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# Origin of the Kleva Ni-Cu sulphide mineralisation in Småland, southeast Sweden

Karolina Bjärnberg



**LUND**  
UNIVERSITY

Lithosphere and Biosphere Science  
Department of Geology

DOCTORAL DISSERTATION

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To be defended at Pangea, Geocentrum II. Date December 11, 2015 and time 09.15.

*Faculty opponent*

Kjell Billström

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Cover: A photo-scanned slice of mineralised gabbro from the Kleva Ni-Cu sulphide deposit (sample K1; the collections of the Department of Geology at Lund University). Sulphides (pyrrhotite, chalcopyrite and pentlandite) occur as network type mineralisation enclosing the silicate crystals of the gabbro. The height of the rock slice is c. 4 cm.

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Title and subtitle Origin of the Kleva Ni-Cu sulphide mineralisation in Småland, southeast Sweden		
<p>Abstract</p> <p>The Kleva Ni-Cu sulphide deposit is situated within a gabbro-diorite intrusive complex in southeast Sweden. The basement north of the intrusive complex is dominated by 1.81–1.77 Ga granites of the Palaeoproterozoic Transscandinavian Igneous Belt (TIB). Slightly older (1.83–1.82 Ga) rocks of the Oskarshamn Jönköping Belt, which hosts numerous syngenetic and epigenetic base metal mineralisations, occur just south of the Kleva intrusive complex. The aim of this PhD-thesis is to deduce the origin of the Kleva deposit, the mineralisation itself as well as its host rocks through geochemical, geochronological and petrological studies.</p> <p>U-Pb age determination of zircon dates igneous crystallisation to 1.79 Ga, which is the age of the Kleva intrusive complex and confirms its temporal association with the voluminous TIB magmatism. Major- and trace element systematics are in accordance with a basaltic magma that formed through partial melting of a metasomatically refertilised mantle wedge underneath an Andean-type continental magmatic arc. Lu-Hf signatures of zircon, together with other rocks of Palaeoproterozoic Fennoscandia indicate alternating stages of extension and compression across the subduction zone, facilitating ascent of the mafic magma. Evidence for contamination of the magma through crustal assimilation during its ascent are inconclusive. Low IPGE/Ni together with high S/Se, indicate sulphide melt saturation prior to final emplacement, possibly induced by crustal contamination. Nb/La vs La/Sm indicate contamination with mid-crustal rocks, and radiogenic Os of magmatic pyrite suggests &lt;10% contamination with Archean crust. OJB aged rocks are thus unlikely contaminants, despite the numerous rock inclusions of similar geochemical composition within the intrusive complex. <math>\delta^{34}\text{S}</math> of Kleva mineralised rocks and the country rocks corresponds with the mantle range, and local or mantle origin of S can neither be proven nor rejected.</p> <p>Sulphide melt segregated from an evolved magma and partially accumulated into massive lenses, which is in accordance with a magmatic conduit setting. The mineralisation contains massive, net-textured and disseminated sulphides of typical magmatic association and is interpreted to be contemporaneous with silicate melt crystallisation, consistent with a Re-Os 1.71 <math>\pm</math> 0.2 Ga isochron for massive pyrite with magmatic texture. Re-Os isochrons of secondary pyrite indicate metamorphic disturbance of the mineralisation at least twice; at c. 1.61 Ga and 1.39 Ga, which can be linked to orogenic events further to the south and west. The mineralisation was heterogeneously affected by tectonic disturbance, resulting in remobilisation of chalcopyrite into veins, plastic deformation of sulphides and host rock, micro-faulting and brittle deformation of oxides and sulphides and recrystallisation of pyrite in fractures. To summarise, the deposit is an example of a subduction related magmatic Ni-Cu mineralisation affected by multi-stage deformation and alteration.</p>		
Key words Ni-Cu sulphide deposit, ore genesis, arc, mantle, gabbro-diorite, sulphide remobilisation, geochemistry, geochronology, Fennoscandia, Palaeoproterozoic		
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# List of papers

This thesis includes four papers which are listed below. Paper I is a peer-reviewed paper published in GFF. Paper II is a manuscript submitted to Geology and is under consideration. Paper III and IV are unpublished manuscripts.

## Paper I:

Geochronology and geochemical evidence for a magmatic arc setting for the Ni-Cu mineralised 1.79 Ga Kleva gabbro–diorite intrusive complex, southeast Sweden, by K. Bjärnborg, A. Scherstén, U. Söderlund and W.D. Maier, 2015. GFF 137:83–101; DOI: 10.1080/11035897.2015.1015265.

## Paper II:

Tracing Proterozoic mantle wedge composition through coupled zircon U-Pb and Lu-Hf isotopes (manuscript), by A. Petersson, K. Bjärnborg, A. Gerdes and A. Scherstén. Submitted to Geology 2015-06-02, under review.

## Paper III:

Re-Os constraints on the origin and remobilisation of sulphide minerals in the Kleva Ni-Cu sulphide deposit, southern Sweden (manuscript), by K. Bjärnborg, A. Scherstén, R.A. Creaser and W.D. Maier.

## Paper IV:

Tracing sulphide melt saturation in the magmatic Kleva Ni-Cu sulphide deposit, southeast Sweden – combining in-situ and bulk-rock  $^{34}\text{S}/^{32}\text{S}$  analyses (manuscript), by K. Bjärnborg, A. Scherstén, M. Whitehouse, Y. Lahaye and W.D. Maier.

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One of the benefits of being a PhD-student is to visit labs and departments in different parts of the world, which is a great opportunity for learning about analytical methods, topic-related theories and the academic world itself but also to meet skilled and inspiring researchers. I want to thank all you, and co-authors, both at the department in Lund and at other departments around the world.

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Tack till er alla!

# Abbreviations

AFC = Assimilation Fractional Crystallisation  
 CAB = Continental Arc Basalt  
 CC = Continental Crust  
 Ccp = Chalcopyrite  
 CHUR = Chondritic Uniform Reservoir  
 EDS = Energy Dispersive X-ray analysis  
 E-MORB = Enriched Mid Oceanic Ridge Basalt  
 EMPA = Electron Micro-probe Analysis  
 Ga = billions of years before present  
 HFSE = High Field Strength Element  
 HREE = Heavy Rare Earth Element  
 IPGE = Iridium-group Platinum Group Element  
 iss = intermediate solid solution  
 LA-MC-ICP-MS = Laser Ablation Multicollector  
 Inductively coupled mass spectrometry  
 LILE = Large Ion Lithophile element  
 LREE = Light Rare Earth Element  
 Ma = millions of years before present  
 MASH = Melting Assimilation Storage Homogeni-  
 sation  
 mss = monosulphide solid solution  
 N-MORB = Normal Mid Oceanic Ridge Basalt  
 NTIMS = Negative Thermal Ionisation Mass  
 Spectrometry  
 OAB = Ocean Arc Basalt  
 OJB = Oskarshamn Jönköping Belt  
 P = Pressure  
 PGE = Platinum Group Element  
 Pn = Pentlandite  
 Po = Pyrrhotite  
 PPGE = Palladium-group Platinum Group Element  
 Py = Pyrite  
 REE = Rare Earth Element  
 SCLM = Sub-continental Lithospheric Mantle  
 SD = Standard Deviations  
 SEM = Scanning Electron Microscope  
 SIMS = Secondary Ion Mass Spectrometry  
 T = Temperature  
 TIB = Transscandinavian Igneous Belt  
 TIMS = Thermal Ionisation Mass Spectrometry  
 WDS = Wavelength Dispersive X-ray analysis  
 WR = Whole Rock

## *Elements*

Ag = Silver  
 Al = Aluminium  
 Ar = Argon  
 Au = Gold  
 Ba = Barium  
 Ce = Cerium  
 Co = Cobalt  
 Cr = Chromium  
 Cs = Caesium  
 Cu = Copper  
 Dy = Dysprosium  
 Er = Erbium  
 Eu = Europium  
 Fe = Iron  
 Gd = Gadolinium  
 Hf = Hafnium  
 Ho = Holmium  
 Ir = Iridium  
 K = Potassium  
 La = Lanthanum  
 Lu = Lutetium  
 Mg = Magnesium  
 Nb = Niobium  
 Nd = Neodymium  
 Ni = Nickel  
 O = Oxygen  
 Os = Osmium  
 Pb = Lead  
 Pd = Palladium  
 Pr = Praseodymium  
 Pt = Platinum  
 Rb = Rubidium  
 Re = Rhenium  
 Rh = Rhodium  
 Ru = Ruthenium  
 S = Sulphur  
 Si = Silica  
 Sm = Samarium  
 Sr = Strontium  
 Ta = Tantalum  
 Tb = Terbium  
 Ti = Titanium  
 Th = Thorium  
 Tm = Thulium  
 U = Uranium  
 Y = Yttrium  
 Yb = Ytterbium  
 Zn = Zinc  
 Zr = Zirconium

# 1 Introduction

The definition of ore is

“a naturally occurring solid material from which a metal or valuable mineral can be extracted profitably” (Oxford dictionaries).

In other words, what constitutes an ore varies with time as a function of what is economically viable to mine. In turn, this might depend on the metal content in the ore minerals, possibly unwanted trace metals (such as arsenic), the contents of ore minerals in the host rock, and the structural state and accessibility of the ore within the host rock. The here studied Kleva nickel-copper (Ni-Cu) sulphide deposit is situated within a marked hill; *Klevaberget* (Kleva hill), 258 metres above sea level, in the Småland Highlands of southeast Sweden. Historically, the hill has been named Stora Clew, Clewaberget and Klefva; the name Kleva translates to cleft or steep hill-side. At the time of mining it was an important base metal asset for the Swedish metal industry, similar to many other minor deposits in the region. It is the only important Ni-Cu deposit in southeast Sweden. Mining operations ended after several centuries of mining due to economic and practical difficulties. The known ore is mined out and the site is now converted to a cultural heritage site and a historic mine that is open for tourists (Fig. 1).

The aim of this PhD-thesis is to deduce the origin of the Kleva deposit, the mineralisation itself as well as its host rocks through geochemical, geochronological and petrological studies. The sulphide assemblage together with the gabbro-diorite host rocks at Kleva is characteristic for a magmatic Ni-Cu deposit. Magmatic deposits around the World are abundant and well-studied. Minor deposits, of which some occur in geologic contexts previously overlooked, are less studied and might be important assets in the future, together with recycled metals, in order to meet the ever-increasing demand for metals.

Kleva is a minor deposit and its reserves are mined out, so why study Kleva in particular? Firstly, apart from geologic reports from the 1880's the Kleva deposit has been poorly studied, and being a tourist mine makes it accessible for studies. Secondly, the Kleva deposit is solitary and distant to the other magmatic deposits in the Archaean cratons of northern Finland and Sweden. Thus its geologic context is intriguing.



Fig 1 The Kleva underground mine

A lattice gate allows visitors to peek in to the historic mine but also keeps them at a safe distance from the entrance to the deep Karls schakt from the top of the hill.

## 1.1 The history of the Kleva mine

The Kleva mine is located approximately 13 km east of Vetlanda in Småland, southeast Sweden (see Fig. 7). The history of the Kleva mine stretches back to the end of the 17<sup>th</sup> century and includes mining of both Cu and Ni. The mine has successively grown and it reaches a total depth of about 100 metres and a width of about 200 metres (Fig. 1). The mine is partly filled with water and visitors have access to the drained 75 metres level, which can be entered through the 280 metres long, narrow, passage *Aschans stoll*. The larger mining galleries located at the 75 metres level are *Storgruvan* (the large mine), *Lillgruven* (the small mine) and *Malmkyrkan* (the ore church).

All passages, stopes, adits, shafts and major fractures have historic names that refer to persons. Examples are: *Karls schakt* (Karl's shaft) that is located next to *Malmkyrkan*, *Fadersskölen* (Father's fracture) running southwards from Karl's schakt and *Swabs släppa* (Swab's fault) running eastwards from *Storgruvan*. These are commonly referred to in historic reports of the mine and in mining maps (Fig. 2). More recent names used in the visitor's mine apply to physical characteristics or folklore; *Mörka gången* (the dark passage), *Bergakungens sal* (King of the mountain's gallery) and *Klarvattnet* (the



**Fig 2 Mining map**

Map of the Kleva mine edited from von Post (1886), updated with addition of stopes and adits in the early 20<sup>th</sup> century. A) The 75 metres level of the mine, with names of main galleries, shafts and passages marked out. Main lineaments (yellow with sulphides = släppa; blue with alteration minerals = sköl) are marked out in fig. 1A and 1B; Fadersskölen (1), Modersskölen (2), Stjufmoder sköl (3), Swabs släppa (4), Berzelii släppa (5) and Cronstedts släppa (6). A vertical section along profile A–B is shown in map B) where the 75 m level, and current water table, is marked with a purple dashed line. The second visitor access at 45 m level, Nilssons stoll, is also marked out.

*Who was the local parish clerk?*

The clerk worked in Skede parish, west of Kleva, but his name is no longer known. The duties of a 17<sup>th</sup> century clerk were likely numerous. He worked for the priest, although the salary or social position was not as high. He was likely responsible for the maintenance and safe-keeping of the church inventories such as the key, church bells, the baptismal font and the candles, preparations for services such as to ring the church bells, singing, and to teach the youth to sing and write (Andersson 2007).

According to historic notes, the clerk's discovery of the Kleva mineralisation was also his misfortune as he presumably ended his life in chains.

“Och så snart Arbetet med flit påbegynt blifvit; har Klockaren I förtid börjat grunda efter Maschiners inrättande til; en mindre Kostsam upfodring af en förmodad outdöelig Rikedom; men hans häftiga Eftertanka har ej tagit lyckligare slut, än att han i förstone börjat Yra och sluteligen kommit så aldeles ifrån sina Sinnen at han med Boijer och band; häftad i skärskilt Hus; vid Wäggen fastslåss måste; Gemene Man hysa den Mening; at han Yppat och Rubbat något Underjordiskt Rå som honom derföre sitt Förstånd borttagit.” (Magnus Linder 23 augusti 1736).

The excerpt from Magnus Linder's testimony, Gyafors 23<sup>rd</sup> of August 1736, tells that the clerk thought of the ore to be infinite and put such effort into mining it that he lost his mind. The common view of that time was that he must have disturbed a sprite of the underground who therefore took his sanity away. His findings of pyrite truly turned into fool's gold.

clear water). The industrial history of the mine has been documented by, e.g. Hallgren (1910), Tegengren (1924) and Mansfeld (2000), but the most recent summary can be found in Torstensson et al. (2008).

### 1.1.1 Mining of copper

In 1691, a sulphide mineralisation was discovered at Kleva hill by a local parish clerk, and the interest for copper mining in the area soon aroused. Within a few years, the preparations for mining at Kleva began and in 1696 the first test-run of copper smelting in a furnace was done. The mining of the copper ore was problematic, however, and the mine was only run periodically during the following decades, and with little profit. The copper produced in the smelting furnace became hard, brittle and was not pure enough. In addition, the discovery of gold in the nearby Gyafors area (Ädelfors) shifted the interest away from Kleva.

