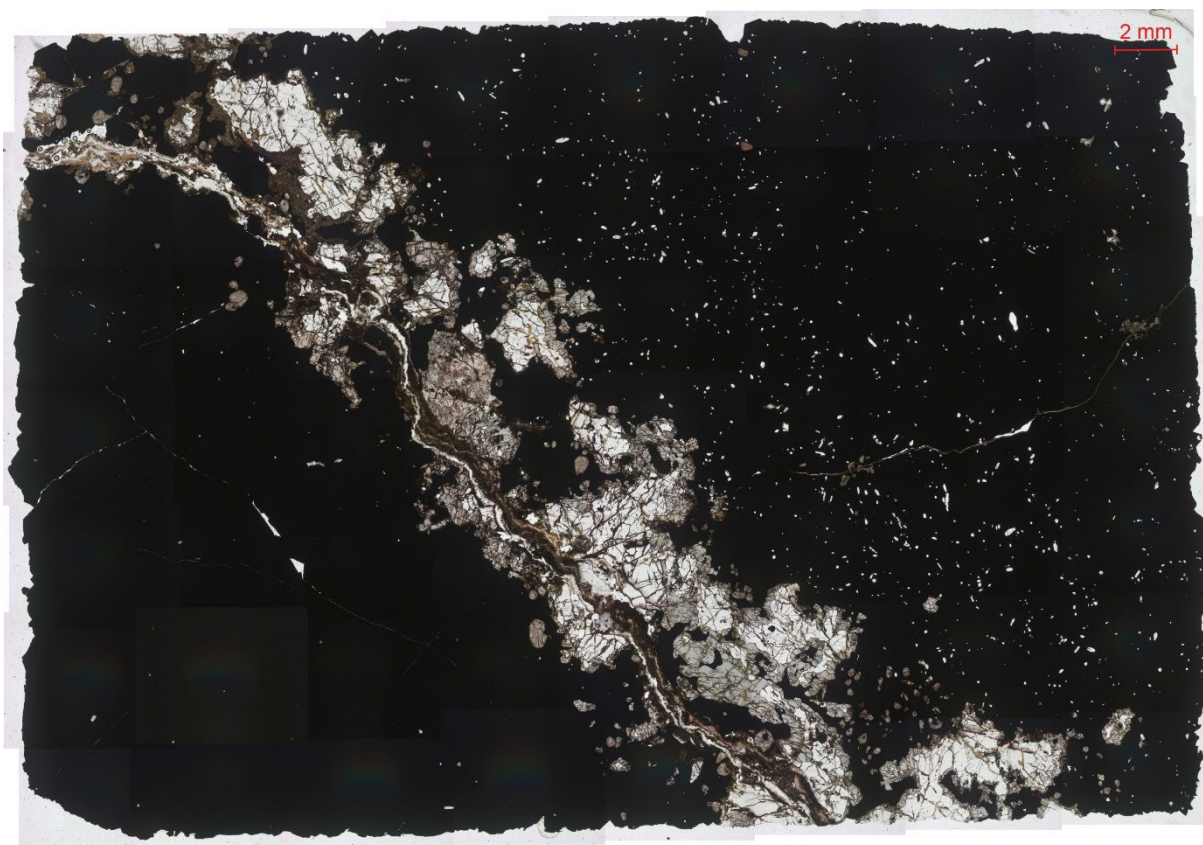


Figure C3. A well-preserved sample, apart from some olivine alteration. The thin section consists mostly of magnetite and some ilmenite, with a central portion of mostly olivine and minor clinopyroxene. The olivine has clinopyroxene as interstitial rims, often developed towards the opaque minerals. Sulphides occur as droplets and fracture fillings. Thin section sampled from Kramsta core K-D-29, DCL223015A at 94.31–94.36 m depth (from massive magnetite layer). Geochemical data from DCL223054A, 94.50–95.50 m depth, from a gabbro with magnetite, Fe_2O_3 21.6%, TiO_2 2.36%, V 799 ppm. Petrophysical data from DCL223016A, 94.36–94.47 m depth, from a massive magnetite layer, 4 872 kg/m^3 , 6.9 SI, 95 900 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

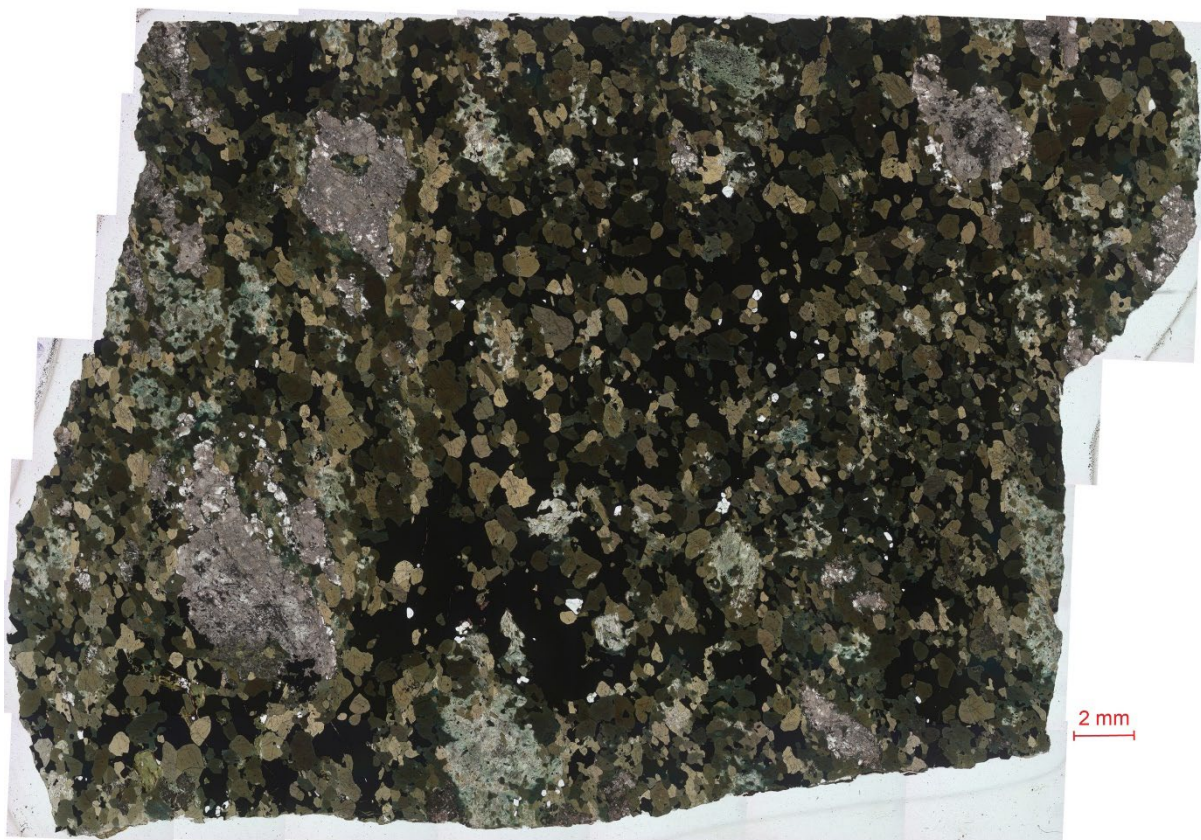
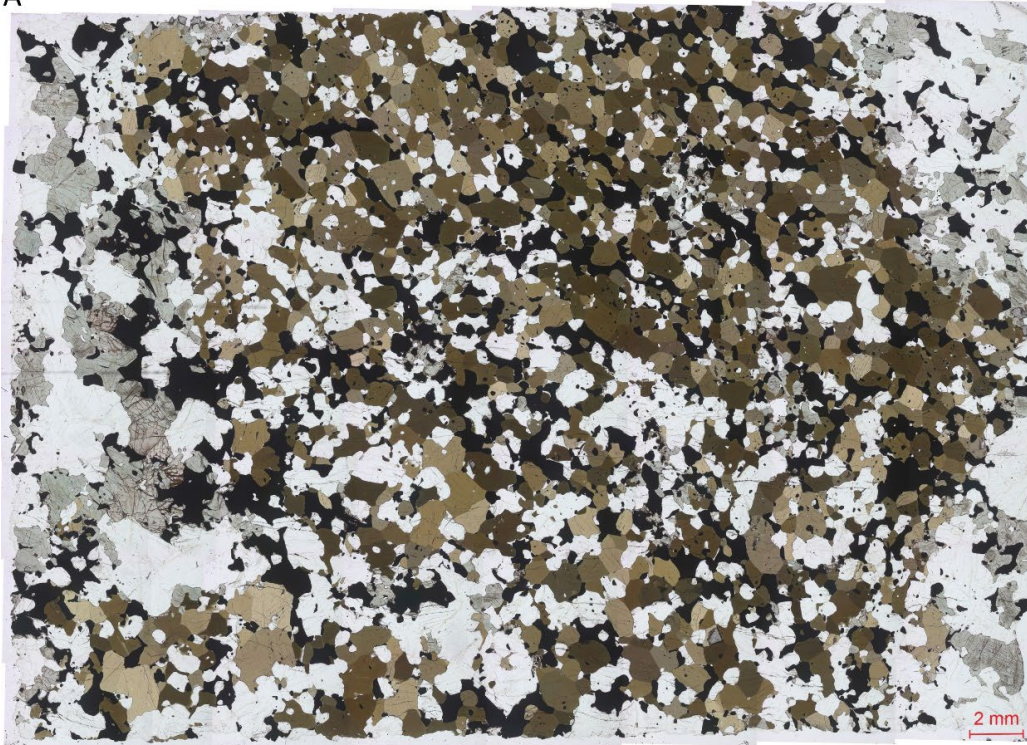


Figure C4. Hornblende is the main silicate mineral in this sample occurring as subhedral to euhedral- and round large grains. Clinopyroxene is mostly altered into a secondary mush of amphibole, although portions are still reminiscent of the original clinopyroxene with lamellae etc. A few grains of plagioclase appear unaltered, but the mineral is most often severely altered to sericite-saussurite. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides are present as large grains and droplets. Quartz occurs as relatively small, anhedral grains, included in opaque minerals. Thin section sampled from Gartsbo outcrop, HRE220049B with geochemical data: Fe_2O_3 35.2%, TiO_2 7.61%, V 1 310 ppm and petrophysical data: 3 872 kg/m^3 , 1.78 SI, 158 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B



Figure C5. A well-preserved sample. Hornblende occurs as large subhedral to euhedral grains. Olivine occurs mostly as small anhedral grains, probably interstitially. Clinopyroxene occurs as large subhedral grains with some lamellae and some exsolution of opaque minerals. Plagioclase occurs as large subhedral grains. Magnetite and ilmenite occur interstitially. Sulphides are relatively abundant as grains, droplets and interstitially. Thin section from Simesvallen drill core SIM82006, DCL222005B, from 27.76–27.80 m depth. Geochemical data from DCL222038A, 27.90–28.90 m depth, Fe_2O_3 30.0%, TiO_2 5.14%, V 1 895 ppm. Petrophysical data from DCL222005A, 27.80–27.90 m depth, 3 380 kg/m^3 , 0.44 SI, 59 300 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

