NGU Rapport 2009.035

# The Geological Setting of the Hamn Nickel Deposit, Senja, Troms

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Norges geologiske undersøkelse
7491 TRONDHEIM
Tlf. 73 90 40 00
Telefaks 73 92 16 20

# REPORT

| | | | |
|---|---|---|---|
| Report no.: 2009.035 | ISSN 0800-3416 | Grading: ~~Confidential~~ Open | |
| Tittel: The Geological Setting of the Hamn Nickel Deposit, Senja, Troms | | | |
| Authors: R. Boyd and M. Often | | Clients: Store Norske Gull and NGU | |
| County: Troms | | Municipality: Berg | |
| Map sheet (M=1:250.000) Tromsø | | Map sheet no. and name (M=1:50.000) 1331 I Gryllefjord | |
| Deposit name and coordinates: Hamn, UTM zone 33, 58450 E, 7701775 N | | Pages: Price: Map enclosures: | |
| Fieldwork carried out: | Report date: 15.06.09 | Project no.: 514300 | Responsible: Rognvald Boyd |

Abstract:

The Hamn gabbro on Senja is an arcuate body extending from Hamn in the N to Gryllefjordbotn in the S, a distance of just under 10 km: its average width is ca. 2 km. Its age is 1800±3 Ma, based on U-Pb dating of zircon. The Ni mineralization at the shore at Hamn was mined from 1872-1886, yielding 105,000 t of ore: c. 1000 t of nickel and cobalt and 500 t of copper were produced from ore with an average grade of 0.9% Ni. The main ore lens at Hamn is c. 80 m long and 15 m wide at the surface, plunging and wedging out downwards towards the ESE. This report is based on data provided by Store Norske Gull – a report by Makkonen (2007) and the results from six holes drilled in 2008 – and on data from NGU's databases, as well as a limited amount of fieldwork.

The surface expression of the Hamn gabbro and associated rocks is the result of multiple intrusive and tectonic events, including fractionation processes in a magma chamber at a lower level in the crust, crystallization from a derived magma at a higher level and imbrication (and rotation) of the resulting products before these were emplaced at their current level. The magma from which most of the rocks seen at Hamn was derived was already depleted in Ni prior to crystallization of olivine cumulates from it. This depletion was due to early sulphur saturation in the lower-crustal level magma chamber and removal of sulphides, possibly those which now form the mined mineralization at Hamn. The magma from which the olivine cumulates seen at Hamn was derived must, because of the uniform content of Ni in the olivines, have been homogeneously depleted in Ni and cannot have been subject to any episode of sulphur saturation while these olivines were crystallizing. The rocks exposed at Hamn may not provide a complete picture of the fractionation products of the parent magma(s) and these have, in any case, been subject to deformation at different times in their evolution.

Mineralizations of the type mined at Hamn are probably the sole target with potential economic interest. The destruction, by a complex magmatic development and multiple deformation episodes, of the regular type of cumulate stratigraphy seen in many pristine layered intrusions means that geophysical methods, combined with an understanding of the deformation events are the main methods which can be applied in searching for such mineralizations. The available evidence does not give a good case for the intrusion concealing much larger mineralizations than that found at Hamn: what is more likely is that geophysical methods could reveal further mineralizations of similar or smaller size in favourable structural traps.



| | | |
|---|---|---|
| Key words: Nickel | Copper | Gabbro |
| Proterozoic | Troms | |
| | | |

**CONTENT**



**FIGURES**

## 1. INTRODUCTION

This report was written as part of input from the Geological Survey of Norway to the prospecting campaign being implemented by Store Norske Gull in the period from 2007. It is based on:

- Pre-existing sources, including:
  - Published literature and maps
  - Chemical data in NGU's ore database
  - Makkonen, H., 2007: Ore geological study of the Senja mafic-ultramafic intrusion, Norway
  - Limited fieldwork in the vicinity of Hamn, chemical data on sampling in profiles across the intrusion (H. Hansen) and field work at the Botnvatnet and Bardstinden mineralizations (H. Hansen, M. Often)
- Logging of 6 cores drilled near the Hamn Ni deposit in 2008 (H. Hansen, R. Boyd, M. Often), including full analytical data.

## 2. REGIONAL SETTING OF THE HAMN GABBRO

The West Troms Basement Complex (WTBC) (Armitage & Bergh, 2005, Kullerud et al., 2006) (Figure 1) consists of blocks and lenses of Palaeoproterozoic and Archaean rocks extending from Senja to Vanna. The WTBC is cut by several NW-SE-trending ductile shear zones, several of which are collectively defined as the Senja Shear Belt. These are associated with belts of highly deformed mafic and ultramafic rocks and supracrustal rocks, metamorphosed at least at amphibolite facies. The minimum age of the shearing is 1768± 4 Ma. The WTBC is overlain to the SE by Caledonian nappes. It is thought (Henkel, 1987, Olesen and Sandstad 1993) that the Senja Shear Belt may be related to a network of Svecofennian shear zones extending under the Caledonian nappes to the Gulf of Bothnia, and named the Bothnian-Senja Fault Zone. The supracrustal sequences include, in addition to volcanic units, psammitic gneisses and marble horizons. The WTBC is intersected by fault zones related to Caledonian and Post-Caledonian deformation.

The Hamn gabbro (Figure 2) has been mapped (Zwaan, Fareth & Grogan, 1998; Zwaan, Fareth & Johannesen, 2003) as an arcuate body extending from Hamn in the N to Gryllefjordbotn in the S, with a break (on the surface, though not necessarily at depth) in the pass E of Gryllefjordbotn, a total distance of just under 10 km: its average width is ca. 2 km: its age is given by Zwaan, Fareth & Grogan (1998) as 1800±3 Ma, based on U-Pb dating of zircon (Zwaan & Walker, unpublished data). Parts of the body are well exposed due to coastal sections and the rugged topography. The Ni mineralization at the shore at Hamn was mined from 1872-1886, yielding 105,000 t of ore: approximately 1,000 t of nickel and cobalt and 500 t of copper were produced from ore with average grade of 0.9% Ni. The main ore lens at Hamn is some 80 m long and 15 m wide at the surface, wedging out down-plunge to the ESE. Mining was stopped at a depth of 75 meters because of flooding by seawater.

Makkonen (2007) reported the results of 10 days of fieldwork in the coastal area of the intrusion and around Storvatnet, the latter area having been prioritised because of the search for a south-eastwards extension of the sulphide-bearing ultramafic unit hosting the Ni-Cu mineralisation at Hamn. He describes the intrusion as layered, the layering where clear, striking at 305-320$^o$ and dipping 50-80$^o$ NE: he states that the main part of the intrusion is composed of "medium-grained, quite homogeneous gabbro" in the middle of which is found a unit of peridotitic-pyroxenitic rocks, "some tens of meters" thick and apparently conformable to the layering in the gabbro. He confirmed the extension of the ultramafic unit from the Ni-Cu deposit to Storvatnet .

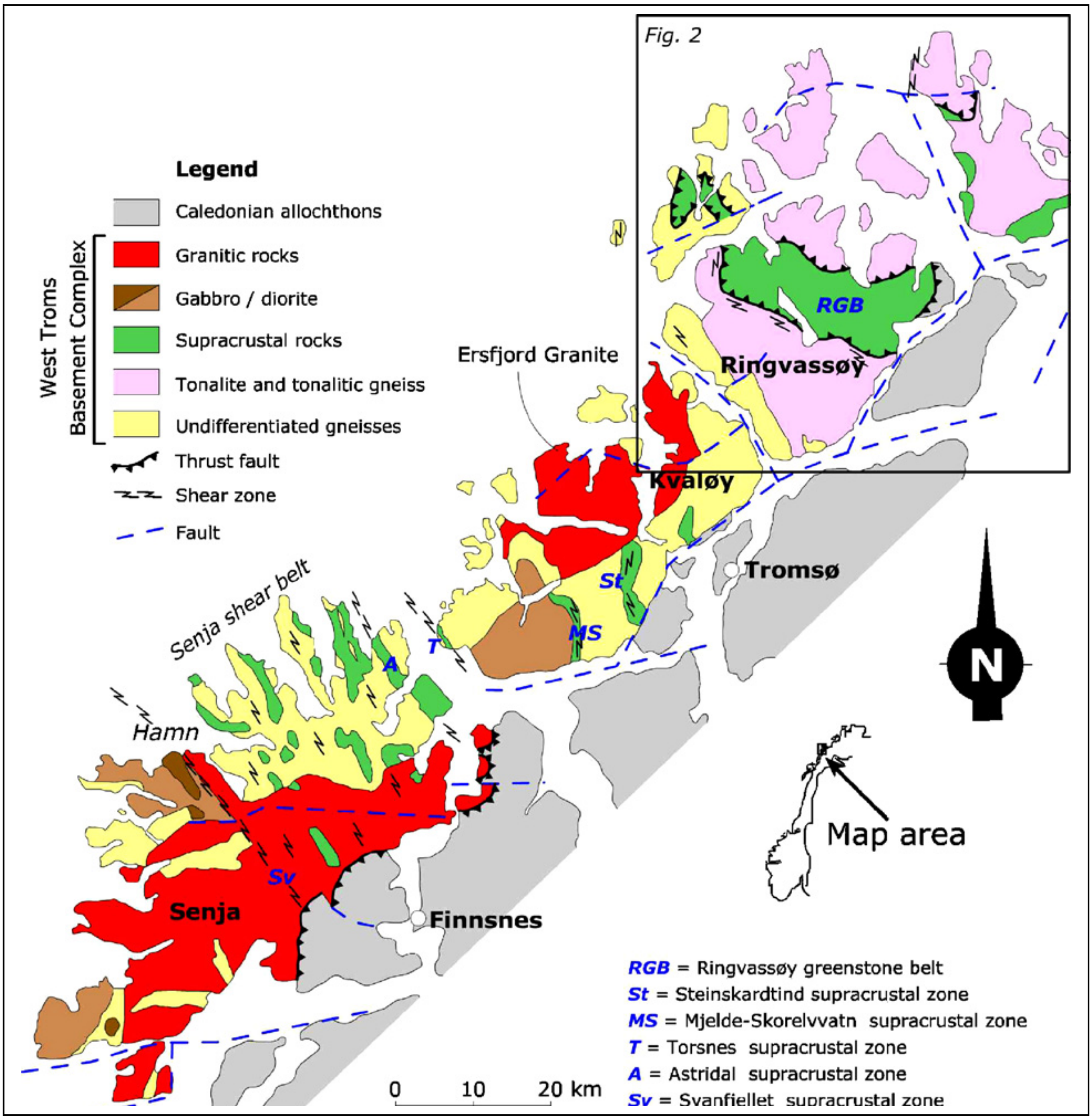



Figure 1: Regional setting of the Hamn gabbro (Kullerud, Skjerlie, Corfu & de la Rosa (2006)

