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Ni-Cu-PGE potential of the Råna Intrusion: 2006 drilling program

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REPORT

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Summary:

This report considers: 1) The prospectivity of different parts of the Råna intrusion: 2) Data sets generated from core drilled in 2006 (and relevant core drilled by Outokumpu and NGU) and possible correlations indicated by the geology of the cores, 3) The significance of microprobe data from different parts of the Råna intrusion and 4) Possible targets for further work.

Key conclusions/proposals include:

- Variations in the assemblage of cumulate minerals suggests that there may be lateral variations in the Ultramafic Series, which explain some of the contrasts between the rocks seen at Arnes, at Bruvann and in Rånbogen.
- The cumulates intersected by the SH holes at Rånbogen may be part of a sequence, which is not seen at Arnes or Bruvann – they contain very little clinopyroxene.
- The Ultramafic Series in the southern part of the intrusion reveals part of the overall differentiation sequence (carrying olivine with lower Fo content), which is not exposed on the northern periphery of the intrusion. Though there is limited mineral-chemical data from the core of the intrusion, it may also be that the Mafic Series, as exposed, is also incomplete, parts of the chamber having been displaced by tectonic instability during crystallization (as indicated by the dykes in Råndal)..
- Amounts of nickel, which are significant in low-grade disseminated mineralization, enter into olivine and lesser amounts into orthopyroxene. Sulphide-bearing core should therefore be analyzed for sulphide-bound Ni, Cu and Co (bromine-methanol). As a check it would be useful to have a student do a microprobe project on the trace metal contents of olivine and opx in key zones.
- It could be useful to present certain problems to an expert on high-precision gravity surveys, e.g. Brudalen, the section between Bruvann and Arnes, possibly a wider area.
- The SH team could consider looking at the Saltvik area, where mineralizations investigated in pits and short adits <u>may</u> be linked by a weak EM anomaly 1000m long in norite (scattered samples show ~2% Ni_S) (Singsaas & Flood, 1963). It is <u>not</u> certain that the most sulphidic samples have the highest Ni_S. This <u>could be</u> an analogue for the mineralizations drilled in Rånbogen.
- Targets at Brudalen, Bruvann SW, Saltvik and possibly between Arnes and Bruvann W should be considered.
- The conclusion still stands that it is unlikely that the Bruvann mineralization is the richest in the complex. The gravity data indicate that the lowermost portions of the northern part of the complex, down to c. 2 km below sea level along its NW periphery, are dominated by ultramafic rocks. Investigation of this volume of rocks, even at a reconnaissance level, would require several deep drillholes. Application of the most sophisticated geophysical methods available would be a logical precursor to drilling.

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APPENDIX

1. INTRODUCTION

This report has the following main purposes:

- To give a perspective on various assessments of the prospectivity of different parts of the Råna intrusion in Nordland.
- To assess the data sets generated on the basis of holes drilled by Scandinavian Highlands in 2006 (and corresponding data sets from core drilled by Outokumpu and NGU).
- To assess possible correlations between the geology in these cores and surface geology and core from earlier projects, including the implications of eventual correlations for the prospectivity of the targeted areas.
- To assess the significance of microprobe data from different parts of the Råna intrusion for understanding of its petrology.
- To propose new targets, if appropriate.

2. REGIONAL CONTEXT

The Råna intrusion is one of a suite of intrusions and ophiolite complexes, which have very similar, early Silurian ages and which can be characterised as intraorogenic bodies within the Scandian orogen. These bodies are shown on Figure 1 and, with some additions, in Table 1.

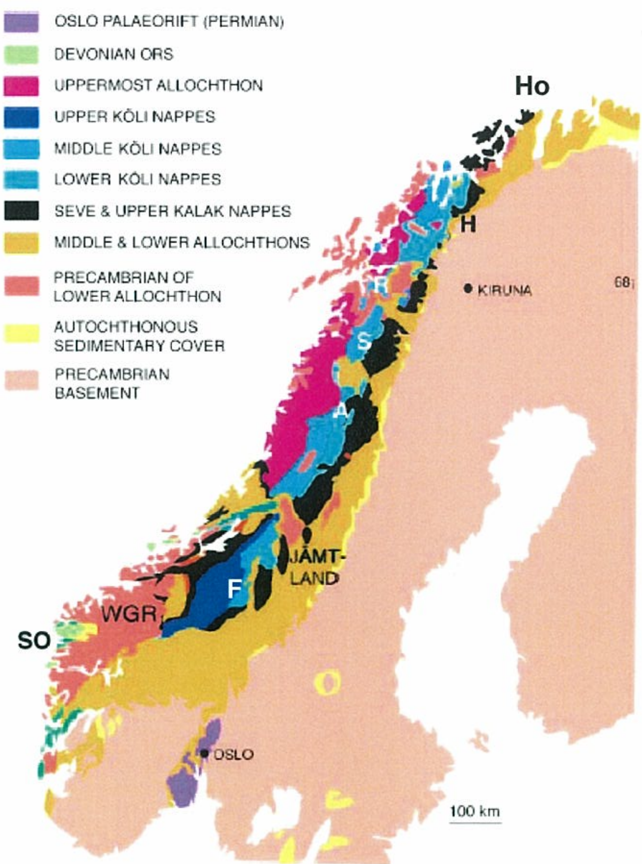

Figure1: (from Andréasson et al., 2003: Major allochthons and 445-430 Ma mafic igneous complexes in the Scandinavian Caledonides. Localities indicated, from north to south, are: Ho: Honningsvåg; H: Haldit; R: Råna; S: Sulitjelma; A: Artfjäll; F: Fongen-Hyllingen; SO: Solund.

NAME	TYPE	AGE	METHOD	REFERENCE
Honningsvåg	Layered intrusion	**438.2**+/- 0.7	U-Pb	Corfu et al., 2006
Haldit	Layered intrusion	**434**+/-4	U-Pb	Vaasjoki & Sipilä, 2004
Råna	Layered intrusion	**437**+1/-2	U-Pb	Tucker et al., 1990
Sulitjelma	Ophiolite	**437**+/-2	U-Pb	Pedersen et al., 1991.
Krutfjell	Massive gabbro	**437 +/-22**	Sm-Nd	Mørk et al., 1997
Artfjäll	Layered intrusion	**434**+/-5	U-Pb	Senior & Andriessen, 1990
Skjækerdalen	Polyphase intrusion	**436**	U-Pb	Tucker, in Hildreth et al., 2001
Fongen	Layered intrusion	**426** +8/-2	U-Pb	Wilson et al., 1983
Solund	Ophiolite	**443** +/-3	U-Pb	Dunning & Pedersen, 1988
Innset	Norite-trondhjemite	**435.8** +/-0.9	U-Pb	Nilsen et al., 2003

Table 1: Mafic intrusions of Early Silurian age in the Scandinavian Caledonides.

The existence of this suite of intrusions is interpreted to be due to a period of extension immediately prior to continent-continent collision in the Scandian Orogeny (Andréasson et al., 2003). The internal features and ratio of ultramafic to mafic components in the intrusions vary considerably. Only two of the suite, Råna and Skjækerdalen carry Ni-Cu mineralizations. Avaailable evidence suggests that Råna is the intrusion with the highest proportion of ultramafic rocks and the most magnesian olivine: it appears to be the only intrusion in which the crystallization order: olivine-orthopyroxene-plagioclase-clinopyroxene is dominant.

The Råna intrusion is located within the Narvik Nappe complex in the Upper Allochthon of the Caledonides (= Lower Köli Nappes on Figure 1). Structural relationships within and around the intrusion (Figure 2) make it clear that the host rocks were exposed to at least one phase of isoclinal folding prior to emplacement of the mafic magma, and that the intrusion and its host rocks were subjected to at least three deformation phases during and after solidification.

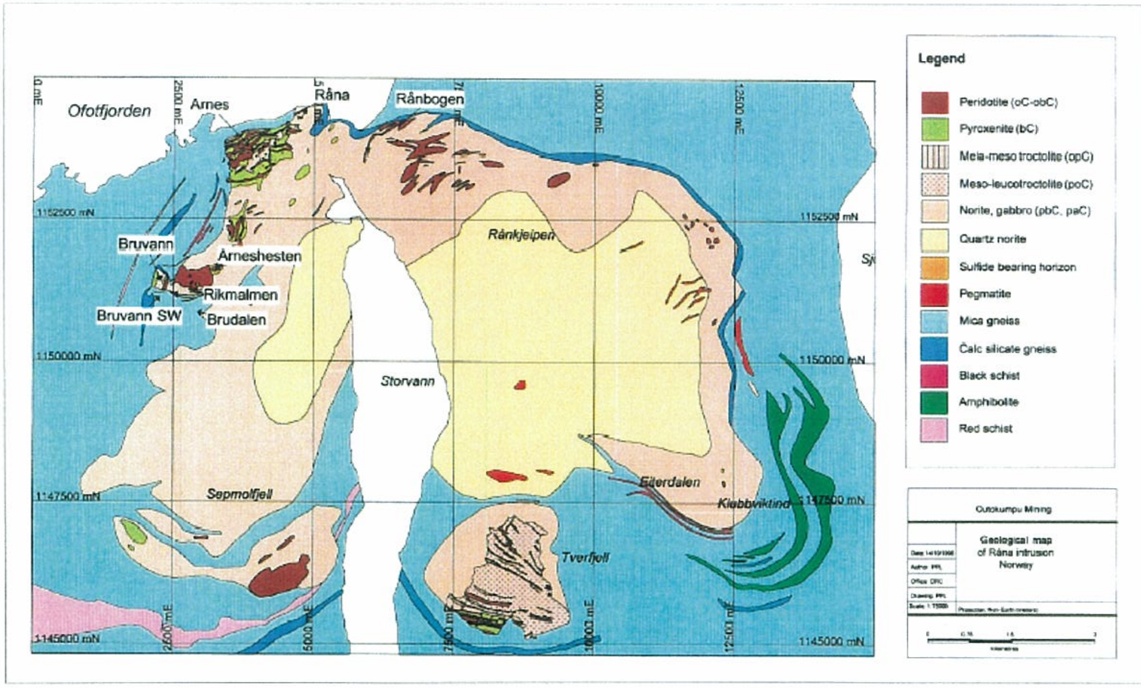

Figure 2: Geology of the Råna intrusion (after Boyd & Mathiesen, 1979; Barnes, 1986 and Karppanen, 1999).

It may be noted that bodies with petrological similarities to the Råna intrusion can be found at the same tectonostratigraphic level further south. An ultramafic body occurs near Sørfjord, on the S side of Tysfjord, 30 km SW of the Råna intrusion (Foslie, 1947). The Marko gabbro (Crowley, 1983) in Sweden lies 25 km ESE of the Sørfjord body, also at the same level: Crowley describes the Marko body as consisting of layered olivine- 2 pyroxene-plagioclase cumulates. It is conceivable that a further analogous body lies concealed under the Gicce glacier, between Sørfjord and Marko.

The surface expression of the intrusion and gravity data indicate that it has the overall form of an inverted cone, its deepest part, also containing the highest proportion of ultramafic rocks, being on the northwestern and northern margins, where predominantly ultramafic rocks extend down to a depth of at least 2.5 km below sea level, based on modelling of gravity data. Southern parts of the intrusion are much shallower: central parts of the intrusion, east of Storvatnet do not extend to any great depth below sea level and contain no significant component of ultramafic rocks. The crudely conical form is, however, probably a result of tectonic compression, bringing originally subhorizontal cumulate layers close to the N margin of the intrusion into a subvertical position. There are also clear indications in drillhole profiles from the Bruvann area, in certain outcrops (e.g. in Råndal c. 700m S of the bridge) and in some of the core described in this report of instability and intrusive relationships within the magma chamber prior to its complete solidification.

The Tverrfjell klippen, E of Storvatnet, the only near-surface part of the intrusion to show classical layering features, lies in an open E-W-trending synform: gravity data indicate that the mafic body may not extend below sea level. Synformal structures exist in the southwestern part of the intrusion but these are tight to isoclinal and are probably linked to a belt of compression and shearing, which extends eastwards along Eiterdal, structurally above the Tverrfjell klippen and possibly postdating the fold that defines the Tverrfjell structure. There are clear indications of SE-directed thrusting along the NW margin of the intrusion, the most important expression of which is the "block" extending from Bruvann to Råna, which is bounded to the SE by a series of shear zones with which several EM anomalies area associated (Singsaas, 1973). These, and possibly earlier phases of movement have resulted in the incorporation of extensive sheets of country rock, some of which are graphite- and sulphide-bearing into the intrusion.