The operation of the Kleva mine was resumed in 1828 after having been abandoned for slightly more than 50 years. The 75 metres level entrance and drainage passage to the Storgruvan was finished under the leadership of the local industrial investor Johan Lorenz Aschan; hence the name Aschans stoll (i.e. Aschan's passage). Despite improved mining procedures, the availability of dynamite and simplified ore transportation, difficulties arose again due to the poor copper quality and decreasing ore reserves. Aschan investigated the poor copper quality, and through analyses of the ores performed by Jöns Jacob Berzelius, it was found to contain as much as c. 3% Ni (Berzelius 1842). This was the start of the nickel-mining era of the Kleva deposit.

### 1.1.2 Mining of nickel

Electroplated products, containing nickel, were in high fashion during the 19<sup>th</sup> century, and in 1845 nickel-production was initiated at Kleva. The following 30 years became the mine's golden era and it was one of the main Swedish producers of nickel at the time. However, the financial conditions changed abruptly as high-grade nickel ore was discovered in New Caledonia, a group of islands 1200 km east of Australia, which remains one of the World's major sources of nickel. The price of nickel thereby decreased and undermined the interest for the more expensive nickel from Kleva and many other mines in Scandinavia.



**Fig 3 Kleva sulphide samples**

Three samples of the Kleva mineralisation from the collections of the Department of Geology in Lund; K1 (top) net-textured sulphides, K2 (left) banded sample with coarse pyrite crystals and K3 (right) chalcopyrite dominated vein in fine grained mafic rock.

The 1880's were marked by a low production of nickel, but exploration of the deposit continued. Three different reports were written by Swedish and Norwegian geologists active at that time; Waldemar Christofer Brøgger (1851–1940), Johan Herman Lie Vogt (1858–1932), Birger Santesson (1845–1893) and Hans von Post (1852–1905). Their reports were the basis on which the future of the Kleva mine was outlined. Although there were indications of yet undiscovered ore bodies in Kleva (Brøgger and Vogt 1888), exploration was fruitless. Closing of the mine was proposed, and was carried out in 1889. The mine was reopened briefly for production during World War I (1914–1919). During the World War II, the mine was not reopened for production, but ore previously extracted from Kleva was shipped for processing to Boliden, in northern Sweden.

### 1.1.3 The Kleva deposit

The reports of Brøgger and Vogt (1887), Santesson (1887) and von Post (1887) were the first geologic documentation of the Kleva deposit, apart from mining maps and economic reports. It is to a large extent their descriptions, measurements and thoughts of the Kleva mineralisation that remain the most recent source of information on the Kleva deposit until this day, as the known ore-body is mined out. Here follows a summary.

The host rocks of the deposit are medium-grained gabbro or diorite (von Post 1887) and copper and nickel were extracted from both massive and disseminated ores. The massive Ni-bearing pyrrhotite ore occurred as vertical massive stock and pipe-like bodies with irregular morphologies; massive stock-like ores 15 metres wide, 20 metres long and 30 metres deep have been reported (e.g. in Malmkyrkan), as well as others that are less than a metre wide (Santesson 1887). The grade decreased outwards into disseminated ore (von Post 1887; Santesson 1887).

Exploration of Ni-ore was preferentially done along the fracture systems of the mine (skölar and släppor; Fig. 2). Fractures cut ores and host rocks, and range from being barren, filled with alteration minerals or filled with chalcopyrite and pyrite (Fig. 3; Brøgger and Vogt 1887; Von Post 1887; Santesson 1887). The thickness of the sulphide fracture-fillings ranged from a few mm to 50 cm and they were often aligned east–west. This fracture system was at least 250 metres wide and 88 metres deep (Santesson 1887). The secondary fractures were 10–30 cm wide and north–south trending and cut the sulphide filled fractures, but do not dislocate or alter them (Santesson 1887; von Post 1887; Brøgger and Vogt 1887).

Santesson (1887) and von Post (1887) considered the sulphide filled fractures to be feeder dykes for the ores, whereas Brøgger and Vogt (1887) on the other



Fig 4 Mining debris

View from the top of Kleva hill, where there are old, weathered, piles of mining rock debris. What you see is only the top of the piles, the entire hillside is clad in rocks hoisted from Kleva hill.

hand, thought they were fault planes that cut off and dislocated parts of the massive Ni-ore. Furthermore, Von Post (1887) argued that the ore bodies had no preferred orientation, while Brøgger and Vogt (1887) argued that they formed WSW–ENE trending sub-parallel bodies. Brøgger and Vogt (1887) considered the massive Ni-ores and host rocks as contemporaneous, but that later events had rearranged the ore bodies.

The vast amount of rock debris, mining waste piles and the hollow Kleva hill bear witnesses of the large amount of ore that was hoisted from the Kleva hill (Fig. 4). The information on the amounts of mined ore, the grade and its main composition is fragmentary. It has been estimated that the Ni-ore contained 2–2.5 % Ni and 0.5 % Cu (Santesson 1887). Roughly, 55000 tonnes of Ni-ore generated approximately 1000 tonnes Ni. For copper there are no solid figures but the production was in the order of a few tens of tonnes of Cu.

## 1.2 Magmatic Ni-Cu deposits

The highly variable ore deposits known around the world are primarily divided and characterised based on their geologic association. *Syngenetic* deposits are formed simultaneous with the rock in which they are situated whereas *epigenetic* deposits are structurally younger than their host rocks. Magmatic, sedimentary and volcanic deposits are generally syngenetic whereas metamorphic remobilised deposits and hydrothermal deposits (precipitated from hydrothermal fluids either altering the host rock, or deposited as veins) are epigenetic. Further divisions are based on, e.g., main metals and ore genesis.

The ore mineral assemblage in Kleva, namely: *pyrrhotite* ( $\text{Fe}_{1-x}\text{S}$  ( $x = 0$  to  $0.17$ )), *pentlandite* ( $(\text{Fe,Ni})_9\text{S}_8$ ), *chalcopyrite* ( $\text{CuFeS}_2$ ) and *pyrite* ( $\text{FeS}_2$ ), is characteristic for a magmatic origin (Naldrett 1989). The main groups of magmatic ore deposits associated with mafic–ultramafic rocks are Ni-Cu deposits, platinum group element (PGE) deposits, and Cr deposits. They originate from mantle melts. The geologic environments and processes from mantle melting, through magma ascent, to crystallisation in the crust all play a role in the ore potential of a mafic magma. Four processes are considered to be of particular importance for the formation of an ore deposit; I) formation of a metal-rich primary magma through partial melting of the mantle, II) magma interaction with wall rocks during ascent through the crust causing sulphide melt saturation and segregation, III) metal tenor enrichment of the sulphides through interaction with a large volume of magma and IV) accumulation of metal rich sulphides (e.g. Naldrett 1989; Arndt et al. 2005).

### 1.2.1 Mantle melting

The mantle makes up the zone between Earth's outer core and its crust (Fig. 5). It is further divided into zones; the lower mantle (700–2890 km depth from Earth's surface), a transition zone (410–700 km depth) and the upper mantle (<410 km depth). The crust and the rigid uppermost part of the upper mantle make up the lithosphere (0–280 km depth; depending on tectonic environment) whereas the lower part of the upper mantle make up the plastic asthenosphere. Most primitive melts originate from partial melting of the upper mantle, which is dominated by lherzolite (olivine-orthopyroxene-clinopyroxene peridotite) and hartzburgite (olivine-orthopyroxene peridotite), the latter being a restite after partial melting of lherzolite. Depending primarily on pressure, the Al-component in the lherzolite consists of plagioclase (<30 km), spinel (30–75 km) and garnet (>75 km).

The mantle composition and the depth, mode and degree of partial melting all play a role in the melt composition and thus the primary ore potential (Arndt et al. 2005). Ni is mostly controlled by olivine and pyroxene (but also sulphides), Cu, Ag and Au sit in sulphides whereas PGEs occur both with sulphides and as alloys associated with oxides and silicates (Barnes and Maier 1999). During partial melting, low-abundance phases such as the Al-phase and clinopyroxene are consumed first, whereas the portion of olivine and orthopyroxene increase in the melt fraction during increasing degrees of melting. Low degrees of melting thus generate Al-rich melts whereas high degrees generate Mg-rich melts.

The melt composition largely depends on the specific environment in which it was generated, and there are some general trends for source magmas for Ni-Cu deposits. High degrees of melting (even up to >50%) generates ultramafic komatiite. These are predominantly of Archaean age due to the higher heat fluxes in the early Earth. Komatiites are rich in Ni, Cr, Co and PGEs but are sulphur depleted. A type example is Kambalda, in Australia (e.g. Cowden 1988; Barnes 2006). At c. 30–50% of partial melting picrites are formed. These are Mg-rich ultramafic rocks that are common hosts for Ni deposits, such as at Pechenga, Kola Peninsula in Russia (Brügmann et al. 2000) and Kabanga, Tanzania (Maier et al. 2010). Basalts form at <30% of partial melting and are the most common primitive melts on Earth's surface. Ni-Cu deposits related to basaltic magmatism occur however, such as Noril'sk, Russia (e.g. Barnes and Lightfoot 2005).

### 1.2.2 Crustal assimilation

During the ascent through the mantle and the crust, magma might interact with surrounding wall rocks. The extent of magma-wall rock interaction depends on the dynamics and physical properties of the magma and the structure and physical properties of the crust. Extensive

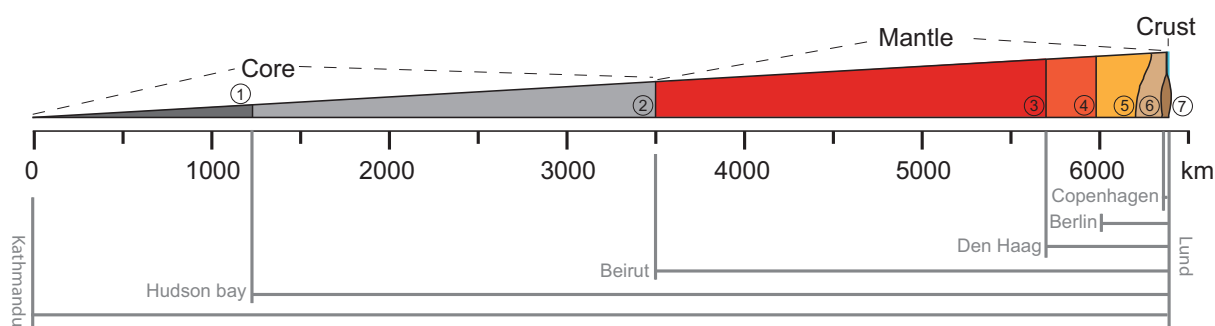


Fig 5 A slice of the Earth

Schematic section of the differentiated Earth showing the proportions of the different zones and the distances from Lund to well known geographical locations for depth-wise comparison (e.g. the depth-wise distance from the crust to the core–mantle boundary roughly equals the distance from Lund to Beirut. From the centre of Earth to its crust; inner solid core (1), outer liquid core (2), lower mantle (3), transition-zone (4), asthenospheric mantle (5), lithospheric mantle, (6), crust (7).

wall-rock assimilation might be driven by rapid magma ascent, long-term magma–wall rock contact in a magma chamber or thermal erosion of wall rocks by turbulent magma (Arndt et al. 2005). Crustal assimilation is likely to occur at several stages during magma ascent, and the addition of new material affects the chemical and physical properties of the magma. In the formation of magmatic ore deposits, it is an important or even crucial process for saturation of sulphur in the magma leading to the precipitation of immiscible sulphide liquid from the silicate melt.

Depending on the primary composition of the mantle and the depth of partial melting, the magma might be undersaturated or saturated in sulphur as it leaves the mantle. For sulphur saturated magma, rapid emplacement is crucial as the decreasing pressure during ascent counteracts the decreasing temperature, whereby the magma remains sulphur undersaturated until it reaches emplacement levels (e.g. Lesher and Groves 1986; Mavrogenes and O'Neill 1999). For sulphur undersaturated magma, assimilation of crustal rocks during ascent enables sulphide liquid saturation at emplacement levels. External causes for sulphur saturation of a magma can be addition of sulphur, e.g. from sedimentary rocks, or addition of silica and alkalis, which reduce the sulphur solubility in the magma (c.f. Keys and Lightfoot 2010; Ripley and Li 2013; Robertson et al. 2015).

### 1.2.3 Metal enrichment

A high concentration of sulphur in a magma is not sufficient for generating a deposit, but a high metal tenor in the sulphides is required for profitable mining. The desirable metals are attracted to the sulphide liquid with varying efficiency; PGEs have stronger affinity than Ni and Cu, but occur in lower concentrations in the magma. As sulphide liquid interacts with the silicate

magma, metals are attracted to the sulphide liquid; thus dynamic interaction with a large magma volume leads to more successful metal enrichment and high Ni, Cu and PGE tenors (R-factor; Campbell and Naldrett 1979). Also, if sulphide melt saturation is reached prior to the crystallisation of olivine, Ni and IPGEs (iridium-group PGEs i.e. Os, Ir, Ru; as opposed to PPGEs which are palladium-group PGEs i.e. Rh, Pt, Pd) contents are still high in the magma which is favourable for high Ni tenors in sulphides (Keays 1995).

The dynamics of magma and magma chamber geometry is variable among magmatic deposits. PGE-deposits, are often found in layered intrusions, which constitute relatively stable environments with fractional crystallisation and possibly late cumulate reconstitution as main processes of enrichment (e.g. the Merensky Reef, Bushveld, South Africa; Godel et al. 2007). Ni-Cu deposits are often found in conduits and sill or dyke like intrusions, with large amounts of magma passing through relatively narrow passages, producing a dynamic environment with efficient upgrading of metal tenors (e.g. the Kabanga deposit, Tanzania; Maier et al. 2010). Renewed upgrading of already segregated sulphides might also occur repeatedly, as new batches of magma pass through the conduit.