After a thorough treatment of the mineralogy and chemistry of the samples collected, Makkonen (2007) concluded, i.a., that the intrusion was formed from a basaltic magma containing ca. 12 wt. % MgO and that its internal structure was due to two main magma pulses, the first producing the gabbros and the second the ultramafic unit, which he considered to have potential for Ni-Cu mineralisation. The southwesternmost gabbro was found to be mt-bearing and therefore was suggested to be the upper part of a magma pulse, distinct from the northeasternmost gabbro. Makkonen does not indicate what he believes may have happened to lower parts of that magma pulse. The increasing content of plagioclase northeastwards from Storvatnet is interpreted as signifying that "up" is to the NE and that the "stratigraphic footwall" is along the southwestern margin of the ultramafic unit. Makkonen notes the presence of "fine-grained gabbro" in some outcrops, mentioning his sample 45-KJJ-07, collected on the shore ca. 130m S of the east end of the mine: he notes that this rock may be "a dyke or chilled margin".

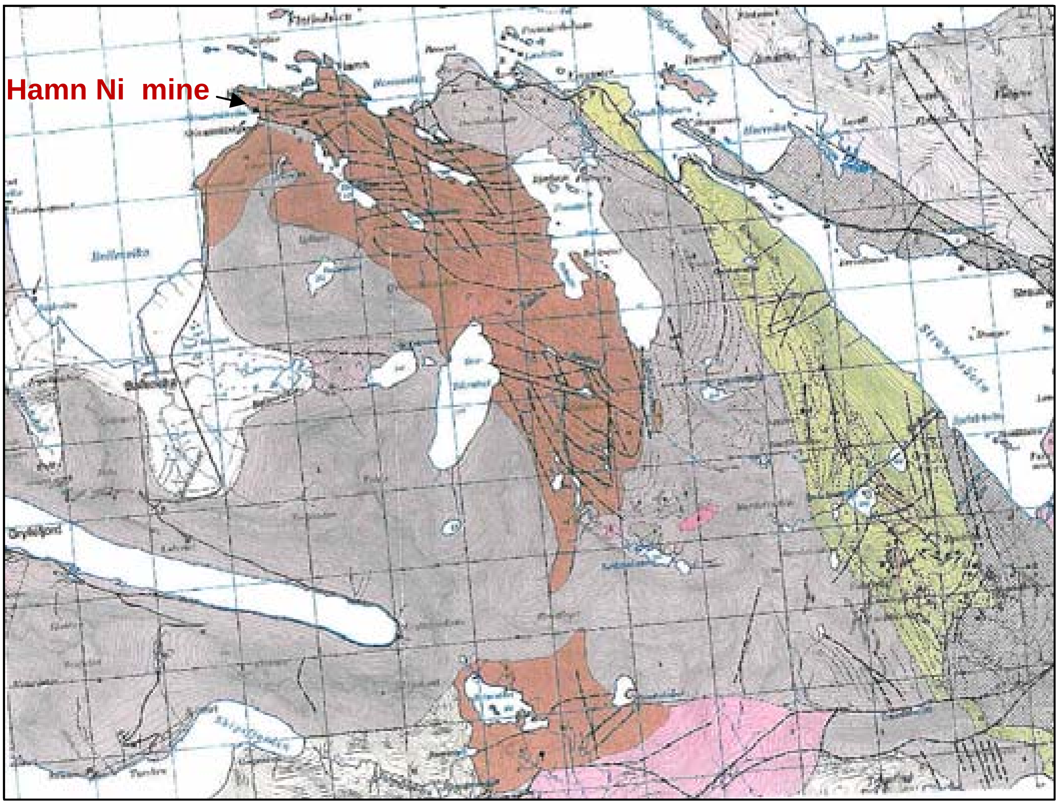



Figure 2: Geology of the Hamn gabbro (Zwaan, Fareth and Johannesen, 2003)

## 3. GEOLOGY OF THE IMMEDIATE AREA OF THE HAMN NICKEL DEPOSIT

The current fieldwork has confirmed the broad surface distribution of the lithologies described by Makkonen (2007) (Figure 2). Observations which supplement this picture include the following:

- The eastern contact of the gabbro against country-rock tonalitic gneiss is exposed at the east end of a road tunnel on RV 86 ca. 2 km due E of the mine site. Within the contact the gabbro, where visible in the tunnel, has a variable texture and sporadic, small amounts of sulphide. The contact is marked, on the S side of the road, by a breccia/shear zone 1-2 m wide oriented at 160/65. The wall rock is tonalitic gneiss, which, over a distance of 15-20 m, is cut by diabase dykes in which sulphides are visible, especially as crack fillings: this zone also contains lenses of gabbro. On the N, shore side, the contact is marked by a 50-cm thick sulphidic zone, bounded by shear zones at 240/70 on each side and with irregular veins of massive sulphide up to 1-2 cm thick "within" (on the intrusion side of) this zone. These relationships suggest the following:
    - Sulphur saturation took place at different "levels" in the intrusion.
    - It is very unlikely, in the absence of a chilled margin or contact-metamorphic features in the country rock, that the contact is primary. A further indication is the absence of xenoliths of country rock in the adjacent gabbro.
    - The relationships suggest a tectonic contact with multiple phases of movement (enabling interleaving of gabbro and tonalitic gneiss) and mobility of sulphides to a late stage in these movements.
    - The presence of the diabases may indicate exploitation of a mechanically favourable location close to an already vertical contact.

- The road cutting from which DDH-3 was drilled (also the location of Makkonen's observation 71-KKJ-07) (Figures 3,5) reveals some of the complexity in the relationship between the gabbro host rock and diabase intrusions. The host gabbro is homogeneous over large areas but locally contains pegmatitic lenses up to several cm thick in which the grain size is ≥ 1 cm. The following relationships are exposed:
    - Xenoliths of a diabase up to a few cm. thick and with a general orientation of ca. 90/30. Below these there is a zone of pegmatitic gabbro up to 2 dm thick, suggesting that the originally continuous diabase may have formed a trap for fluids before final solidification of the gabbro. The xenoliths have pale-coloured reaction rims. These relationships clearly indicate the emplacement of diabase before final solidification of the gabbro. The diabase is oriented at approximately $90^{o}$ to the attitude of the lithologies in the northernmost part of the intrusion, which suggests that it is a dyke.
    - At the E end of the cutting the host gabbro is cut by two generations of diabase (Figure 3). The earliest is oriented at ca. 90/10: it is cut by a later diabase at ca. 166/60. Both are 30-40 cm thick and both have an "interfingering" relationship with the host gabbro.

Figure 3: Cross-cutting diabase near the location of DDH 3.

    - These relationships suggest that the Hamn gabbro lies in a feeder channel which was open for emplacement of basaltic magma at several times during crystallization and deformation/tilting of the intrusion:
        - Late-magmatic
        - Post-magmatic, pre-tilting
        - Post-deformation/tilting: this episode may coincide with the dykes found E of the eastern contact of the intrusion, described above.

    There are numerous steeply inclined diabases in the gneisses surrounding the Hamn gabbro and in the region in general. Too little is known about these for any speculation about their possible relationship with the parent magma for the gabbro. It is possible, however, that the gabbro exists because one or more periodically active feeder channels was sufficiently open for a sufficient period between deformation episodes to allow crystallization of cumulate sequences.

- Makkonen (2007) showed that the southwesternmost gabbro is mt-bearing and suggested that it is the upper part of a magma pulse, distinct from the northeasternmost gabbro (but see section 5). A further distinctive feature of this gabbroic unit, which may support Makkonen's conclusion, is the profusion of xenoliths in this body, at least in the vicinity of the Hamn peninsula. They occur as follows:
  - Tonalitic gneiss forms xenoliths of variable size, up to definable dimensions of 5 x 2m on the surface and larger bodies occupying whole outcrops. These appear to be particularly clearly seen in the coastal exposures W and S of the mine. Some of the xenoliths have tectonic contacts against gabbro, e.g. a gneiss block S of the W end of the mine.
  - Lenses of paragneiss and quartzite occur in gabbro NW of the mine.
  - Close to the lighthouse at E 584026, N 7701916, there is a xenolith with a rectangular surface section, 7m SE-NW and 6m SW-NE (Figure 4). The block has sharp contacts to the SE and NW, without any obvious shearing. It shows the following "lithostratigraphy" from SW to NE:
    - 2-3 dm basic metavolcanic rock,
    - 3 m conglomerate, containing rounded and angular fragments of metavolcanic rock and various types of gneiss, including psammitic gneiss, up to 1-2 dm in size.
    - 2-3m psammitic gneiss (uppermost in Figure 4).

Figure 4: Xenolith on shore NW of Ni mine, Hamn.

None of the components show any clear sign of thermal effects due to emplacement in the gabbro, which suggests that the block was incorporated at a late stage in crystallization of the gabbro, probably when it was almost solid. Supracrustal sequences occur in several parts of the WTBC but have not been described from the vicinity of the Hamn gabbro.