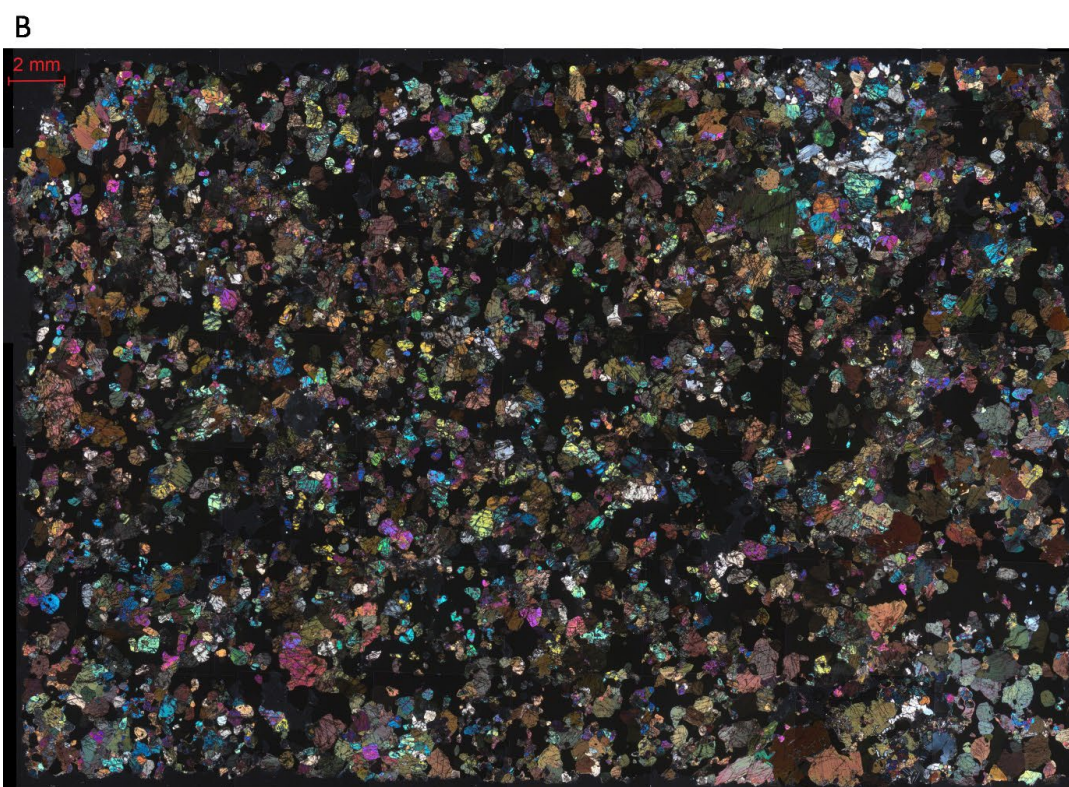
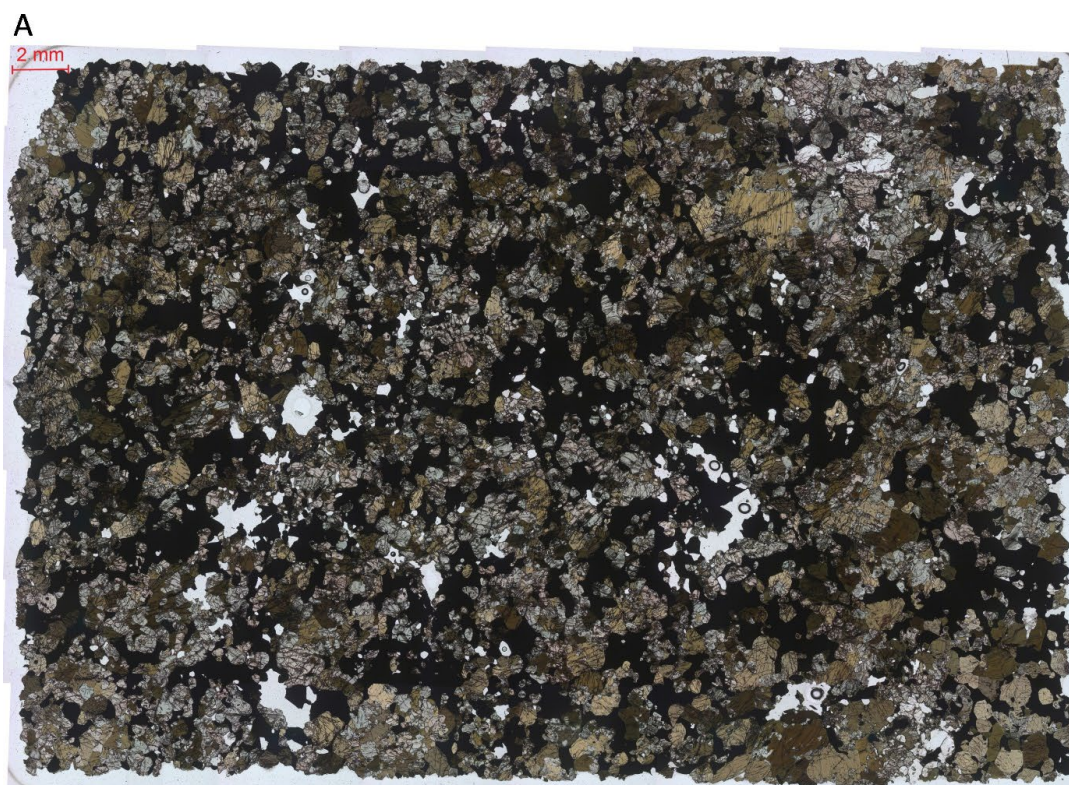


Figure C6. A well-preserved sample. Portions of minerals have been chipped out whilst preparing the thin section, possibly mostly opaque minerals. Hornblende occurs as large subhedral-anhedral to round grains, interstitially. Olivine occurs as small and large anhedral-round grains. Clinopyroxene occurs as small and large anhedral-round grains. Plagioclase grains are rare, occurring as large subhedral-anhedral grains. Grains of magnetite and ilmenite form a framework, while rare, small grains of sulphide occur interstitially. Thin section sampled from Simesvallen outcrop, HRE220011A. Geochemical data from sample: Fe_2O_3 40.5%, TiO_2 7.2%, V 2 540 ppm. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

A



B

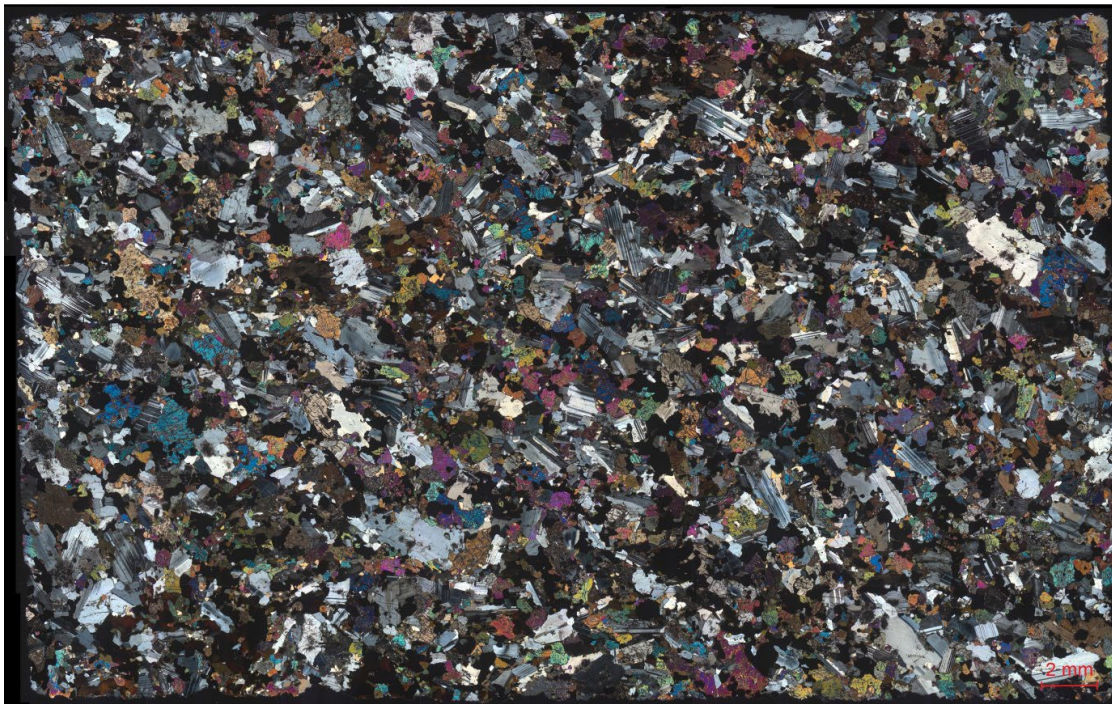


Figure C7. A well-preserved sample. Clinopyroxene is the main mafic mineral which occurs as small-large subhedral-anhedral grains with lamellae and opaque exsolution. Hornblende is a minor mineral which occurs as small-large subhedral-anhedral grains and interstitially. Olivine is a minor mineral which occurs as small-large subhedral-anhedral grains. Plagioclase occurs as small-large subhedral-anhedral grains with patchy sericite-saussurite alteration. Biotite occurs in two generations, the first has brownish red to brown pleochroism and the second has brownish red to tan-(green) pleochroism and is relatively abundant. Quartz occurs as rare grains with slightly undulose extinction. Magnetite and ilmenite grains occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Blistra outcrop, HRE220035A. Geochemical data from sample: Fe_2O_3 28.8%, TiO_2 3.97%, V 1 800 ppm. Petrophysical data from sample: 3 261 kg/m^3 , 0.295 SI, 15 400 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

A



B

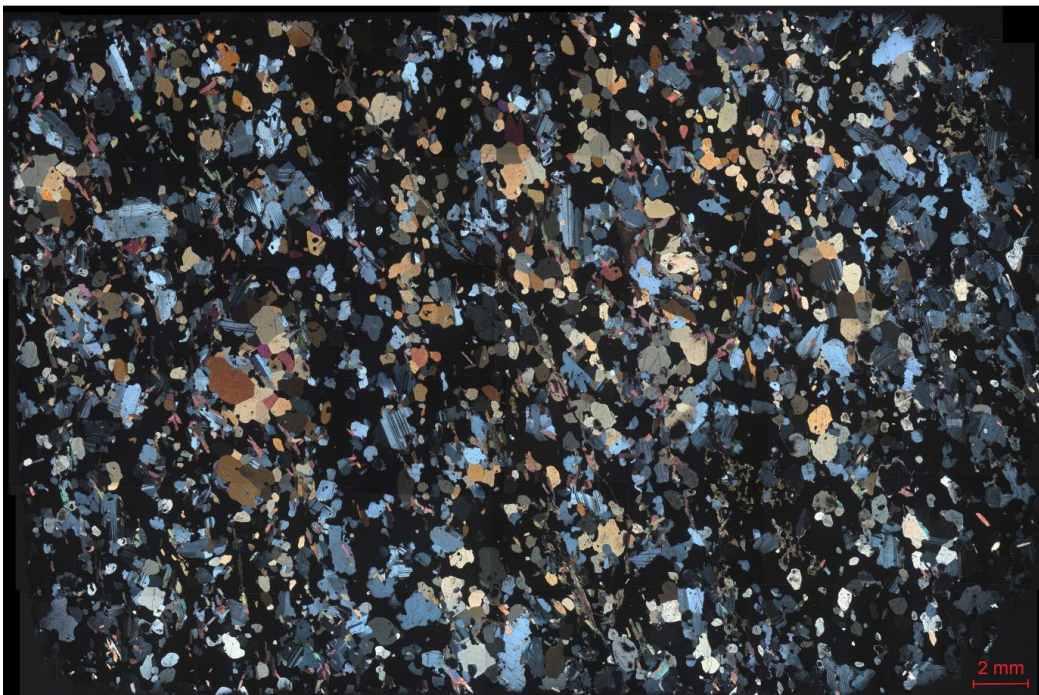


Figure C8. A mostly well-preserved sample with a preferred orientation of minerals. Alteration occurs along fractures. Hornblende occurs as small and large euhedral-subhedral-anhedral grains and interstitially. Clinopyroxene occurs as anhedral interstitial grains in small amounts. These grains have low order birefringence and close to straight extinction, and are partly to severely altered. Plagioclase occurs as large-small subhedral-anhedral grains. Some plagioclase grains look consumed-dissolved in contact with opaque minerals. Biotite occurs as small and large grains with brownish red to light tan pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur interstitially, as grains, fracture filling, and droplets. Thin section sampled from Bläckmyran drill core BLA82012, DCL222026B, from 39.11–39.19 m depth. Geochemical data from DCL222063A, 39.28–40.26 m depth, Fe_2O_3 45.5%, TiO_2 6.82%, V 4 720 ppm. Petrophysical data from DCL222026A, 39.19–39.28 m depth, 3 250 kg/m^3 , 0.43 SI, 331 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.