### 1.2.4 Sulphide accumulation

As the immiscible sulphide liquid is segregated from the silicate magma, the ore potential of the intrusion depends on the final distribution of the sulphides. Accumulated sulphides can be mined more efficiently than dispersed sulphides, and sulphide accumulation is largely a function of magma chamber dynamics. Segregated metal-rich immiscible sulphide liquid droplets might accumulate at the base of a magma chamber or in low velocity flow-dynamic traps as *massive mineralisation* (Fig. 6A) in conduit type deposits. This requires sulphur

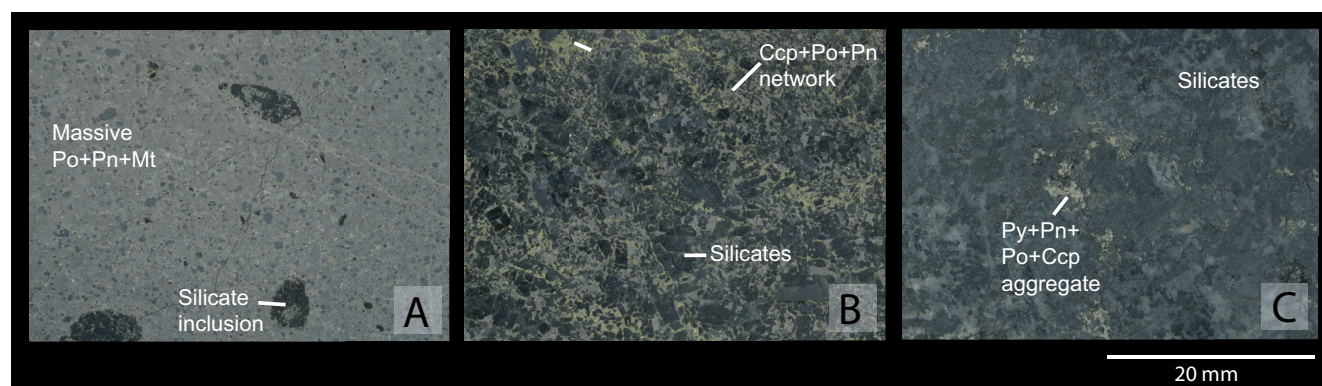


Fig 6 Accumulation textures

The sulphides are accumulated with varying efficiency, leading to different proportions of sulphides and silicates. A) Massive mineralisation of pyrrhotite with pentlandite, minor chalcopyrite, pyrite and rounded inclusions of magnetite-ilmenite (Kleva sample KLV2). There are dark, rounded, silicate inclusions that were trapped in the silicate liquid. B) Net textured mineralisation of chalcopyrite, pyrrhotite and pentlandite, with magnetite-ilmenite and angular silicate crystals in between sulphide grains (Kleva sample K1). C) Disseminated mineralisation with aggregates of pyrite, pentlandite, pyrrhotite, chalcopyrite and magnetite-ilmenite within a medium-grained silicate matrix (Kleva sample LG1).

saturation prior to, or early on during, the crystallisation of the silicate melt. Inclusions of silicate droplets, oxides and wall rock fragments are common, and with increased contents of silicate in the sulphides the mineralisations are termed *semi-massive* to *net-textured*. In *net textured mineralisation*, (Fig. 6B) the silicates form inclusions in a sulphide matrix. In a cooler magma, which has partially crystallised, sulphide aggregates occur dispersed in a silicate matrix. This is termed *disseminated sulphide mineralisation* (Fig. 6C). Sulphide depleted magmas, or magmas low in sulphur from the start, have low abundances of dispersed individual sulphide grains, which is termed *sparse mineralisation*, or the rocks are *barren*.

After separation of the base metal sulphide liquid from the silicate magma, and as temperature decreases sulphide phases crystallise. The first phase to crystallise is the Fe-rich *monosulphide solid solution* (mss), leaving a sulphide melt rich in Cu and PPGEs which subsequently

crystallise Cu-rich *intermediate solid solution* (e.g. Naldrett 1989; Li et al. 1996; Prichard et al. 2004). Generally, the mss exsolves pyrrhotite, pentlandite and accessory pyrite, whereas the iss exsolves chalcopyrite and other phases. Mss is enriched in Fe, Ni and IPGEs, whereas iss is enriched in Cu, Au, and PPGEs (Kelly and Vaughan 1983). The sulphide droplets might cool *in-situ* as globules within a silicate matrix (disseminated mineralisation), which hold both mss and iss, or the iss might be separated from the base metal sulphide liquid and remobilise into fractures of the wall rocks. During post-magmatic tectonic rearrangements of the host rocks, mineralisations might be disturbed either due to tectonics, cooling effects or metamorphic disturbances (e.g. Marshall and Gilligan 1993). Different degrees of remobilisations have been observed, from local recrystallisation to remobilisation of sulphides tens or even hundreds of meters from the original location of the mineralisation (e.g. Barnes 1987; Duuring et al. 2010; Collins et al. 2012).

## 2 Geologic context

Palaeoproterozoic (1.9–1.5 Ga) intrusive rocks dominate the bedrock of southeast Sweden, which have been affected by several post-intrusive tectono-metamorphic events (e.g. Bogdanova 2001; Bingen et al. 2005). The Kleva deposit is situated within a gabbro–diorite intrusive complex that borders rocks of two different Palaeoproterozoic suites; rocks of the Transscandinavian Igneous Belt (TIB) and rocks of the Oskarshamn Jönköping Belt (OJB) (Fig 7).

### 2.1 Crustal evolution of southeastern Fennoscandia

#### 2.1.1 Palaeoproterozoic (2500–1600 Ma) evolution

During the Palaeoproterozoic, new crust was accreted to the Archaean cratons in northeastern proto-Fennoscandia (the bedrock of today's Norway, Sweden, Finland and northwestern Russia). These rocks, termed Svecofennian, mark a long-lived orogeny accompanied by crustal reworking and deformation, and include sedimentary, volcanic and intrusive rocks that range in age from c. 1.92–1.79 Ga and extend to south central Sweden, (Korja and Heikkinen 2005; Lahtinen et al. 2005). Svecofennian rocks are rare in southeast Sweden, with the exception of the southeast trending Oskarshamn–Jönköping belt (OJB; Fig. 7), which is a remnant of a late Svecofennian 1.83–1.82 Ga island arc or continental margin (Åhäll et al. 2002; Mansfeld et al. 2005). The OJB consists of sedimentary and calc-alkaline igneous rocks that are variably deformed and metamorphosed (Röshoff 1975; Persson 1989). The supracrustal rocks of the Vetlanda area (Röshoff 1975) consist of interlayered sedimentary and volcanic rocks, of which the volcanic rocks dominate.

Substantial Andean-type subduction magmatism (i.e. subduction of oceanic lithosphere under continental crust) marks the 1.85–1.67 Ga interval along the western and southern margins of the Svecofennian proto-continent in Sweden (e.g.; Nyström 1982; Wilson et al. 1986; Söderlund and Rodhe 1998; Gorbatshev 2004; Appelquist et al. 2009). This is reflected in the voluminous Transscandinavian Igneous Belt (TIB), which comprises predominantly alkali-rich, feldspar porphyritic granites and felsic volcanic rocks and stretches

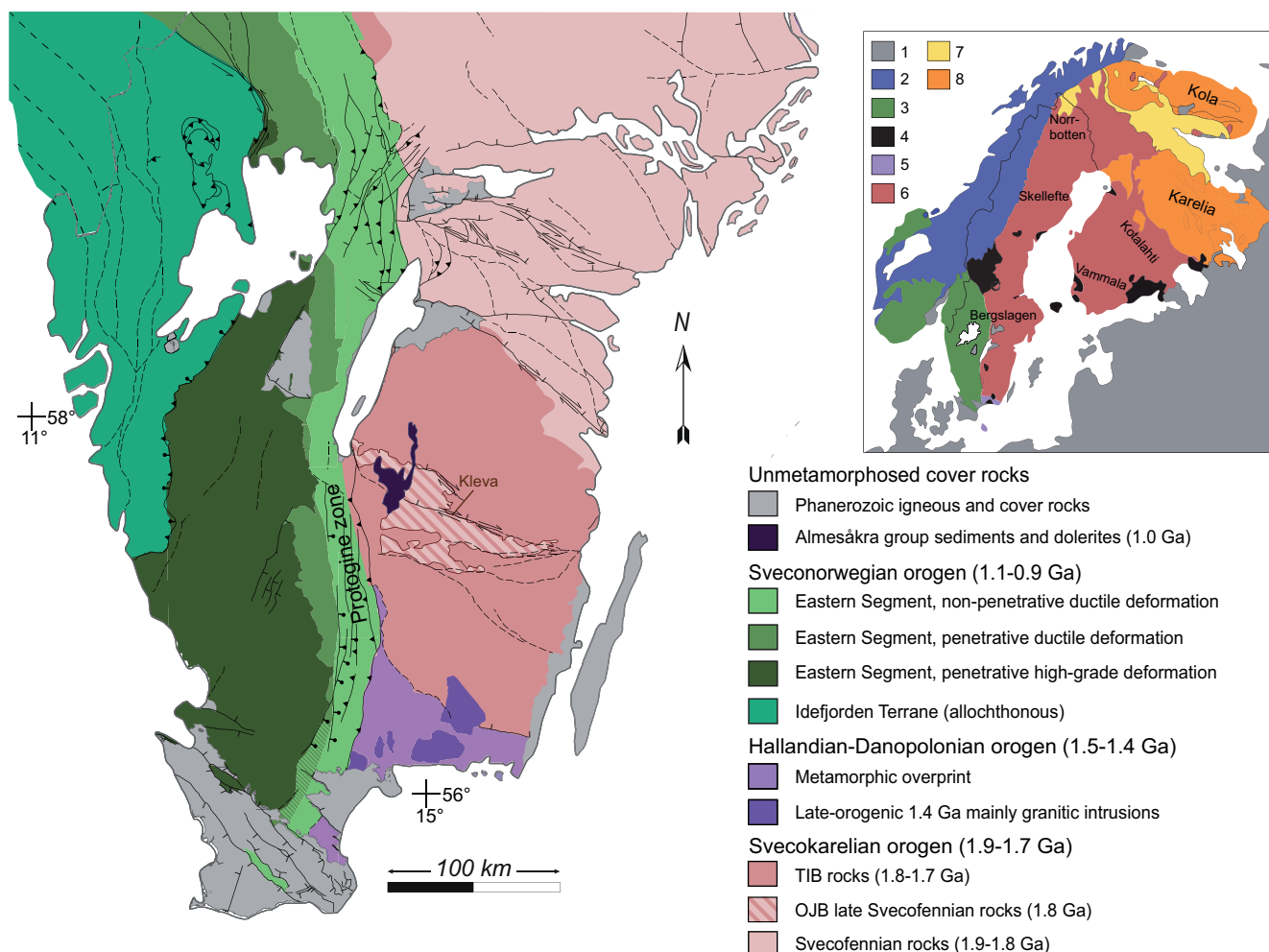
from northern Norway to southeast Sweden (e.g. Gorbatshev 2004). The TIB-related magmatism might have been episodic, concentrating around 1.86–1.84 Ga (TIB 0; e.g. Ahl et al. 2001), at 1.81–1.76 Ga (TIB 1; Larson and Berglund 1992; Gorbatshev 2004) and at 1.71–1.65 Ga (TIB 2; sometimes subdivided into TIB 2 and TIB 3; c.f. Larson and Berglund 1992; Gorbatshev 2004). In southeast Sweden the TIB rocks have been dated to c. 1.81–1.77 Ga, and c. 1.71–1.65 Ga (i.e. TIB-1 and TIB-2), respectively) and mafic intrusions that are considered to be coeval with the felsic magmatism are common (Mansfeld 2004; Andersson et al. 2007). These have arc-like geochemical signatures ranging from shoshonites in the north to tholeiites in the south, possibly indicating oceanward movement of the subduction zone, and were derived from a depleted mantle metasomatically enriched in LILE (large ion lithophile elements) and LREE (light rare earth elements) (Andersson et al. 2007). The TIB rocks occur in close spatial association with the OJB, and their relationship has been discussed (Åhäll et al. 2002; Appelqvist et al. 2009).

#### 2.1.2 Meso- to Neoproterozoic (1600–541 Ma) evolution

Subduction and a subsequent orogeny south of the Fennoscandian continent caused deformation and renewed magmatism at c. 1.47–1.40 Ga (Hallandian–Danopolonian event; Bogdanova 2001; Brander and Söderlund 2009). The Hallandian–Danopolonian event (Fig. 7) was associated with high T/P-metamorphism in accordance with an accretionary orogenic setting (Ulmius et al. 2013). The extent of metamorphic overprint in southeast Sweden remains poorly constrained but is often associated with contact metamorphism, such as local recrystallisation and deformation of granites south of Jönköping (Brander et al. 2012) and fractures in the Oskarshamn area (Drake et al. 2012). Extension related mafic magmatism is traced further north in e.g. Småland (data and compilation by Brander and Söderlund 2009).

The Protogine zone (Fig. 7) is a 15–20 km north–south trending deformation zone, approximately 65 km west of Kleva, within which the oldest dated mafic magmatism occurred between 1.58 and 1.56 Ga (e.g. Söderlund and Ask 2006). Renewed magmatic activity occurred at 1.22–1.20 Ga and it has been suggested that it relates to extension prior to the Grenvillian orogeny (Söderlund and Ask 2006).

The Protogine zone also marks the eastern boundary for penetrative deformation of the Sveconorwegian orogen (1.1–0.9 Ga; Bertelsen 1980; Wahlgren et al. 1994; Bingen et al. 2005). The Sveconorwegian orogeny is characterised by high-grade metamorphism in the western part of the Eastern Segment while the easternmost part of the Eastern Segment records little



**Fig 7 Schematic map of the country rocks of southern Sweden**

Map of the major geological units in southern Sweden, edited after Petersson et al. (2013) and Mansfeld et al. (2005). The schematic inset map shows the main geologic domains of Fennoscandia with base metal mineralised areas written out. Key (inset): 1, Neoproterozoic and Phanerozoic sedimentary and intrusive rocks; 2, Caledonides (0.5–0.4 Ga); 3, Sveconorwegian orogen (1.1–0.9 Ga); 4, post-Svecokarelian igneous and sedimentary rocks (1.7–1.0 Ga); 5, Palaeo- and Mesoproterozoic rocks severely reworked by 1.5–1.4 Ga Hallandian (Dano-Polonian) orogenesis; 6, Svecokarelian Province (1.9–1.8 Ga); 7, reworked Archaean continental nucleus inside the Svecokarelian orogen; 8, pre-Svecokarelian Palaeoproterozoic and Archaean rocks little affected by Svecokarelian orogenesis

evidence for Sveconorwegian recrystallisation (Fig. 7; Möller et al. 2007; Söderlund et al. 2004; Brander et al. 2012). Exhumation of the Eastern Segment is manifested in the Protogine zone by ductile and brittle deformation between 0.96 and 0.93 Ga (Andréasson and Dallmayer 1997). Around this time, the north-southtrending 0.98–0.95 Ga Blekinge-Dalarna dolerites intruded east of the Protogine zone, c. 30 km west of Kleva (e.g. Söderlund et al. 2005a). Low temperature fracture fillings have been dated to c. 0.99 Ga c. 70 km east of Kleva (Drake et al. 2009).

### 2.1.3 The Phanerozoic (541 Ma–recent)

The erosional surface of southeast Sweden is constrained by remnants of the sub-Cambrian peneplain (Lidmar-Bergström 1993; 1996). Sedimentary cover rocks that were deposited during the Phanerozoic are preserved

along the Baltic Sea coastline, on the islands of Gotland and Öland, on Visingsö in Lake Vättern, in the Vadstena area northeast of Lake Vättern, and in the county of Skåne of southernmost Sweden (Fig. 7). Low temperature fracture fillings, 70 km southeast of Kleva, dated to c. 400 Ma, are coeval with the collision of Baltica and Laurentia (Drake et al. 2009 and references therein), forming the Scandinavian Caledonides in northern Sweden. Subsidence from sedimentary cover in southeast Sweden heated the bedrock to >100°C during the Phanerozoic (at 189 Ma, 25 km southwest of Kleva; Cederbom 2001; c. 250 Ma, 70 km southeast of Kleva; Söderlund et al. 2005b).