  - C. 75m N of the block described above there is a lens of mylonitised conglomerate up to 2 m thick and >10 m long containing flattened lenses of leucocratic gneiss and metavolcanic rock. The mylonite is oriented at 325/80 and is terminated at its NW extremity against a shear zone at 270/70.

Outcrop and blocks fallen from the mountains in the part of the southwesternmost gabbro SW of Hamn towards the outer contact do not appear to contain abundant xenoliths. The confinement of the xenoliths to one specific "level" in the gabbro can be interpreted in at least two ways:

- The existence of a shelf of supracrustal country rock in an originally horizontally layered magma chamber. Contamination of mafic magma from melting of such a shelf would enhance sulphur saturation but this is not, however, a favoured option as contact metamorphic features which would be expected after prolonged contact between the xenoliths and the mafic magma are absent and there is no indication of associated sulphides.
- This "level" was close to the original roof of part of the magma chamber: blocks of country rock were detached and fell into the magma chamber at a late stage in its development as a result of tectonic disturbance. This model indicates that the current distribution of the major rock units results either from imbrication (or another form of tectonic juxtaposition) of units originally at separate levels in a magma chamber or that the ultramafic units and northeastern gabbro were emplaced above the already near-solid southwestern gabbro.

- Part of the lithological sequence in which the Ni-mineralization occurs is well exposed in the road cutting ESE of the mine. This shows homogeneous peridotite with traces of sulphide separated from inhomogeneous sulphide-bearing gabbro by a shear zone 60-70 cm thick in which certain zones are rich in sulphide, i.e. a further indication of mobilization of sulphides. The mined sulphide body plunges to the ESE but old workings show that a sulphide-bearing zone is present on the surface, also following an ESE direction up the S side of the ridge E of the mine.

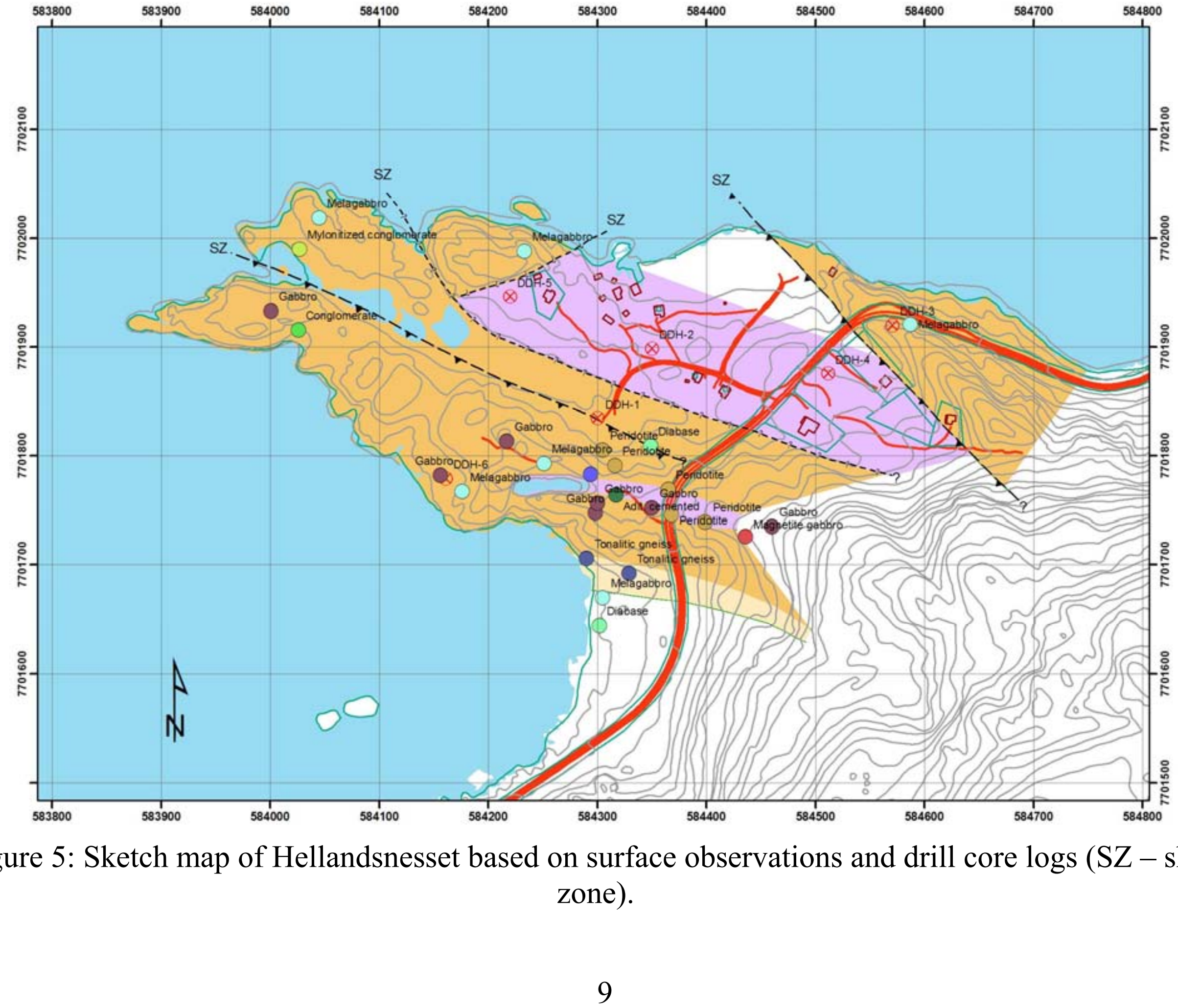



Figure 5: Sketch map of Hellandsnesset based on surface observations and drill core logs (SZ – shear zone).

4. **COMMENTS ON THE GEOLOGY OF THE DRILL CORES**

General comments

The drilling programme implemented in 2008 leads to the following conclusions on the distribution of lithologies and structures in the vicinity of the Hamn mine (Figures 5 and 6):

- The clear difference in lithologies found in the upper parts of DDH 3 and 4 (absence of ultramafic rocks in DDH 3) suggests the presence of a fault or shear zone between these two holes: such a structure may well be reflected in the prominent valley between the two drillhole sites. There are, in fact, no clearly correlatable sequences in these two holes, which contrast suggests that the possible shear zone must be parallel to their plunge. Zones of breccia are found at several levels in DDH 4: these may be splays from a major structural feature. Such zones have not been observed in DDH 3
- Drillholes DDH 2, 4 and 5 have several features in common, suggesting clear possibilities for correlation:
    - Olivine-bearing cumulates in the uppermost metres in all three holes.
    - Ultramafic cumulates at two similar levels further down in each hole.
    - Holes DDH 2 and 4 show zones of breccia at several levels below the major peridotite at the surface in each hole. Any attempt at correlation between these would be completely speculative – but the zones could represent splays of a shear-zone complex sub-parallel to a line joining the holes. It would then be expected that such a zone would intersect the surface between holes DDH 3 and 4, probably with a WNW-ESE strike.
- DDH 1 can be correlated with the above-mentioned three holes as illustrated in Figure 7 in which holes 1, 2 and 6 have been rotated into one, approximately WNW-ESE profile:
    - The uppermost peridotite in DDH 1 corresponds to the pyroxenitic ultramafic unit at 148-158 m in holes DDH 2.
    - The pyroxenite at the bottom of DDH 1 corresponds to the unit close to the bottom of DDH 2 (and to correlative units at the bottom of DDH 4 and 5).
    - The breccia/shear zone at the top of hole DDH 1 corresponds to those seen below the uppermost peridotites in holes DDH 2 and 4.
    - The ultramafic units (and the breccia/shear zones) are all subvertical as required by modelling of the geophysical data (see Figure 7).
- The only possible point of correlation between DDH 6 and the holes to the NE is that the websterite at the top of the hole corresponds to that found at the bottom of holes DDH 1, 5 and 2. This would make the websterite subvertical.