The youngest tectonic features seen are steep-to-vertical N-S-striking faults, thin shears and fractures, among them the faults which displace the southern contact of the Tverrfjell klippen, and probably structures which influence the location of Storvatn.

3. PROSPECTING CONCEPTS

The earliest prospecting activities in the Råna intrusion took place almost 100 years ago. Numerous prospecting campaigns have been carried out, especially in the Bruvann area: these resulted in a general picture of the intrusion and of the location of the most propsepctive areas. This section will focus on the concepts, which guided prospecting in the 1970s (Stavanger Staal – NGU) and the 1990s (Nikkel og Olivin – Outokumpu), as well as the concepts presented by Lamberg (2005).

Stavanger Staal-NGU

The prospecting campaign in the 1970s aimed to apply all appropriate methods available to NGU in a systematic manner. Elements included:

- Preparation of topographic maps at 1:10,000 scale.
- Erection of a grid of profiles using the coordinates of the map series and linkage of all field activities (geological and geophysical mapping, and drilling) to the grid.
- Colour aerial photography.

- EM and VLF measurements in the area extending from Bruvann to Rånbogen (earlier surveys had covered the area from Rånbogen to Klubbvikvann (Singsaas & Flood, 1964) and Eiterdalen (Singsaas, 1964).
- Geological mapping
- Systematic drilling of the Bruvann area on 50m and 100m intersections.
- Reconnaissance drilling at six locations NE of Bruvann.

The results achieved in the Bruvann area are known (Boyd & Mathiesen, 1979; Boyd, 1980) and will not be described here.

Outside the Bruvann area the prospecting campaign was governed by the following aims:

- To check on any possibility of the presence of peridotites within easy reach of the Bruvann mineralizations – hence the two holes intersecting the central parts of Arneshesten (310-218B and 360-160), respectively oblique to the SE and vertical. The magmatic rocks in each of the holes are dominated by norite, with thin olivine-bearing layers and no mineralization of any significance. Hole 360-160 has a >65m intersection of country rock at a level compatible with it being a continuation of the wedge of country rock extending northeast-wards from the area S of Bruvann. This aim also motivated holes 245-190 and 260-170, both of which penetrated the underground westward extension of the norite ridge, which forms the northern boundary of the ore-bearing peridotites at Bruvann. The theory has also been proposed that it could be possible to intersect an underground, southwest-wards extension of the Arnes block of peridotites and pyroxenite, north of the above-mentioned ridge, in the area N and NE of Bruvann. Extreme deviation of hole 245-190 reduced the usefulness of that hole in relation to both purposes.
- To acquire information on the ultramafic rocks at Arnes and at Råna at depth. Hole 345-400 was drilled to a depth of 665m, providing an intersection of much of the package of ultramafic rocks in the Arnes block. The intersection showed the same type of geology as observed on the surface and, aside from thin zones of massive sulphide, revealed only weak dissemination. Hole 475-447 was drilled from a small roadside quarry near Råna to a depth of >600m below sea level, mainly because of the indications from gravity data that ultramafic rocks dominated the geology of this part of the intrusion at depth. The core revealed significant intersections of ultramafic rock, but with little sulphide. Other features of the hole are numerous intersections of country rock and profuse lenses of graphitic rock, some of them vuggs.
- To acquire information on the ultramafic rocks at Rånbogen at depth. Two holes were drilled at c. 6450E 4130N, towards 215°, with plunges of 45 and 60°. The cores gave geological information, but did not reveal any sulphide of significance (see later section on Rånbogen and Figure 15).
- To assess the PGE potential of the Tverrfjell klippen, based on the observation that its cumulates have been derived from mixing of magma pulses of different composition, a situation which, in other intrusions (e.g. Stillwater) has led to enrichment of PGE. There are peaks in PGE content at the appropriate levels in the Tverrfjell cumulates (Barnes, 1986), but these are at levels which are much too low to be of economic interest. Barnes (1986, 1987) concluded that a small amount (0.15 – 0.4%) of sulphides had been segregated from the parent magma, prior to the formation of any of the sulphides seen at or near the surface in the Råna intrusion, and that the parent magma of the lowermost Tverrfjell cumulates also reflect prior depletion of 15% olivine. The latter conclusion suggests that the Tverrfjell klippen was derived from magma pulses, which may have been generated or "remained" after crystallization of the Bruvann cumulates.

Outokumpu

Outokumpu carried out an exploration program in the NW part of the Råna intrusion in the period 1996-98 (Karppanen et al.. 1999). The programme included application of a wide range of methods. Petrological criteria, developed during the GeoNickel project, included:

1. Primitiveness of magma (expressed through MgO content of the rock and Fo content of olivine)
2. Crystallization series – ol-opx-pl was regarded as favourable.
3. Contamination features
4. Sulphide segregation
5. Open-system cumulates – adcumulates derived from a magma being continuously replenished (there could be alternative models for generation of adcumulates, related to expulsion of intercumulus liquid in a stable chamber).

Application of these criteria and voluminous analytical data, led to the following ranking of targets: 1) Arnes, 2) Råmbogen, 3) Arneshesten, 4) Bruvann SW and 5) Råna. Primitive compositions and contamination were decisive in this ranking.

The overall ranking of the targets considered, including proximity to existing infrastructure as a factor, was:

1. Bruvann SW
2. Rikmalmen (Bruvann)
3. Arnes
4. Rånbogen
5. Arneshesten
6. Brudalen
7. Råna
8. Råntindvann

Bruvann SW: This area represents a deep extension of the Western ore, which was not known until the 1990s (a conductor was located by Singsaas (1973) but was not investigated). It includes ultramafic units corresponding to the ore-bearing horizons in the Western ore and containing some sections with interesting Ni grades. Down-hole Protem data indicates that this horizon continues southwards with a dip of c. 40°. The extent to which this mineralization was followed up and extracted during the period 1999-2003 is not clear, but should be checked definitively.

Rikmalmen: This name was given to another southwards extension of the Bruvann mineralisation, in this case from the Eastern ore, beyond earlier identified massive ore, under the eastern shore of Bruvann. Several holes in this region intersected mineralization with >1% Ni. One of the interesting features of this area is that at least two of the holes intersected Ni-Cu sulphides hosted by calcsilicate gneiss, i.e. possible "offset" mineralizations. Such mineralizations are not a common feature around the Råna intrusion.

Arnes: This area was prioritised again, by virtue of its lithologies, primitive olivine and common occurrence of weak sulphide dissemination. The area was remapped in detail (Figure 3), giving a more precise picture than that which was available in the 1970s. Four holes were drilled (see section on Arnes) but the results did not reveal any attractive targets.

Rånbogen: Outokumpu carried out an airborne geophysical survey in this area and located several interesting targets. Part of the area was remapped. Massive sulphides in shear zones and "rich" disseminations in olivine-plagioclase-bearing cumulates were found, but both types of mineralization gave grades <2% Ni in massive sulphide.

Arneshesten: Outokumpu considered this body (immediately northeast of the ore-bearing peridotites at Bruvann, and separated from these by shear zones) to be an important target, but it was not drilled due to lack of funding. The writer considers it to be very likely that this body and others further to the northeast on top of Arneshesten are quite shallow and thus of marginal interest economically.

Brudalen: This target is a group of geophysical anomalies caused by bodies thought to lie below the synform of gneiss and other country rocks SE of Bruvann. This target was not known prior to the 1990s and has not been checked by drilling. The possibility of refining the modelling of these bodies through detailed gravity work should be considered.

Råntindvann: This target is a peridotite body with an elliptical outcrop, lying midway between the Saltvik plateau and Råntindvann. There is little information about this body in any of the reports on the intrusion.

Karppanen et al. (1999) make the following confession: *"The complexity and importance of tectonics at Bruvann were realized too late in order to study it as an essential part of the Project."*

Lamberg

Pertti Lamberg's doctoral thesis includes work on nine intrusions, not all of which carry Ni-Cu sulphides. Bruvann and other targets in the Råna intrusion have, however, an important place in the work, which represents a further development of ideas employed in the GeoNickel project in the 1990s. Lamberg (2005) advocates the use of seven criteria in a fertility analysis:

1. Primitiveness of magma (expressed through MgO content of the rock and Fo content of olivine)
2. Extent of sulphide segregation (using contamination and sulphides as indicators)
3. Ni-rich, chalcophile-undepleted magma.
4. Sulphides are magmatic and have equilibrated with a large amount of magma (= R-factor of Campbell & Naldrett (1979).
5. Coeval primitiveness (silicates and sulphides)
6. Sulphide accumulation
7. Fractionation or mobilisation of sulphides
8. Auxiliary parameters
    a. Parental magma
    b. Intrusion type
    c. Primitiveness of cumulates
    d. Type of pyroxene – orthopyroxene is most favourable.

Lamberg gives a detailed analysis of the petrology and ore geology of well-analyzed sections through the Bruvann mineralization. The following are among his key conclusions:

- The parent magma was relatively primitive, with ca. 12% MgO.
- PGE are depleted (new data are included, indicating that some sections contain significant grades of PGE in sulphides.
- The host rocks at Bruvann are divided into a Basal series, an Ultramafic series and a Mafic series, the latter two containing several cyclic units. Thee Basal series was derived from a contaminated magma pulse.
- Clinopyroxene becomes a cumulus phase first in the Mafic series.
- The sequence at Bruvann is considered to be inverted (also the conclusion of Boyd (1980).
- The sulphur in disseminated mineralization is predominantly of mantle origin, while massive sulphide has a more important crustal component (also the conclusion of Boyd & Mathiesen (1979)). The mineralizations, however, have a broader geochemical signature

indicating that contamination by country rock black schist, possibly at several different levels, has been important.
- The magma was saturated in sulphur throughout its crystallization.

Lamberg tests the tools developed for the fertility analysis (on the basis of data from all eleven intrusions) on a number of intrusions or groups of intrusions, including Råna. His analysis gives the following ranking:

1. Råna
2. Arnes
3. Bruvann S (called "Lake Bruvann")
4. Bruvann
5. Rånbogen
6. Arneshesten
7. Tverrfjell

Some elements in the ranking are due to artefacts of the data available, e.g. the lack of Co data for the Tverrfjell samples (though the low ranking of Tverrfjell may nevertheless be correct.)
Some aspects of the method lead to questions:

- Is the ranking of three targets above the known ore body at Bruvann a conclusion that might suggest some weaknesses in the balance of the method?
- This question is also raised by the fact that drilling of the most prospective layers at Arnes did not intersect significant mineralization.
- The method is purely petrological. Could the method be giving answers which are correct in relation to the nature of the cyclic units, but which do not tell anything about the location of eventual mineralization within these? Put another way, could there be mineralization 500-1000 metres down strike in these units?
-

Other comments:

- Arneshesten should not be included in the test because the targets are shallow.
- An alternative approach, especially with drillcore data available from several of the targets, would be to use the method to try to identify similarities and links between target areas, rather than contrasts. Intuitively it is most likely that all the targets in the northwestern part of the intrusion must represent intersections through a sequence of "events" and rocks, some of which almost certainly overlap. This approach necessitates concepts for the structure and tectonic development of the intrusion, as well as for its petrology.

4. CORE DATA

This section gives comments on, and questions relating to the data provided on core drilled in 2006. The comments relate only to features, which are thought to rate additional attention: those in this version will undoubtedly be subject to editing in later versions.