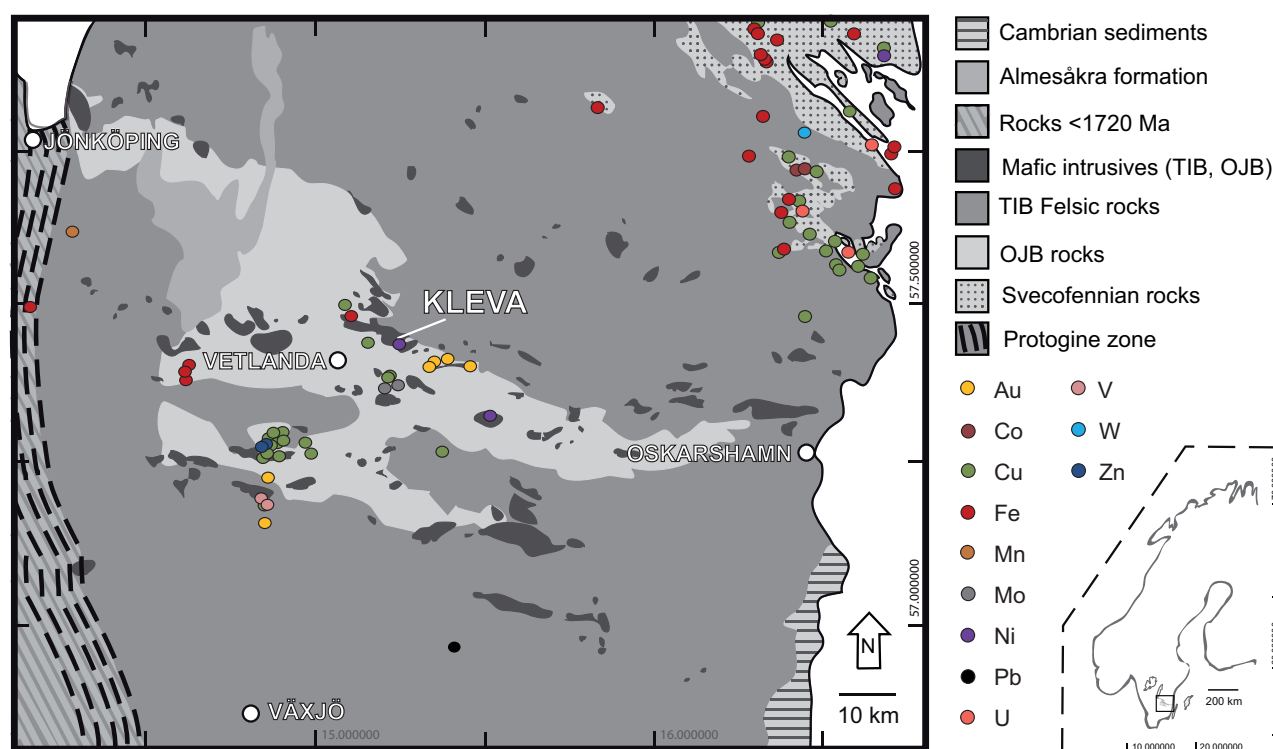


Fig 8 Schematic map of the mineral deposits of the Småland area

Sketch of the main geologic units in the Småland area, compiled from Högdahl et al. 2004, Mansfeld et al. 2005 and, Andersson et al. 2007. The location of the map is shown in the small line-drawn map of Scandinavia in the lower right corner. The coordinates are according to the WGS84 decimal system. The mineral deposits are marked out according to coordinates of Shaikh et al. (1989), Bruun et al. (1991) and Kornfelt et al. (1990) and are categorised based on their main metal asset, although most have findings of other metals as well. Small discrepancies between actual and marked out location are likely due to transfer from coordinate system to another.

## 2.2 The ore deposits of southeast Sweden

The Ni-Cu ores and mineralisations of the Fennoscandian Shield are abundant and are found in various rock associations. The Archaean provinces of northern Finland, Sweden and Russia; the Kola Peninsula, Karelia, and the Norrbotten craton (Fig. 7) host numerous significant magmatic Ni-Cu and PGE deposits and other minor base-metal deposits (Weihed et al. 2005). The Palaeoproterozoic ore districts; the Skellefte field, the Norrbotten region and the Bergslagen region of Sweden and the Kotlahti and Vammala belts of Finland host numerous base metal deposits of various genesis (Weihed et al. 2005). Ni-Cu deposits are especially abundant and substantial in Finland (e.g. Papunen and Gorbunov 1985), whereas around 30 minor Ni-Cu deposits are known in Sweden (Nilsson 1985) and around 10 in Norway (Boyd

and Nixon 1985). Only a few minor Phanerozoic Ni-Cu deposits are known within the Norwegian Caledonides (Boyd and Nixon 1985).

In the Småland area, base metal deposits are predominantly found in the Svecofennian rocks of southernmost Bergslagen and in the late Svecofennian OJB-rocks, whereas deposits in the TIB-rocks are rare (Fig. 8). Deposits within OJB have variable associations from synvolcanic Cu-Zn-Pb sulphide mineralisation (Fredriksberg; Sunblad, et al. 1997) and magmatic Ni-Cu mineralisations (Virserum and Kleva; Persson 1989; Shaikh et al. 1989) to epigenetic Cu-W-Mo skarn (Sunnerskog; Persson 1989) and gold-bearing quartz veins (Ädelfors; Gaál and Sundblad 1990). The most important deposits within TIB are the Solstad Cu-Ag-Au mineralisation (Ahl 1989), the Ramnebo Cu mineralisation (Söderhielm and Sundblad 1996) and the Ålatorp Pb-Zn mineralisations (Sundblad 1997).

## 3 Materials and methods

### 3.1 Sampling

At the time of mining of the Kleva Ni-Cu sulphide deposit the methods of exploration and documentation were different from those that are used today. Core drillings and descriptions of ore textures, structures and grades are therefore lacking. Previous authors have described and discussed the ores and their formation according to the geologic understanding at the time (von Post 1886; Brøgger and Vogt 1887; Santesson 1887; von Post 1887; Tegengren 1924; Grip 1961; Nilsson 1985; Zakrzewski 1988), and described the complexity and variety of the Kleva rocks (Brøgger and Vogt 1887; Santesson 1887; Nilsson 1989).

The rocks and sulphide mineralisation in the Kleva intrusive complex have a wide compositional range and structures are hard to delineate. Given this and the aims of this project, the focus of sampling was to cover the lithological variation seen in the field, although the actual compositional and textural range in the complex is unknown.

There have been three periods of field-work and sampling of rocks in the Kleva area; March 2013 as an orientation of the Kleva area, June–July 2012 for detailed mapping and sampling foremost around and within the mine, and July 2013 for completion of mapping and sampling. Samples were collected for petrographic and geochemical characterisation of the intrusive complex and geochronological work. Care was taken to sample rocks with minimal alteration to avoid metamorphic overprint of the magmatic age and primary composition.

The Kleva intrusive complex stretches from Fageräng, north of Vetlanda, to Horsabäck, northeast of Alseda (Persson 1989). Sampling has focused on the area close to the mine, called Holsbyåkra; predominantly the Kleva hill and the hills north, east and south of the Kleva hill. Field observation localities are referred to as e.g. (K001). Geologic samples are referred to as e.g. (sample K001).

The Kleva collection of the department of Geology, Lund University, has been an important sample source as within-mine sampling is limited. The collection includes mineralised rock samples with well-preserved net texture and massive pyrite and chalcopyrite dominated samples whereas massive Ni-ore samples are weathered and

unrecognisable. These samples were collected by several geologists in the past and cover a wide time span; the oldest are likely a century old and specific location and context are unknown. Additional to the historic samples are in situ disseminated and vein-textured sulphides samples collected within the mine during field work, and massive Ni sample collected from an underground mine dump.

### 3.2 Geochemical concepts

Geochemical and geochronological data together with petrographic studies enable interpretations of the origin of magmatic rocks, as well as primary and secondary processes affecting their composition. The contents, and relative abundance, of a certain element in a rock can be traced back to the physical behaviour of the element and its hosting crystal in specific environments; e.g. the compatibility of the element in crystals, the fractionation of the crystals in the melt and its ability to withstand metamorphic alterations. Of particular interest are trace elements, which normally occur at ppm–‰ concentrations, as these can sometimes pinpoint the geologic environment the rock was derived from.

Incompatible elements such as rare earth elements (REEs; elements La–Lu and  $\text{Eu}^{3+}$ ), high field strength elements (HFSEs; Ti, Hf, Zr,  $\text{Pb}^{4+}$ , Ce,  $\text{U}^{4+}$ , Th, Ta, Nb, and  $\text{U}^{6+}$ ) and large ion lithophile elements (LILEs; Cs, Rb, K, Ba, Sr  $\text{Pb}^{2+}$  and  $\text{Eu}^{2+}$ ) have difficulties in fitting into crystal structures due to high charge or ionic radius and therefore have an affinity for the melt during partial melting and magma crystallisation. At small degrees of partial melting these elements become enriched in the melt compared to the source rock, whereas at larger degrees of partial melting their concentrations are diluted. Conversely, elements with an affinity for the source rock (compatible elements) are weakly to moderately enriched in melts at higher degrees of partial melting. During crystallisation, compatible elements are incorporated into the first forming minerals and removed from the melt, while the incompatible elements become increasingly enriched in the residual melt. In short, this means that the crust is enriched in incompatible elements compared to the mantle.

During crystal fractionation, highly incompatible element ratios (e.g. La/Lu, Nb/Hf) tend to be constant since their concentration increase in the residual melt is similar. Ideally, the ratios reflect the magma source and thus also the mantle it was derived from. Incorporation of exotic material to the magma, such as crustal fragments or magma mixing might corrupt the original incompatible element ratios. Careful testing of such contamination effects must thus be done prior to interpretation of source characteristics. Likewise, it is important to constrain

post-magmatic geological events as this might mobilise some elements, which leads to disturbed primary signals. More specifically, HFSEs and REEs are particularly useful as they are less mobile than e.g. LILEs and thus less susceptible to metamorphic disturbances. Normalisation of the trace element concentrations to either chondritic or primitive mantle values (e.g. Sun and McDonough 1989; Palme and O'Neill 2003) provides a simple way to compare trace element patterns which have implications for tectonic origin.

On the other side of the spectrum, the highly compatible elements such as the platinum group elements (PGEs; Os, Ir, Rh, Rd, Pd and Pt) are enriched in early crystallising chromite and olivine, but most importantly, in sulphides. PGEs in conjunction with other chalcophile and siderophile elements, such as Ni, Cu and Au, are used as tracers for ore characterisation. By comparing the ratios of these elements, normalised to primitive mantle (Palme and O'Neill 2003; Barnes and Lightfoot 2005), ore potential and fractionation within the deposit is identified.

Stable isotopes (e.g. sulphur and oxygen) are suitable as genetic tracers as they do not fractionate significantly in normal magmatic environments. However, at temperature conditions equivalent to the surface of the Earth, sulphur isotope fractionation occurs. On this basis, it is possible to trace the origin of sulphur in a magmatic system, which is important for constraining e.g. effects of crust assimilation to the saturation of sulphur in the melt (see section 1.2.2). The measured  $^{34}\text{S}/^{32}\text{S}$  is normalised to a chondritic S standard where the deviation in parts per mil is expressed as  $\delta^{34}\text{S}_{\text{V-CDT}}$ . Standardisation is made with the silver sulphide IAES-S-1 standard (Coplen and Krouse 1998) which is  $\delta^{34}\text{S}$  -0.3 ‰ compared to the Vienna Canyon Diablo Troilite VCDT  $^{34}\text{S}/^{32}\text{S} = 4.50045 \times 10^{-3}$ ,  $\delta^{34}\text{S}_{\text{V-CDT}}$  0.0 ‰ per definition.

The decay of radiogenic isotopes in a closed system (e.g. a mineral) makes up the basis for geochronology. The U-Pb system is widely used for dating magmatic events through crystallisation of zircon or baddeleyite. It relies on the two decay chains:  $^{238}\text{U}$ – $^{206}\text{Pb}$  with a half-life of 4.47 Ga and  $^{235}\text{U}$ – $^{207}\text{Pb}$  with a half-life of 704 Ma. The decay of  $^{187}\text{Re}$ – $^{187}\text{Os}$  (half-life 41.2 Ga) is used for direct age determination of sulphides, through the crystallisation of e.g. pyrite.

Radiogenic isotope systems are also useful for tracing long-term effects of mantle and crust evolution. For example, the Re-Os and the  $^{176}\text{Lu}$ – $^{176}\text{Hf}$  (with a half-life of 37.8 Ga) systems will have initial isotope ratios that reflect the long-term evolution of the source rocks. To this end, zircon is particularly useful for Lu-Hf studies as it can be precisely dated using the U-Pb system. Also, as Hf is strongly enriched compared to Lu in zircon, the Hf isotope composition of zircon will directly reflect the source melt it crystallised from. For simplicity, Hf and Os isotope signatures are expressed as  $\epsilon\text{Hf}_t$  and  $\gamma\text{Os}_t$ , which is

the deviation from CHUR (chondritic uniform reservoir; the assumed bulk Earth composition at time  $t$ ) in part per ten thousands and percent respectively.

### 3.3 Methods

Rock materials have been chemically analysed for composition and dating purposes. In order to achieve the right level of data and precision, the choice of method needs to be considered. Such consideration must account for precision required, sample homogeneity, element of interest and elemental concentrations. Limiting factors are also sample volume and quality, as well as time and analytical costs.

Petrographical transmitted- and reflected light microscopy was used for silicate and sulphide samples, respectively. Scanning electron microscopy (SEM) was used for textural observations coupled with mineral chemical composition analyses through energy dispersive x-ray analysis (EDS). The EDS method is quick, virtually non-destructive and suitable for analysis of elements that occur at wt%-concentration level.

Element-specific methods are required for measuring minor elements in minerals. Electron microprobe analysis (EMPA) has been used for measuring concentrations of major and minor elements in minerals such as plagioclase, pyroxene and sulphides in thin sections and polished rock section. The method is similar to SEM, but the wavelength dispersive detectors (WDS) give lower detection limits (c.f Paper III).

Analyses of mineral isotope composition and trace element composition utilise different systems of mass spectrometry that are based on different mode of ionisation. For zircon and baddeleyite U-Pb dating, secondary ion mass spectrometry (SIMS) and thermal ionisation mass spectrometry (TIMS) were used (Paper I). Zircon U-Pb and Lu-Hf isotope analyses were done with laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS; Paper II). SIMS and LA-MC-ICP-MS were also used for sulphide S-isotope analyses (Paper IV). Sulphide Re-Os was analysed with negative ion thermal ionisation mass spectrometry (N-TIMS; Paper III). A summary of the analytical techniques are presented below and in table 1.

The plasma in ICP-MS is generated by adding electrons to an Ar gas flow, thus ionising the Ar to  $\text{Ar}^+$  and  $\text{e}^-$ . The introduced sample is separated into individual atoms in a high temperature plasma and the ions are accelerated through the mass spectrometer. The ICP method is particularly efficient at ionising elements with high first ionisation potential, specifically Hf, PGEs and many HFSE. The sample is normally introduced through a nebuliser that vaporises dissolved liquid samples (e.g. PGE-analyses; Paper III), or through laser ablation

**Table 1 ICP-methods**

Examples of ICP-methods, analyses and labs used during the project.