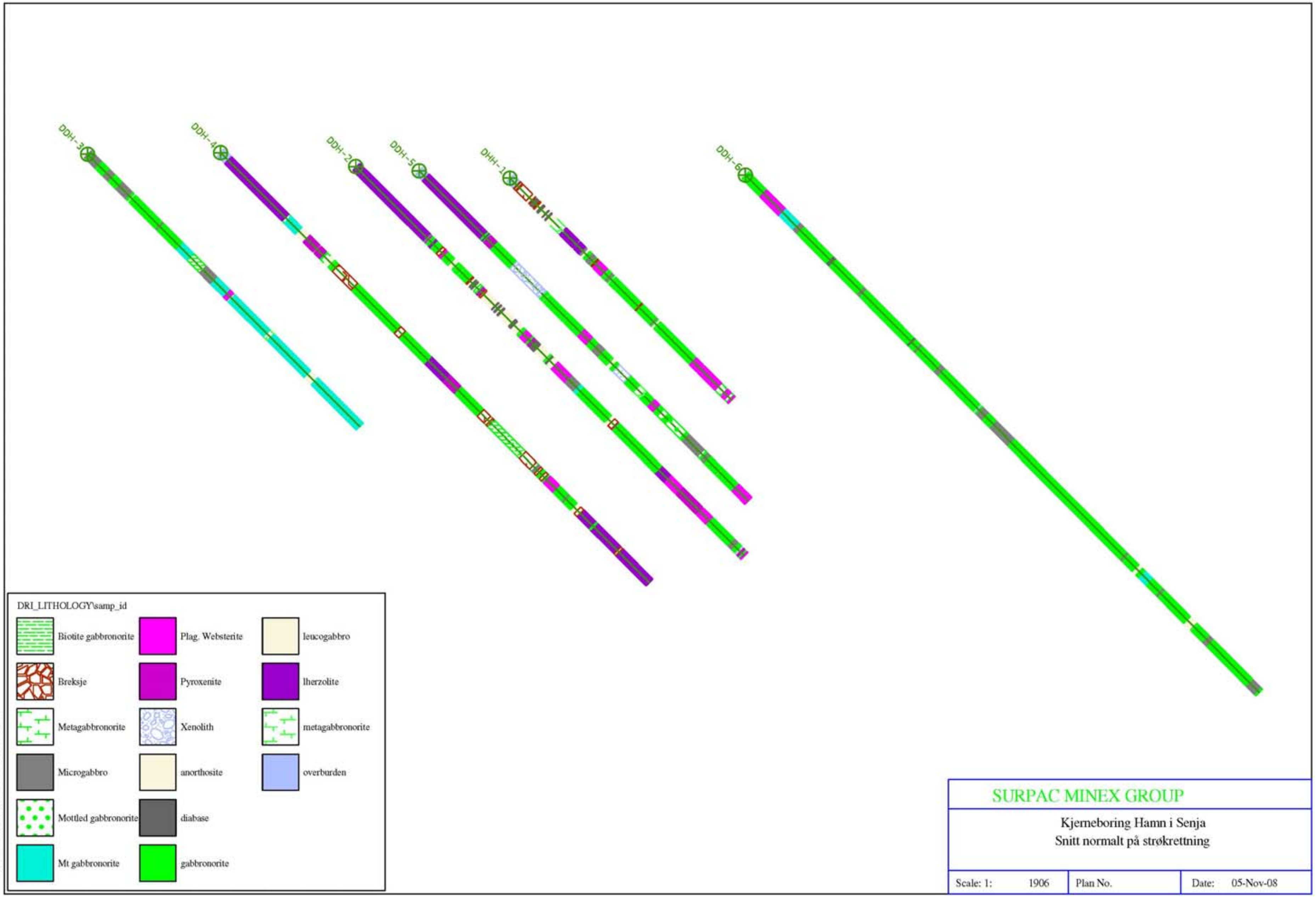


Figure 6: Profile of drillholes projected into a NE-SW section (H. Hansen., personal communication).

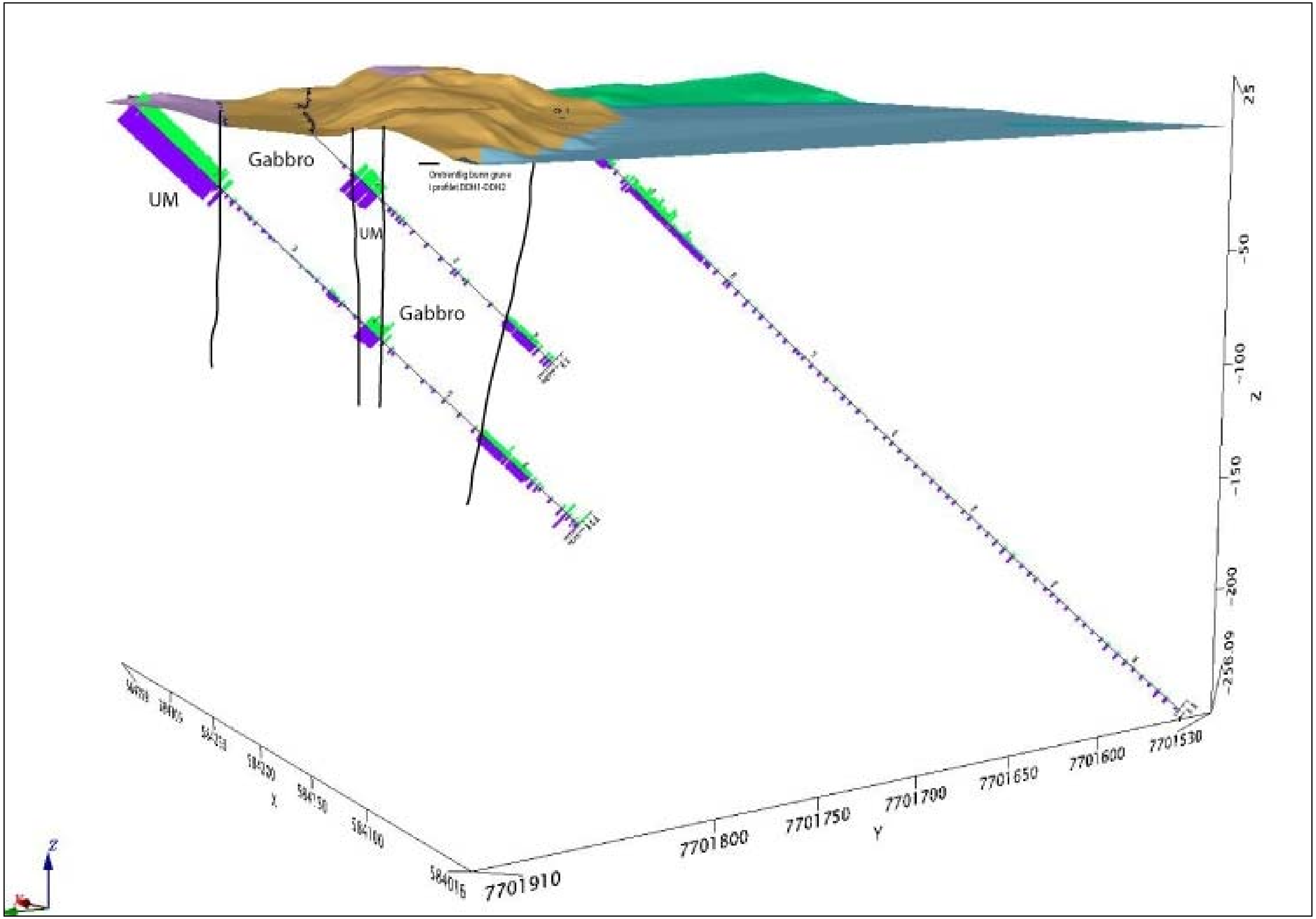



Figure 7: Block diagram of Hellandsnesset looking towards the SE, showing drillholes 2, 1 and 6.

DDH 1

From the top of the core this hole shows:

- 32 m dominated by units of tonalitic gneiss and diabase alternating on scales of 0,1 – 3 m, with minor units of metagabbro and microgabbro. Several of the diabase units contain xenoliths of gabbro and microgabbro. The tonaltic gneiss locally contains traces of sulphide. This lithology is similar to that seen at the eastern contact of the intrusion (see above).
- 22 m dominated by chemically homogeneous olivine cumulates , the lower boundary consisting of several dm of highly deformed chloritic metagabbro/amphibolite.
- 88 m dominated by gabbroic rocks of many varieties with minor units of other lithologies, including websterite, microgabbro and tonalitic gneiss, and numerous shear zones, several of them mylonitic.
- 22m, most of the lowermost part of the hole, consisting of chemically homogeneous plagioclase pyroxenite, probably with a certain amount of cumulus olivine. This unit resembles the lowermost ultramafic unit in DDH 2, which lies in the same profile: if these are the same unit it dips at c. $80^o$ NE. They have a chemistry which is similar to that of the ultramafic unit intersected near the top of DDH 6, though the latter unit has a slightly higher content of plagioclase.

DDH 2

From the top of the core this hole shows:

- 53 m of chemically homogeneous olivine cumulate. Chemical data confirm the insignificance of the sulphide content of the unit.
- 72 m dominated by varieties of gabbro with seven intersections of diabase dikes up to 2 m thick in the lowermost 40 m.
- 3 m peridotite.
- Ca. 94 m, mainly of varieties of gabbro and plagioclase-bearing pyroxenite, with intersections of diabase up to 3 m thick.
- 10 m peridotite.
- 56 m mainly of gabbro and pyroxenite.

DDH 3

- This hole is almost completely free of ultramafic rocks, there being only one 1m analysis with > 9 wt % MgO: the analysis, at 104-105m indicates that the rock is a plagioclase peridotite. From the top of the core this hole shows:
- 68 m dominated by gabbronorite with an MgO:FeO ratio of ca. 1:1 (see Figure 6a).
- 132m , to the end of the hole at 200m, dominated by magnetite gabbronorite, containing, from 68.5 – 128 m ca. 3-6% apatite, and overall, 12.4 – 18.4 wt % Fe as FeO. This section adds important information to our understanding of the geology of the area, not only because it contrasts with Makkonen's (2007) belief, based on surface observations that magnetite gabbro was predominantly found SW of the ultramafic unit. This unit clearly represents quite highly fractionated gabbro (the MgO:FeO ratios are ca. 1:3) but it lies immediately under the peridotite which is found in the uppermost 48 m of DDH 4: it is clear that there is a major break between these units. There is certainly a tectonic break as noted above, but it is also

possible that these units were juxtaposed after emplacement from different levels in a deeper-seated chamber in which they originally formed.

DDH 4

From the top of the core this hole shows:

- 48 m of olivine cumulate, interrupted by two thin units of plagioclase-bearing cumulates. The rock is otherwise chemically homogeneous but differs from the olivine cumulate in the uppermost part of DDH 2. In DDH 4 the rock has a 2-3% higher MgO content and lower contents of the other major oxides except $SiO_2$. This suggests that there are lateral variations in the cumulate mineralogy of the same unit, a common feature in certain layered intrusions.
- 10 m of magnetite-apatite gabbronorite, a unit similar to that in the lower parts of DDH 3 but which, again, cannot have had an original position close to the olivine cumulate immediately above it.
- 15 m of olivine cumulate, similar to that at the top of the hole but with two bands, 2 and 1 m thick, of leucogabbro, containing >50% plagioclase, again an anomalous juxtaposition unless these two bands are actually cross-cutting veins, which is not necessarily obvious in drill core.
- 61 m dominated by magnetite gabbronorite with erratic accessory apatite ***(? Feil i Fig. 4).*** The zone include several m of breccia with > 22 wt % FeO and intersects a xenolith of titanomagnetite-rich gabbro containing 26.5 wt % FeO and 4.5 wt % $TiO_2$. This unit is underlain by 14 m of normal gabbronorite.
- 22m of chemically homogeneous olivine cumulate.
- 93 m dominated by units of pyroxene cumulate and gabbronorite.
- 11 m of olivine cumulate
- 34 m of plagioclase pyroxenite (or perhaps melagabbro as the chemistry suggests it contains ~20% plagioclase) to the end of the hole.