Figure C9. A well-preserved sample with minor alteration. Hornblende occurs as small-large euhedral-subhedral-anhedral grains and interstitially. Plagioclase occurs as small-large subhedral-anhedral grains. Plagioclase is sometimes rimmed with opaque minerals, which also infill fractures within the plagioclase grains. Biotite occurs, possibly from two generations. The first generation has brownish red pleochroism and the second has brownish red to tan pleochroism. Biotite occurs interstitially and as grains, with exsolution of opaque minerals. Magnetite and ilmenite occur interstitially and as framework minerals. The opaque minerals sometimes form rims and fracture filling, which indicates very late crystallisation in places. Sulphides occur interstitially and as grains and droplets. Thin section sampled from Bläckmyran drill core BLA81001, DCL223033A, from 44.31–44.35 m depth. Geochemical data from DCL223066A, 44.46–45.44 m depth, Fe_2O_3 38.7%, TiO_2 5.81%, V 3 160 ppm. Petrophysical data from DCL223032A, 44.35–44.46 m depth, 3 560 kg/m^3 , 0.712 SI, 169 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C10. A mostly well-preserved sample. Hornblende occurs as small and large, subhedral-anhedral grains. Plagioclase (sometimes severely sericite-saussurite altered) occurs as large-small, subhedral-anhedral grains. Biotite occurs as small and large grains, with brownish red to tan pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as fracture-filling, interstitially, as grains, and as droplets. Thin section sampled from Bläckmyran drill core BLA82007, DCL230003A, from 96.23–96.31 m depth. Geochemical data from DCL230036A, 94.78–95.76 m depth, Fe_2O_3 44.6%, TiO_2 6.60%, V 3 700 ppm. Petrophysical data from DSR230004A, 94.66–94.76 m depth, 3 739 kg/m^3 , 1.27 SI, 274 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

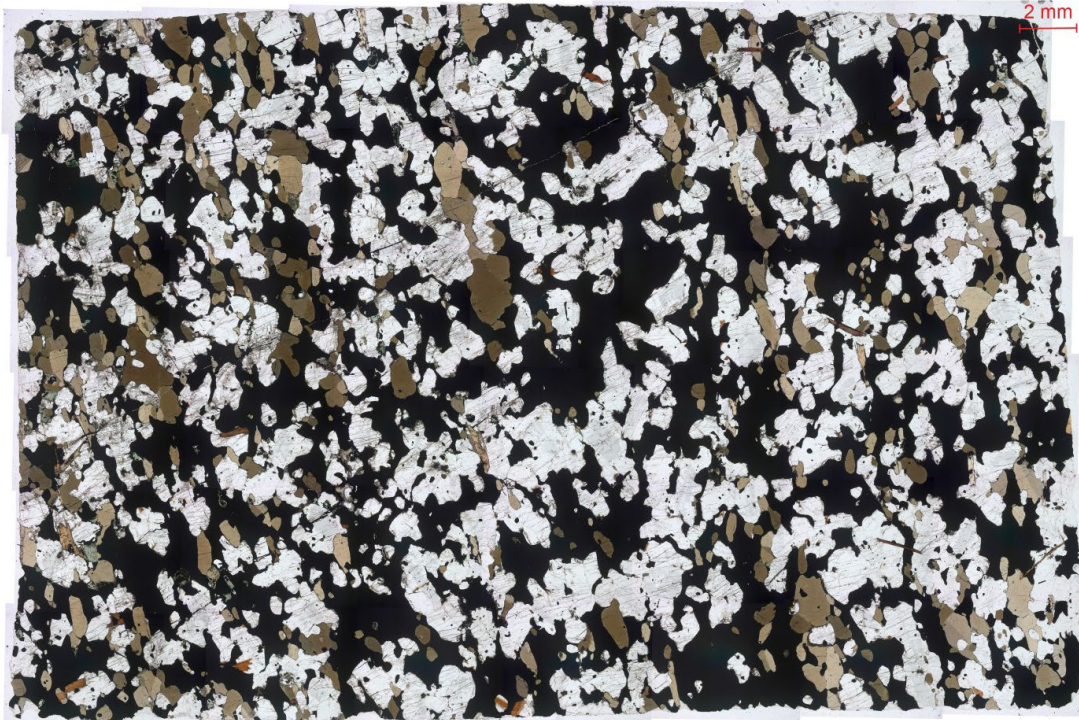


Figure C11. A mostly well-preserved sample. Hornblende occurs as small and large subhedral-anhedral grains. Plagioclase occurs as large-small subhedral-anhedral grains. Biotite occurs as small and large grains with brownish red to tan pleochroism. Magnetite and ilmenite grains form a framework. Sulphides occur as fracture-filling, interstitially, as grains, and as droplets. Thin section sampled from Bläckmyran drill core BLA82003, DCL230005A, from 62.00–62.06 m depth. Geochemical data from DCL230032A, 60.47–61.45 m depth, Fe_2O_3 44.7%, TiO_2 6.50%, V 3 840 ppm. Petrophysical data from DSR230007A, 60.39–60.47 m depth, 3 585 kg/m^3 , 0.873 SI, 785 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C12. Alteration occurs along fractures in this sample but elsewhere it is well-preserved with a strong preferred orientation of minerals. Hornblende occurs as small and large, subhedral-anhedral grains. Plagioclase occurs as large-small, subhedral-anhedral grains, some of which are severely altered to sericite-saussurite. Biotite occurs as small and large grains with brownish red to tan pleochroism. Magnetite forms the framework and occurs interstitially, while ilmenite occurs as grains. Sulphides occur as interstitial grains and droplets. Thin section sampled from Bläckmyran drill core BLA82002, DCL230006A, from 7.52–7.58 m depth. Geochemical data from DCL230031A, 7.67–8.65 m depth, Fe_2O_3 46.5%, TiO_2 6.81%, V 4 160 ppm. Petrophysical data from DSR230009A, 7.58–7.67 m depth, 3 676 kg/m^3 , 0.944 SI, 253 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B

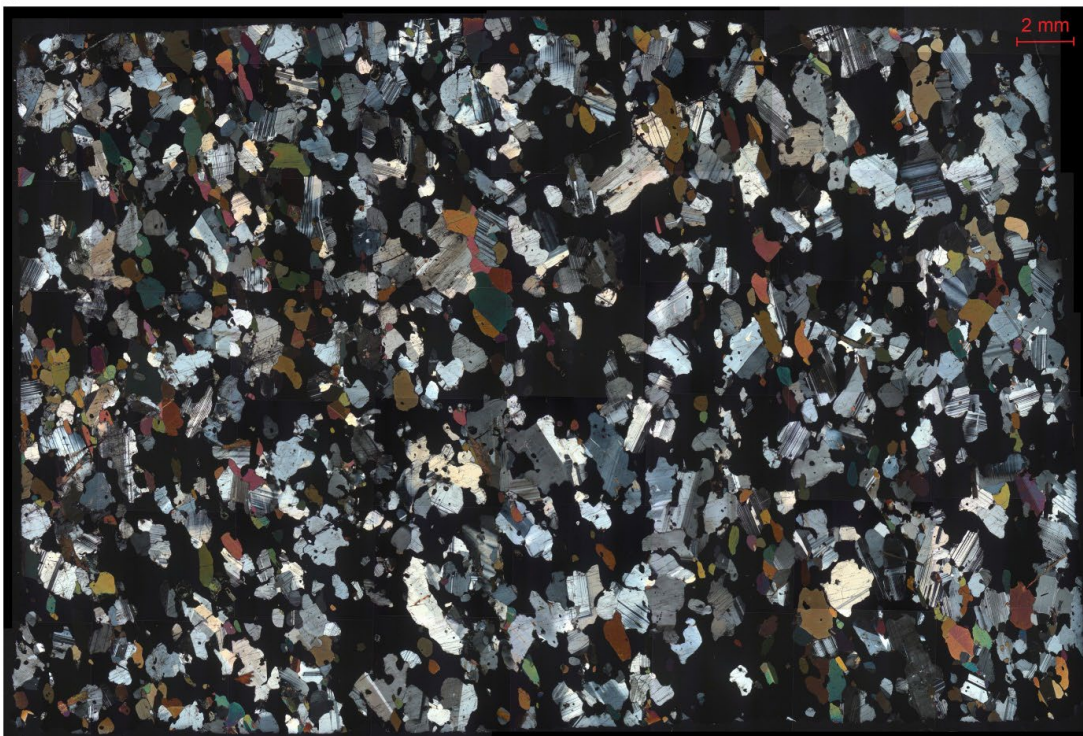


Figure C13. A mostly well-preserved sample. Hornblende forms the main mafic silicate mineral in this sample and occurs interstitially and as small-large, subhedral-anhedral-round grains. Very minor occurrences of secondary green amphibole are present. Plagioclase occurs as small-large, subhedral-anhedral grains, some of which exhibit sericite-saussurite alteration. Opaque minerals occur as rims and infill fractures in plagioclase grains. Some plagioclase crystals appear consumed-dissolved in contact with opaque minerals. Biotite occurs as small-large grains with brownish red to tan pleochroism. Magnetite forms the framework and occurs interstitially, while ilmenite occurs as grains. Sulphides are relatively abundant, occurring interstitially and as grains, fracture filling, and as droplets. Thin section sampled from Bläckmyran drill core BLA82006, DCL234001A, from 58.90–58.95 m depth. Geochemical data from DCL234013A, 59.50–60.48 m depth, Fe_2O_3 44.9%, TiO_2 6.34%, V 3 910 ppm. Petrophysical data from DSR230071A, 58.95–59.05 m depth, 3 531 kg/m^3 , 0.809 SI, 1 010 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.



Figure C14. A mostly well-preserved sample. Hornblende is the main mafic silicate mineral, which occurs interstitially and as small-large, euhedral-subhedral-anhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains, some of which exhibit sericite-saussurite alteration. Opaque minerals occur as rims or within fractures within plagioclase grains. Biotite occurs as small-large grains with brownish red to tan pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur interstitially and as grains and droplets. Thin section sampled from Bläckmyran drill core BLA82009, DCL234003A, from 37.60–37.65 m depth. Geochemical data from DCL234016A, 37.74–38.72 m depth, Fe_2O_3 40.2%, TiO_2 6.09%, V 3 450 ppm. Petrophysical data from DSR230074A, 37.65–37.74 m depth, 3 318 kg/m^3 , 0.425 SI, 92 700 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B