Analysis	Sample	Target element/ isotope	Lab
<i>ICP-MS</i>			
Lu-Hf isotopes	Polished zircon	<sup>172</sup> Yb, <sup>173</sup> Yb, <sup>175</sup> Lu, <sup>176</sup> Hf, <sup>177</sup> Hf, <sup>178</sup> Hf, <sup>179</sup> Hf, <sup>180</sup> Hf, <sup>181</sup> Ta	Goethe Universität, Frankfurt am Main
PGE WR	Dissolved rock	Ru, Rh, Pd, Os, Ir, Pt, Au	LabMaTer, University of Quebec
S-isotopes	Polished sulphide	<sup>32</sup> S, <sup>34</sup> S	Finland Isotope Geosciences Laboratory, Espoo
U-Pb dating	Polished zircon	<sup>204</sup> Pb, <sup>206</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb, <sup>232</sup> Th, <sup>235</sup> U, <sup>238</sup> U	Goethe Universität, Frankfurt am Main
<i>SIMS</i>			
S-isotopes	Polished sulphide.	<sup>32</sup> S, <sup>34</sup> S	NordSIM, Stockholm
U-Pb dating	Polished zircon	<sup>90</sup> Zr, <sup>92</sup> Zr, <sup>94</sup> Zr, <sup>204</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb, <sup>177</sup> Hf, <sup>232</sup> Th, <sup>235</sup> U, <sup>238</sup> U	NordSIM, Stockholm
<i>TIMS</i>			
Os-isotopes	Os concentrate	<sup>184</sup> Os, <sup>186</sup> Os, <sup>187</sup> Os, <sup>188</sup> Os, <sup>189</sup> Os, <sup>190</sup> Os, <sup>192</sup> Os, <sup>185</sup> Re	Canadian Centre of Isotopic Microanalysis, University of Alberta
Re-isotopes	Re concentrate	<sup>185</sup> Re, <sup>187</sup> Re	Canadian Centre of Isotopic Microanalysis, University of Alberta
U-Pb dating	U-Pb concentrate	<sup>204</sup> Pb, <sup>205</sup> Pb, <sup>206</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb	Swedish Museum of Natural History, Stockholm

(LA), where a laser beam is focused onto a mineral sample surface. Mass separation is either done with quadrupole or a magnetic sector field mass analyser. Ion beam detection varies between optical spectroscopy, ion counters and faraday cups, either in single or in multi-detector configurations. High precision analyses are done in multi-detector set-ups, while trace element abundance as more commonly determined in ion counters.

LA-ICP-MS has been used for isotopic analyses of U-Pb and Lu-Hf in zircon and  $\delta^{34}\text{S}$  in sulphides where zircon and sulphide samples were mounted in epoxy and polished. LA ablates a cylindrical pit that is typically 20–50  $\mu\text{m}$  in diameter and 5–20  $\mu\text{m}$  deep, depending on beam size, beam energy and ablation time. Although these data are time-resolved where the time is corresponding to drill depth, the precision of the method relies on isotopically homogeneous sample volumes.

In SIMS, an ion beam ( $\text{O}^-$  or  $\text{Ce}^+$  for U-Pb dating in zircon and  $\delta^{34}\text{S}$  in sulphides, respectively) is focused on a polished mineral surface, ionising the sample, whereby the emitted secondary ions are accelerated through the mass spectrometer. The ionized sample size is small, c. 10  $\mu\text{m}$  diameter with a negligible drill depth, thus allowing small mineral sizes and good possibilities of high spatial resolution. Like all similar methods, the precision relies on the chemical homogeneity of standards and instrumental control.

In TIMS the purified sample is dried onto an outgassed metal filament (Rh for U and Pb analyses, Pt for Os analyses, and Ni for Re analyses), which is heated in vacuum whereby the sample is ionised. A magnetic sector field is used to separate ions or compounds of different masses, which are detected either with faraday cups or ion counter.

## 4 Summary of papers

### 4.1 Paper I

Geochronology and geochemical evidence for a magmatic arc setting for the Ni-Cu mineralised 1.79 Ga Kleva gabbro–diorite intrusive complex, southeast Sweden, by K. Bjärnberg, A. Scherstén, U. Söderlund and W.D. Maier, 2015. GFF 137:83–101, DOI: 10.1080/11035897.2015.1015265.

This paper reports U-Pb zircon and baddeleyite age determinations of the Kleva gabbro–diorite intrusive complex, together with its petrographic and geochemical characteristics. The aim of the study is to set the intrusive complex into its regional geologic context. Mafic intrusions are common in the area, but have so far not been dated but are instead assumed to be coeval with the c. 1.81–1.77 Ga magmatism of the Transscandinavian Igneous Belt (TIB). SIMS dating of zircon from Kleva diorite and a granite dyke that cuts the mafic rocks within the intrusion yield  $^{207}\text{Pb}$ – $^{206}\text{Pb}$  dates of  $1788 \pm 5$  Ma and  $1792 \pm 3$  Ma, respectively. TIMS dating of baddeleyite from a Kleva gabbro yield a  $^{207}\text{Pb}$ – $^{206}\text{Pb}$  date of  $1788 \pm 4$  Ma. The three independent dates overlap and a 1790 Ma date is the best estimate of the crystallisation of the Kleva intrusive complex. It is thus contemporaneous with the voluminous TIB magmatism of the area.

Although the primary plagioclase–pyroxene dominated mineralogy is altered through seritisation and uralitisation, primary textures are generally preserved, deformation is discrete and the degree of metamorphic recrystallisation is local. Rare earth elements (REE) and HFSE ratios point to a slightly evolved basaltic magma that was derived from a mantle in a subduction-related tectonic setting. This is in line with the regional geologic interpretation of the TIB-rocks.

The abundant fine-grained rock inclusions in the Kleva intrusive complex, autoliths as well as xenoliths, range in composition from rhyolite to norite. The different rock varieties, internal field relationships and geochemical variation are in line with differentiation from a relatively homogenous source, but with crystallisation from several different magma batches. The varitextured gabbro–diorite and the abundant rock inclusions testify to a dynamic magmatic environment, common for Ni-Cu sulphide deposits. The origin of the xenoliths is unknown, but we

speculate that they were derived from the neighbouring, supracrustal dominated, Oskarshamn–Jönköping belt: a late Svecofennian potential relict volcanic arc. Despite abundant felsic and mafic supracrustal inclusions, there is no strong geochemical imprint of crustal assimilation.

### 4.2 Paper II

Tracing Proterozoic mantle wedge composition through coupled zircon U-Pb and Lu-Hf isotopes (manuscript), by A. Petersson, K. Bjärnberg, A. Gerdes, A. Scherstén

Subduction zones is an important crust-generating environment, but also a site of crustal recycling to the mantle. As part of this process, large amounts of mafic melts are derived from the mantle wedge in between the subducting and overriding plates. This magmatism adds new material to the crust, which subsequently becomes source material for the successively felsic rocks formed from partial melting of the intruded rocks. The process is counterbalanced by recycling of crustal material to the mantle in the subduction zone. However, some elements are mobilised into the mantle wedge through dehydration of the hydrous subducting slab, which re-fertilises the mantle wedge, leaving it comparably enriched in incompatible elements. The amount of recycling depends on whether the arc system is retreating or advancing, which affects the degree of mantle depletion. We argue that coupled U-Pb–Lu–Hf isotope systematics of zircon from primitive syn-orogenic intrusions provides constraints on the temporal shifts in mantle depletion in a convergent orogeny.

The results, from intrusive rocks from Kleva and Rymmen, show that the mantle beneath Fennoscandia during the Palaeoproterozoic was enriched compared to the normal depleted mantle model in similar geologic settings. The data also lend some support for the assumption that mantle depletion should be non-linear as a function of compressional and extensional periods of the subduction zone. The main implication of the results is improved constraints for the Lu–Hf isotopic system on model ages, crustal residence times and the fraction of juvenile versus reworked continental crust in crustal evolution models. From a Kleva perspective, it is plausible to have a comparatively enriched primitive magma generated from the mantle wedge in a compressional regime, being emplaced during a period of extension.

### 4.3 Paper III

Re-Os constraints on the origin and remobilisation of sulphide minerals in the Kleve Ni-Cu sulphide deposit, southern Sweden (manuscript), by K. Bjärnberg, A. Scherstén, R.A. Creaser and W.D. Maier.

Since the Palaeoproterozoic, the crust of southeastern Sweden has been repeatedly reworked and affected by far-field tectonic events, but the effect on the rocks in the Kleve area remains unconstrained. The structural setting of the deposit indicates that such processes might have affected the ore; the Ni-ore bodies were oriented parallel to the general deformation of the area, wide-stretching sulphur filled fractures and faults cut the ore bodies and faulting can also be traced on micro-scale.

Re-Os dating of sulphides enables testing whether the mineralisation is primary magmatic or to what extent metamorphic recrystallisation has occurred. Isochron initial Os-ratios also put constraints on the origin of the Os, and by inference other metals. Pyrite from three texturally distinct samples were analysed;  $^{187}\text{Re}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  for an undeformed magmatic pyrite-dominated sample plot along a  $1709 \pm 180$  Ma isochron,  $^{187}\text{Re}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  for coarse prismatic pyrite in a banded sulphide sample plot along a  $1612 \pm 65$  Ma, whereas three duplicate sample sets of a massive pyrite sample with fracture fillings of chalcopyrite define internal two-point isochrones with a weighted mean of  $1393 \pm 41$  Ma. The primary magmatic age of the deposit is thus within error of the silicate host rock age at c. 1.79 Ga. The Re-Os system has been reset at least twice, and the 1612 and 1393 Ma dates are in agreement with orogenic events further to the west.

The highly varying radiogenic Os component of the three samples indicates variable crustal contamination of the mantle-derived magma. The magmatic textured sample has  $\gamma\text{Os}_{t(1790)} = 60 \pm 44$  ( $\pm 2\text{SD}$ ), which suggest a crustal origin of the Os and associated metals. The coarse prismatic pyrite has initial  $^{187}\text{Os}/^{188}\text{Os} \sim 1$  which likely represent an external source of crustal contamination, in a regional scale open system at c.  $1612 \pm 65$  Ma. Primitive mantle-normalised depletion in PGEs vs. Ni and Cu and low IPGE/PPGE in the sampled mineralised samples indicate that these samples formed from relatively evolved magmas that equilibrated with sulphide liquid prior to final emplacement.

### 4.4 Paper IV

Tracing sulphide melt saturation in the magmatic Kleve Ni-Cu sulphide deposit, southeast Sweden – combining in-situ and bulk-rock  $^{34}\text{S}/^{32}\text{S}$  analyses (manuscript), by K. Bjärnberg, A. Scherstén, M. Whitehouse, Y. Lahaye and W.D. Maier.

Crustal contamination is believed to play an important role in the formation of a magmatic Ni-Cu deposit, in its metal tenor and its mining potential. Abundant xenoliths and radiogenic initial  $^{187}\text{Os}/^{188}\text{Os}$  of the Kleve intrusive complex demonstrate a strong crustal imprint on the Kleve rocks. Here we present results from sulphur isotopic analyses of sulphides, to constrain the source of sulphur in the Kleve magmatic system. In-situ SIMS and LA-ICP-MS analyses of individual sulphide grains were combined with bulk-rock analyses of Kleve rocks. These data are compared with regional deposits and rocks. The aim is two-fold, to constrain the source of sulphur and to determine sulphur isotope fractionation trends to discern different stages and types of mineralisation. However, due to analytical difficulties and the low contrast in sulphur isotopic composition of the sample set, results are inconclusive.  $\delta^{34}\text{S}_{\text{VCDT}}$  for the Kleve mineralised samples range between  $-3$  and  $+5$  ‰, which is in line with a mantle origin of the sulphur. The in-situ analyses yield distinct  $\delta^{34}\text{S}$  for the different sulphides, but the results of the two methods did not correlate. Samples of country rock have similar  $\delta^{34}\text{S}$  to the Kleve samples and the extent of crustal contamination can neither be proven nor rejected.

However, the S/Se in Kleve is generally higher than the mantle range, which might suggest a contribution of crustal sulphur. Alternatively, the high S/Se can be explained by early segregation of a sulphide phase, which would deplete Se in the residual melt. The alternative explanation is in line with previous PGE results from the Kleve mineralisations. Furthermore, the coherence in in-situ  $\delta^{34}\text{S}$  for individual sulphides point to a relatively homogeneous magmatic system during sulphide segregation and crystallisation.

## 5 The Kleva gabbro–diorite intrusive complex

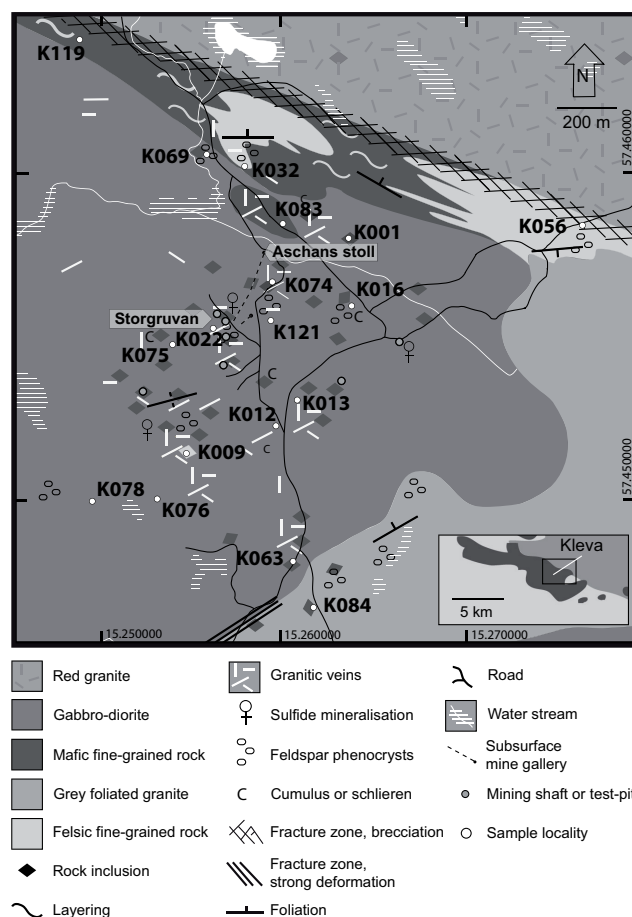
### 5.1 Structural context

The Kleva gabbro–diorite intrusive complex forms an elongate body that strikes towards the southeast and is aligned with the regional structural trend of the area. It is located in between TIB granites to the north and intrusive and volcanic rocks that presumably belong to the OJB to the south and west (Fig. 9). Though generalised in maps as one intrusive body (e.g. Persson 1989) it contains abundant rock inclusions, dykes and the intrusive rocks span in composition from quartz-diorite to norite (Björnberg et al. 2015). All contact relationships with the country rocks are covered by soil and vegetation.

An ESE trending fault structure runs along the contact zone between TIB and OJB rocks in the Småland area (Fig. 7) and it is assumed that it separates the Kleva intrusive complex from the TIB rocks to the north. The TIB granite is pink and medium grained with distinct grey–blue quartz grains towards the contact with the Kleva gabbro–diorite intrusive complex. TIB granite further to the east is red and medium grained. In general, granite in the area ranges from medium-coarse grained Växjö type to porphyritic Filipstad type (Persson 1989). Mafic inclusions occur along the northern contact to the Kleva intrusive complex (Persson et al. 1989).

The southeastern part of the intrusive complex is occasionally foliated and rocks to the south and east are variably deformed and commonly red-stained. To the south observed rocks are microcrystalline felsic rocks with feldspar phenocrysts and foliated or gneissic fine-grained to medium-grained felsic rocks. Deformed mafic lenses occur along the foliation of gneissic rocks, and foliated mafic inclusions or dykes occur within foliated granites. Felsic fine-grained rocks directly to the east are brecciated and contain abundant haematite. Further east granites of TIB type dominate, but there are no clear contacts with the felsic probably volcanic rock.