DDH 5

From the top of the core this hole shows:

- 48 m of olivine cumulate, chemically homogeneous down to 37 m, but with a systematical decline in MgO and increasing FeO and CaO in the lowermost 11 m
- 187 m of varying types of gabbroic rock, including several sections of magnetite gabbronorite and three intersections of magnetite-bearing microgabbro: the fine grainsize could be an indication that these units are intrusive into coarser-grained cumulates.
- 10 m of plagioclase pyroxenite (or perhaps melagabbro as the chemistry suggests it contains ~20% plagioclase) to the end of the hole. This rock is chemically identical to that found at the bottom of DDH 4.

DDH 6

This hole is totally dominated by gabbronorite, with 15 m of plagioclase pyroxenite from 13-28 m, followed by 10m of magnetite gabbronorite. The gabbronorite in the remainder of the hole is broken only by thin units of magnetite gabbronorite and magnetite microgabbro.

## 5. **PETROLOGY OF THE GABBRO**

*Chemical data*

The complete data set which formed the starting point for this section includes:

- 259 samples collected by Harald Hansen in 2008
- 25 samples collected by the authors in 2008
- 647 samples from core drilled in 2008.

Certain samples and groups of samples have been deleted from the set in order to permit the plotting of binary variation diagrams using linear, rather than logarithmic scales, or because they represent country-rock lithologies. The deleted samples, in addition to country rock, include:

- 2 samples of leucogranitic veins containing > 75% $SiO_2$.
- 3 samples of apatite-rich veins containing > 8% $P_2O_5$. One of these samples contains ~50% apatite, c. 5% sulphides with 1420 ppm Cu and 104 ppm Ni in the rock.
- 1 sample of sulphidic gabbro, containing 8.73% S, 1.495% Cu, 0.107% Ni and insignificant contents of noble metals (sample 117-HAH-2008). The maximum Cu content in the remaining data set is 1310 ppm, in a sample of gabbro (82-HAH-2008)containing 901 ppm Ni and c. 5.5% total sulphides.

The number of samples remaining was 914.

The chemical data were processed using Petrograph software, version 1.0.2 (Petrelli, 2005). Use of Petrograph involves formatting the data set in Excel. Data for all trace elements for which the majority of samples gave values below, at or close to detection levels were deleted.

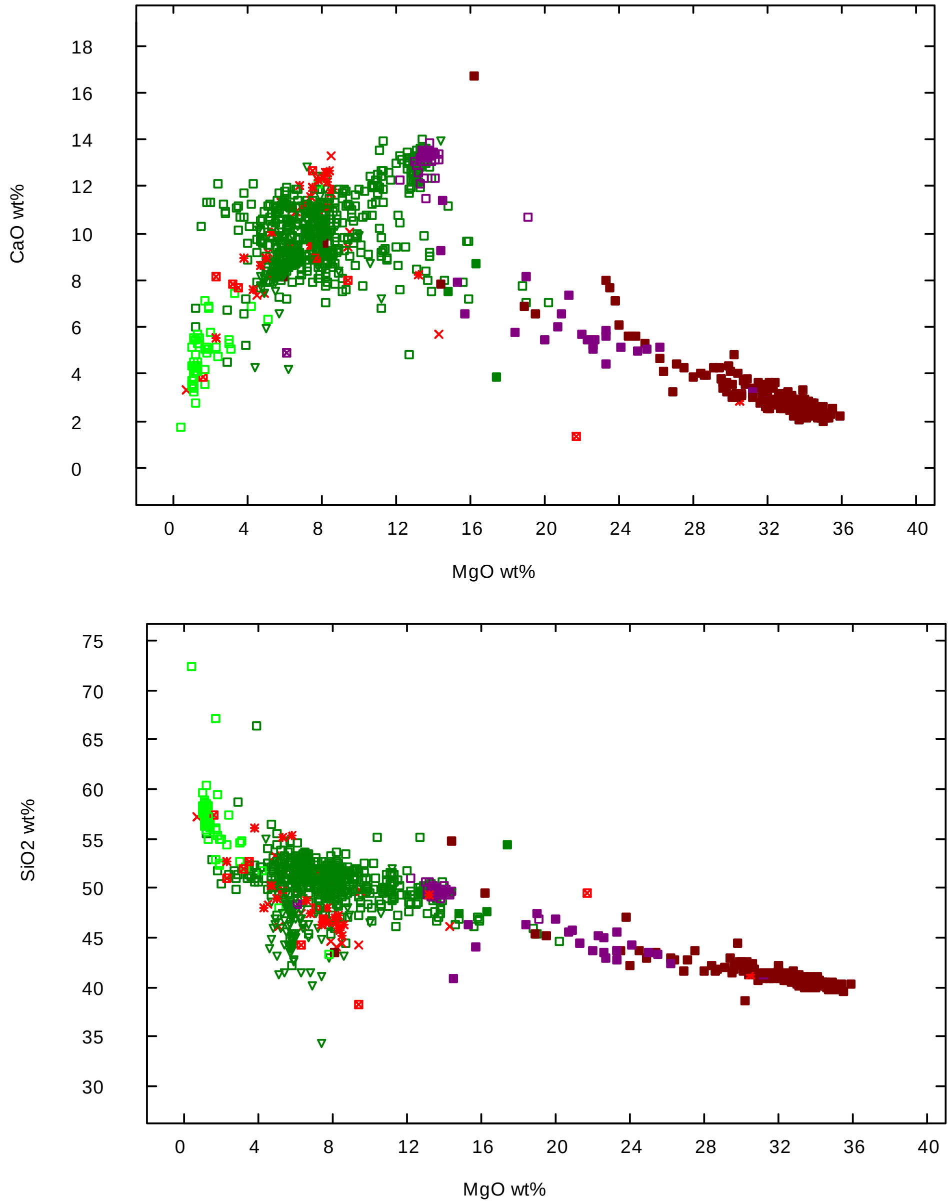



Figure 7: Variation diagrams showing: a) CaO and b) $SiO_2$ plotted against MgO. Filled squares: red – olivine-rich cumulates, violet – pyroxene-rich cumulates; open squares: dark green – gabbro, pale green – leucogabbro; dark green triangles: magnetite gabbro; single red crosses: diabase; double red crosses: microgabbro; red squares with cross: breccia.

As pointed out by Makkonen (2007) the composition of the most primitive olivine found at Hamn suggests that the primary magma contained c. 12% MgO. Figure 7a indicates that a magma of this composition was "driven" to less magnesian and more calcic compositions by crystallization, primarily of olivine with cimpositions in the range $Fo_{75}$ – $Fo_{85}$ (Makkonen, 2007) and, with fractionation, of olivine and orthopyroxene. The silica content of the most magnesian cumulates does not "permit" significant proportions of primary orthopyroxene. Further, the figure suggests that the mafic components of the complex, formed after cessation of crystallization of forsterite, and after the magma composition had reached a lower MgO content, are dominated by clinopyroxene (augite) and plagioclase, because of the presence of pyroxenitic cumulates with ave. CaO contents of 12-13%. Both figures a and b indicate that the final products of the fractionation process had a minor content of mafic minerals and, considering their $Al_2O_3$ content, were dominated by a plagioclase close to $Ab_{80}$.

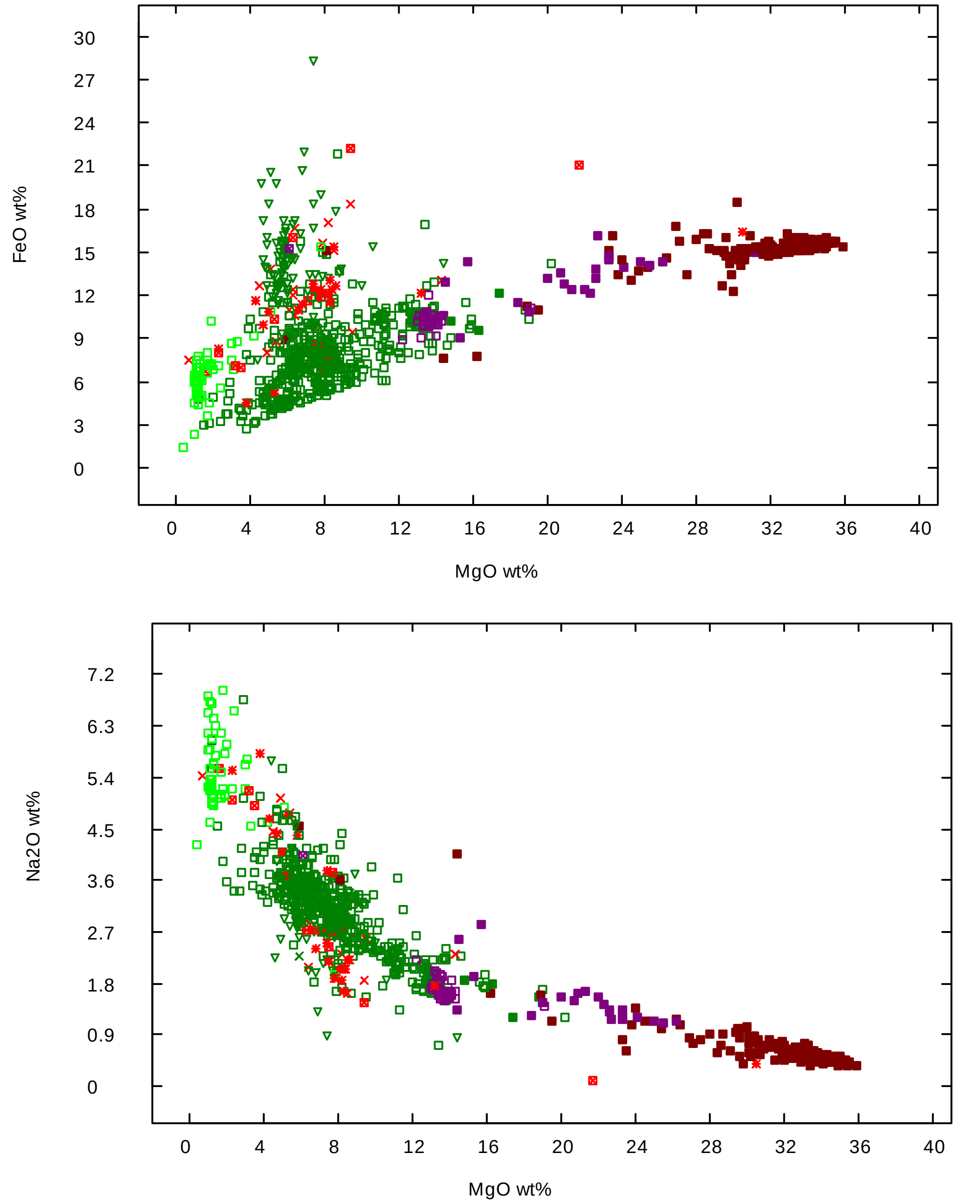



Figure 8: Variation diagram showing: a) total iron as FeO and b) $Na_2O$ plotted against MgO. Filled squares: red – olivine-rich cumulates, violet – pyroxene-rich cumulates; open squares: dark green – gabbro, pale green – leucogabbro; dark green triangles: magnetite gabbro; single red crosses: diabase; double red crosses: microgabbro; red squares with cross: breccia.