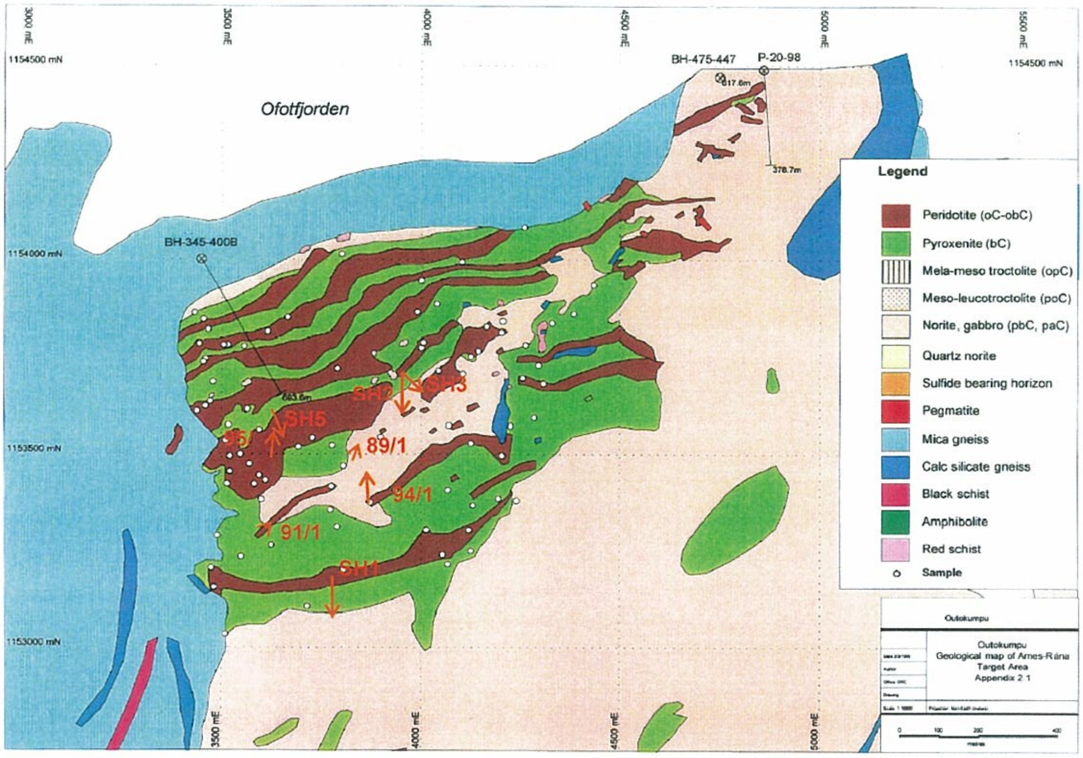

Figure 3: Geology of the Arnes area from (Karppanen, 1999). Approximate positions and directions of recent drillholes are indicated (NB: Hole 91/1 is near vertical).

Drillhole SH 001

This hole (Figure 4) is located at Arnes (Figure 3) and was drilled at 45° due S.

Bulk chemical data

The profiles indicate that the hole intersected c. 25m of dunite, and thereafter penetrated 175m of rock with gradually declining contents of SiO_2 and MgO. These trends are matched by increasing contents of Al_2O_3, Na_2O and CaO, which indicate that "up" is to the south. Variations in the overall trend at 100-120m indicate the presence of an orthopyroxene-rich layer, which interrupts rather than reversing the overall trend. This may indicate that the orthopyroxene-rich layer is a crystal-mush flow "intruding" a cyclic unit under development. The bottom part of the core, below 200m, shows abrupt variations on a scale of < 5m.

There are clear indications of trace contents of sulphides in the dunite in the first 25m of core and in the bottom 33m. The trends for Zn, and possibly Co, strongly suggest that these elements are entering into non-sulphidic phases, either as trace amounts in spinel, in a silicate or as exsolution lamellae in a silicate. Core et al. (2005) demonstrate that pyroxenes may contain 300-500 ppm Zn, even in a sulphide-bearing environment. Jagoutz et al. (2007) present data from the Chilas Complex in NW Pakistan, showing the levels of various trace elements in olivine, ortho- and clinopyroxene and plagioclase.

	Ni	Cu	Co	Zn	Sr
Olivine (Fo 78.7 - 90.1)	146 - 2467	-	-	-	-
Orthopyroxene (En 36.4 - 83.3)	191 - 234	max. 2.7	66.1 - 114	270 -262	max. 0.4
Clinopyroxene	114 - 171	max. 1.5	19.2 - 46.4	0 - 56	19 - 68.5
Plagioclase (An 49.8 - 96.7)	max. 1.8	max. 0.3	max. 0.3	4.2 - 15.5	547 - 1062

Table 2: Mineral trace element data for the Chilas Complex, Pakistan (Jagoutz et al., 2007)

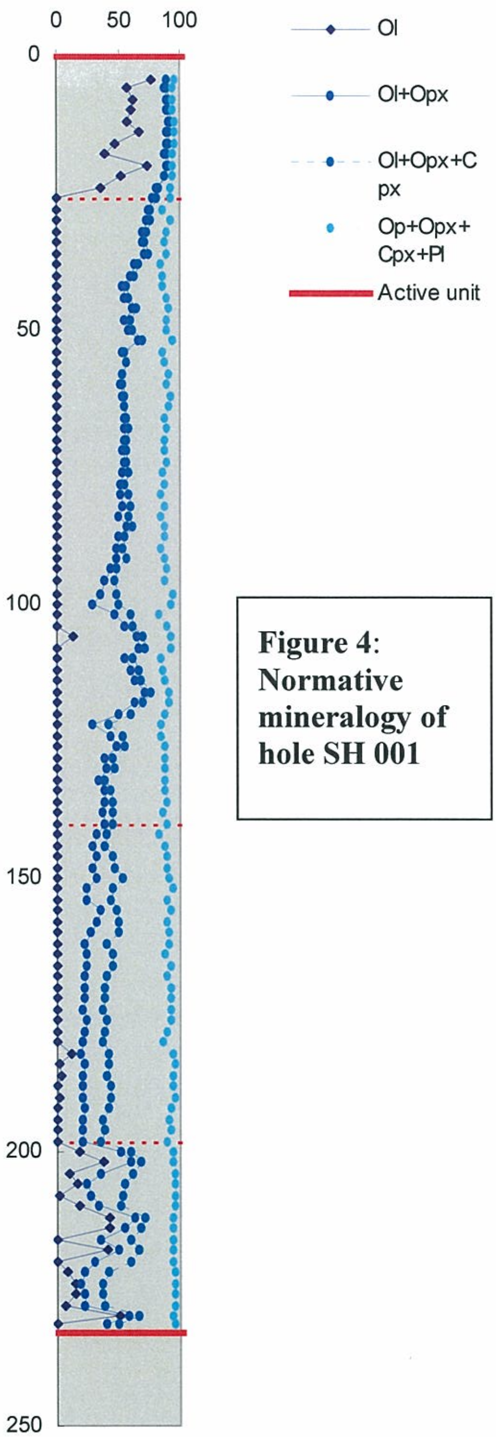

Figure 4: Normative mineralogy of hole SH 001

Normative mineralogy

The trends are as can be anticipated. Olivine is almost totally absent from 25 to 200m: this zone, except for 100-120m (see above), shows a quite steady decline in orthopyroxene and increasing plagioclase. Contents of normative clinopyroxene reach ?20% below 140m, which probably suggests that it is a cumulus phase.. The overall development suggests that this core, down to 200m, reflects products of the crystallization order: ol-opx-plag-cpx. The An content of plagioclase shows little variation. Trace contents of the oxides can be related to the overall lithology of the core – enrichment of chromite above the dunite, an overall decline in chromite and magnetite contents from 25 – 200m, and an increase in ilmenite below 150m.

Assimilation indicators

SrO reflects the normative content of plagioclase very closely. V_2O_3 and MnO show slight variations, which can be linked to variations in the norm. Co# is not a useful indicator if it is based on total Co, nor when concentrations are low (see Lamberg (2005) p. 157). (see also Table 1) The same applies to Ni/MgO.

Harker diagrams

The usefulness of Harker diagrams in relation to cumulates is limited. They would be useful if the composition or range of compositions of the main cumulate phases could be plotted as well. This would give some impression of the composition of the parental magma for the cyclic unit and of the direction in which it would be driven during, e.g. settling of olivine.

Unit definition

There is a distinct unit from c. 100m to c. 125m. There are numerous layers from 198m to 232m – this would be clearer at a different scale.

Tenor diagrams

The Co and Ni values are total values, not sulphide-bound, and are therefore misleading. It is unclear why the elevated values of Cu and Co occur at lower S values, than those for Ni. The highest two values for Cu (and most of the values for Co) are unusually high relative to the Ni values.

Other comments

- Two, different figures are entitled "Opx in norm"

- Some of the text on the last two figures (UprdZ, MPrdZ and "Nickel depleted magma" is not clearly related to the data on the core).

Drillhole SH 002

This hole (Figure 5) is located at Arnes (Figure 3) and was drilled at 65° due S.

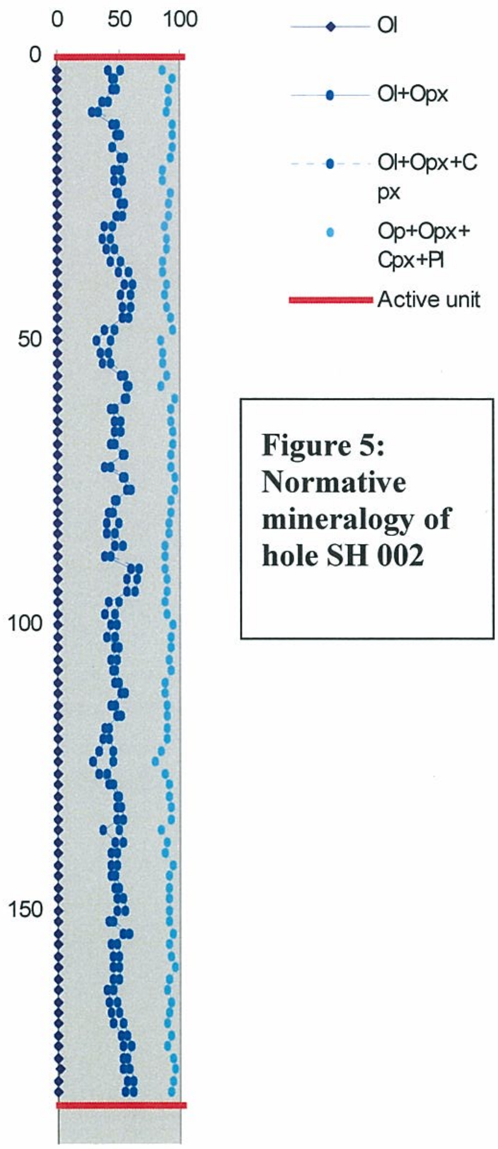

Figure 5: Normative mineralogy of hole SH 002

Bulk chemical data

The chemical profiles for this hole differ greatly from those in SH 001. They show clearly that there are no ultramafic units and no trends on a scale greater than 20 m. The profiles for most of the major elements indicate that the core consists of alternating layers, most of them 5-10m thick, controlled by variations in orthopyroxene and plagioclase contents, but with no adcumulate horizons. The lowermost 40m are more homogeneous and show a slight increase in MgO downwards. Zn (and, with the eye of faith Co) vary in step with MgO: the nature of the host rocks makes it unlikely that spinel is present to host these elements, leaving orthopyroxene or exsolution lamellae as host candidates (see above).

Normative mineralogy

These profiles confirm that the whole core is norite, without olivine and with local trace contents of clinopyroxene, certainly as an intercumulus phase. There is little variation in the An content of the plagioclase. It appears that this hole was drilled into the noritic body which appears to intrude the ultarmafic sequence at Arnes (though the reason for its location was probably an EM anomaly).

Assimilation indicators

SrO reflects the normative content of plagioclase very closely. V_2O_3 and MnO show slight variations, which can be linked to variations in the norm.

Harker diagrams

These confirm the homogeneity of the core in this hole.

Other comments

- Two, different figures are entitled "Opx in norm"
- Some of the text on the last two figures (UprdZ, MPrdZ and "Nickel depleted magma") is not clearly related to the data on the core..
- See comments on tenor diagram for SH 001.

Drillhole SH 003
This hole (Figure 6) is located at Arnes (Figure 3) at the same position as SH 002, but was drilled at 45° towards 139°.