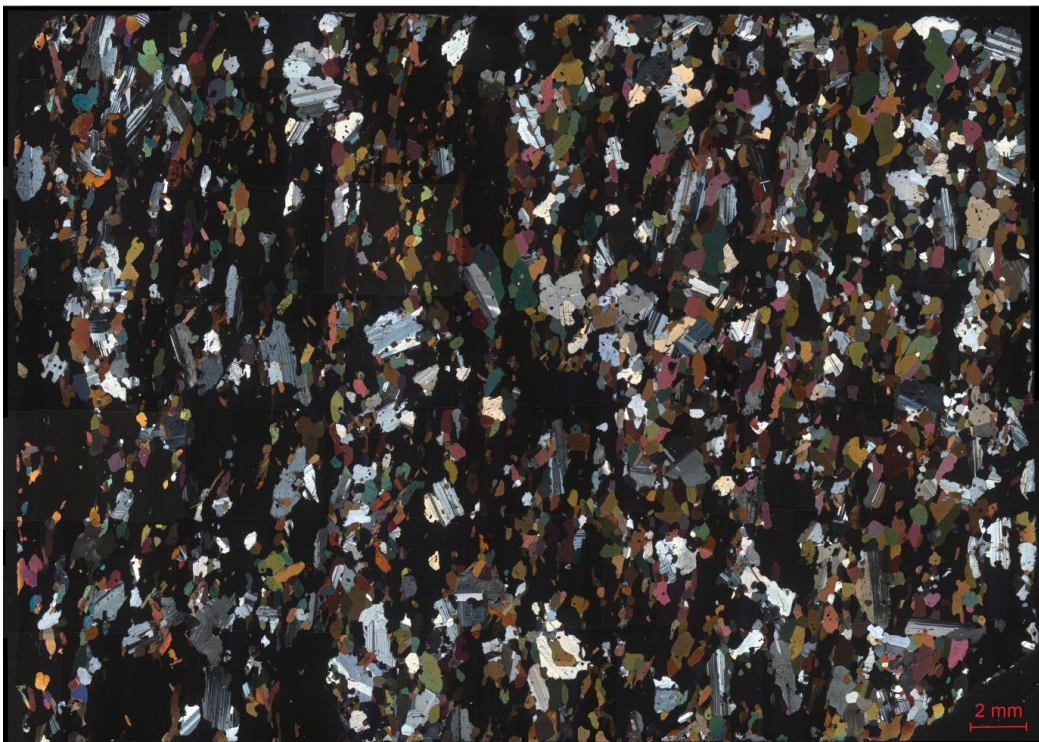
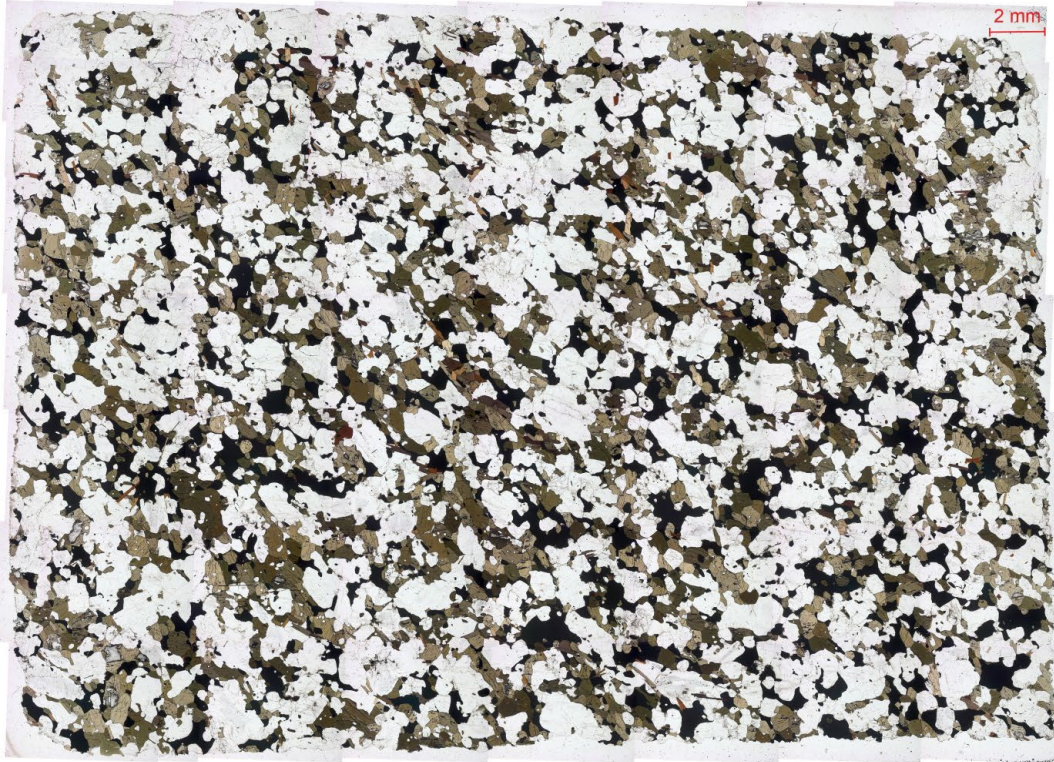


Figure C15. A well-preserved sample with a strong preferred orientation of minerals. Hornblende is the main mafic silicate mineral, which occurs interstitially and as small-large, subhedral-anhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains. Some of these grains have inclusions, which consist mainly of hornblende but sometimes biotite. Biotite is relatively abundant, occurring as small-large grains, with brownish red to tan pleochroism. Exsolution of opaque minerals with biotite can occur. Quartz is rare, occurring as small grains. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides are relatively abundant and occur interstitially and as grains and droplets. Thin section sampled from Bläckmyran drill core BLA82011, DCL234006A, from 7.48–7.53 m depth. Geochemical data from DCL234019A, 7.60–8.58 m depth, Fe_2O_3 58.5%, TiO_2 7.99%, V 6 040 ppm. Petrophysical data from DSR230077A, 7.53–7.60 m depth, 4 019 kg/m^3 , 1.53 SI, 907 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.



Figure C16. A well-preserved sample. Hornblende is the main mafic silicate mineral occurring interstitially and as small-large, subhedral-anhedral-round grains. Plagioclase occurs as small-large, subhedral-anhedral-round grains, with occasional inclusions of hornblende and biotite. Biotite occurs as small-large grains, with brownish red to tan pleochroism. In rare cases prehnite occurs as alterations within biotite. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur interstitially and as small grains and droplets. Thin section sampled from Bläckmyran outcrop, HRE220009A. Geochemistry data: Fe_2O_3 46.2%, TiO_2 6.75%, V 4 020 ppm. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B

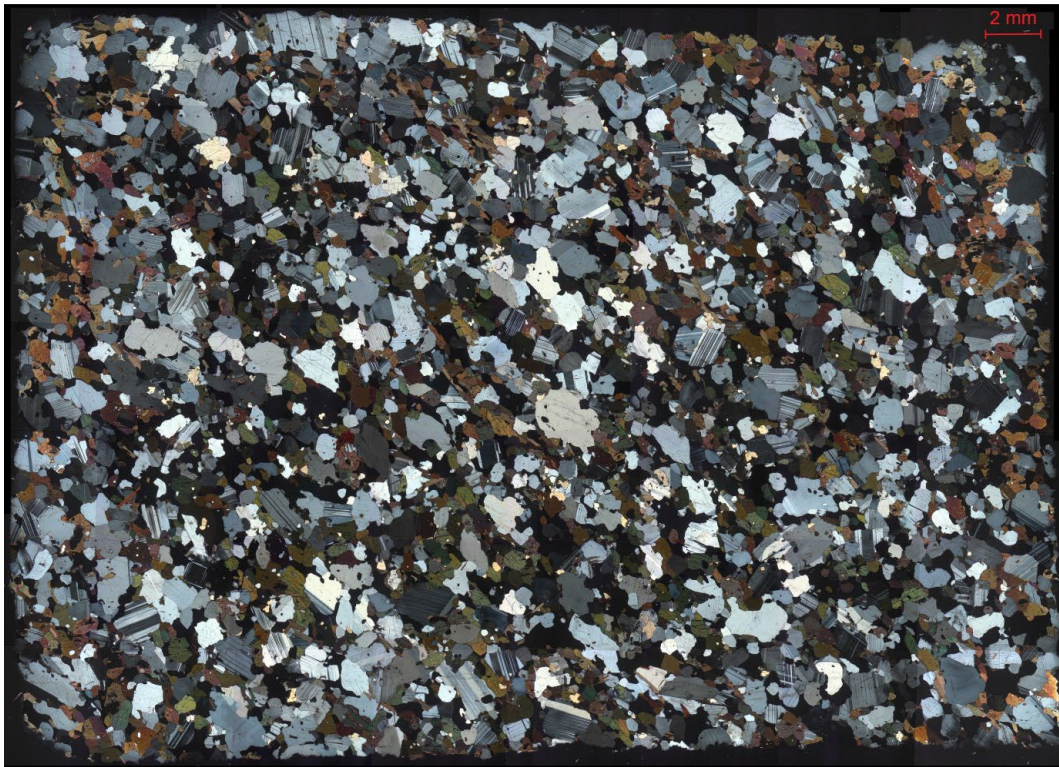


Figure C17. A well-preserved sample. Hornblende is the main mafic silicate mineral occurring interstitially and as small-large, euhedral-subhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains. Biotite occurs as possibly two generations, the first has red to light brown pleochroism and the second has brownish red to tan pleochroism. Biotite occurs interstitially and as grains with exsolution of opaque minerals. Quartz grains occur with slightly undulose extinction. Magnetite and ilmenite occur interstitially and as framework minerals, both exhibit exsolution. Sulphides occur as grains and interstitially. Thin section sampled from Masungsberget drill core MAB83003, DCL222001B, from 28.64–28.68 m depth. Geochemical data from DCL222030A, from 24.90–25.85 m depth, Fe_2O_3 36.4%, TiO_2 5.58%, V 3 010 ppm. Petrophysical data from DCL222001A, 24.70–24.80 m depth, 3 288 kg/m^3 , 0.518 SI, 260 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

A



B



Figure C18. A well-preserved sample. Hornblende occurs interstitially and as subhedral-anhedral grains. Olivine occurs interstitially as anhedral grains. Clinopyroxene occurs interstitially and as small and large, subhedral-anhedral grains, and with lamellae and exsolution of opaque minerals. Plagioclase occurs as small-large, subhedral-anhedral grains with slight sericite-saussurite alteration in patches. Some bending or kinking appears to have occurred (potentially, while hot). Biotite occurs which possibly has two generations. The first has red to light brown pleochroism and the second brownish red to tan pleochroism. Biotite occurs interstitially and as grains with exsolution of opaque minerals. Quartz grains occur with slightly undulose extinction. Magnetite and ilmenite occur interstitially and as framework minerals, both exhibit exsolution. Sulphides occur relatively abundantly, interstitially, as grains and as droplets. Thin section sampled from Masungsberget drill core MAB83004, DCL222002B, from 86.20–86.25 m depth. Geochemical data from DCL222033A, 85.20–86.20 m depth, Fe_2O_3 28.7%, TiO_2 4.47%, V 2 190 ppm. Petrophysical data from DCL222002A, 88.70–88.80 m depth, 3 257 kg/m^3 , 0.524 SI, 353 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