Figure 8 a) shows clearly the enrichment of FeO (up to > 20%) in a number of samples of magnetite gabbro while the general trend is governed by decreasing FeO (and MgO) due to crystallization and increase in the normative content of plagioclase. The most magnetite-rich gabbros contain 2-5% $TiO_2$.

Makkonen (2007) explains the apparent compositional "gap" in the MgO-$SiO_2$ variation diagram in his report as being due to the gabbroic and ultramafic units "representing different magma pulses, which produced their own crystallisation series". The following comments can be made:

- The "gap" is less prominent in the above figures.
- The ultramafic rocks are, in any case, cumulates which Makkonen himself stated formed from a magma with 12% MgO, i.e. within 4% of a mixing line between the trend formed

on Fig. 7a between clinopyroxene- rich cumulates and more plagioclase rich products, derived after crystallization of the clinopyroxene.

- While there is little doubt (see below) that the rocks exposed do not reveal the whole range of products of the primary magma there is no evidence for multiple crystallisation series. It is be argued here that the "gap" is due, not to multiple magma pulses, but to the role of deformation processes in juxtaposing components originally formed at different levels relative to each other (and excising others), probably in a magma chamber at a different level in the crust.

The Hamn gabbro has strong similarities to the Group I Svecofennian mafic-ultramafic intrusions in Finland, described i.a. by Peltonen (2005). The most prominent belt of this intrusion type is located close to the boundary between Archaean crust in the Karelian terrain and the Svecofennian domain to the SW: the intrusions range in age from1870 to 1900 Ma and the Group I intrusions (relative to Groups II and III) are noted for their Ni-Cu ores. Though it is younger, the overall structural context of the Hamn gabbro may be similar. Peltonen (2005) writes: *"Spacial association of shear zones and intrusions is especially evident adjacent to the suture zone in the southeast"* and, in relation to closure between the Svecofennian arc complex and the Archaean craton *" Synchronous or subsequent to the amalgamation, transtensional shear systems developed at the continental margin, locally facilitating the ascent of melts along subvertical shear zones. …. Within shear zones, magmas are expected to rise faster and undergo less fractionation during emplacement thus also retaining higher potential to saturate nickeliferous sulphides. During the $D_3$ phase these zones were further reactivated, deforming and brecciating the intrusions."* Peltonen (2005) concludes that these intrusions were derived from a magma containing 12% MgO and states specifically that the ultramafic cumulates in them were not derived from an ultramafic magma.

Most of the samples of brecciated rock fall within the compositional range of gabbro samples analysed and were probably derived from gabbro or leucogabbro. The same applies to samples of diabase (only two samples from DDH 2) and microgabbro shown with crosses: it is not surprising that the diabases/microgabbros have a gabbroic composition. The data available for diabases are insufficient for use of discriminant diagrams which could have indicated their tectonic environment.

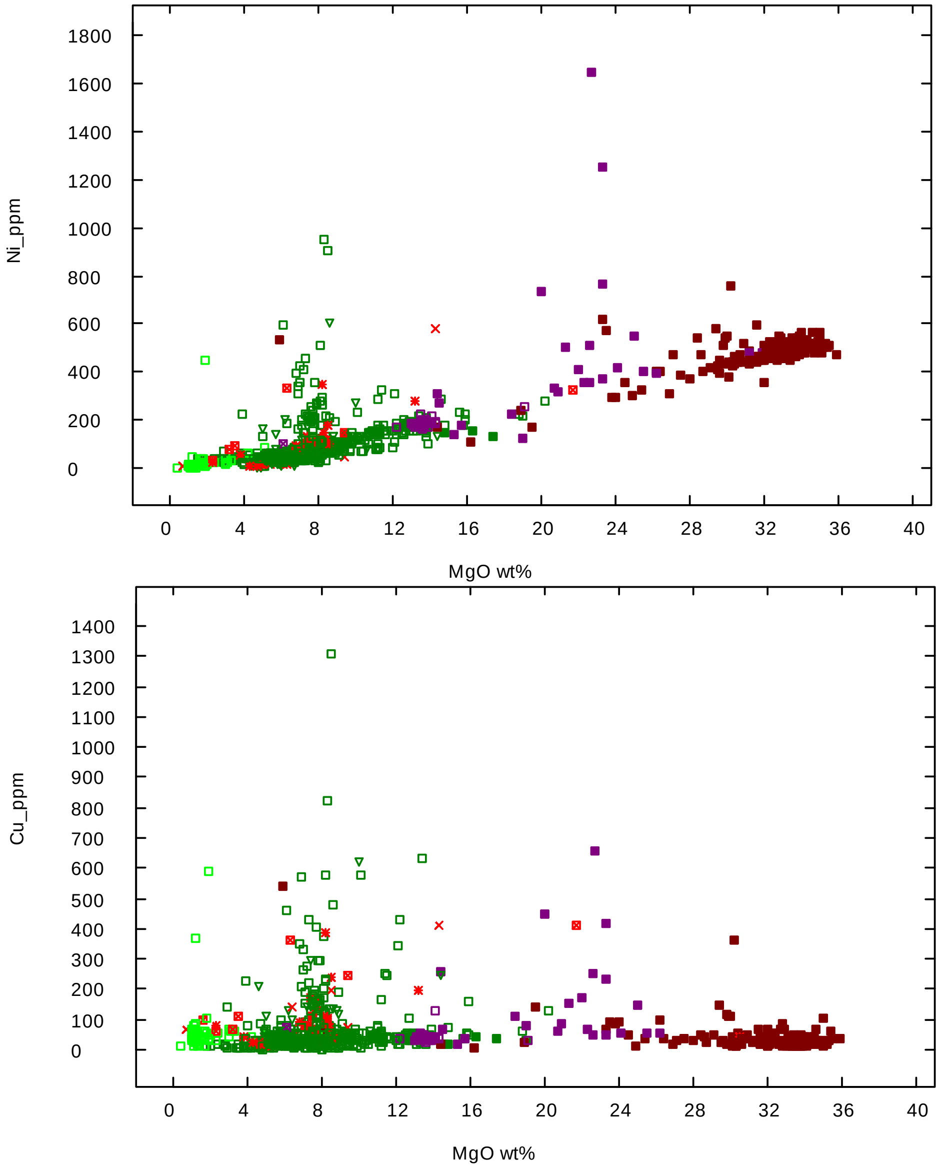
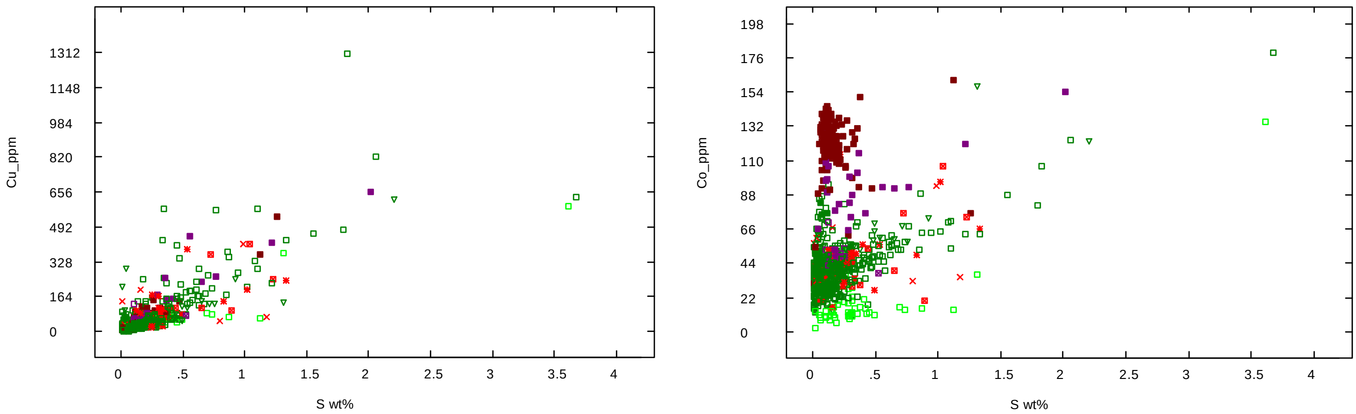



Figure 9: Variation diagrams showing a) Ni and b) Cu plotted against MgO. Filled squares: red – olivine-rich cumulates, violet – pyroxene-rich cumulates; open squares: dark green – gabbro, pale green – leucogabbro; dark green triangles: magnetite gabbro; single red crosses: diabase; double red crosses: microgabbro; red squares with cross: breccia.