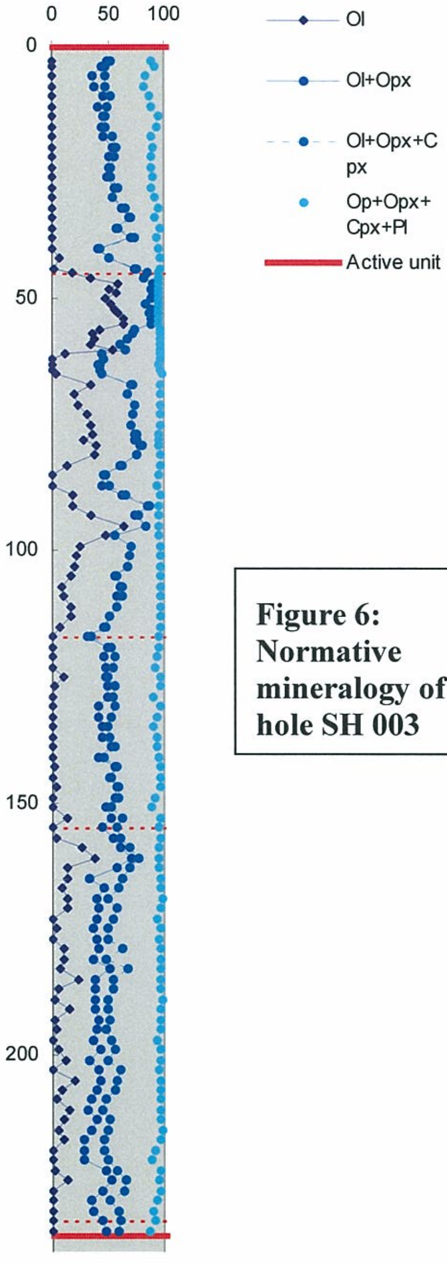

Figure 6: Normative mineralogy of hole SH 003

Bulk chemical data
The chemistry of the first ca. 45m of the hole resembles that of hole SH 002. Thereafter there are marked contrasts. From 45m to ca. 120m there is a zone with falling MgO content, with some reversals from >30% to <20%, with a parallel variation in FeO and an antithetic variation in Al_2O_3, Na_2O and CaO. There follows a quite homogeneous zone to ca. 155m, overlain by a thin, more mafic horizon, and below that, another quite homogeneous zone, with higher CaO content, down to the bottom of the hole at 236 m.

The trace elements Ni, Cu, Co and Zn show variations following closely those in MgO down to 155m. Variations in Ni, Cu and Co are irregular in the lowermost part of the hole: Zn contents are more stable, showing small peaks closely matching those in MgO.

Normative mineralogy
The norms show an increasing content of opx in norite down to c. 45m, where there is a sharp boundary to harzburgite, with 50-60% olivine below. Thereafter, there are layers of olivine norite, norite, olivine norite, norite, harzburgite and olivine norite, to c. 115m. This overall sequence and the fine detail of the mineral proportions all suggest that "up" is down the hole, i.e. towards the S. The following 40m consist of quite homogeneous norite. The lowermost 70m of the hole is gabbro, with 10-20% cpx, probably as a cumulus phase, and with erratic traces of olivine. The cpx content increases slightly downwards in the hole. The presence of cumulus cpx, combined with the renewed presence of olivine indicates the introduction of a fresh, more calcic magma pulse.

Assimilation indicators
SrO reflects the normative content of plagioclase very closely. V_2O_3 and MnO show slight variations, which can be linked to variations in the norm. Co# is not a useful indicator if it is based on total Co, nor when concentrations are low (see Lamberg (2005) p. 157). (see also comment relating to Co above) The same applies to Ni/MgO.

Most of the hole is essentially sulphide-free, including the harzburgite at 50-60m. There is clearly irregular sulphide dissemination (up to 5%) in the gabbroic unit at the bottom of the hole, which is compatible with this being the product of a fresh magma pulse: concentrations of total Cu and Ni are, however < 500 ppm, suggesting that the sulphide phase is depleted.

Tenor diagrams
See comments on SH001. The highest two values for Co are unusually high.

Drillhole SH 005
This hole (Figure 7) at Arnes (Figure 3) was drilled at 75° towards 157°.

Bulk chemical data
The profiles show a fall in SiO_2 and a rise in FeO and MgO down to c. 90m. This would normally indicate "up" to the NW. Thereafter there are approximately symmetrical rises in Al_2O_3 and Na_2O on both sides of an olivine-rich layer at c. 170-190m (see Figure 8). CaO has a stepwise rise above the olivine-rich zone. FeO and MgO show symmetrical declining trends towards the peaks due to the olivine-rich layer. Co and Zn clearly follow the same trends as FeO and MgO, confirming the indications from other cores that both elements are primarily bound to silicates or oxides. Cu and Ni have peaks coincident with the olivine-rich layer and increasing trends downwards from a low level below (but not above) the layer.

Normative mineralogy
The core has two layers with compositions close to plagioclase orthopyroxenite (0-20m and 95-120m) (see Figure 8). From 20-95m the core is harzburgitic, with an olivine content, which increases irregularly downwards.

Below 120m there is a marked peak in content of cpx (almost 50%), and below that a gradual decline in cpx, mirrored by an increase in plagioclase and with irregular variations in contents of ol and opx. The sudden influx of cpx-rich cumulates suggests a fresh magma pulse, with "up" being down the hole, i.e. towards the SE. The trend of falling cpx and rising plag is interrupted abruptly at c. 170m by a 20m thick layer of harzburgite contining no cpx and almost no plag. Plag contents vary symmetrically above and below this layer, whereas the falling cpx trend appears to continue. Below 210m there is another layer of harzburgite.

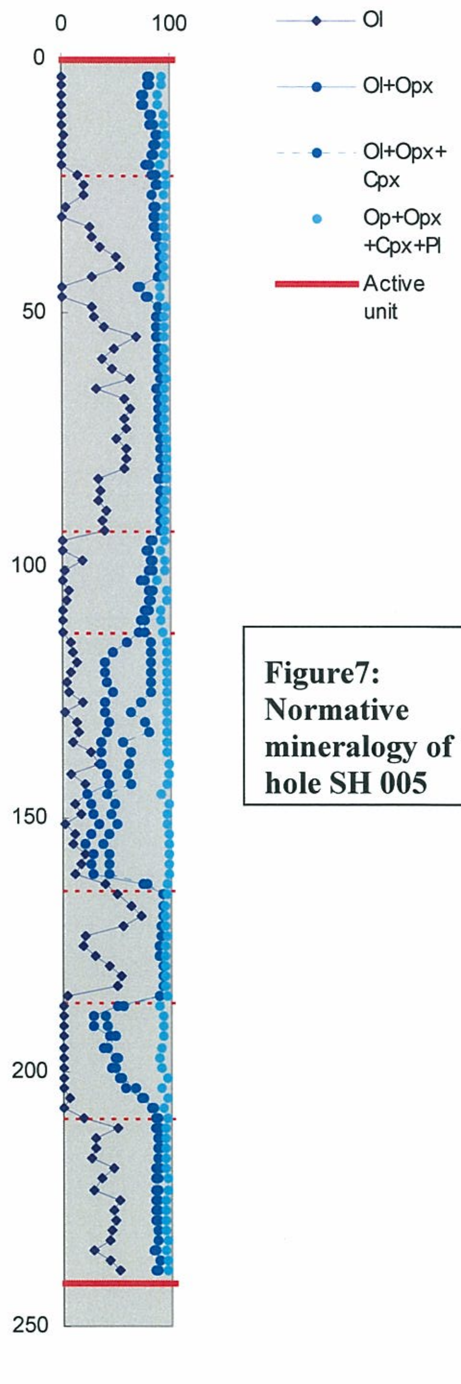

Figure7: Normative mineralogy of hole SH 005

The pattern of variations of the main phases suggests that a cyclic unit of begins with the cpx peak at 120m and that this is interrupted by a flow of ol-opx-bearing crystal mush: intercumulus liquid was then expelled from the ultramafic layer both upwards and downwards, giving plagioclase enrichment in both directions.

The variation in Il follows that of cpx to a significant extent, while that of Mt can be correlated with ol.

Indicators
V_2O_3 follows cpx closely and SrO matches plag. The sulphide content is highest in the top 90m, where Ni and Cu are low, and falls within the layer of ol-opx cumulate at 164-186m (in which Ni, Cu and Co rise).

Harker diagrams
See comments relating to SH 001.

Tenor diagrams
The Co and Ni values are total values, not sulphide-bound, and are therefore misleading. It is unclear why the elevated values of Cu and Co occur at lower S values, than those for Ni. Some of the samples are anomalously rich in Cu and Co relative to Ni.

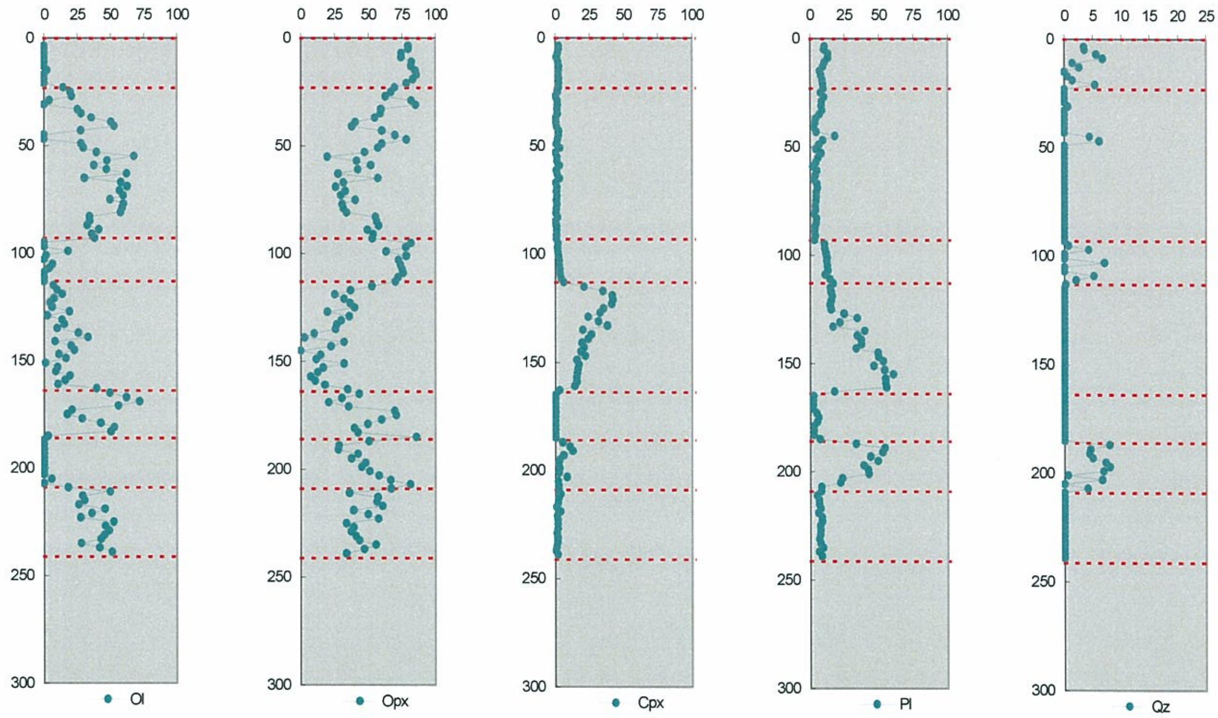

Figure 8: Normative percentages of silicates in SH005.

Drillhole 89-01
This hole (Figure 9) was drilled at Arnes (Figure 3) at c. 391-350, with a plunge of 77° towards 21°. The data provided indicate that the hole was drilled to 200m.

Bulk chemical data
The major element data show clearly that there are no major units of adcumulates in the core and that there are several intersections showing gradational changes on a scale of 10-20m. The general level of Al_2O_3 indicates that most of the core contains significant amounts of cumulus plagioclase.