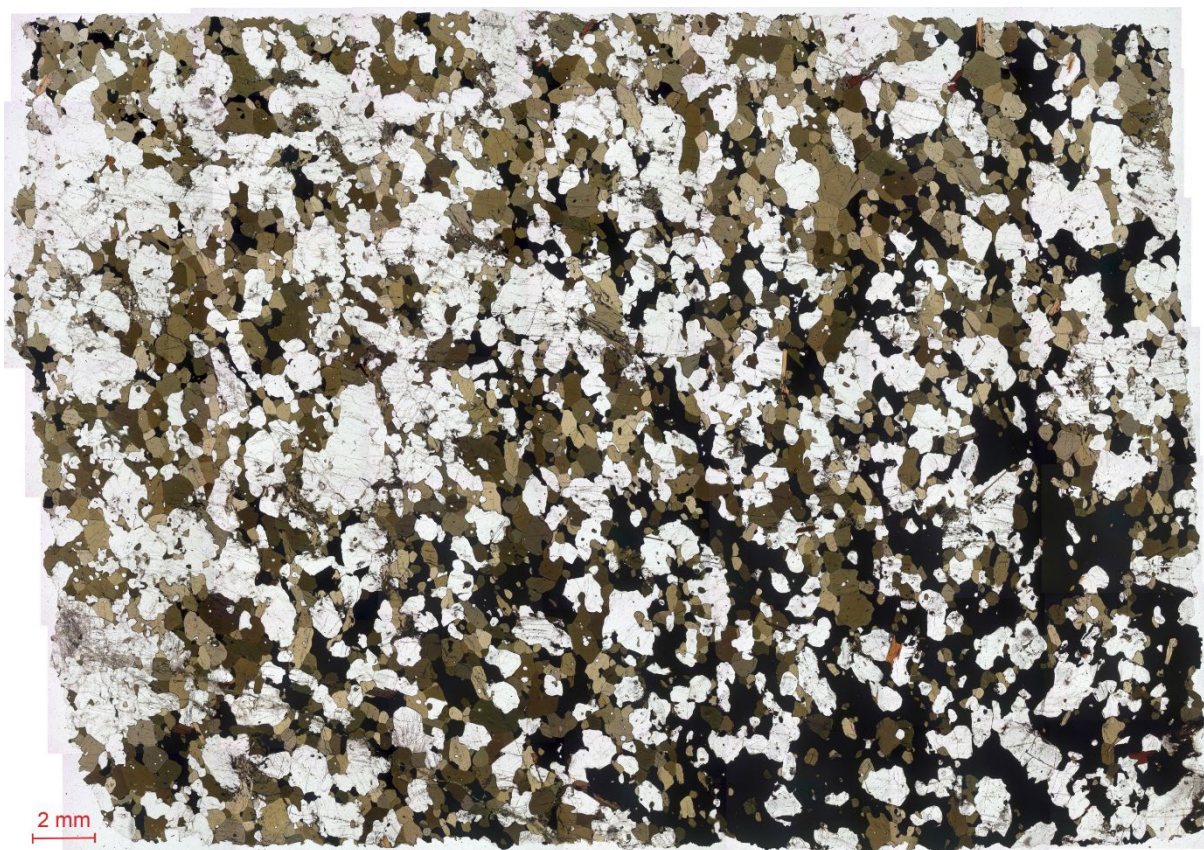


Figure C19. A well-preserved sample showing preferred orientation of minerals. Hornblende is the main mafic silicate mineral occurring interstitially and as small-large, euhedral-anhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains. Minor alteration along fractures to sericite-saussurite is observed. Biotite grains are brownish red to light brown. Apatite occurs as grains and aggregates. Quartz grains occur with slightly undulose extinction. Magnetite and ilmenite occur interstitially and as framework minerals. There are minor occurrences of sulphides, interstitially and as grains. Thin section sampled from Masungsberget drill core MAB83001, DCL223026A, from 29.68–29.72 m depth. Geochemical data from DCL223060A, 29.72–30.72 m depth, Fe_2O_3 33.7%, TiO_2 4.82%, V 2 490 ppm. Petrophysical data from DCL223027A, 29.52–29.62 m depth, 3 407 kg/m^3 , 0.599 SI, 213 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C20. In general, a well-preserved section, with some parts exhibiting alteration of both clinopyroxene and plagioclase. There are minor amounts of hornblende which occurs interstitially and as small-large, subhedral-anhedral, grains. Clinopyroxene is the main mafic mineral, occurring as small-large, subhedral-anhedral grains. Clinopyroxene exhibits also lamellae and opaque exsolution. Plagioclase occurs as small-large, subhedral-anhedral grains with patchy sericite-saussurite alteration, which in some cases is severe. Biotite of two generations is abundant, the first of which has brownish red-brown pleochroism and the second of which has brownish red to light tan pleochroism. K-feldspar or alkali feldspar occurs as a few, relatively large aggregates. Quartz grains with slightly undulose extinction also occur. Magnetite forms the framework and occurs interstitially, while ilmenite occurs as grains. Alteration of ilmenite to rutile or hematite is observed. Sulphides occur as grains and interstitially. Thin section sampled from Masugnsberget drill core MAB83005, DCL234010A, from 176.45–176.51 m depth. Geochemical data from DCL234034A, 175.37–176.35 m depth, Fe_2O_3 24.5%, TiO_2 4.07%, V 1 480 ppm. Petrophysical data from DSR230084A, 176.35–176.44 m depth, 3 093 kg/m^3 , 0.224 SI, 39 400 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

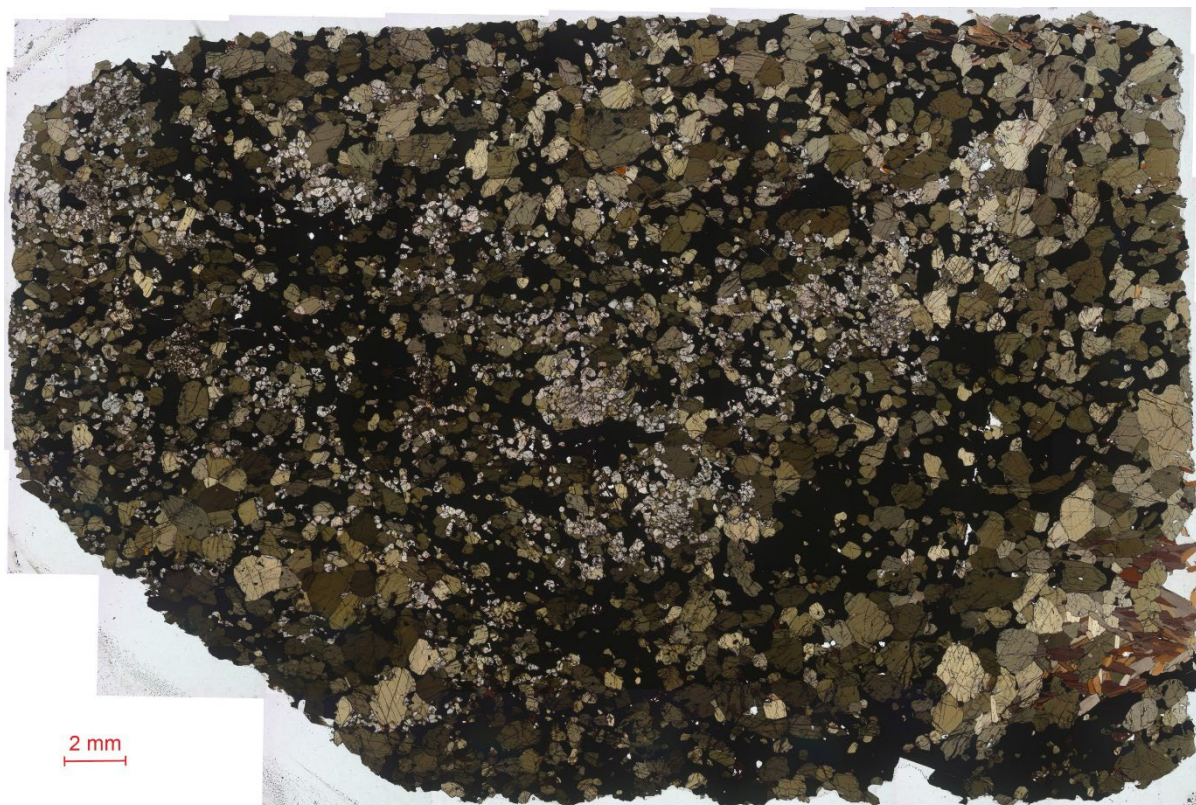


Figure C21. A well-preserved ultramafic section with a framework rich in opaque minerals. Hornblende is the main silicate mineral, occurring interstitially or as large-small, euhedral-subhedral-round grains. Olivine occurs as many small grains within the opaque framework. Some small grains of clinopyroxene occur within the opaque framework, some with lamellae. Plagioclase occurs rarely as very small interstitial grains. Biotite occurs as a minor component, as large grains which are brownish red to light beige in colour. Magnetite and ilmenite form the framework minerals, with some large interstitial rutile grains. No sulphide crystals are observed. Thin section sampled from Skalberget outcrop, HRE230039A. Geochemical data: Fe_2O_3 48.2%, TiO_2 5.69%, V 3 630 ppm and petrophysical data: 3 612 kg/m^3 , 0.863 SI, 50 200 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C22. A well-preserved section. Hornblende is the main mafic silicate mineral, which occurs interstitially and as small-large, euhedral-anhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains. Biotite occurs in two generations, the first with brownish red to brown pleochroism and the second with brownish red to light tan pleochroism. A few small apatite crystals are observed. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön drill core SUM81005, DCL222012B, from 32.40–32.47 m depth. Geochemical data from DCL222045A, 31.10–32.08 m depth, Fe_2O_3 37.2%, TiO_2 5.39%, V 3 440 ppm. Petrophysical data from DCL222012A, 32.08–32.18 m depth, 3 285 kg/m^3 , 0.498 SI, 16 600 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C23. A well-preserved section. Relatively small amounts of hornblende can be observed, which occur interstitially or as small grains. Olivine occurs as interstitially or as small-large, anhedral grains. Clinopyroxene occurs interstitially or as small-large, subhedral-anhedral grains. Clinopyroxene also exhibits lamellae and opaque exsolution. Plagioclase occurs as small-large, subhedral-anhedral grains. Biotite occurs in two generations, the first with brownish red pleochroism and the second with brownish red to tan pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön drill core SUM82010, DCL222017B, from 31.00–31.05 m depth. Geochemical data from DCL222050A, 31.15–32.11 m depth, Fe_2O_3 29.5%, TiO_2 4.41%, V 2 590 ppm. Petrophysical data from DCL222017A, 31.05–31.15 m depth, 3 283 kg/m^3 , 0.496 SI, 17 200 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

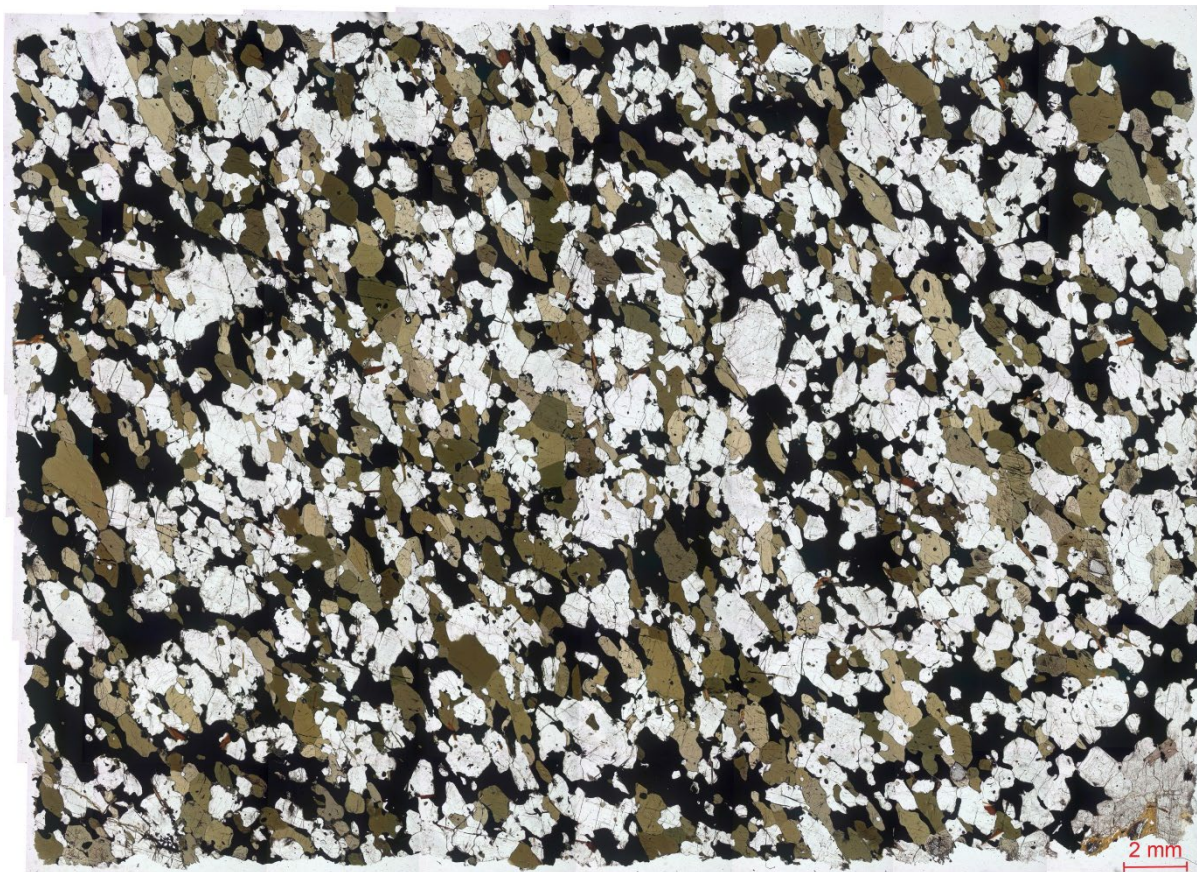


Figure C24. A well-preserved section with a strong preferred orientation of minerals. Hornblende is the main mafic silicate mineral and occurs interstitially and as small-large, subhedral-anhedral grains. Plagioclase occurs interstitially or as small-large, subhedral-anhedral grains. Minor sericite-saussurite alteration can be observed. Relatively few biotite grains are observed with brownish red to light brown pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön drill core SUM82007, DCL222020B, from 21.66–21.73 m depth. Geochemical data from DCL222055A, 20.55–21.53 m depth, Fe_2O_3 28.4%, TiO_2 3.91%, V 2 640 ppm. Petrophysical data from DCL222020A, 21.53–21.63 m depth, 3 524 kg/m^3 , 0.852 SI, 425 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