The linear trend shown in Figure 9a clearly indicates that the olivine in the ultramafic cumulates at Hamn contained ca. 600 ppm Ni, which proves that it crystallized from a magma which had already been depleted in Ni (undepleted olivines in the Råna intrusion in Ofoten contain 1500 – 2400 ppm Ni, whereas depleted olivines at Råna can contain, in effect 0 Ni. Orthopyroxenes in the Råna intrusion show up to 300 ppm Ni). The consistency of the trend, including the apparent absence of ultramafic cumulates with even lower Ni contents indicates that the magma from which these silicates crystallized was not affected by any significant event of sulphide saturation during their crystallization (because this would have caused a further drop in silicate-bound Ni). This can be reconciled with the presence of the mined Ni-Cu sulphide body and of numerous lesser mineralizations if these are "exotic" in relation to their current host rocks, i.e. formed at a different level in the crust (prior to Ni depletion of the magma from which the ultramafic cumulates were derived) and emplaced at their current location as a result of mobilization and deformation processes. The coincidence of elevated values of Ni and Cu in a limited number of samples proves that the values of Ni (up to 1600 ppm) above the general linear trend are due to traces of vein sulphide and not to silicates crystallized from a pulse of undepleted mafic magma.

## 6. SULPHIDE CHEMISTRY AND MINERALIZATIONS IN THE GABBRO



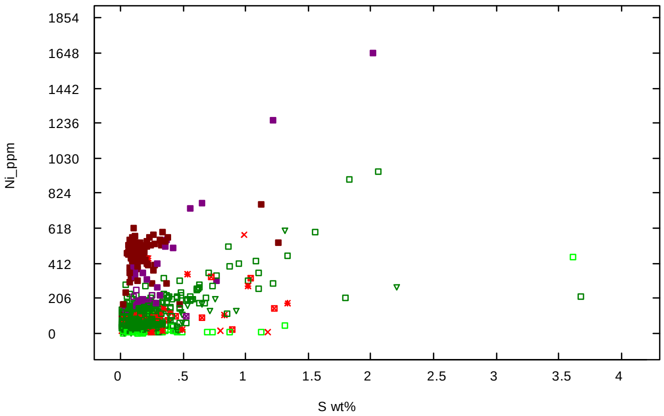




Figure 10: Variation diagrams showing a) Cu, b) Ni and c) Co plotted against S. Filled squares: red – olivine-rich cumulates, violet – pyroxene-rich cumulates; open squares: dark green – gabbro, pale green – leucogabbro; dark green triangles: magnetite gabbro; single red crosses: diabase; double red crosses: microgabbro; red squares with cross: breccia.

Few of the core samples analysed (Figure 10) contain significant sulphides. The maximum content of S is found in a hand sample of gabbro with 3.7 % S, corresponding to ca. 11% sulphides. This sample contains 218 ppm Ni, 633 ppm Cu, 179 ppm Co and 13.37% MgO. The sample contains 10 ppb Pt. Several of the clusters of samples with elevated contents of Ni and Co contain little sulphur, clearly indicating that several hundred ppm Ni and 100-140 ppm Co are contained in silicates. The sample with highest Ni content (1650 ppm) is from 0.9m of sulphide-bearing plagioclase pyroxenite at 248.0-248.9 m in DDH 4: the next-highest content (1250 ppm) is at 246-247 m in the same hole. The samples contain 58 and 61 ppb Pt+Pd respectively, the highest PGE values in the core samples analysed for PGE. The intervening sample is the third highest and the 245-246 m sample shows similar chemistry at lower levels. The location of this intersection is compatible with the mineralization being related to a down-plunge extension of the mined ore (see also below).

Traces of sulphide are common in many of the rocks at Hamn. These may be the results of renewed sulphur saturation at the level at which these rocks crystallized and due to contamination from xenoliths and direct from wall rocks. These traces would not appear to have any economic significance.

A separate Excel file has been created in order to assess samples for which the main metals and noble metal data (actual numbers for Pt, Pd and Au) are available and which include sulphide-rich samples: it includes samples from Hamn (6) and Gryllefjordbotn (4) in NGUs database, 12 core samples from the 2008 drilling programme and 21 samples from Makkonen

(2007). Only Makkonen's samples were analysed for the complete suite of PGE (including Os, Ir, Ru and Rh): where these returned values below the detection levels (in the low or sub-ppb range) half of the detection limit is used in the file, in order to facilitate statistical manipulation.

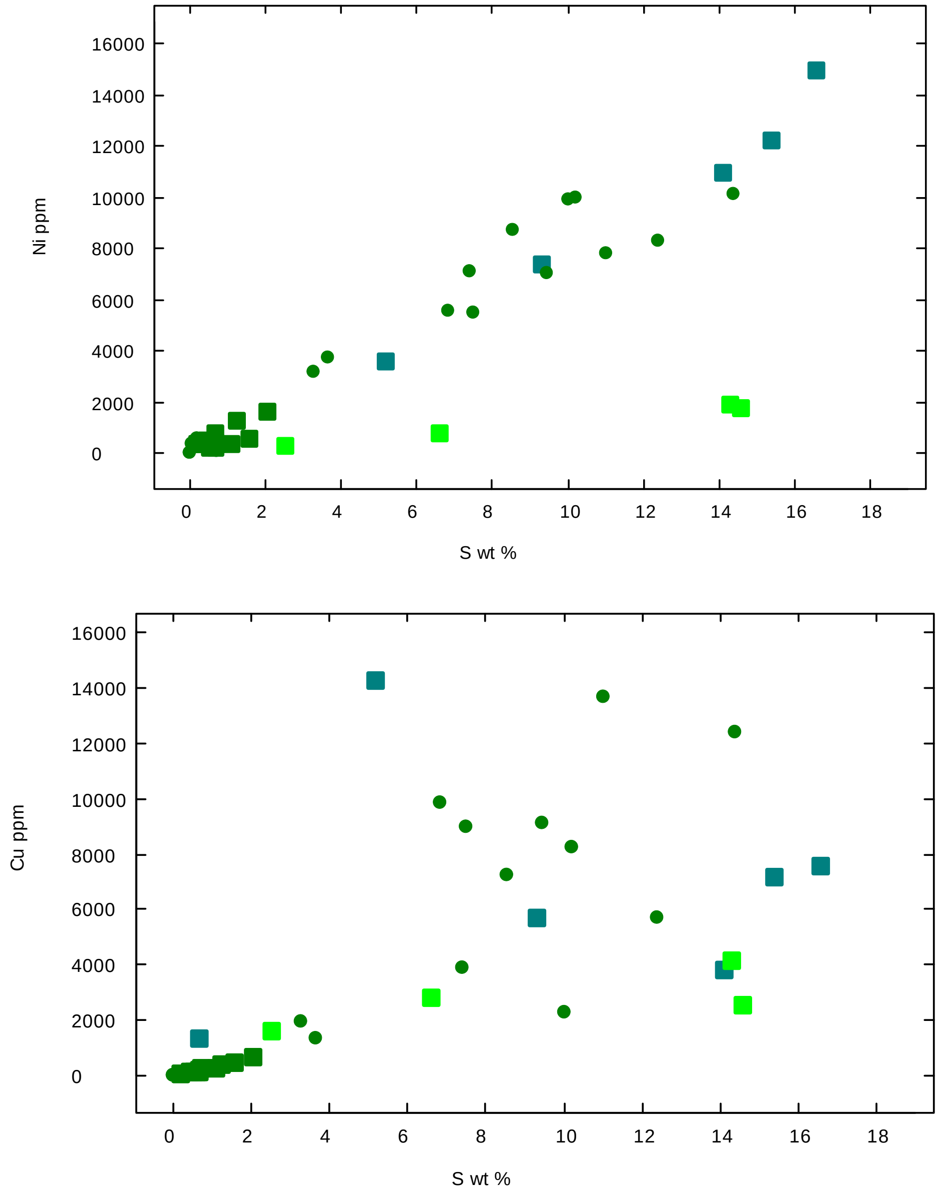



Figure 11 a) Ni v S, b) Cu v S: Filled squares: blue – NGU samples from Hamn; dark green - SNG samples from Hamn; pale green – NGU samples from Gryllefjordbotn: filled circles – Makkonen's samples (2007) from Hamn.

Figure 11a indicates that the main sulphide mineralisation at Hamn, including the sections in DDH 4, probably formed during one episode of sulphur saturation. The low, consistent level of Ni in olivine cumulates documented above clearly suggests that this episode of sulphur saturation did not take place simultaneously with crystallization of the olivine cumulates seen close to the mined ore body. Sulphur saturation (and sinking of the sulphides to form a quite massive body) must have taken place in a chamber at a lower level in the crust, depleting the magma in Ni prior to formation of the homogeneous low-Ni olivine cumulates. This assumes that the sulphides and olivine cumulates were brought to their present location by tectonic processes, possibly after imbrication of the components in the original, deeper-seated magma chamber.

The samples from Gryllefjordbotn clearly indicate formation of sulphides from a magma which was already severely depleted in Ni. Their low content of metals in the sulphide phase implies that they do not have a significant economic potential.

The scatter of Cu values shown in Figure 11b is probably due to mobilization of a Cu-rich fraction of the sulphide liquid.