The core shows low-level peaks of Ni, Cu and Co at c. 100m, 130m and 150m and generally slightly higher background concentrations from 160-200m

Normative mineralogy
Most of the core is olivine gabbro or olivine gabbronorite. There is a c. 10m thick unit, which has olivine lherzolite at c. 130m and an increasing content of plagioclase and decreasing olivine 10 m down the hole. The cpx may well be intercumulus for most of this section, but shows a slight increase downwards. Olivine is absent in most of the core from c. 70 – 130m but aside from the peak already mentioned, and another at c. 180, varies irregularly between very low levels and 20-15%. There are no clear, consistent "way up" criteria in the mineralogical variations: apparent trends in certain zones may be "reversed" in the next one.

Tenor diagrams
About 30 samples contain 2-8% sulphides. The Ni tenor is low, generally 1-2%, which is unusual for dissemination in ultramafic rock. Two samples have unusually high values for Cu and Co tenor (but not Ni). The most sulphidic sample (>12%) has low metal values.

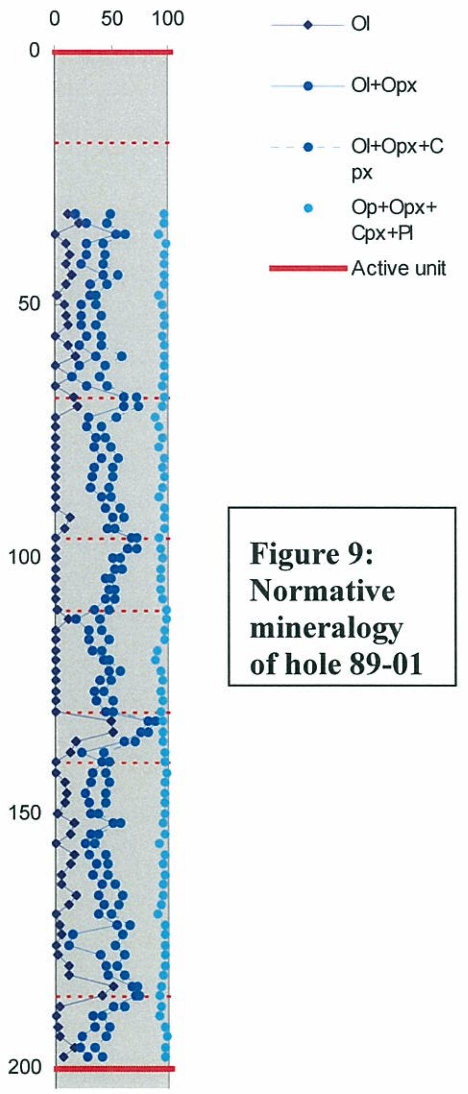

Figure 9: Normative mineralogy of hole 89-01

Drillhole 91-01
This hole (Figure 10) was drilled at Arnes (Figure 3) west of all the SH holes, with a plunge of 85° at 45°. The data provided indicate that the hole was drilled to c. 58m.

Bulk chemical data
MgO and FeO show a slight decline at c. 10 m down the hole, matched by a gradual increase in SiO_2. Ni, Cu, Co and Zn follow the same trend as MgO but at low concentrations.

Normative mineralogy
The first 10m are harzburgite and the rest of the hole is predominantly orthopyroxenite (as mapped on the surface), with thin olivine-bearing zones at c. 44m and 50m. The core appears to contain up to 10% quartz from 20m and downwards, without a significant impact on the major minerals. This may be due to secondary phenomena – e.g. pegmatites.

Tenor diagrams
These diagrams do not reflect the metal concentrations in the down-hole histograms, but show two samples with elevated grades for Cu and Co (but not Ni), which do not appear on the histograms. There would seem to be an error in the calculations.

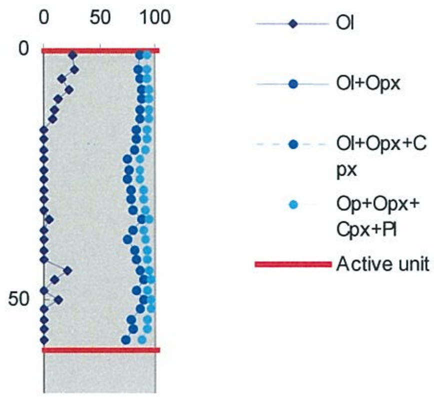

Figure 10: Normative mineralogy of hole 91-01.

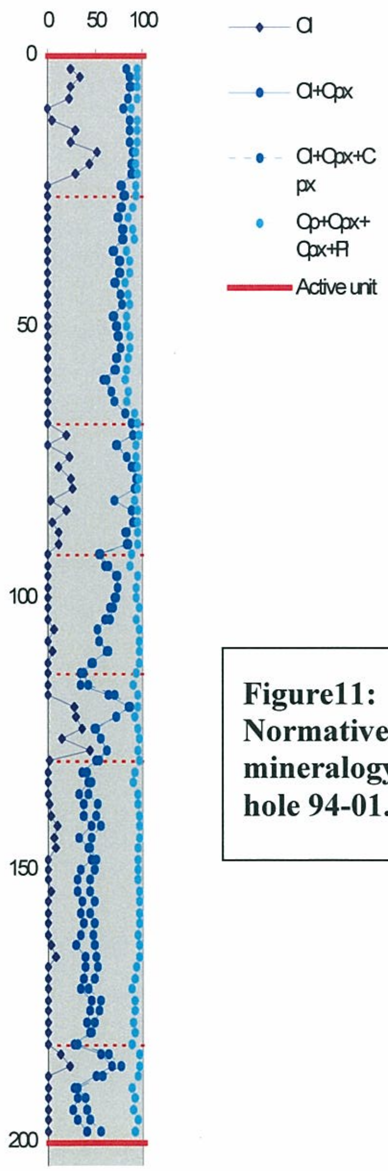

Figure11: Normative mineralogy of hole 94-01.

Drillhole 94-01

This hole (Figure 11) was drilled at Arnes (Figure 3) (389-333), with a plunge of 60° at 5° W of N. It is close to being 161m due S of hole 89-01 The data provided indicate that the hole was drilled to 199.4m.

Bulk chemical data

This core contains three more or less homogeneous zones ((22-70m, 70-90m and 130-180m) separated by zones which are irregular or gradational There is a clear gradational zone from c. 80m to c. 120m, showing falling MgO and rising CaO and Al_2O_3. This clearly indicates that "up" is to the N, the opposite of the trend seen in other holes at Arnes (it could BE that this hole is in the "Marginal Norite" of Lamberg (2005). Ni, Cu and Co show low-level peaks coincident with those for MgO. Zn follows the same pattern except for the peak at 70-90m

Normative mineralogy

The more or less homogeneous layers are:

- 22-70m: opx-rich norite
- 70-90m: olivine pyroxenite, with minor plagioclase
- 130-180m: noritic gabbro. The cpx content is <15% and may be intercumulus.

The graded layer from 80 – 120m shows an irregular decline in opx and rising plag, indicating "up" to the N.

Indicators

Normative sulphide appears to follow normative opx in the upper 130m of the hole. Variations lower down in the hole appear to be related to normative Qz.

Tenor diagrams

Samples with >3% total sulphides have low metal contents (<2% Ni), but with the Ni:Cu:Co ratios typical of disseminated sulphides at Bruvann. At lower total sulphide contents the metal contents rise to levels close to those found at Bruvann.

Drillhole 95-01

This hole (Figure 12) was drilled at Arnes (Figure 3), with a plunge of 54° towards 6° E of N The data provided indicate that the hole was drilled to 200.5m. The hole is close to the profile of NGU hole 345-400

Bulk chemical data

The most striking feature is the homogeneity of the CaO-rich, MgO-poor layer at c. 80-105m. CaO is otherwise, quite low throughout the core, and MgO generally ≤ 30%.

Ni varies in step with MgO in the upper 80m of the core. One of the curious features of the data is the increase in Ni and Cu from 150 to 200m, an increase which seems to be unrelated to variations in the content and chemistry of the silicates. Co shows an increase from 105m, similar to that in FeO and MgO.

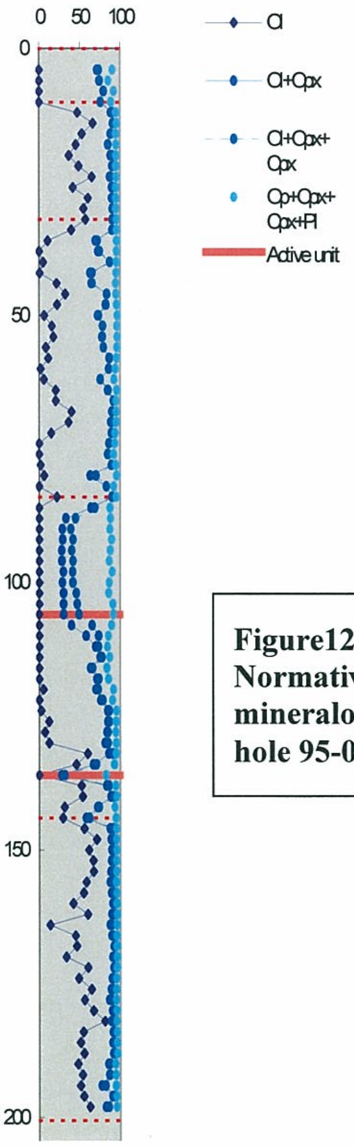

Figure12: Normative mineralogy of hole 95-01.

Normative mineralogy

The 80-105m layer consists of gabbro, with a cpx maximum and plag minimum at the base of the layer in the core (which would indicate "up" to the S). This is the only part of the core, which contains cpx. The first c. 10m of core is plag pyroxenite, followed by c. 25m of harzburgite and thereafter 50m of pyroxenitic rock with variable contents of ol and plag. From 105-35m there is a fairly homogeneous unit of plag pyroxenite, followed to the bottom of the hole by harzburgite, though with a higher content of ol than the unit from 10-35m.

Assimilation indicators

V_2O_3 and SrO vary in parallel with plag. Total sulphides are at a low level, without a clear link to the variations in silicates and without any apparent increase towards the bottom of the core, in which there is a regular increase in Ni and Cu in the last 50m

Tenor diagrams

As with all the tenor diagrams the elevated values for Cu and Co are at lower total sulphide contents than those for Ni. This must be due to an artefact of the calculation method. The absolute values reach those found in the richest ore at Bruvann and have the same metal ratios. Cu appears to have a trimodal distribution, with peaks in tenor at c. 0.5%, at 1.5-2% and at 3-4.5%.

Drillhole 345-400B

This hole (Figure 13) was drilled at Arnes, first 259m in 1977 and the remainder in 1979 (Figure 3), with a plunge of 45° towards 168°. The hole was drilled to 693.6m. Deviation measurements showed that the plunge of the hole was c. 30° when it was terminated. A profile is included in NGU Report 1582A I (Boyd, 1980).

Bulk chemical data

The chemical data confirm the original log of the core regarding the location of metasedimentary units. The hole intersects 71m of gneiss and then 14.5 m mainly of calcsilicate rock before entering the intrusion. There was significant core loss in the calcsilicate rock. At least the last 5.5m before the contact consisted of alternating gneiss and calcsilicate rock, suggesting shearing or folding close to the contact. The presence of calcsilicate rock close to the contact suggests continuity with the sector E of Råna where calcsilicate rock can be followed as far as the Klubbvikvann area. A further unit of gneiss is clearly shown at c. 260m.

The levels of MgO and FeO in relation to SiO_2, CaO and Al_2O_3 clearly indicate that the core is predominantly ultramafic. The data indicate the presence of a pegmatite at c. 580m. There is a clear, general correlation between peaks in Ni and Cu content and elevated MgO. Co peaks are much more moderate and may reflect the fact that much of the Co is in silicates. There are several marked As peaks, one of them in the gneiss close to the contact.

Normative mineralogy

The core is dominated (Fig. 13) by ultramafic rocks, mainly harzburgite (ol-opx cumulates) and pyroxenite, as is seen on the surface. There are several major units, up to c. 50m thick, with >75% normative opx, intercumulus plagioclase and no olivine. There are several thin units with c. 75% cumulus olivine at c. 600m. Between the ultramafic units there are units up to 20m thick containing cumulus plagioclase, many of them also containing cumulus cpx. Cumulus cpx dominates certain thin zones.