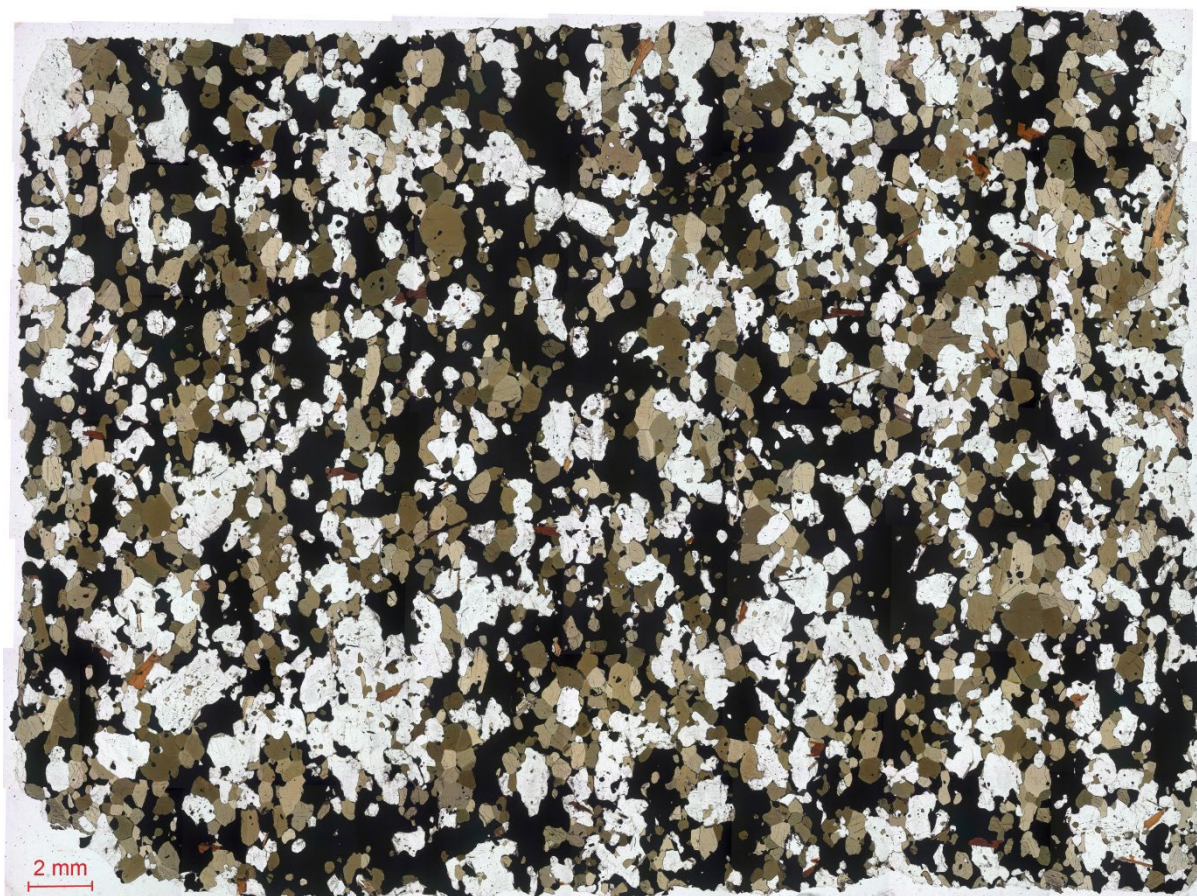


Figure C25. A well-preserved section. Hornblende is the main mafic silicate mineral, which occurs interstitially or as small-large, subhedral-anhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains. Biotite occurs in two generations, the first with brownish red to light brown pleochroism and the second with brownish red to tan pleochroism. Quartz occurs in small quantities as small grains with a weak undulose extinction. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön drill core SUM82004, DCL222022B, from 6.12–6.17 m depth. Geochemical data from DCL222057A, 4.49–5.47 m depth, Fe_2O_3 35.1%, TiO_2 5.01%, V 3 530 ppm. Petrophysical data from DCL222022A, 5.72–5.82 m depth, 3 593 kg/m^3 , 0.871 SI, 31 400 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B

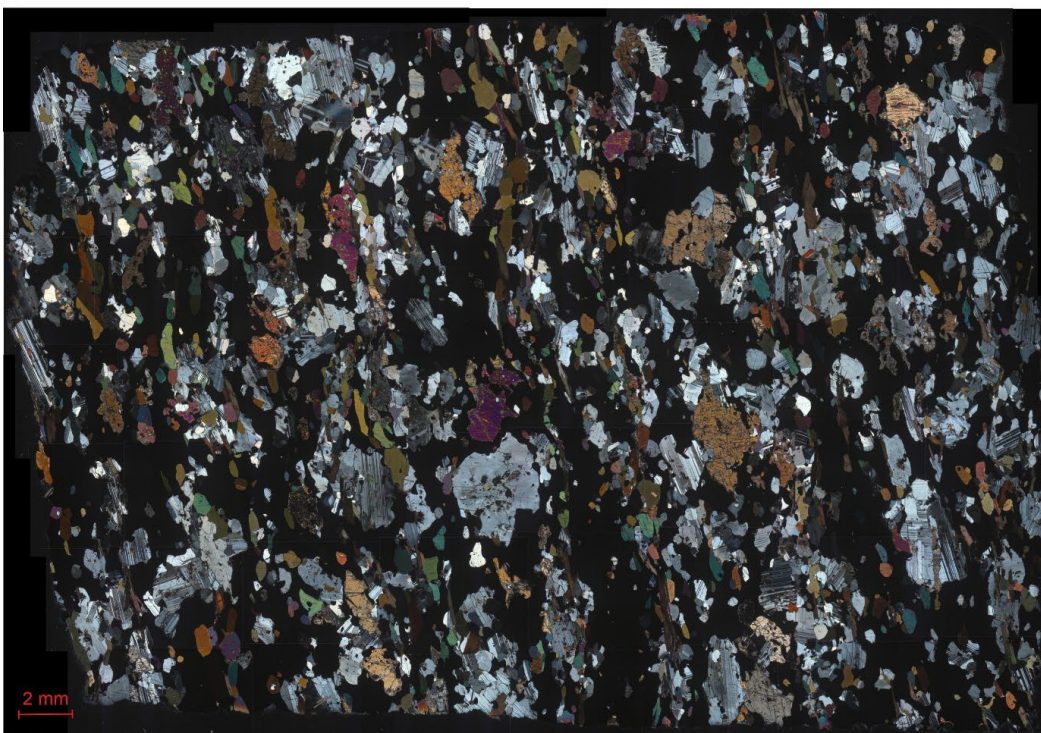


Figure C26. A well-preserved section, with a distinct fabric of parallel minerals. Patches of sericite-saussurite alteration and green amphibole can be observed. Hornblende occurs interstitially and as subhedral-anhedral grains. Olivine occurs interstitially and as small-large, subhedral-anhedral grains. Clinopyroxene occurs interstitially and as small-large, subhedral-anhedral grains. Plagioclase occurs interstitially and as small-large, subhedral-anhedral grains with minor patches of sericite-saussurite alteration. Biotite occurs in two generations, the first has brownish red pleochroism and the second has brownish red to tan pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön drill core SUM82004, DCL222023B, from 37.85–37.89 m depth. Geochemical data from DCL222059A, 36.87–37.85 m depth, Fe_2O_3 40.9%, TiO_2 5.7%, V 4 260 ppm. Petrophysical data from DCL222023A, 37.89–37.98 m depth, 3 773 kg/m^3 , 1.20 SI, 4 065 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.



Figure C27. A well-preserved, mostly fine-grained section. Hornblende occurs as small-large, subhedral-anhedral grains. Olivine occurs as small-large, subhedral-anhedral grains. Clinopyroxene occurs as small-large, subhedral-anhedral grains, where exsolution of opaque minerals can be observed. Plagioclase occurs as small-large, subhedral-anhedral grains. Biotite grains occur with brownish red to tan pleochroism. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön, drill core SUM82014, DCL222024B, from 87.97–88.03 m depth. Geochemical data from DCL222061A, 88.11–88.73 m depth, Fe_2O_3 57.6%, TiO_2 7.96%, V 6 220 ppm. Petrophysical data from DCL222024A, 88.03–88.11 m depth, 4 060 kg/m^3 , 1.22 SI, 312 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C28. This is generally a well-preserved section but is altered in some areas. Hornblende is the main mafic silicate mineral, which occurs interstitially and as small-large, subhedral-anhedral grains. Some severe green amphibole alteration is observed in association with fractures. Plagioclase occurs as small-large, subhedral-anhedral grains with patchy sericite-saussurite alteration. Biotite occurs as small grains with brownish red to tan pleochroism, which in some parts is altered to chlorite. Some relatively large crystals of K-feldspar or alkali feldspar are observed in the magnetite aggregate. Quartz occurs as small-large grains with slightly undulose extinction. More than half of the thin section is made up of a large aggregate of magnetite with minor ilmenite. The remaining portion of the thin section is dominated by silicate minerals and has rare occurrences of small sulphide crystals. Note the difference in grain-size between the two different parts. Thin section sampled from Gruvberget–Sumåssjön drill core SUM81005, DCL230023A, from 105.94–106.00 m depth. Petrophysics data from DSR230033A, 105.87–105.94 m depth, 3 590 kg/m³, 2.14 SI, 822 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

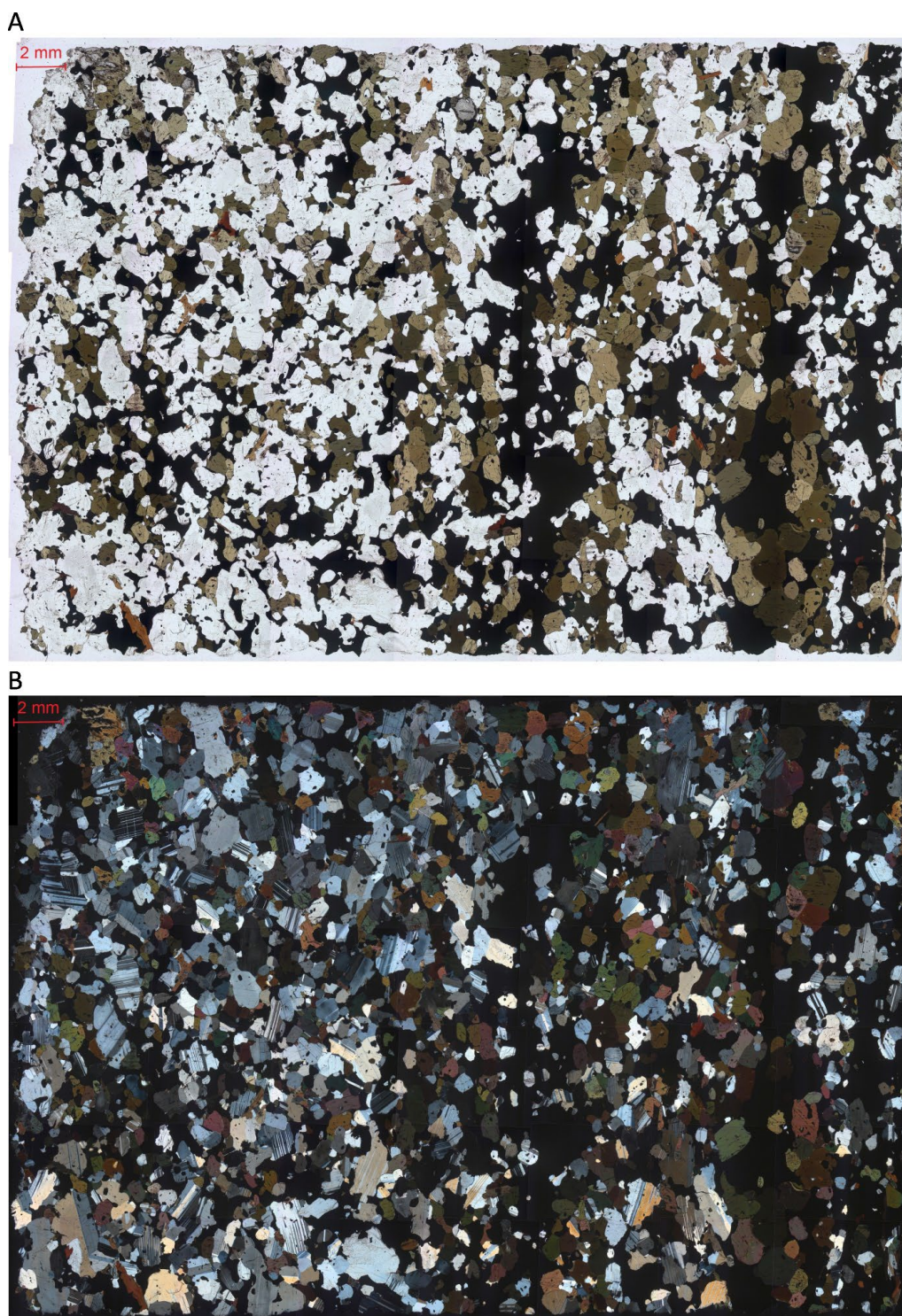


Figure C29. A well-preserved section with mineral compositional layering. Hornblende is the main mafic silicate mineral, which occurs interstitially and as small-large, euhedral-anhedral grains. Plagioclase occurs as small-large, subhedral-anhedral grains. Some plagioclase grains appear to have been consumed-dissolved in contact with opaque minerals. Biotite occurs in two generations, the first has brownish red to brown pleochroism and the second has brownish red to tan pleochroism. A few apatite grains can be observed as subhedral crystals. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as grains and droplets. Thin section sampled from Gruvberget–Sumåssjön drill core SUM81014, DCL230026A, from 91.45–91.52 m depth. Geochemical data from DCL230054A, 90.35–91.38 m depth, Fe_2O_3 49.6%, TiO_2 7.24%, V 4 550 ppm. Petrophysical data from DSR230037A, 91.38–91.45 m depth, 3 799 kg/m^3 , 1.27 SI, 1 070 000 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