Felsic and mafic fine-grained rock inclusions are abundant in the southeast part of the intrusive complex (Fig. 9; 10). Contacts between gabbro and larger rock inclusions are rarely exposed. Observed contacts are mostly sharp and inclusions are commonly angular. Most of the mafic inclusions could be autoliths, but the felsic



**Fig 9 Map of the southeast part of the Kleva intrusive complex**  
Schematic map of the bedrock around Kleva Hill, based on observed field relations, Geological survey of Sweden bedrock, structural geologic and magnetometric maps of the area (scale 1:50 000; Persson 1989). Samples collected for geochemical analyses are marked out with sample numbers. The coordinates are according to the WGS84 decimal system according to the WGS84 decimal system.

and severely altered mafic inclusions are likely stopped from the metavolcanic country rock (Paper I). The inclusions are found in large quantities both on the south and the north side of the intrusive complex and it is likely that they are related to the neighbouring rocks of the present bedrock surface.

### 5.2 Internal structures

The intrusive complex is heterogeneously deformed (Fig. 11; Paper I; Paper III). There are only a few, highly uncertain, outcrop observations with primary magmatic layering, and there appears to be no distinct magmatic zonation of the different rock units, however rock contacts are rarely exposed within the complex. Rocks are mostly massive and foliation is variably pronounced. Shear zones have been observed in several localities and have a width of c. 50 cm. The shear zones are not linear and their strike and dip vary.

Fractures are common; both sealed and dry, and have varying strike. The most pronounced are the granite or pegmatite dykes, which reaches widths of 1 m but are mostly 10–20 cm wide. Quartz filled fractures are common and are mostly 1–5 cm wide and have short extensions; some are lens-shaped or sigmoidal. In mafic rocks, and especially in fine grained varieties, thin fractures are filled with chlorite, but one locality have lens-shaped fracture fillings of amphibole (K004). Other fracture related minerals are epidote and calcite.

Major fracture zones, ESE–southeast trending, cross the intrusive complex and zones of strongly crushed rock occur on both sides of the intrusive complex (Persson 1989). Minor fracture zones are predominantly aligned NNE. Bromley-Challenor and Andersson (1991) report that quartz filled fractures are predominantly northwest–southeast and southwest–northeast directed, whereas foliation of the rocks is normally striking east–west.

### 5.3 Petrography and rock textures

Petrography and rock textures are described in Paper I, but the main characteristics are outlined here. The mafic rock suite in the intrusive complex ranges from quartz-diorite through diorite to gabbro for medium grained rocks and ranges from rhyolite through andesite/diorite to anorthosite, gabbro and norite for fine- to medium grained inclusions. For the mafic and intermediate rocks, regardless of grain size, mineral components are similar but the proportions vary. Calcic plagioclase and Fe-rich amphiboles are the dominating minerals, whereas magnetite, ilmenite, quartz and biotite are common. F-apatite, zircon, chromite, K-feldspar, titanite,

allanite and baddeleyite are minor components. Relict clinopyroxene and orthopyroxene are observed in places, and the alteration minerals epidote, chlorite, calcite and sericite (in plagioclase) are observed in more altered samples. Pyrite, chalcopyrite, pyrrhotite and pentlandite are usually rare but occur in higher concentrations close to the mineralisation.

The gabbro is generally sub-ophitic, but some rocks show ophitic or granular textures, and in places contain feldspar phenocrysts. The diorite is granular and contains variable amounts of feldspar phenocrysts. For fine-grained mafic rocks, textures are sub-ophitic to granular with equidimensional plagioclase and clusters of amphiboles. Banded rocks with accumulations of amphibole and equidimensional grains of plagioclase occur (mafic as well as intermediate) and with pseudomorphs after orthopyroxene or other mafic minerals.

The felsic fine-grained rocks are mainly composed of feldspar and quartz and have 2–5 mm sized feldspar phenocrysts within a fine-grained matrix. They are light grey with a slight pinkish tint.

Samples are variably deformed and altered. Examples of deformation on mineral scale are mineral foliations and lineations (amphiboles), bent lamellae in plagioclase and ilmenite and crushed magnetite grains. The most common mineral alterations are uralitisation of clinopyroxene and orthopyroxene (alteration into amphiboles), sericitisation and saussuritisation of plagioclase (alteration into mica and epidote, respectively), alteration of ilmenite into patchy titanite and haematite, k-feldspar and prehnite inclusions in biotite and alteration rims on pyrite in sparsely mineralised samples. Fine-grained mafic rocks are commonly altered and green-coloured from large quantities of epidote and chlorite and with networks of coarser amphiboles and plagioclase.



Fig 10 Mafic rock inclusions

Rock inclusions of both mafic and felsic composition are common in the intrusive complex. They commonly have altered mineral composition but contacts with the gabbro or diorite are sharp. Outcrop K014, just north of K013, the pine needles are c. 5 cm long.



Fig 11 Gabbro outcrop with alterations

Alteration and deformation is often local, with less altered mafic rocks close by alteration zones. Outcrop K040, just southeast of K009. A rock pick (head length 20 cm) is used as a scale.

## 6 The ore genesis

### 6.1 Tectonic context

#### 6.1.1 Age constraints

All age determinations of Zr-bearing minerals from the Kleva intrusive complex correlate, and the date at c. 1.79 Ga is considered the crystallisation age of the silicate rocks (c.f. Fig. 12; Paper I; Paper II). There is a slight shift towards older ages for LA-ICP-MS analyses, but this difference is within error of the other analyses and it is impossible to resolve any temporal variances for mafic rocks within the intrusive complex. The rock inclusions are thus  $\geq 1.79$  Ga. The age determinations are consistent with the voluminous TIB magmatism (e.g. Åhäll and Larson 2000); granites belonging to this suite are found just north of the Kleva intrusive complex, but they are younger than the supracrustal rocks of the OJB to the south (Mansfeld et al. 2005).

#### 6.1.2 A subduction-related environment

The current tectonic model for the TIB magmatism in Fennoscandia is one of a long-lived Andean type continental arc (e.g.; Nyström 1982; Wilson et al. 1986; Söderlund and Rodhe 1998; Gorbatshev 2004; Appelquist et al. 2009). Geochemical data for the Kleva intrusive complex suggest an origin from evolved mafic magmas that formed in a subduction-related tectonic setting (Paper I), in keeping with existing models. Felsic and mafic magmatism is contemporaneous in the region (e.g. Andersson 2007), which is also the case at Kleva where a TIB granite to the northeast of the intrusive complex is dated to c. 1.80 Ga (Paper II). Th/Yb vs Nb/Yb of local rocks trend towards an E-MORB component (Fig. 13; Paper I).

Subduction zones are convergent plate margins where oceanic crust is recycled to the mantle and where continental crust is produced. The balance between constructive and destructive processes of crust varies over time, particularly in tectonically complex continental arcs. Primary mantle melts that pass the thick continental crust can be affected by crustal contamination at several stages. Contamination from wall rock (AFC processes; assimilation, fractional crystallisation) during the ascent and emplacement of primary magmas is significant; however crustal contamination is not only a crustal process but starts in the mantle.

Incompatible element ratios are characterised by low Nb/La, Ti/Gd (i.e. HFSE/REE) and high La/Lu (LREE/HREE), which is also a compositional

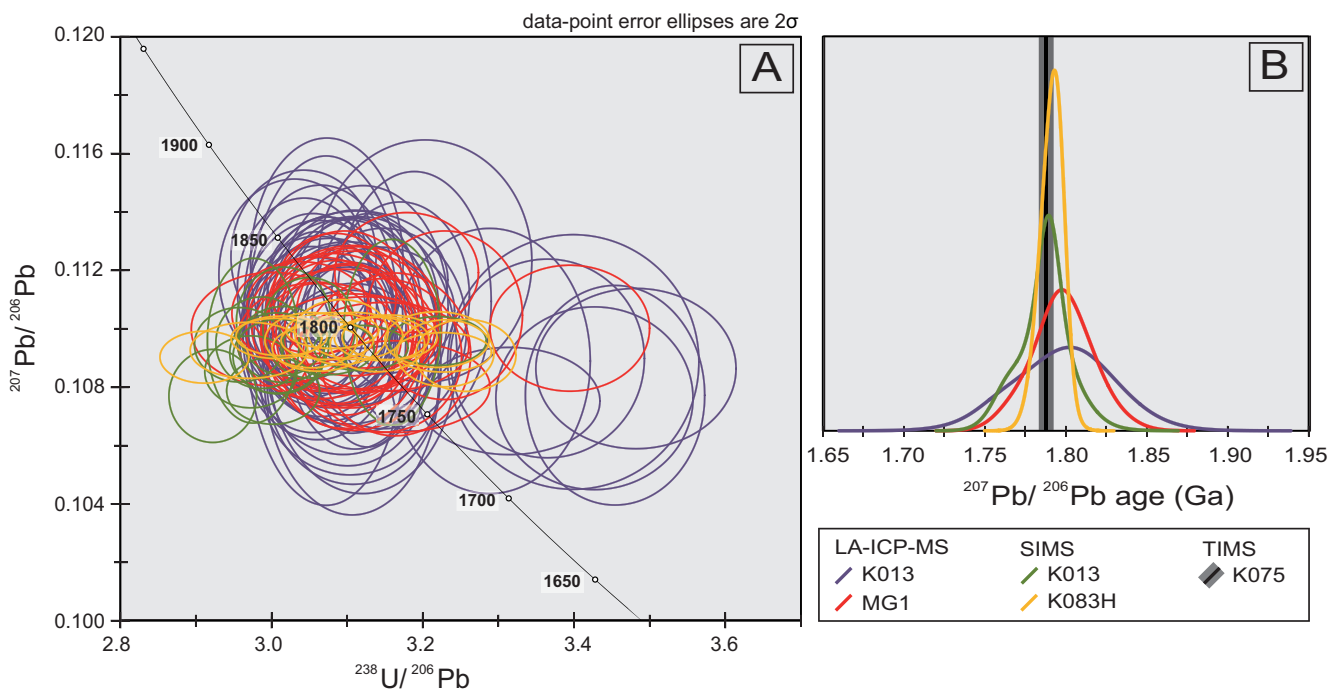


Fig 12 U-Pb age determinations of the Kleva intrusive complex

The U-Pb age determinations of zircon, using SIMS and LA-ICP-MS, and baddeleyite, using TIMS, all overlap at c. 1.79 Ga. A. U-Pb Concordia plot of all the zircon analyses. B. Probability plot of  $^{207}\text{Pb}/^{206}\text{Pb} \pm 2$  SD for the zircon analysed. The baddeleyite analysis is represented as a line, with the grey field representing 2 SD.

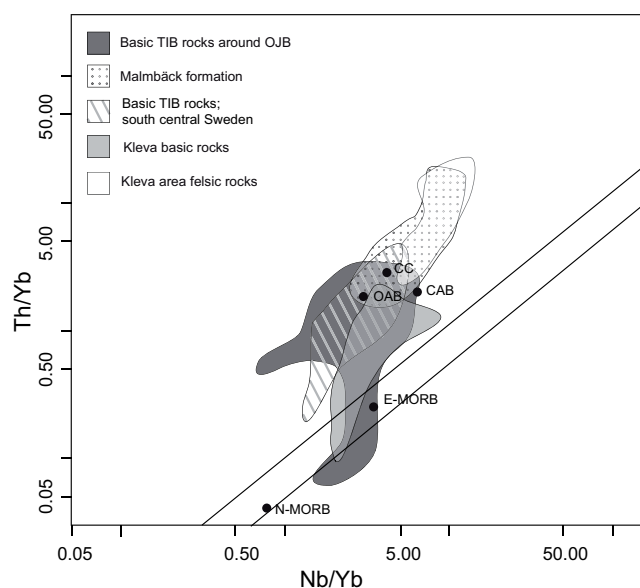


Fig 13 Th/Yb vs. Nb/Yb

Plot of Th/Yb vs. Nb/Yb for rocks from the Kleva area, together with other Palaeoproterozoic rocks in the region; Basic TIB rocks around OJB (Andersson et al. 2007), Malmbäck formation (Appelquist et al. 2009) and Basic TIB rocks in southcentral Sweden (Rutanen and Andersson 2009). For comparison N-MORB (Sun and McDonough 1989); E-MORB (Sun and McDonough 1989); CC, average continental crust (Rudnick and Gao 2003); CAB, average Andean continental arc basalt (Kelemen et al. 2003); OAB, average Lesser Antilles ocean arc basalt (Kelemen et al. 2003).

characteristic of arc rocks (Fig. 14; Paper I). Due to the low density of the overlying and often thick continental crust that characterises continental arcs and that is envisaged here, primitive melts pond at the top of the lithospheric mantle or base of the crust. Heating the base of the crust might lead to melting and mixing with the pooling fractionating magma. This hypothetical zone and process is termed MASH (melting, assimilation, storage and homogenisation).

## 6.2 Magmatic processes

### 6.2.1 Partial melting of the mantle

Ultramafic rocks are lacking in the Kleva intrusive complex and the main rock components are gabbro and diorite. Based on the sample material available, it is most likely that they formed from an evolved basaltic melt (Paper I). From an ore forming perspective, the highest potential regarding Ni, PGEs and Cu, is reached within mantle melts that formed at large (>25%) degrees of partial melting, i.e. picrite or komatiite (Keays 1995). Basalts, on the other hand, form at <30% partial melting of the mantle. However, the mantle is likely more oxidised in arc regions than in other tectonic settings

(Evans et al. 2012; Kelley and Cottrell 2009). High oxygen fugacity promotes enrichment of chalcophile elements, even in relatively small degree melts (<10% partial melts; Song and Li 2009). In oxidised melts sulphur is present as sulphate, which has much higher solubility in the magma than sulphide, leading to complete dissolution of all mantle sulphur (e.g. Jugo et al. 2005; Baker and Moretti 2011).

The Kleva intrusive complex forms an event that is part of long-lived subduction beneath the Fennoscandian proto-continent during the Palaeoproterozoic. Depending on the rate and character of subduction, the degree of metasomatic refertilisation by subducted crustal rocks likely varied, with enhanced crustal input during periods of compression succeeded by periods of less intensity with extension due to ocean-ward movement of the subduction zone, which might have affected the relative depletion of the mantle (c.f. Paper II; Stephens and Andersson 2015). Rocks north of the OJB are more alkaline whereas the rocks to the south are relatively more calc-alkaline-tholeiitic (Andersson et al. 2007). The emplacement of the TIB intrusive rocks has been assigned to extensional stages within the subduction system (Lahtinen et al. 2005; Stephens et al. 2009), consistent with a MORB-like character of some OJB-rocks (Sundblad 1997).

### 6.2.2 Ascent into the crust

As noted above, mafic mantle melts might be trapped at the base of the crust, causing mafic underplating, which has recently been suggested for the Bergslagen area north of the Småland area during the Palaeoproterozoic (Stephens and Andersson 2015). The lack of ultramafic rocks in Kleva and the depletion in PGEs compared to Ni and Cu (especially the IPGES) in sulphides can be explained by fractionation of these phases prior to emplacement of the intrusive complex (Paper II; Borisov and Palme 2000; Barnes and Lightfoot 2005). This inference is in accordance with the high S/Se in Kleva (Paper IV), which either indicates depletion in Se due to early sulphide fractionation or crustal contamination

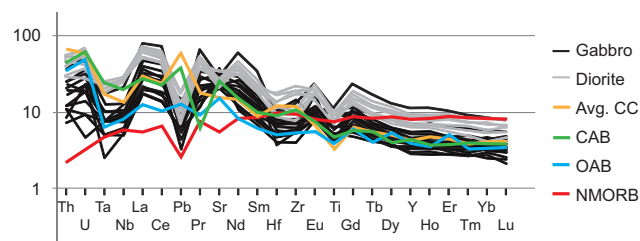


Fig 14 Incompatible element plot

Incompatible element plots, normalised to primitive mantle compositions (Palme & O'Neill 2003), of the gabbro and diorite from Kleva, plotted together with average continental crust (CC; Rudnick and Gao 2003), average continental arc basalt (the Andes; Kelemen et al. 2003), average island arc basalt (the lesser antilles; Kelemen et al. 2003) and NMORB (Sun and McDonough 1989).