Several intersections show crude gradations: this applies to the pyroxenitic unit, which, from c. 320 to c. 400m shows a gradual decline in normative opx and a simultaneous increase, from c. 380m in cpx and plagioclase. The last 100m of core show first a layer of olivine cumulates, followed by a unit similar to that described above, opx-rich cumulate with increasing contents of cpx and plag towards the bottom of the hole. Two of the intersections, which are enriched in Ni and

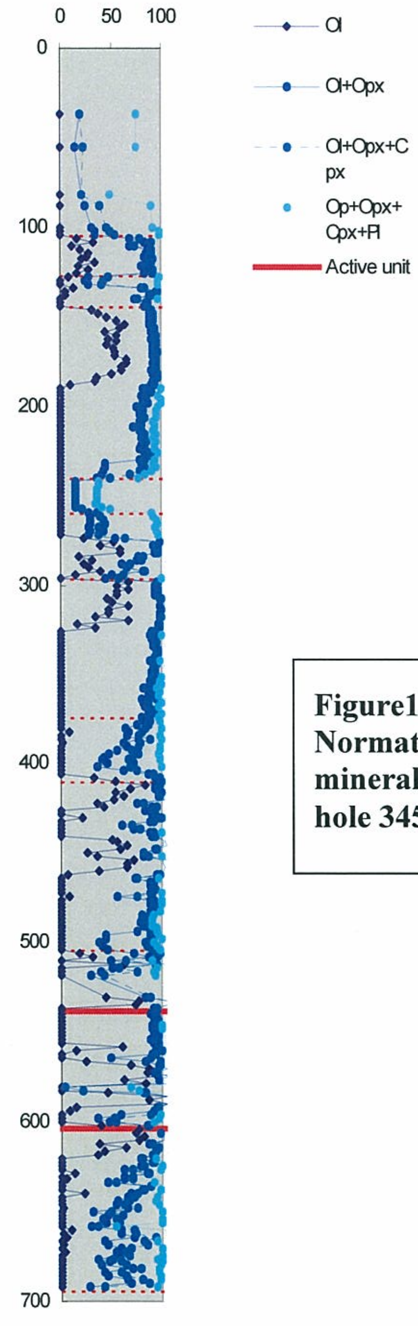

Figure13: Normative mineralogy of hole 345-400.

Cu (from 140m down and from 300m down), show gradually decreasing levels downwards: only the second of these is matched by a parallel trend in normative total sulphide.. All these gradations indicate "up" to the S, in accord with most of the other evidence from Arnes.

Assimilation indicators
V_2O_3 and SrO are clearly linked to silicates, respectively pyroxenes and plagioclase. There does not appear to be any clear relationship between sulphide enrichment and olivine cumulates.

Tenor diagrams
Samples with <3% total sulphides have unusually high metal contents: samples with>4% total sulphides have low to very low metal contents (<2% Ni).

Drillhole SH 004
This hole (Figure 14) is at Rånbogen and was drilled at the same site as SH 006, but was drilled at 65° towards 300°. The coordinates in the database are not correct.

Bulk chemical data
This core shows a complex alternation of more or less homogeneous layers with layers, which show gradations. There are

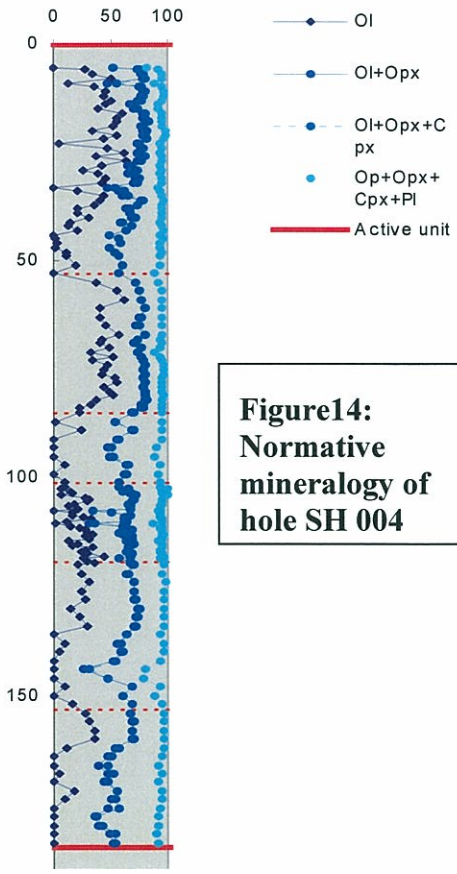

Figure14: Normative mineralogy of hole SH 004

clearly no adcumulate layers.

There are elevated concentrations of Ni, Cu, Co, As and Pb from 100 – 120m (also in narrower zones at lower levels higher up in the hole), but no Zn.

Normative mineralogy
Most of the hole consists of olivine norite – except for olivine-free zones at c. 45m, 85-100m, 140-150m, below 175m and certain thinner olivine-free zones at other levels. From 25 to c. 50m there are increasing contents of plag and opx, and a fall in the content of olivine, but from 55 – 85m there is quite homogeneous olivine norite. There is little variation in the An content of plagioclase, except for a zone of labradorite at c. 150m: this zone has several anomalous features, possibly indicating pegmatite or shearing.

The core does not contain any significant content of cpx, and much more limited normative Qz than the first three holes.. Of the trace minerals there are clear indications of enrichment in ilmenite and apatite in the zones in which Ni and Cu are elevated.

Assimilation indicators
V_2O_3 and MnO do not "see" the sulphidic zones at 100-120m.If anything the variations in V_2O_3 appear to follow those in SrO, which follow normative plagioclase.

Tenor diagrams
The Cu and Co grades are unusually high at low sulphide levels. Equally it is quite strange that the most sulphidic sample has c. 3% Ni and 0.25% Co, but no Cu.

Drillhole SH 006
This hole (Figure 15) is at Rånbogen (Figure 3): it was drilled at 510m a.s.l. at 85° towards 300°. It may be that the easting of SH004 is incorrect and that SH004 was drilled from the same location.

Bulk chemical data

This core consists of three zones, 0 – 60m, 60 – 120m and then remainder of the hole to 166m. There are "anomalous" zones at 40m, 60m, 86m, 115m, 135m and 140m. Some of these are probably related to pegmatites, with or without shearing (several have anomalous levels of K_2O and Na_2O.

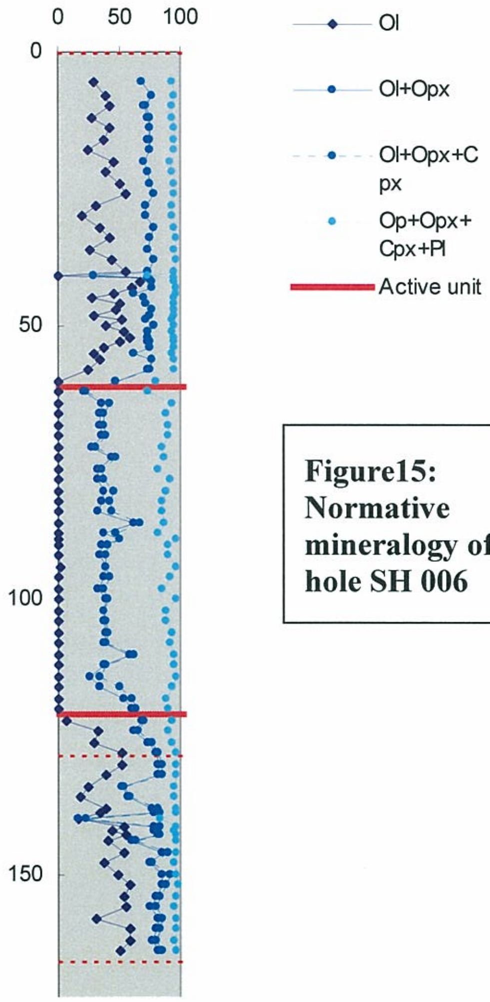

Figure15: Normative mineralogy of hole SH 006

Ni, Cu, Co and Zn are elevated in the top 60m – along with MgO. Ni, Cu, Co and Mo show peaks at 90m, 118m and 142m – these are unrelated to anomalous levels of MgO.

Normative mineralogy

The uppermost zone is olivine norite, with cumulus ol, opx and plag. The lowermost zone is more harzburgitic. The middle zone is ol-free norite, with traces of intercumulus cpx and possibly intercumulus qz.

Assimilation indicators

V_2O_3, MnO and SrO show clear variations related to the major silicates, except for the Sr= peak at 140m. Sulphide peaks coincide with those for Ni, Cu and Co (see above).

Harker diagrams

These illustrate the relative homogeneity of the units intersected in this hole – even more so if some of the "outliers" are related to pegmatites or sulphide veins. This hole (and several of the layers in others) provides clear evidence that several different types of process, involving differing influences from gravity-related processes, diffusion-related processes, possibly lateral variations within layers and instability in the magma chamber have been active.

Tenor diagrams

The Co and Ni values are total values, not sulphide-bound, and are therefore misleading. It is unclear why the elevated values of Cu and Co occur at lower S values, than those for Ni. Some of the samples are anomalously rich in Co relative to Cu and Ni.

Holes 645-413B and C

Figure 16 gives a slightly simplified version of the geology of these two holes, which were drilled in Rånbogen in 1979. The holes were drilled from approximately the same point, at different plunges, in the same direction. The only way of explaining the contrast in the geology in the uppermost 70m of the holes is that the peridotite intersected in hole 645-413C dips very steeply and was not cored in the uppermost 20m of hole 645-413B.

Most of the bottom 58m of hole 645-413C consists of calcsilicate rock. This lies close to the level of a zone of 70m in which the core was lost in hole 645-413B (with thin zones of strongly deformed calcsilicate rock, in norite, above and below). The possible correlation is that the calcsilicate unit dips SW and was lost in 645-413B.

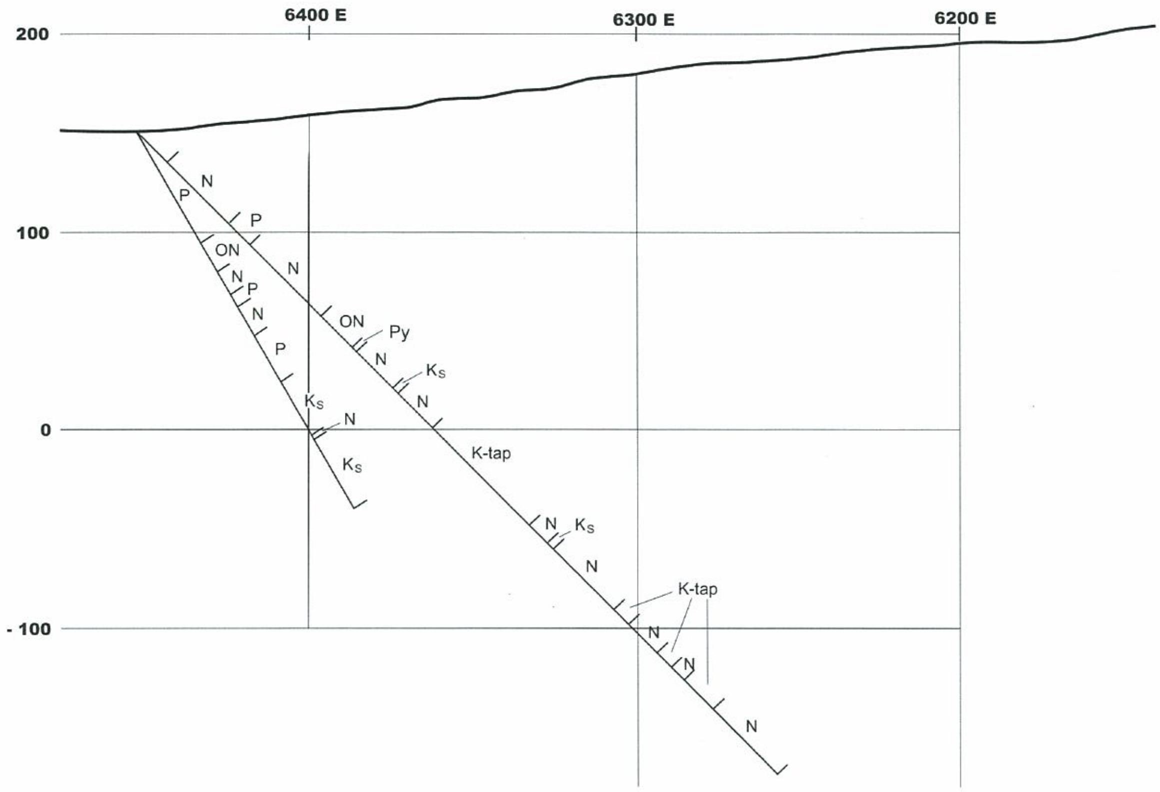

Figure 16: Profile towards 215^0 through drillholes 645-413B and C. (P = peridotite, Py = pyroxenite, N = norite, ON = olivine norite, Ks = calcsilicate rock, Ktap = core loss)

The bottom 150m of hole 645-413B consists almost entirely of norite (except for several sections in which core was lost): the absence of olivine-bearing rocks is notable. Another feature is that the lowermost 30m includes three dykes of micronorite. Rocks of this type are found in road cuttings in Råndal. 645-413B contains dm-Cm intersections of massive sulphide veins and matrix-sulphide, all in norite. Analytical data are in accord with surface sampling of massive sulphides, showing low contents of metals in total sulphide (the highest metal values are 0,27% Ni, 0,17% Cu og 0,013% Co in a sample with 7,14% S).