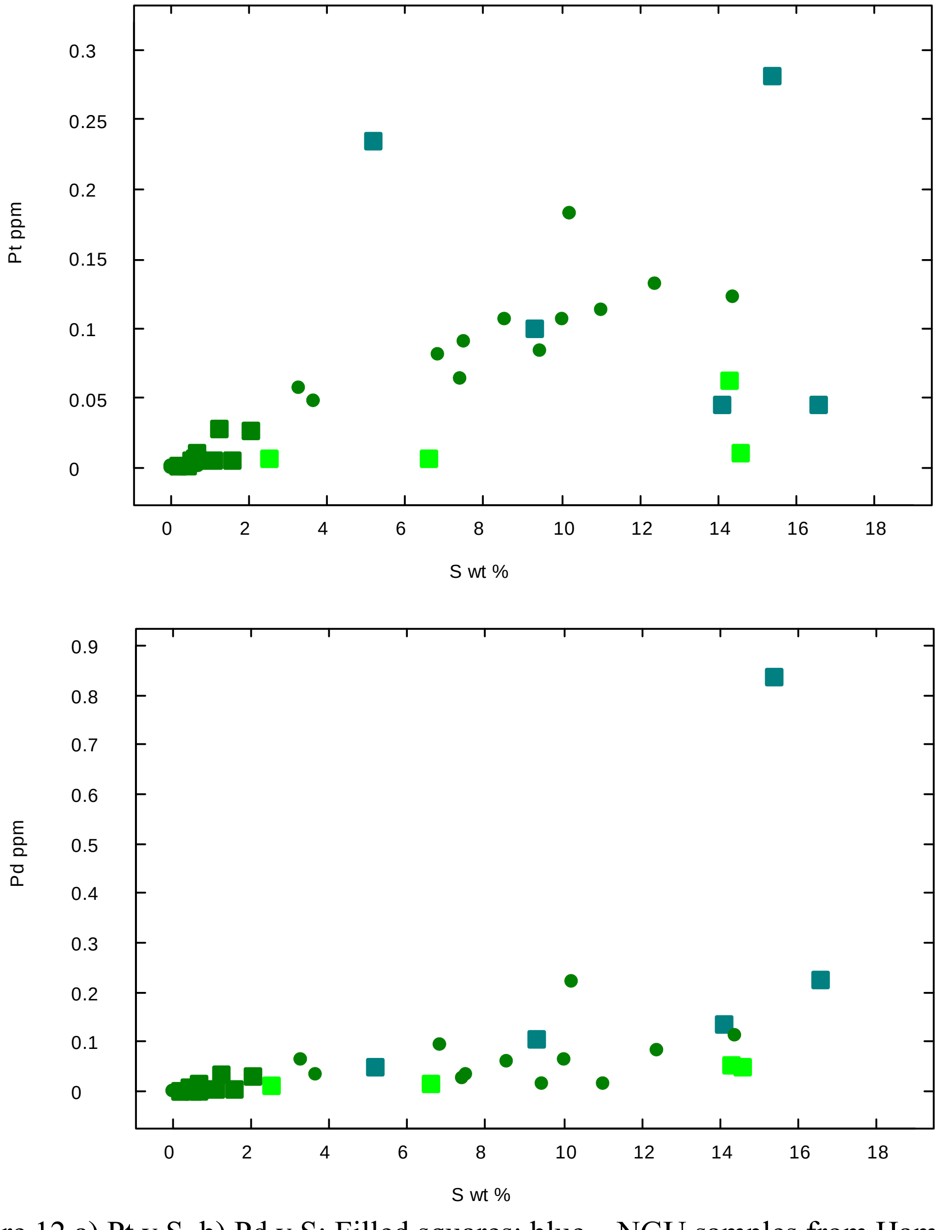



Figure 12 a) Pt v S, b) Pd v S: Filled squares: blue – NGU samples from Hamn; dark green - SNG samples from Hamn; pale green – NGU samples from Gryllefjordbotn: filled circles – Makkonen's samples (2007) from Hamn.

Figure 12 shows that the more sulphidic samples collected by NGU show a considerable scatter for Pt and Pd, while Makkonen's samples (analysed by much more sophisticated methods at GTK) mainly follow a more linear trend: the same samples show a considerable scatter of Cu values, the contrast indicating that the PGE-bearing phases are associated with pentlandite.

PGE data are commonly displayed in normalized diagrams of the type shown in Figure 13.

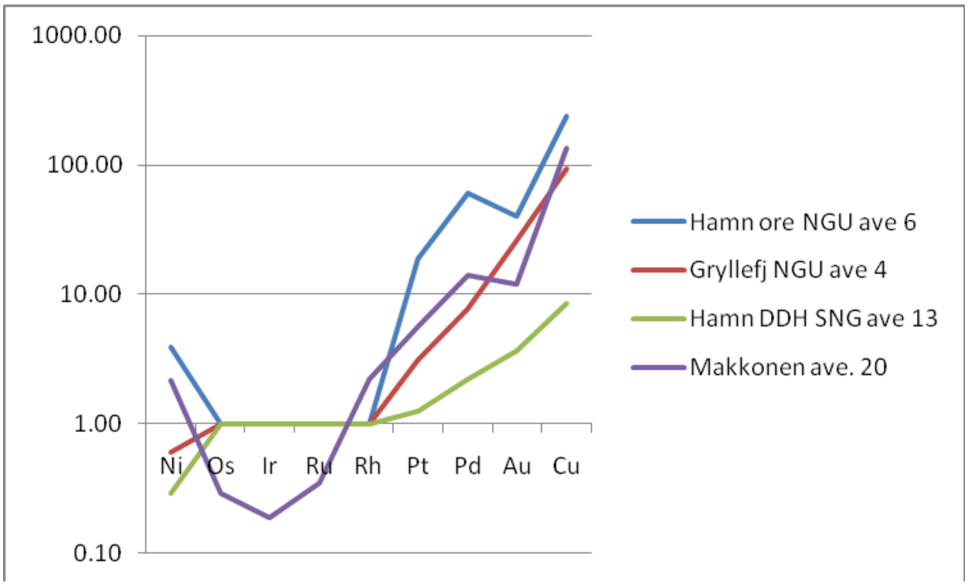



Figure 13: Mantle-normalized values for Ni, noble metals and Cu (mantle values from Barnes & Lightfoot, 2007). Note that only samples from Makkonen (2007) include values for Os. Ir, Ru and Rh.

Figure 13 illustrates several of the conclusions drawn from other diagrams above (depletion of the Gryllefjord mineralisation and of most of the samples from the 2008 drilling). The main purpose of including this diagram is illustration of Makkonen's data. Os, Ir and Ru are, in ultramafic cumulates, normally associated with chromite, commonly occurring as inclusions within chromite or as discrete grains associated with chromite. The depletion of these elements relative to mantle values indicated in Makkonen's data may indicate that the samples were derived from a magma from which chromite had already been removed.

As a curiosity it can be mentioned that mylybdenite has been observed in a roadside exposure of gabbro near Hamn. Only three samples contain > 10 ppm Mo: the richest (sample 132-HAH-2008) contains 606 ppm.

## 7. **CONCLUSIONS**

The surface expression of the Hamn gabbro and associated rocks is the result of multiple intrusive and tectonic events, including fractionation processes in a magma chamber at a lower level in the crust, crystallization from a derived magma at a higher level and imbrication (and rotation) of the resulting products before these were emplaced at their current level. The magma from which most of the rocks seen at Hamn was derived was already depleted in Ni prior to crystallization of olivine cumulates from it. This depletion may have been due to early sulphur saturation and removal of the sulphides which formed the mined mineralisation at Hamn, possibly in the lower-crustal level magma chamber (which can explain why the magma from which the olivine cumulates were derived must have been homogeneously depleted in olivine). The magma from which the olivine cumulates at Hamn crystallized was not subject to sulphur saturation while these olivines were crystallizing The rocks exposed at Hamn may not provide a complete picture of the fractionation products of the parent magma(s) and these have, in any case, been subject to deformation at different times in their evolution.

Sulphur saturation at the level at which the ultramafic and mafic rocks seen at Hamn crystallized would yield mineralizations of the type seen at Gryllefjordbotn, i.e. with low contents of metal in sulphide, because of the already depleted nature of the magma from which they were derived.

Mineralizations of the type mined at Hamn are probably the sole target with potential economic interest. The destruction, by multiple deformation episodes, of the regular type of cumulate stratigraphy seen in many pristine layered intrusions means that geophysical methods, combined with an understanding of the deformation events are the main methods which can be applied in searching for such mineralizations. The available evidence does not give a good case for the intrusion concealing much larger mineralizations than that found at Hamn: what is more likely is that geophysical methods could reveal further mineralizations of similar or smaller size in favourable structural traps.

## REFERENCES


Armitage, P.E.B. & Bergh, S.G., 2005: Structural development of the Mjelde-Skorelvvatn Zone on Kvaløya, Troms: a metasupracrustal shear belt in the Precambrian West Troms Basement Complex, North Norway. Norwegian Journal of Geology 85, 117-132.

Barnes & Lightfoot, 2007 Barnes, S.J., Lightfoot, P.C., 2005. Formation of magmatic nickel sulfide deposits and processes affecting their copper and platinum group element contents. Economic Geology 100th Anniversary Volume, pp. 179–213.

Henkel, H., 1987: Magnetic crustal structures in northern Fennoscandia, Tectonophysics 192, 57-79.

Kullerud, K., Skjerlie, K.P., Corfu, F. & de la Rosa, J.D. (2006) The 2.40 Ga Ringvassøy mafic dykes, West Troms Basement Complex, Norway: The concluding act of early Palaeoproterozoic continental breakup. Precambrian Research 150, 183-200.

Makkonen, H., 2007: Ore geological study of the Senja mafic-ultramafic intrusion, Norway, report to Store Norske Gull Ltd.

Olesen, O. & Sandstad, J. S., 2003: Interpretation of the Proterozoic Kautokeino Greenstone Belt, Finnmark, Norway from combined geophysical and geological data. Norges geologiske undersøkelse Bulletin 425, 42-62.

Peltonen, P., 2005: Svecofennian mafic-ultramafic intrusions. In: Lehtinen, M., Nurmi, P.A. & Rämö, O.T.: Precambrian geology of Finland, Elsevier, Amsterdam, 407-442.

Petrelli, M., 2005: Petrograph, version 1.0.2. http://www.unipg.it/~maurip/SOFTWARE.htm

Zwaan, K.B., Fareth, E. & Grogan, P.W., 1998: Berggrunnskart; Tromsø; 1:250 000, Norges geologiske undersøkelse .

Zwaan, K.B., Fareth, E. & Johannesen, G.A., 2003. Berggrunnskart Gryllefjord 1331 I, M 1:50.000, foreløpig utgave Norges geologiske undersøkelse.