(c.f. Leshner et al. 2001; Quefferus and Barnes 2015). Alternatively, the depletion in IPGEs could be a primary signature due to relatively small degrees of melting (c.f. Brennan et al. 2003; Bockrath et al. 2004; Peregoedova et al. 2004).

Incompatible trace element ratios of Kleva rocks (Nb/La vs La/Sm; Fig. 15; Paper I), and radiogenic Re and Os (Paper III) provide evidence for crustal contamination of the magma. Up to 10 % contamination of an Archean source is possible, based on radiogenic Os ( $\gamma\text{Os}_{t(1790)} = 60 \pm 44$ ) of magmatic pyrite. Given the high initial Os-isotope ratio, a comparatively old contaminant is required, while the small age difference between the OJB rocks and the Kleva magma makes OJB-contamination alone less likely. Furthermore, the enriched La/Sm in felsic country rocks compared to Kleva rocks negates local bedrock contamination (Paper I; Fig. 15). The diorites instead trend towards slightly higher Nb/La, found in average mid continental crust, and the anomalous norite sample (K083H) trends towards lower continental crust, possibly highlighting the importance of lower crustal processes.

Although there are abundant supracrustal inclusions in the Kleva complex, the sharp contacts instead point to large temperature differences between inclusions and magma. This would prevent assimilation of rock inclusions and chemical mixing with the intruding

magma (Paper I). Derivation of sulphur from xenoliths to the magma is less dependent on melting of the xenoliths as devolatilisation and fluid transport are viable processes (Robertson et al. 2015). Kleva rock inclusions are often altered, possibly a result of interaction with the hydrous magma, or pre-Kleva alteration of the country rocks (c.f. paper I). The geochemical and petrographical similarity of the rock inclusions with the neighbouring country rocks makes incorporation of upper crustal wall rocks of OJB affinity plausible.

The introduction of sulphur from xenolithic sediments could lead to reduction of an oxidised magma. The isotopic signature of mineralised and barren rocks broadly coincides with that of mantle values, as well as that of the local bedrock. Thus, S-isotope data of the source of sulphur in Kleva are inconclusive (Paper IV). The mineralisation in Kleva is evidence in itself that sulphide melt saturation was reached prior to crystallisation of the magma. As the overall sulphur content is low in the country rocks, with the exception of mineralisations in the region, another possibility is that the introduction of Si to the magma was an important factor, as will be discussed below.

### 6.2.3 Fractional crystallisation and sulphide segregation

The fine-grained, mafic (micro-gabbro, norite and anorthosite) rock inclusions in Kleva are interpreted as autoliths of earlier crystallisation products of the magmatic system (Paper I). The different mafic rocks form distinct groups with respect to their major elements, independently of grain size. This reflects mixing of magmatic and possibly crustal sources, fractionation, episodic magma replenishment and metamorphic overprint, or a combination of these processes. The composition of the diorites cannot be explained by contamination or fractional crystallisation alone, but requires a more complex model, which might be explained by AFC-processes.

Mantle normalised incompatible elements are relatively fractionated but show little intra-sample variability, consistent with magmatic differentiation within the groups (Fig. 14) and it is likely that the Kleva intrusive complex formed from emplacement of several different batches of melt from a homogeneous source (Paper I). The known mineralisation is concentrated to the Kleva hill, which implies that the enrichment in sulphides is restricted to distinct time periods or magma batches (unless sulphides were remobilised at some point). The increasing initial  $^{187}\text{Os}/^{188}\text{Os}$  in magmatic sulphides, from massive towards disseminated ore types, indicates assimilation of a radiogenic crustal component during AFC-processes (Paper III). The mafic rocks lack normative and modal olivine, but relict clinopyroxene

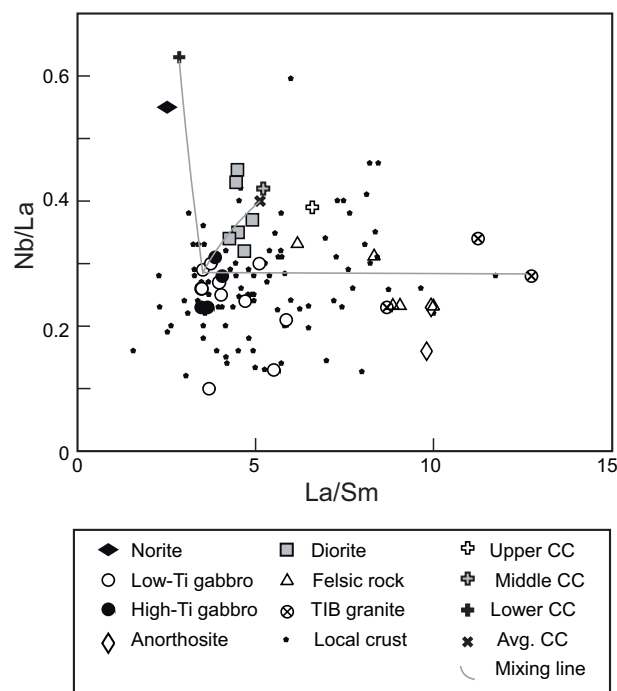


Fig 15 La/Sm vs Nb/La

The Nb/La vs. La/Sm composition of the Kleva rocks plotted together with rocks of TIB and OJB affinity; Felsic rocks, felsic xenoliths and rocks around the Kleva intrusive complex and TIB granites to the north and northeast of Kleva, OJB rocks (Persson 1989; Mansfeld et al. 1996; Sundblad et al. 1997) and TIB rocks (Persson 1989; Andersson et al. 2007; Appelquist et al. 2009), CC, continental crust, mean values according to Rudnick & Gao (2003).

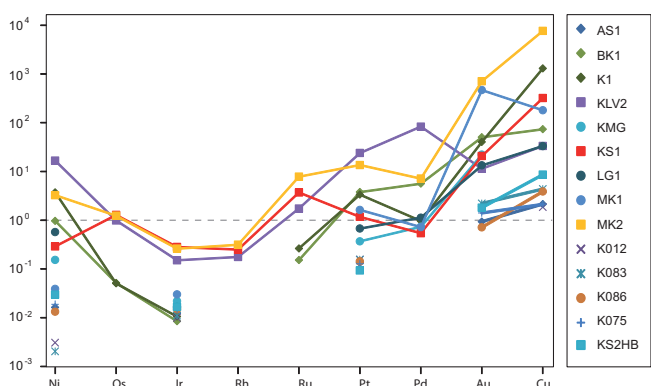


Fig 16 PGE plot

Primitive mantle normalised (Barnes and Lightfoot 2005) base metal and PGE contents in samples from the Kleva Ni-Cu sulphide deposit. The bulk samples are generally depleted in PGEs compared to Ni and Cu. Concentrations are low and below detection limit for many sulphide poor samples. Generally, PPGEs are higher in concentration than IPGEs

and orthopyroxene with maximum  $X_{Mg}$  60–70 ( $X_{Mg} = Mg^{2+}/(Mg^{2+}+Fe^{2+})$ ) occur and indicate silica saturated to oversaturated crystallisation (Paper I). If not a primary signature, silica saturation might have been obtained through assimilation of felsic country rocks (c.f. Ripley and Li 2009). Suppressed olivine crystallisation might in turn maintain higher Ni-concentrations in the fractionating melt as Ni partitioning into pyroxene is considerably less efficient. While Ni might be left in the residual magma during fractional crystallisation, PGE will be partitioned into early crystallising sulphides in the deep crust, leaving a PGE-depleted residual melt.

Due to the depletion in PGEs, and especially IPGEs, in the magma prior to final emplacement (Fig. 16; Paper II), estimates of the efficiency of metal enrichments in the sulphide liquid prior to crystallisation are speculative. Only Ir and Pt occur above detection limits for samples with low sulphide concentration. For Ir the massive samples stand out with c. 10 times enrichment compared to all other samples, which is in line with a higher affinity for Ir into mss (e.g. Li et al. 1996), whereas there is a wider spread for Pt. Normally, calculation of the R-factor:

$$C_C = C_L D(R+1)/(R+D); \text{Campbell and Naldrett (1979)}$$

gives an estimate of the amount of magma needed to generate the measured metal contents in the sulphide i.e. the efficiency of metal tenor enrichment. Assuming normal basaltic contents of PGEs in the Kleva magma ( $C_L = 0.1$  ppb Os;  $D_{Os}^{sulphide/silicate} = 10000$ ; compilation by Barnes and Maier 1997), the R-factor for Os ( $C_C = 15, 4$  and  $10$  ppb, for sample K10, K2 and KS1, respectively; Paper III) in Kleva pyrite would be around 100, which is rather low. This is also suggested by the elevated Cu/Pd or the Kleva mineralised rocks (ranging 3000 to  $10 \times 10^6$ ;

Paper III). However, a lower initial content of metals in the silicate liquid requires higher R-factor for the measured content of metal in the sulphide. Thus, a higher R-factor (and a dynamic system) could be plausible for Kleva. Ni/Cu vs Pd/Ir for disseminated and net-textured samples are similar to other basaltic mineralisations (Barnes and Lightfoot 2005), but the remaining samples and textural varieties fall outside the normal compositions or into the vein-field, due to the depleted PGE contents in Kleva, and possibly also remobilisations.

## 6.2.4 Sulphide concentration

The Ni-ores constituted massive irregular lenses of predominantly pyrrhotite (Brøgger and Vogt 1887; Santesson 1887). This is in line with concentration of sulphide liquid in flow dynamic traps of a magmatic conduit, which provides support for a syn-magmatic ore forming model (c.f. Li and Naldrett 1999). Such a depositional environment requires a dynamic magmatic system, which is also suggested by the high abundance of rock inclusions and varitextured rocks (Paper I). Judging by the range of mineralisation types, with magmatic textured massive sulphide samples dominated by pyrrhotite-pentlandite and pyrite, net textured pyrrhotite-pentlandite-chalcopryrite dominated samples, and disseminated sulphide samples with varying contents of the sulphides (Paper II), the sulphide liquid was likely heterogeneous in metal contents and emplaced sequentially with different magma batches. Massive sulphides indicate immiscible sulphide liquid segregation and accumulation prior to fractional crystallisation, or effective percolation of sulphide liquid through semi-consolidated silicate rocks. Disseminated sulphide likely represent immiscible sulphide liquid droplets trapped among fractionating

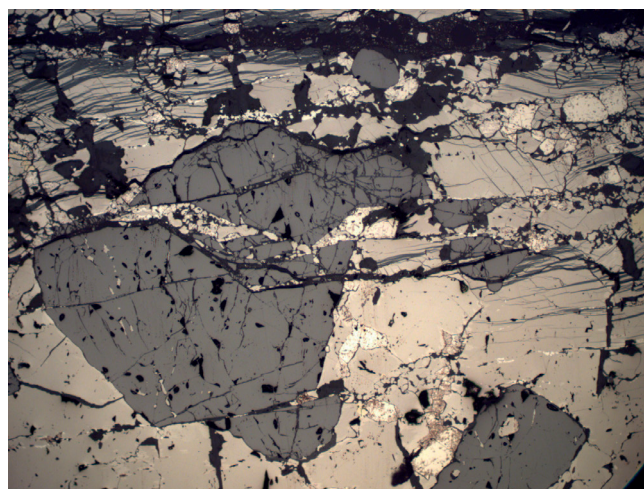


Fig 17 Micro-faulting

Brecciation and micro-faulting of massive pyrrhotite mineralisation (KLV2); the coarse magnetite grain has been fractured and dislocated, with intruding pyrrhotite and pyrite. The width of the magnetite grain is c. 2 mm.



**Fig 18 Chalcopyrite remobilisation**

Chalcopyrite filled fractures in the west wall of Malmkyrkan, Kleva gruva. Fracture width is c. 10 cm.

silicates. If all sulphides originate from the same magma, this would mean that the massive sulphides formed earlier than the disseminated sulphides, consistent with the decreasing Re and Os concentrations away from massive sulphides (sample K10; Paper III).

## 6.3 Metamorphic remobilisation

In addition to the petrographic evidence for magmatic ore forming processes (e.g. disseminated sulphides, pentlandite flames and inclusion of baddeleyite crystals in massive pyrrhotite), there is petrographic evidence for alteration, deformation and metamorphic recrystallisation of the mineralisation in Kleva (Paper III). The extent of secondary effects is highly variable, and was probably caused by several different tectonic events.

Based on the overall high S/Se, the sulphides seem to have lost little or no S during alteration, or S and Se were both lost equally efficiently. Instead, there seems to have been some Fe loss or S gain (Paper IV). Also, there is wide-spread replacement of pyrrhotite with pyrite. Growth of coarse pyrite has been dated to 1.65 Ga and the high  $\gamma$ Os suggests an open system with addition of crustal Os (Paper III). This is in line with the greenschist facies petrography of Kleva silicate rocks, and growth of euhedral pyrite (Craig and Vokes 1993). Pyrite is stable under a wide range of conditions and can grow even at  $T < 100^\circ\text{C}$  (e.g. Wilkin and Barnes 1996), and the replacement of pyrrhotite with pyrite is commonly connected to retrograde metamorphism (e.g. Craig and Vokes 1993). Coarse pyrite is found in many mineralised and silicate samples from Kleva, along fractures as well as within sulphide aggregates, indicating that metamorphic processes were indeed rather penetrative in the Kleva intrusive complex.

Ductile deformation is seen mostly in silicate rocks, whereas sulphides have recrystallised or retained their magmatic textures. One exception however, is a massive and banded chalcopyrite-pyrrhotite-(pentlandite) sulphide sample with fragmented pyrite (MK2; Paper III). Flattening and banding of sulphides has been assigned to low-grade metamorphism (e.g. Marshall and Gilligan 1993; Collins et al. 2012). During deformation; pyrrhotite and chalcopyrite behave plastically at  $T > 200^\circ\text{C}$  and low P (e.g. Clark and Kelly 1973; Kelly and Clark 1975; Cox 1987), whereas pentlandite is brittle at  $T < 400^\circ\text{C}$  and 1.5 kbar (McQueen 1987). Pyrite is mostly deformed in a brittle manner when deformed (Atkinson 1975; Craig and Vokes 1993).

Brittle deformation is common in Kleva, and observed as brecciation of pyrite and magnetite grains and micro-faulting within massive pyrrhotite mineralisation (Fig. 17). Chalcopyrite fillings are found both within brecciated silicates, oxides and sulphides as well as in larger fractures of the host rocks (Fig. 18). Thus, it seems that chalcopyrite was mobile within the mineralisation, and structurally post-dates at least partial re-setting of the Re-Os system in pyrite at 1.39 Ga (KS1; Paper III). Interestingly, the massive pyrite mineralisation itself is set in a fracture system, showing it too was remobilised at some point.