A norittic zone with rich sulphides in dm-thick veins at 86,6 – 89,3 m in hole 645-413C may correspond to a similar zone in hole 645-413B at 60,8 – 63,5m. The analytical results all show low metal contents in relation to S.

5. ARNES: OVERALL FEATURES AND CORRELATION

"Way-up" and its implications

Detailed, comparable data from nine holes at Arnes are described in this report. Four show clear evidence of "way-up" to the S, three show no clear evidence of directional gradations, one show indications of "way-up" to the N, and one core shows evidence of both directions. Of the holes without clear evidence one (SH002) was drilled into norite, which is intrusive into the sequence of ultramafic cumulates, and another (91-01) was near vertical. Collectively, the evidence strongly suggests that "way-up" is to the S, which is compatible with the theory that the ultramafic cumulates at Arnes represent the northern limb of an antiformal structure, cored by norite and with an inverted sequence from country rock, through marginal norite (Basal Series of Lamberg (2005)) and into the Ultramafic Series (Lamberg (2005) defining the structure. Remains of the "uppermost" part of the Ultramafic Series are exposed on the top of Arneshesten and its continuation forms the southern limb of the antiform in the Bruvann area.

The surface geology of the Arnes area (Figure 3) clearly indicates intrusion of norite into the layered cumulates of the Ultramafic Series. Relationships in the southern parts of certain N-S drillhole profiles in the Bruvann area (e.g. 2600 E) may also be due to intrusion of norite into the Ultramafic Series. It is also clear from several N-S drillhole profiles in the Bruvann area (e.g. 2350E and 2450E) that the Ultramafic Series is cut by the norite "core" in the antiformal structure. There are several ways of explaining these relationships: the following is one:

1. Formation of the Basal and Ultramafic Series on the inward-dipping floor of a magma chamber in the form of an inverted cone.
2. Compression from the NW, leading to the overturning of the N margin of the chamber and thrusting of the NW block of the intrusion to the SE <u>before</u> the Norite Series had crystallised (completely).
3. Upward intrusion of norite into the now inverted Ultramafic Series.
4. Continued thrusting of the NW block of the intrusion to the SE, along shear zones on the SE side of Arneshesten. This tectonic phase also led to development of shear zones along internal contacts (e.g. the contacts between the norite core and the Ultramafic Series) and to incorporation of slices of country rock into the intrusion.
5. Late-stage, possible near-brittle shearing and faulting, including the hinge fault at Bruvann.

Crystallization orders in the ultramafic cumulates

There is a concensus between Boyd & Mathiesen (1979), Boyd (1980) and Lamberg (2005) that the Ultramafic Series is dominated by products of the crystallization order: olivine-orthopyroxene-plagioclase-clinopyroxene. Deviations from this order may enable correlation between cumulate sequences,

Hole SH002, drilled into norite, contains low levels of normative clinopyroxene, certainly almost exclusively intercumulus. Holes SH001 and SH003 both show cumulus clinopyroxene in zones in the lower parts of the core: comparison with the abundance of the other cumulus phases shows that the clinopyroxene is clearly the fourth cumulus phase. Hole SH005 has, however, a cyclic unit (Figure 8), in which clinopyroxene appears to follow orthopyroxene (with intercumulus olagioclase and olivine), before plagioclase becomes a major cumulus phase. This magma pulse appears to have some similarity to those described by Lamberg (2005) from the Mafic Series (see his Figure 27), but it has probably had a higher CaO/MgO ratio, leading to earlier introduction of clinopyroxene.. Hole 95/1, located close to SH005, also contains a layer of opx-plag-cpx cumulates (no intercumulus olivine) but without the same gradational features as the zone in hole SH005. It is probable that these are the same zones. The presence of units containing cumulus clinopyroxene at this "level" in the sequence at Arnes suggests, by comparison with Lamberg's data from Bruvann, that this unit lies above the Ultramafic Series. That leads to the question of the status of the units of olivine-orthopyroxene-bearing cumulates mapped on the surface to the SE: note, however, that hole SH001 consists of norite from c. 25m to c. 145m (harzburgite above), suggesting that the continuous zone of pyroxenite S of SH001 shown on Figure 3 may not exist.

Hole 345-400 provides an oblique section, through much of the "lower" part of the Arnes sequence: a close analysis of the variations in abundance of cumulus phases, as shown by the norms, indicates that the cyclic units commonly consist of several tens of metres of olivine-rich cumulates, followed by somewhat thicker units of orthopyroxene-rich cumulates. Above the latter, e.g. at 250m and 500m, there are layers of 10-15m, in which clinopyroxene is an important, if not dominant cumulus phase, prior to the entry of plagioclase as a dominant phase. In other cyclic units plagioclase and clinopyroxene appear to crystallize simultaneously, while below 620m, plagioclase is a major phase before clinopyroxene. The apparently "earlier" presence of clinopyroxene in the cyclic units at Arnes can be interpreted in at least two ways:

- The cyclic units are discontinuous laterally
- The cyclic units are continuous but show clear lateral variations (a common phenomenon in a number of layered intrusions, e.g. Fongen-Hyllingen (Wilson & Sørensen, 1996).

The geometry of hole 345-400 is such that no attempt has been made to make correlations with the more recently drilled holes at Arnes: the closest hole, SH005, is c. 500m from hole 345-400 at their closest point.

6. RÅNBOGEN: OVERALL FEATURES AND CORRELATION

Two of the holes at Rånbogen, SH004 and 645-413C, show clear indications of "way-up" to the S. The other two holes do not show contradictory indications. While this is in accord with the information from the drill holes at Arnes, there is reason to believe that the geology of the Rånbogen area may be more complex. It is clear, from geophysical data, from outcrop and from the NGU holes shown in Figure 15 that at least the northern part of the Rånbogen sector is dissected by a number of laterally extensive shear zones, partly graphitic and partly carrying remobilised sulphides. There are, in some cases, related to structures, which extend to the outer contact of the intrusion and are associated with wedges of calcsilicate rock. Figures 15 suggests that there are numerous slices of calcsilicate rock, but the profile does not make their structural relationships clear.

Neither of the SH holes at Rånbogen shows units carrying cumulus clinopyroxene. Both holes contain major units of olivine norite: cpx-free olivine-orthopyroxene-plagioclase cumulates are not a common feature at Bruvann (Lamberg, 2005 – Figure 27) nor in the holes at Arnes. This may indicate that the cumulates intersected by the SH holes are a part of cyclic units not seen at Bruvann and Arnes, either because of lateral variations in the magma chamber, or because they have been excised tectonically.

7. RANGE OF OLIVINE AND ORTHOPYROXENE COMPOSITIONS

Figure 17 shows a compilation of the range in composition of olivine and orthopyroxene in different sectors of the intrusion. The sources are Barnes (1986), Lamberg (2005) and unpublished microprobe data acquired by the undersigned and Mathiesen in the early 1980s. The data from Barnes (1986) are based on samples collected along three profiles across thecumulates on Tverrfjell and include 153 analyses of olivine and 123 of orthopyroxene. Lamberg (2005) has a database showing that 225 samples from Bruvann have been analysed and that the data include c. 90 analyses of olivine and 67 of orthopyroxene. Thee unpublished NGU data include 100 analyses of olivine from Bruvann and 69 from other parts of the periphery of the intrusion, 48 analyses of orthopyroxene from Bruvann and 62 from other parts of the intrusion.

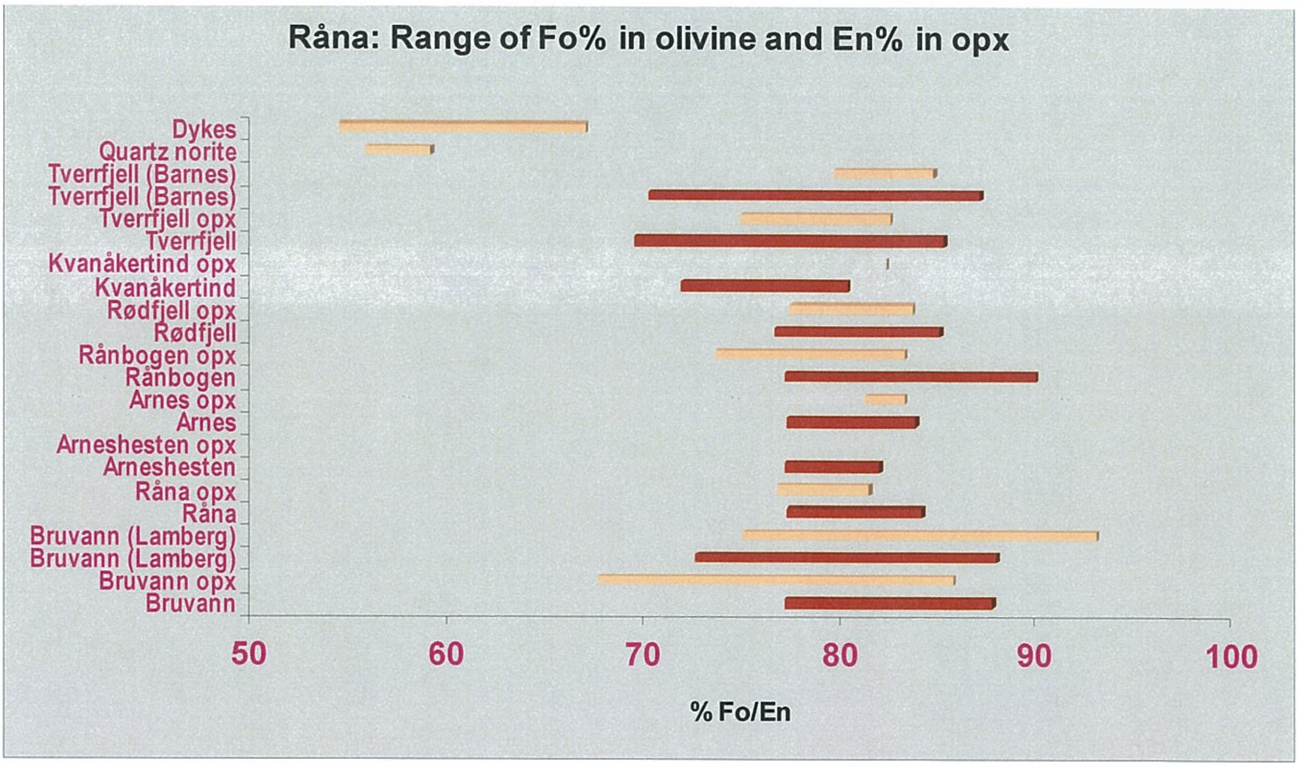

Figure 17: Range of olivine and orthopyroxene compositions in different sectors of the Råna intrusion, including data from Barnes (1986) from Tverrfjell and from Lamberg (2005) from Bruvann. Data for olivine are in brown and for orthopyroxene in fawn.