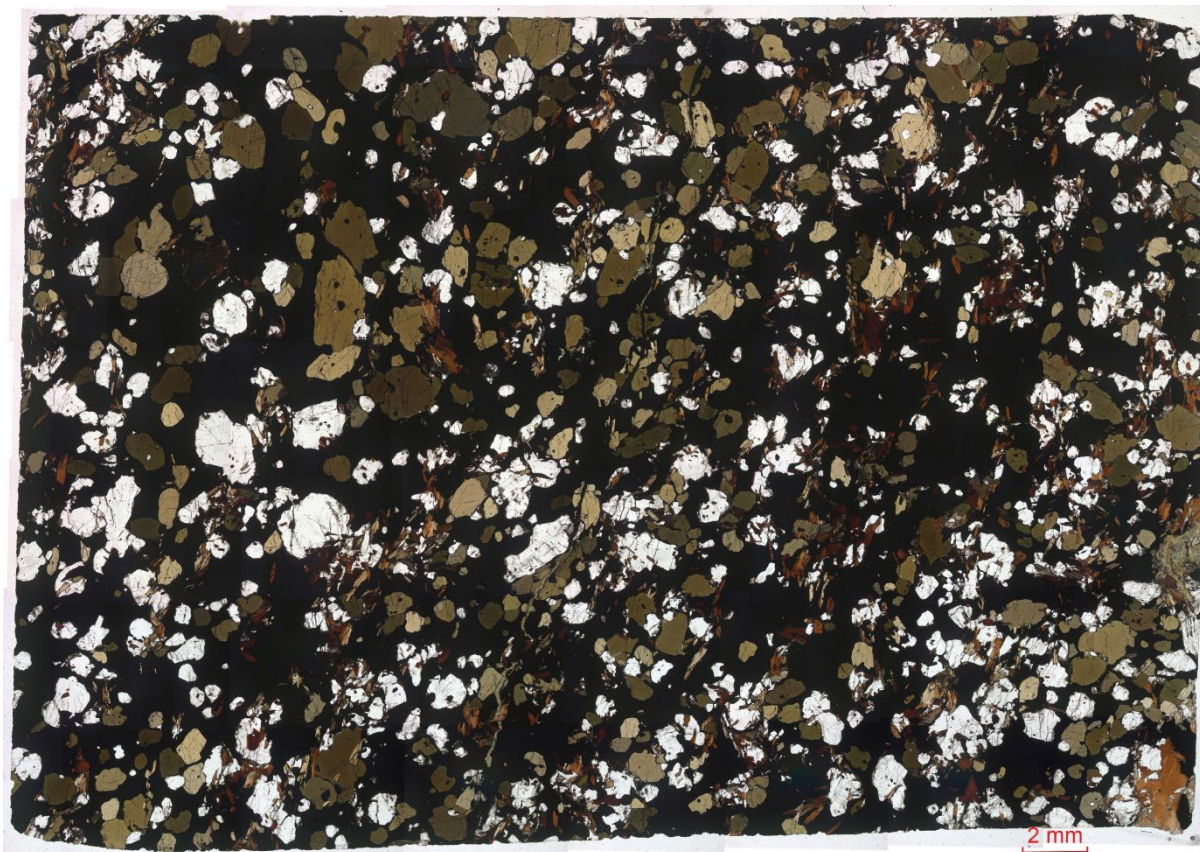
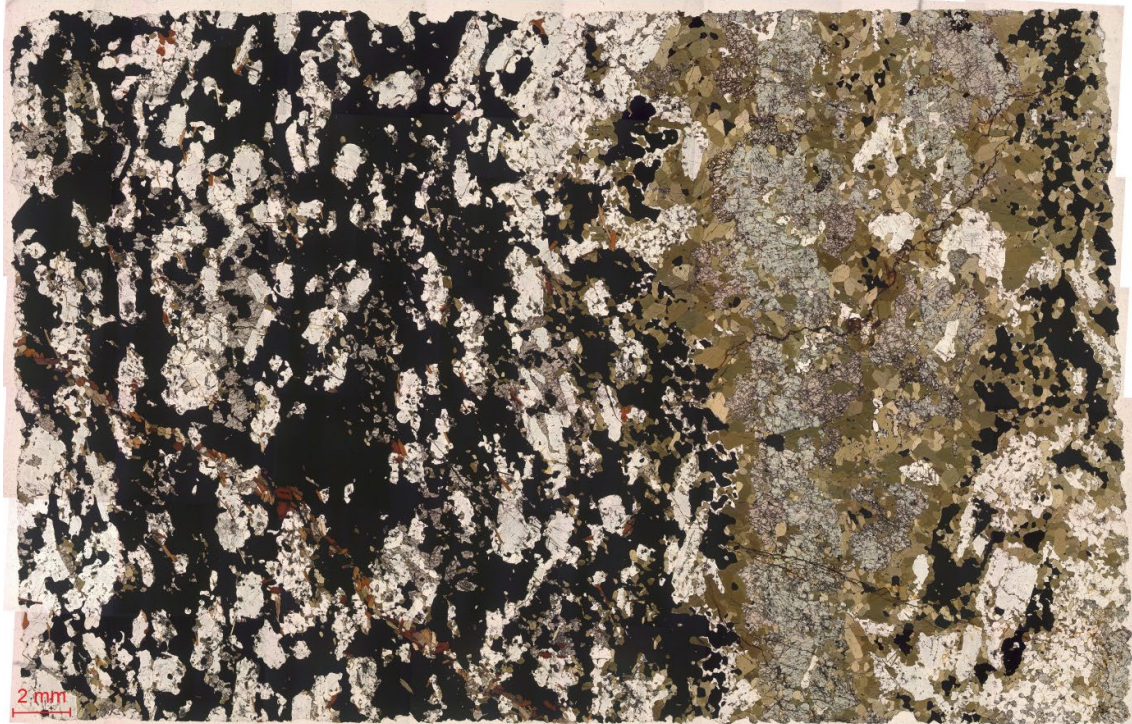


Figure C30. A generally well-preserved section where very minor alteration to green amphibole and sericite-saussurite can be observed. Hornblende is the main mafic silicate mineral, which occurs as small-large, subhedral-anhedral grains, which are mostly isolated within the opaque framework. Plagioclase occurs as small-large, subhedral-anhedral grains, which are mostly isolated within the opaque framework. Bending or kinking of plagioclase grains (while hot) is observed. Biotite occurs abundantly in two generations, the first has brownish red to red pleochroism and the second has brownish red to tan pleochroism. Magnetite and ilmenite form the framework. Sulphides occur as grains and interstitially. Thin section sampled from Gruvberget–Sumåssjön drill core SUM81017, DCL234011A, from 76.62–76.68 m depth. Geochemical data from DCL234027A, 76.68–77.66 m depth, Fe_2O_3 53.3%, TiO_2 7.25%, V 5 320 ppm. Petrophysical data from DSR230088A, 76.54–76.62 m depth, 3 858 kg/m^3 , 1.61 SI, 1 020 000 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.



Figure C31. A well-preserved section with a preferred orientation of minerals. Hornblende is the main mafic silicate mineral, which occurs interstitially and as small-large, subhedral-anhedral grains. In some places hornblende occurs as an aggregate. Plagioclase occurs as small-large, subhedral-anhedral grains with patchy sericite-saussurite alteration. Biotite occurs with brown to light tan pleochroism. In a few parts the biotite has been altered to chlorite. Magnetite and ilmenite form the framework. Sulphides are rare, occurring as small grains. Thin section sampled from Kullberget outcrop, HRE220021A. Geochemical data are: Fe_2O_3 19.8%, TiO_2 2.27%, V 967 ppm. Petrophysical data are: 3 041 kg/m^3 , 0.12 SI, 1 900 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B

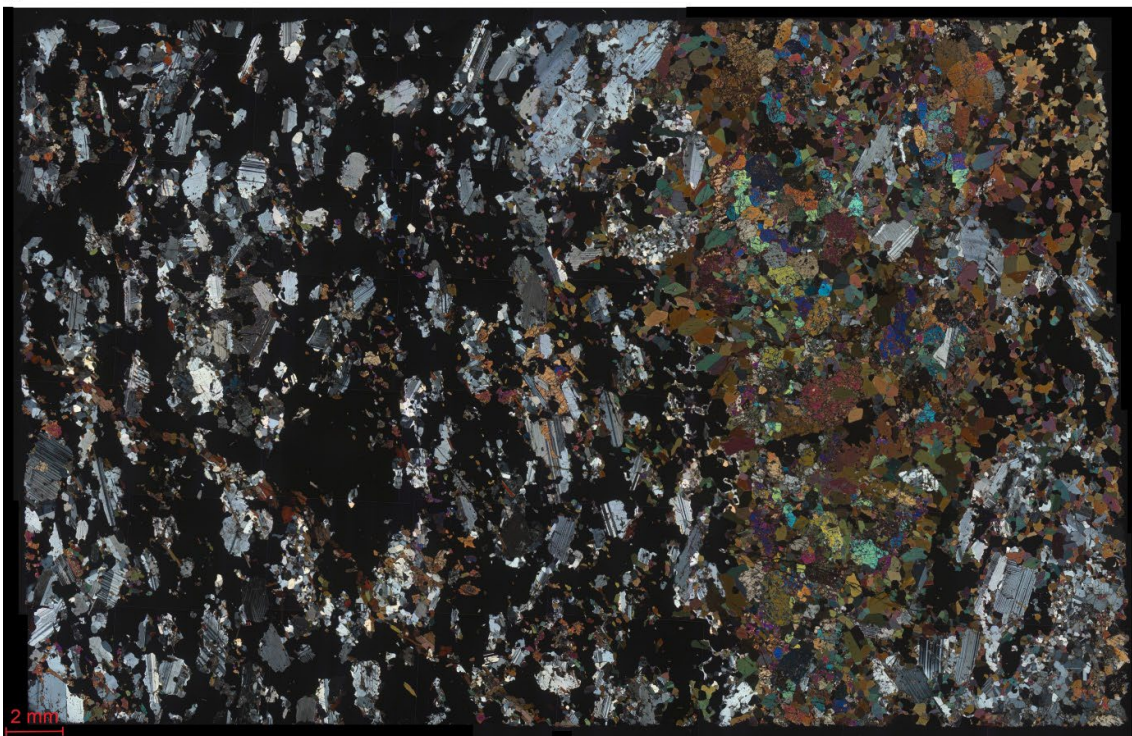


Figure C32. A well-preserved section. More than half of the section consists of an opaque framework, while in other parts of the section the opaque grains are interstitial. Hornblende occurs as small grains within the opaque framework. Elsewhere hornblende occurs as small-large, subhedral-anhedral grains. Olivine occurs as small grains within the opaque framework part and elsewhere as small-large, subhedral-anhedral grains. Clinopyroxene occurs as small grains within the opaque framework part and elsewhere as small-large, subhedral-anhedral grains. Lamellae and opaque exsolution of clinopyroxene can be observed. Plagioclase occurs as small-large, subhedral-anhedral grains with minor sericite-saussurite alteration. Biotite occurs relatively abundantly within the opaque framework part in two generations, the first has brownish red to brown pleochroism and the second has brownish red to tan pleochroism. The opaque framework part consists of magnetite and ilmenite. Sulphides occur as grains and interstitially. Thin section sampled from Kullberget outcrop, HRE220023A. Geochemical data are: Fe_2O_3 54.6%, TiO_2 7.44%, V 4 740 ppm. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.