Current data suggest remobilisation of sulphides due to both metamorphic fluids and deformation, but it remains unclear if the massive Ni-ores were also remobilised. It has been suggested that the massive Ni-ores were aligned with the general structural trend of the area (Brøgger and Vogt 1887), which would promote structural rearrangement and possibly remobilisation of sulphides during deformation. Ductile remobilisation, shearing and dislocations of massive Ni-ores have been observed in other Ni-Cu deposits, with relocations from a few meters up to several hundreds of meters at greenschist-amphibolite facies (e.g. Mukwakwami et al. 2014; Duuring et al. 2010; Collins et al. 2012). At high T the massive pyrrhotite dominated ores could potentially recrystallise to mss, whereby deformation textures are overprinted by recrystallisation of pyrrhotite and coarse pentlandite during cooling (Mukwakwami et al. 2014; Collins et al. 2012).

There is a possibility that the sampled Ni-ore indeed is deformed or remobilised, as the metamorphic grade is similar to other remobilised deposits, but the deformation is overprinted by recrystallisation as textures appear magmatic. Also, coarse pentlandite is common in massive as well as disseminated samples (Paper III). Coarse pentlandite is often assigned to slow cooling of the mss, such as during retrograde metamorphism, whereas flame-like pentlandite exsolves during fast cooling at low T (Kelly and Vaughan 1987). Still, the finding of baddeleyite negates a complete remobilisation of massive Ni-ore, as it is recrystallises to zircon during

metamorphic processes (Heaman and LeCheminant 1993). Instead, remobilisation or relocation of parts of the Ni-ores is more plausible.

The wide span of sulphide textures, together with the varying degree of alteration and deformation of silicate rocks suggest that deformation and alteration within the Kleve deposit was heterogeneous. The scale of potential remobilisations is difficult to estimate, but was likely also heterogeneous depending on type and concentration of sulphides. The disseminated and net-textured ores likely represent primary mineralisation with none or only local remobilisation, as sulphide was locked-in between silicates (c.f. Duuring et al. 2010; Collins et al. 2012). This likely applies also to the massive magmatic pyrite ore. Overall, the mineralisation is restricted to a small volume, of both disseminated and massive ores, and remobilisations were most likely local. Faulting of the massive Ni-ores has also been described, but interpreted with only local dislocations (Brøgger and Vogt 1887).

## 6.4 The origin of the Kleve deposit – a synthesis

As stated above, there are four crucial conditions that need to be fulfilled to increase Ni-Cu ore potential in a magmatic system; *a metal rich primary magma, crust interaction, metal tenor upgrading and sulphide accumulation* (e.g. Naldrett 1989; Arndt et al. 2005). How do these processes sum up with the formation of the Kleve deposit?

*A metal rich primary magma:* The primary magma of the Kleve intrusion was likely basaltic, but being retrieved from an oxidised mantle wedge allowed for potentially high metal contents despite presumed lower degrees of partial melting of the mantle. The low IPGE contents of the sulphides might be a primary melt signature, or might be due to early fractionation of those phases, or both. This did not affect the potential high contents of Ni and Cu in the primary melt however.

*Crustal interaction:* There are indications that crustal interaction has taken place at several stages during the ascent of the magma. There is geochemical evidence for crustal contamination, potentially comprising AFC-processes in a lower magma chamber resulting in fractionation of magma, and sulphide melt saturation. Also, the intrusive complex contains abundant autoliths and country rock xenoliths.

*Metal tenor upgrading:* The silicate rocks formed from several batches of magma, there is no distinct magmatic layering, the rocks are varitextured and there are abundant wall rock fragments, which collectively indicate a dynamic magmatic environment during emplacement. The metal content of non-mineralised rocks is low in comparison with the massive sulphides, which are enriched in Ni, Cu and PPGEs. This indicates efficient metal tenor upgrading (i.e. possibly high R-factor). Metal tenor differs between different ore types, however, suggesting heterogeneous upgrading and different stages of emplacement.

*Sulphide accumulation:* Massive pyrrhotite-dominated ores in lens-shaped accumulations are in line with a conduit type deposit with efficient sulphide accumulation. Part of the immiscible sulphide melt was captured in the silicate melt during crystallisation, resulting in net-textured and disseminated sulphides. The known deposit is also concentrated to a restricted part of the intrusive complex.

In addition to the primary processes that affected the ore potential of the Kleve intrusive complex, secondary processes such as deformation, recrystallisation, remobilisation and mineral alteration of the sulphides might have redistributed sulphides and affected ore grade as well. The extent and relative importance of these processes remains largely unconstrained and requires further investigation, but from the observations of this study most sulphide redistribution appears to have been local. Sulphur enriched/iron depleted fluids have recrystallised pyrrhotite into pyrite with a potential loss of Ni. Chalcopyrite was remobilised into veins and fractures, but could be both redistributed magmatic chalcopyrite, and exotic chalcopyrite.

## 7 Location location location?

### 7.1 Kleva and the OJB

Among the many questions raised during the course of the project, there is one consideration that is of particular importance. Why is Kleva the only magmatic Ni-Cu deposit in a region with abundant coeval mafic intrusions? One possibility is that the mafic intrusions are poorly explored with respect to Ni-Cu mineralisation. It could be that the Kleva deposit formed merely by chance, but it is more appealing to assume that the processes that formed the Kleva mineralisation were operating on a regional scale during a reasonably extended time period. That assumption should encourage further investigation within the region.

As discussed above, the tectonic regime at the time of emplacement was subduction underneath a continent margin. The rate of subduction likely varied over time, leading to periods of enhanced subduction with subsequent crustal contamination of the mantle wedge, intercalated with periods of extension (Paper II). As a consequence of an advancing and retreating arc system, the mantle wedge between the subducting crust and the overriding crust should be heterogeneous due to variable input of subduction recycled material. An increase in the thermal activity has been suggested for the mantle beneath Fennoscandia around 1.81–1.77 Ga (Lahtinen et al. 2005 and references therein), which would enable voluminous mafic magmatism. However, without reaching sulphide melt saturation, no deposit is formed, which is a possibility for the other mafic intrusions in the area. Emplacement into the crust during a period of extension would facilitate for rapid ascent of the magma. The sometimes MORB-character of rocks of the OJB (Sundblad et al. 1997) is in line with an extensional environment at least prior to the emplacement of the Kleva intrusive complex. In that case, assimilation of continental crust during magma ascent could have proven crucial.

The occurrence of the Kleva intrusive complex within rocks of the base metal enriched OJB is thought-provoking. Other mafic intrusions are also found in the OJB, and in the TIB. Based on the petrographic and geochemical data, the interaction with OJB country

rocks did not cause sulphide melt saturation, but that was reached prior to the incorporation of the potential OJB related crust. Instead, lower to middle crust of Archaean age was likely assimilated. Another important aspect is the nature of the deposits of the OJB. There are both syngenetic and epigenetic deposits, and some are potentially associated with TIB magmatism, though the metals might originate from OJB rocks (e.g. Ädelfors; Gaál and Sundblad 1990). If a magmatic origin for the Kleva sulphides is accepted, the influence of upper-crustal metal-enriched OJB rocks on the primary mineralisation is small. However, later remobilisation of sulphides from OJB rocks, induced by tectonic events, is plausible. The tectonic contact between OJB and TIB, running north of Kleva is a potential pathway for fluid remobilisations.

### 7.2 Kleva in a Global perspective

Major Ni-Cu sulphide deposits worldwide are primarily associated with extensional regimes and thick continental crust (Begg et al. 2010; Maier et al. 2011). They may be related to mantle plumes (Zhang et al. 2008; Jowitt and Ernst 2013) that are mixed with or partially melts of the enriched subcontinental lithospheric mantle (SCLM) and emplaced in the marginal parts of the cratons (Begg et al. 2010; Maier et al. 2011). The largest deposits, such as Nor'ilsk-Talnakh and Sudbury (which is impact-related), have known ore resources of >1 billion tonnes, whereas the normal size span of deposits is a few hundred thousand tonnes to ten million tonnes (Eckstrand and Hulbert 2007). Interest has now grown also for deposits that are found in subduction related regimes, though they are often small (Thakurta et al. 2008). Yet, several of these deposits have ore reserves reaching tens of millions of tonnes (Table 2) but in this context, Kleva is a very small deposit with its 55 thousand tonnes of mined ore.

There are a few characteristics that are common for most of the convergent margin associated deposits in Table 2. Sulphur saturation is predominantly triggered by the introduction of crustal rocks rich in Si or S. Also, several of the deposits are PGE-depleted, especially in IPGEs, which has been ascribed to earlier segregation of PGE-rich phases (Maier et al. 2008; Song and Li 2009; Sappin et al. 2011; Thakurta et al. 2014).

Many subduction-related Ni-Cu deposits show a tholeiitic trend (e.g. Vammala belt; Peltonen 1995, Portneuf-Mauricie domain; Sappin et al. 2009), though others such as the Aguablanca deposit, Spain (Casquet et al. 2001) and Kalatongke deposit, China (Song and Li 2009) are considered to belong to a calc-alkaline suite. Kleva rocks show no distinct trend towards calc-alkaline or tholeiite composition (Paper I). The genetic origin of the two sub-alkalic trends remains debated and it has been proposed that the calc-alkaline trend is formed from

**Table 2 Convergent margin deposits**

Convergent margin deposits with their location, age, estimated resource and approximate Ni and Cu tenor of the ores.

Deposit	Location	Age	Tonnage	Ni (%)	Cu (%)	References
Aguablanca	Variscan Belt, ES	350–330 Ma	15.7x10 <sup>6</sup>	0.66	0.47	Tornos et al. 2006; Casquet et al. 2001
Duke Island	Alexander terrane, US	c. 110 Ma	—	—	—	Thakurta et al. 2008
Kalatongke	Central Asian Oro-genic Belt, CN	c. 285 Ma	33x10 <sup>6</sup>	0.8	1.3	Han et al. 2004; Song and Li 2009
Kleva	Fennoscandia, SE	c. 1790 Ma	55000	2	0.5	Santesson 1887; Paper I
Lac Édouard	Grenville Province, CA	c. 1400 Ma	69000	1.5	0.5	Poirer 1998; Sappin et al. 2011
Lainijaur	Fennoscandia, SE	c.1870 Ma	100526	2.2	0.93	Grip 1961; Martinsson 1996
Selebi-Phikwe	Limpopo metamorphic belt, BW	> 2000 Ma	31x10 <sup>6</sup>	1.36	1.12	Maier et al. 2008
Vammala	Fennoscandia, FI	c. 1900 Ma	6.4x10 <sup>6</sup>	0.71	0.44	Peltonen 1995
Yolonggou; Yaga	Hualong arc terrane, CN	c. 440 Ma	500000; 250000	0.9; 0.84	0.9; 0.7	Zhang et al. 2014

differentiation of H<sub>2</sub>O-rich basaltic magmas (Grove et al. 2003; Tatsumi and Suzuki 2009) or that the magma is oxidised during differentiation (Lee et al. 2010). Normally, calc-alkaline magmas are generated from oxidised arc mantle, and an explanation for the tholeiitic signatures of arc-related deposits is through reduction of the oxidised magma by introduction of crustal rock or fluids (Thakurta et al. 2008).

In summary, there are some processes that need further investigation for characterisation of convergent-margin (commonly subduction) related deposits; the oxygenation and depletion of the mantle wedge, the partial melting processes in a mantle wedge affected by the hydrous subducting slab, the ascent through sometimes newly formed continental crust and emplacement into a primarily compressional regime.

of these potential mineralisations are unknown, but with the present interpretation likely not in the upper parts of the crust.

Being closed for a century and today a cultural heritage site, there are many mining galleries to explore for mineralisations for future projects – if not for exploration purposes, but for further understanding of subduction-related deposits and effects of multi-stage alterations and remobilisations of sulphides.

### 7.3 Kleva and the future

The geologists of the 19<sup>th</sup> century concluded that the Kleva ore was mined out, and as this has been foremost a geochemical study with the focus on the petrogenesis of the mineralisation I will not elaborate too much on the possibilities for further exploration of the Kleva deposit. Given the technical development where the possibilities for more efficient ore prospecting are ever increasing, e.g. core-drilling and geophysical surveys of the bedrock, significant deposits might be awaiting discovery. Although the deposit is foremost magmatic, metamorphic events have affected the distribution of the mineralisation and further constraints of the structures of intrusive complexes in the region should prove useful. PGEs are lacking in the mineralisation, and so is olivine – here interpreted as an effect of early stage fractional crystallisation or a primary signature. The whereabouts

# Svensk sammanfattning

För cirka 1,8 miljarder år sedan, medan Skandinavien urberg var under uppbyggnad, kristalliserade en järnrik magma till ett mörkt bergartskomplex av bergarterna gabbro och diorit. Denna magma hade bildats genom delvis uppsmältning av manteln under den dåvarande kontinentkanten, transporterats flera tiotals kilometer uppåt genom sprickor i jordskorpan och på vägen upp dragit med sig bitar av de omgivande bergarterna. Tack vare sammansättningen på mantelsmältan och de bergarter som på vägen inkorporerades i magman bildades en nickel-koppar-mineralisering bestående av metallrika svavelmineral. Denna mineralisering sitter i vad som idag kallas Klevaberget, 258 m.ö.h, som ligger cirka 13 km öster om Vetlanda i Småland. Gruvan i Kleva var aktiv till och från mellan åren 1696 och 1919.

Magmatiska nickel-koppar-fyndigheter förekommer framförallt i Arkeiskt urberg som är mer än 2,5 miljarder år gammalt. I nordligaste Sverige och i Bergslagen finns ett antal fyndigheter av detta slag, men Kleva är den enda fyndigheten i sydöstra Sverige. nickel-koppar-fyndigheter är ofta av stor ekonomisk betydelse, eftersom efterfrågan på metaller är stor idag. Kleva är en relativt liten fyndighet, och anses vara utbruten, men genom att studera dess magmatiska bildningssätt och hur yngre tektoniks aktivitet påverkat mineraliseringen kan man bättre förstå hur liknande fyndigheter skulle kunna se ut och var de kan återfinnas.

De svavelhaltiga malmmineralen i Kleva förekommer både som massiva kroppar, men även som spridda korn i gabbrobergarten och som sprickfyllnader. De är rika på nickel och koppar, men inte på ädelmetaller och platinum-grupp mineral, vilket brukar höra till denna typ av fyndighet. Det tyder på att malmmineral kristalliserat vid två tillfällen under mantelsmältans färd upp genom jordskorpan; det är endast den senare omgången malmmineral vi ser i Kleva, den tidigare som var rikare i platinum-grupp mineral återfinns förmodligen längre ner i jordskorpan.

Uran-bly-datering av mineralen zirkon och baddeleyit visar att värdbergarterna för fyndigheten är 1,79 miljarder år, alltså samtida med de graniter urberget domineras av i området. Baserat på malmmineralens och gabbbrons relationer kan man konstatera att de i huvudsak bildades samtidigt. Dock har åldersbestämningar av malmmineralet pyrit visat att det vid minst två tillfällen efter kristallisationen, för cirka 1.6 och 1.4 miljarder år sedan, skett delvis omförflyttning och omkristallisation till sprickor i den massiva malmen och i gabbbron.

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