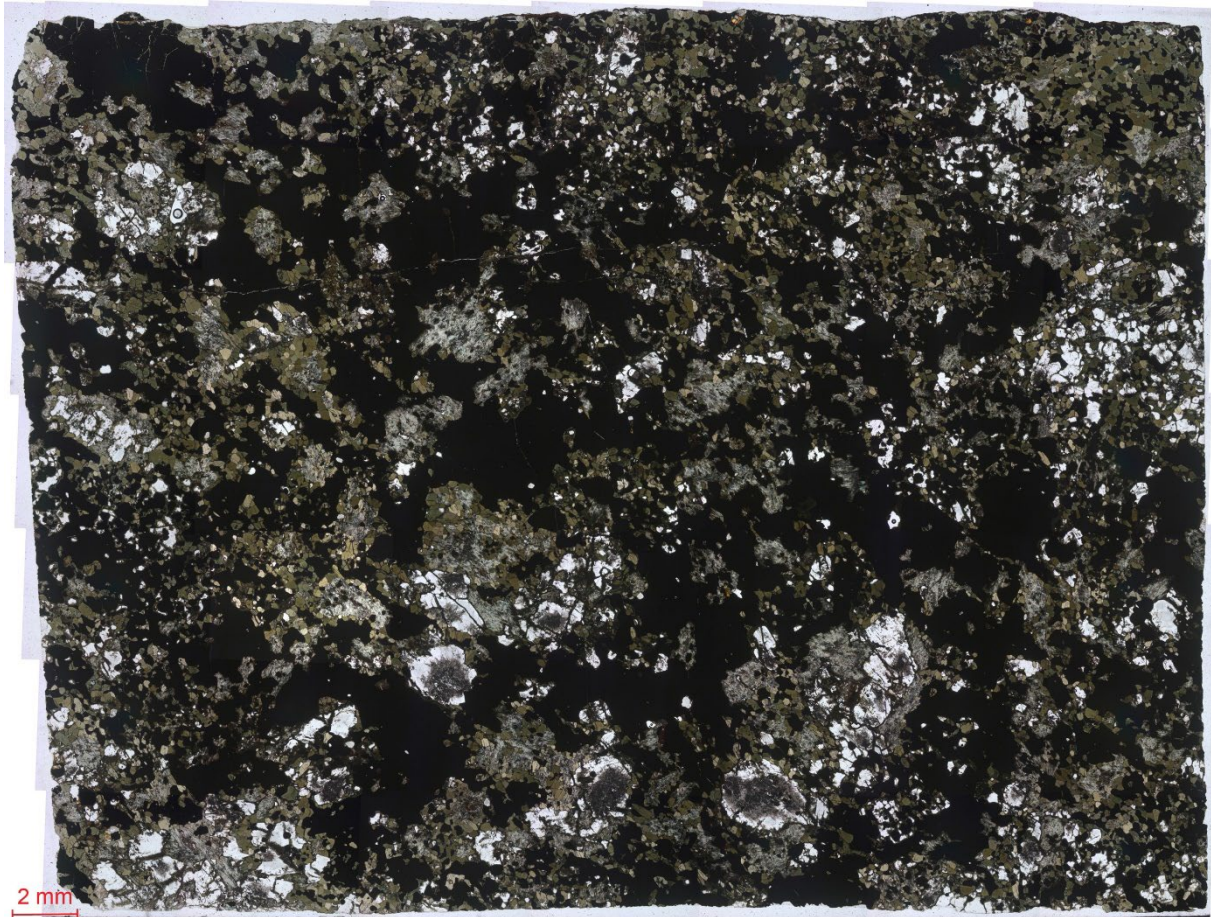
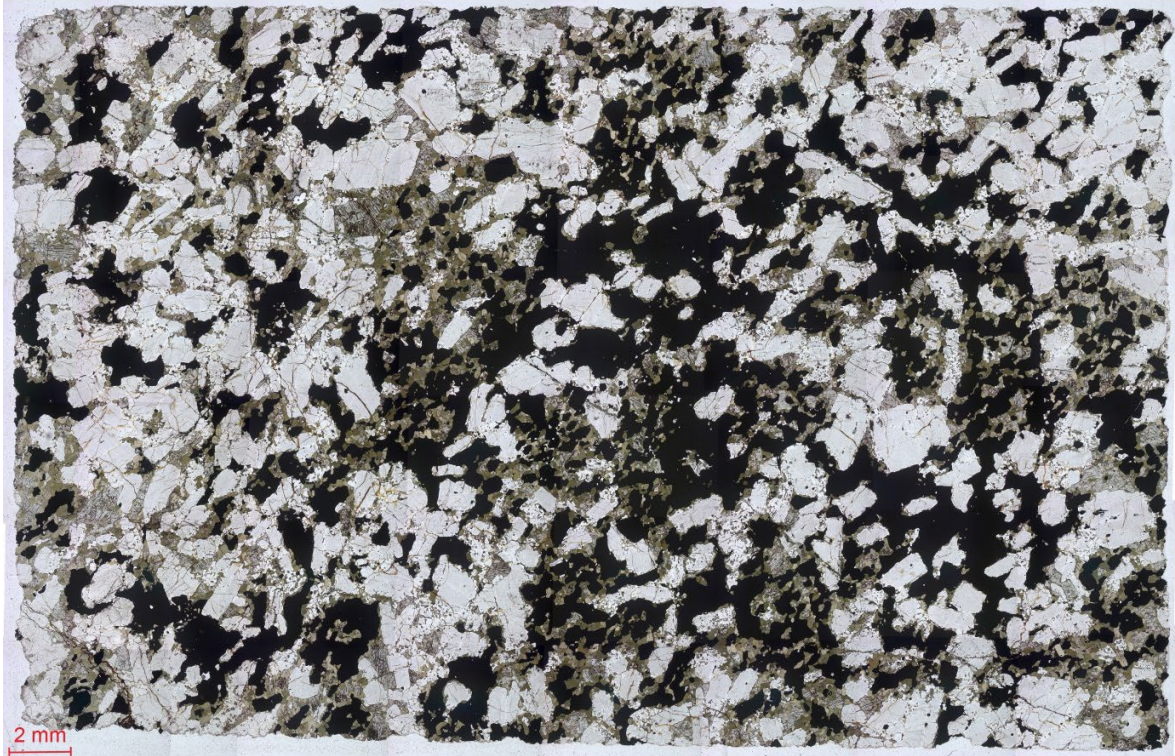


Figure C33. A partly preserved section. Hornblende is the main mafic silicate mineral, which occurs as small and large euhedral-anhedral grains. Many of the large hornblende grains have 120 degrees triple junctions between crystals. Residual traces of a mineral which has been severely altered can be observed, which is interpreted to be clinopyroxene. Plagioclase mostly occurs as small and large, subhedral-anhedral grains. These plagioclase grains exhibit minor to severe sericite-saussurite alteration. Magnetite and ilmenite form the framework. Sulphides occur relatively abundantly as grains and are predominantly chalcopyrite. Thin section sampled from Kattuggelberget outcrop, HRE220033A. Geochemical data are: Fe_2O_3 54.3%, TiO_2 4.48%, V 982 ppm. Petrophysical data are: 3 597 kg/m^3 , 1.41 SI, 5 150 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.

A



B

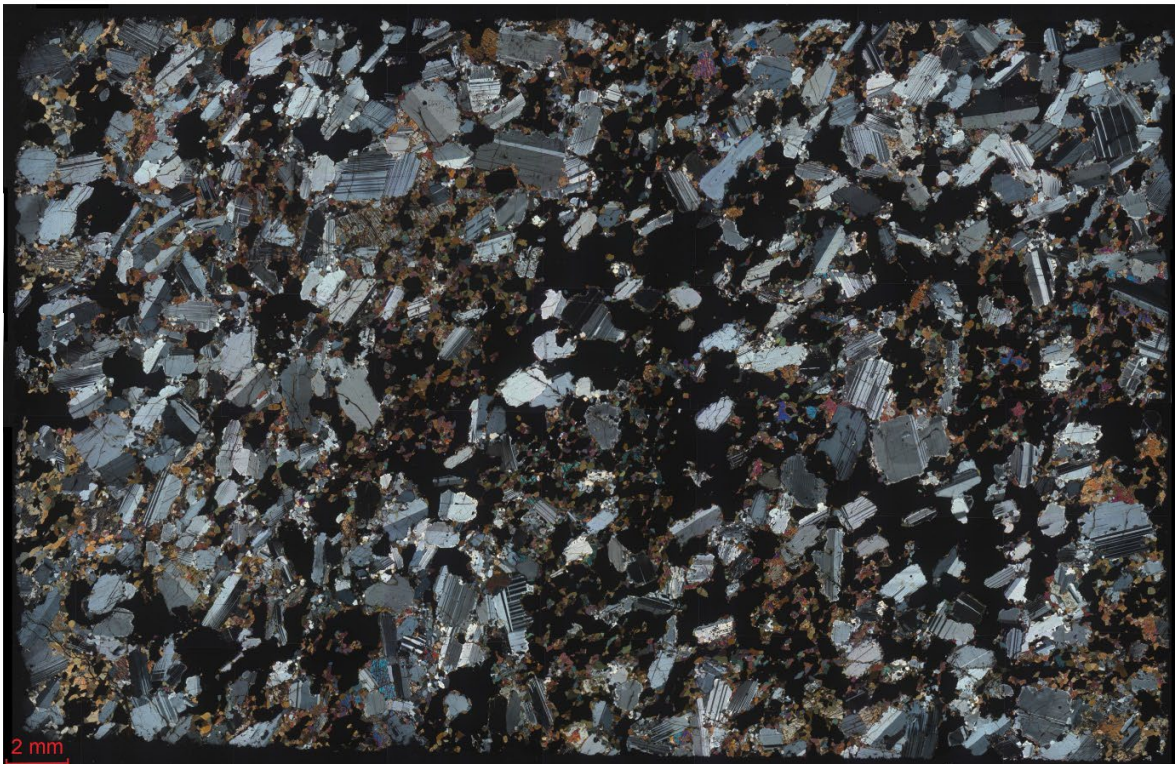


Figure C34. A well-preserved section with roughly equal amounts of hornblende and clinopyroxene. Hornblende occurs interstitially, as aggregates together with opaque minerals, and as small-large, euhedral-anhedral grains. Clinopyroxene occurs interstitially and as small-large, subhedral-anhedral grains. Lamellae, opaque exsolution and alteration of clinopyroxene can be observed. Plagioclase occurs as small-large, subhedral-anhedral grains. Bending or kinking of the plagioclase grains (while hot) can be observed, and some crystals appear consumed and dissolved in contact with opaque minerals. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as small grains. Thin section sampled from Andberget outcrop, HRE220024A. Geochemical data: Fe_2O_3 41.7%, TiO_2 9.37%, V 2 410 ppm. Petrophysical data: 3 626 kg/m^3 , 0.789 SI, 27 100 mA/m. **A.** shows the section in plane-polarised light (ppl) while **B.** shows the section in cross-polarised light (xpl). Photo: Dick Claeson.



Figure C35. A mostly well-preserved section. Hornblende occurs interstitially, as aggregates with opaque minerals, and as small-large, subhedral-anhedral grains. A few small-large, anhedral grains of olivine can be observed. Clinopyroxene is the main mafic silicate mineral, which occurs interstitially and as small-large, subhedral-anhedral grains. Lamellae, opaque exsolution and some green amphibole alteration of clinopyroxene can be observed. Plagioclase occurs as small-large, subhedral-anhedral grains with minor patchy sericite-saussurite alteration. Magnetite and ilmenite occur interstitially and as framework minerals. Sulphides occur as rare small droplets. Thin section sampled from Andberget outcrop, HRE230017A. Geochemical data are: Fe_2O_3 24.6%, TiO_2 5.16%, V 986 ppm. Petrophysical data are: 3 144 kg/m^3 , 0.086 SI, 4 720 mA/m. Section is shown in plane-polarised light (ppl). Photo: Dick Claeson.