A number of observations can be made on the above figure:

- The range of olivine compositions found in samples from Bruvann includes that found in all samples from the northern periphery of the intrusion and at Rødfjell on the eastern contact, with the exception of one sample from Rånbogen, which contains olivine at $Fo_{89,9}$. This is compatible with broad continuity in formation of the Ultramafic Series along the northern rim of the intrusion.
- The range of compositions found by Lamberg (2005) for orthopyroxenes from Bruvann shows that the most magnesian orthopyroxene has a higher Mg# than the most magnesian olivine. This is also the case for cumulates with a similar mineralogy in the Stillwater intrusion in Montana (McCallum, 1996), though not in the Bushveld Complex (Eales & Cawthorn, 1996)..
- The range of olivine compositions found at Tverrfjell by NGU and by Barnes (1986) extends to more fayalitic compositions than those found on the northern periphery of the intrusion. This also applies to the three analyses from the southwestern part of the intrusive (Kvanåkertind). This suggests that there are stages in the magmatic development of the intrusion, which are not exposed on the northern periphery of the intrusion. It is also the case, though not illustrated by this type of figure that the most magnesian olivines and orthopyroxenes at Tverrfjell, in both sets of data, occur well above the outer contact (which is, in any case, tectonic).
- No attempt was made to make a systematic collection of samples of the core of the intrusion: the range of orthopyroxene compositions shown in Figure 16 is probably much less than the true range.
- Most of the samples characterised as "dykes" are from two exposures in Råndal. These show plagioclase pyroxenite intruded successively by augite norite, pegmatitic norite, micronorite, titaniferous micronorite and finally, garnet trondhjemite. The four varieties of norite contain pyroxenes with successively lower Mg#.. These dykes probably represent phases of the development of the intrusion, which are not fully represented in the surface geology, and bear witness to the tectonic instability of the intrusion also in its later magmatic stages.

The sets of mineral analyses show that olivine and orthopyroxene both contain significant contents of nickel.

- The NGU data show that the olivines contain up to 2405 ppm Ni. The most forsteritic olivine contains 1674 ppm Ni, but the most nickel-rich olivine has an Fo content of 77.4%..
- Barnes (1986) found a maximum Ni content of c. 1300 ppm in olivine from Tverrfjell: her data also indicates Ni contents of up to 380 ppm in orthopyroxene.
- Lamberg (2005) shows that the Ni contents of olivine at Bruvann range from c. 375 to c. 1350 ppm and those of orthopyroxene from quite low values up to c. 300 ppm, i.e. values very similar to those from Tverrfjell.

8. CONCLUSIONS AND PROPOSALS

Conclusions

- Variations in the assemblage of cumulate minerals suggests that there may be lateral variations in the Ultramafic Series, which explain some of the contrasts between the rocks seen at Arnes, at Bruvann and in Rånbogen.
- The cumulates intersected by the SH holes at Rånbogen may be part of a sequence, which is not seen at Arnes or Bruvann – they contain very little clinopyroxene – but its possible eastward continuation might bee worth investigation.
- The Ultramafic Series in the southern part of the intrusion reveals part of the overall differentiation sequence (carrying less forsteritic olivine), which is not exposed on the northern periphery of the intrusion. Though there is limited mineral-chemical data from the core of the intrusion, it may also be that the Mafic Series, as exposed, is also incomplete, parts of the chamber having been displaced by tectonic instability during crystallization (as indicated by the dykes in Råndal)..
- It is clear that amounts of nickel, which are significant in low-grade disseminated mineralization, enter into olivine and lesser amounts into orthopyroxene.
- A (much) more ambitious "external" project would be to try to get firmer information on the tectonics of the intrusion (see Karppanen, 1998).
- It is important to register all features suggesting instability at the magmatic stage (e.g. disturbance of cumulate textures, flow features, intrusive features, etc.) and all tectonic features. These can be used as part of the basis for an "event" chronology.
- It could be useful to present certain problems to an expert on high-precision gravity surveys, e.g. Brudalen, the section between Bruvann and Arnes, possibly a wider area. (The last gravity surveys were done 10 years ago).
- The SH team could consider looking at the Saltvik area, where mineralizations investigated in pits and short adits may be linked by a weak EM anomaly 1000m long in norite (scattered samples show ~2% Ni_S and 0.~2% Co_S.) (Singsaas & Flood, 1963). It is not certain that the most sulphidic samples have the highest Ni_S. This could be an analogue for the mineralizations drilled in Rånbogen.
- The conclusion still stands that it is unlikely that the Bruvann mineralization is the richest in the complex. The gravity data indicate that the lowermost portions of the northern part of the complex, down to c. 2 km below sea level along its NW periphery, are dominated by ultramafic rocks. Investigation of this volume of rocks, even at a reconnaissance level, would require several deep drillholes. Application of the most sophisticated geophysical methods available would be a logical precursor to drilling.

Proposals

- Sulphide-bearing core should therefore be analyzed for sulphide-bound Ni, Cu and Co (bromine-methanol).
- As a check it would be useful to have a student do a microprobe project on the trace metal contents of olivine and opx in key zones.
- The core logs should include descriptions of all disturbances in cumulate textures, flow features, intrusive features, etc.) and all tectonic features.
- The potential of using the best available technology in gravity measurements should be investigated.
- Targets at Brudalen, Bruvann SW, Saltvik and possibly between Arnes and Bruvann W should be considered.

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APPENDIX 1: SUMMARY OF NGU MICROPROBE DATA ON OLIVINE AND ORTHOPYROXENE

Olivine									Opx
Probe sample	Region	ØK Ø	ØK N	Depth (-)	Rock	Fo	NiO (wt%)	Ni (ppm)	En
10-1	Råna	4750	4470	-32,4	Peridotite	81.7	0,076	597	
10-2	Råna	4750	4470	-148,5	Peridotite	84,1	0,078	613	
10-3	Råna	4750	4470	-296,6	Olivine pyroxenite	79,1	0,038	299	
18-6	Råna	4750	4470	-327,8	Peridotite	80,7	0,036	283	
10-4	Råna	4750	4470	-445,1	Peridotite	77,3	0,132	1037	
10-5	Råna	4750	4470	-514,5	Peridotite	83,7	0,132	1037	
11-5	Arneshesten	3600	1600	-6,3	Norite	81,6	0,210	1650	
11-6	Arneshesten	3600	1600	-87,9	Peridotite	81,6	0,149	1171	
11-7	Arneshesten	3600	1600	-135,4	Peridotite	81,9	0,023	181	
24-4	Arneshesten	3100	2180	-247,2	Olivine norite	77,1	0,023	181	
24-6	Arneshesten	3100	2180	-425,4	Peridotite	81,3	0,189	1485	
27-3	Arnes	3800	3645	0	Peridotite	81,7	0,033	259	
27-4	Arnes	4000	3300	0	Peridotite	83,8	0,102	802	83,2
27-5	Arnes	4500	3475	0	Peridotite	82,3	0,071	558	81,2
27-6	Råna	5190	3995	0	Olivine norite	77,2	0,016	126	76,7
27-7	Råna	5255	3250	0	Peridotite	82,5	0,040	314	
28-5	Rånbogen	5850	3530	0	Lherzolite	79,2	0,061	479	79,5
28-6	Rånbogen	6070	3770	0	Olivine norite	85,7	0,140	1100	83,2
28-7	Rånbogen	6110	3990	0	Gabbro	-	-	-	73,6
29-1	Rånbogen	6130	3925	0	Peridotite	83,7	0,162	1273	
29-2	Rånbogen	6240	3820	0	Peridotite	89,9	0,213	1674	
29-3	Rånbogen	6150	3375	0	Peridotite	80,0	0,232	1823	
29-4	Rånbogen	7100	4050	0	Olivine norite	86,4	0,093	731	82,0
29-6	Rånbogen	6700	4300	0	Peridotite	77,1	0,016	126	
26-1	Rånbogen	7800	3075	0	Peridotite	81,3	0,158	1242	
26-5	Rånbogen	7260	3700	0	Peridotite	83,4	0,014	110	
26-7	Rånbogen	5880	3530	0	Peridotite	83,7	0,109	857	
27-2	Rånbogen	6670	3800	0	Peridotite	84,7	0,030	236	
28-5	Rånbogen	5880	3530	0	Lherzolite	79,2	0,061	479	
28-6	Rånbogen	6070	3770	0	Olivine norite	85,7	0,140	1100	
29-1	Rånbogen	6130	3925	0	Peridotite	83,7	0,029	228	
29-2	Rånbogen	6240	3820	0	Peridotite	89,9	0,213	1674	
29-3	Rånbogen	6150	3320	0	Peridotite	78,0	0,232	1823	
29-4	Rånbogen	7110	4030	0	Olivine norite	86,4	0,093	731	
32-4	Rånbogen	7330	3970	0	Peridotite	79,8	0,115	904	79,6
32-5	Rånbogen	7260	3770	0	Peridotite	83,4	0,027	212	82,0
32-6	Rånbogen	7200	3250	0	Peridotite	78,0	0,047	369	79,0
32-7	Råntindvann	9550	3260	0	Peridotite	83,0	0,259	2035	82,7
30-2	Rånkjeipen	10350	300S	0	Quartz norite	-	-	-	58,7
26-6	Rødfjell	12050	2150	0	Peridotite	81,1	0,073	574	
28-2	Rødfjell	11600	2550	0	Peridotite	76,6	0,141	1108	77,4
28-3	Rødfjell	12100	2350	0	Peridotite	85,0	0,086	676	83,6
28-4	Rødfjell	12150	2150	0	Peridotite	77,4	0,306	2405	77,9
30-4	Tverrfjell	7800	4550S	0	Peridotite	83,3	0,156	1226	81,2
30-5	Tverrfjell	7755	4480S	0	Troctolite	81,5	0,051	401	
30-6	Tverrfjell	8210	4350S	0	Olivine gabbro	81,9	0,092	723	82,5
30-7	Tverrfjell	8320	4230S	0	Olivine norite	81,9	0,127	998	82,5
31-2	Tverrfjell	8765	3995S	0	Peridotite	75,6	0,116	912	79,8
31-3	Tverrfjell	8150	4750S	0	Peridotite	81,5	0,051	401	
31-4	Tverrfjell	8220	4760S	0	Peridotite	83,2	0,184	1446	
31-5	Tverrfjell	8655	3860S	0	Peridotite	69,5	0,019	149	76,6

Olivine									Opx
Probe sample	Region	ØK Ø	ØK N	Depth (-)	Rock	Fo	NiO (wt%)	Ni (ppm)	En
31-6	Tverrfjell	8655	3860S	0	Troctolite	81,4	0,175	1375	80,8
33-2	Tverrfjell	9040	3060S	0	Peridotite	73,9	0,010	79	
33-3	Tverrfjell	9040	3060S	0	Peridotite	74,0	0,065	511	
33-4	Tverrfjell	9040	3060S	0	Peridotite	77,1	0,034	267	
34-1	Tverrfjell	8840	3360S	0	Peridotite	73,8	0,072	566	
34-2	Tverrfjell	8800	3540S	0	Peridotite	75,4	0,050	393	
34-3	Tverrfjell	8800	3540S	0	Peridotite	77,3	0,146	1147	
34-4	Tverrfjell	8800	3540S	0	Peridotite	79,3	0,055	432	
34-5	Tverrfjell	8635	3560S	0	Peridotite	77,0	0,088	692	80,9
34-6	Tverrfjell	8540	3640S	0	Peridotite	77,4	0,000	0	
35-2	Tverrfjell	8360	4140S	0	Norite	-	-	-	74,9
35-3	Tverrfjell	8340	4500S	0	Peridotite	72,3	0,004	31	76,3
35-4	Tverrfjell	8360	4590S	0	Olivine gabbro	81,6	0,076	597	
35-5	Tverrfjell	8340	4690S	0	Norite	-	-	-	78,9
35-6	Tverrfjell	8330	4770S	0	Peridotite	76,3	0,000	0	78,0
35-7	Tverrfjell	8330	4770S	0	Peridotite	80,5	0,186	1462	80,7
36-1	Tverrfjell	8330	4770S	0	Peridotite	75,1	0,092	723	
36-2	Tverrfjell	8370	4790S	0	Peridotite	85,2	0,091	715	82,1
36-3	Tverrfjell	8370	4790S	0	Peridotite?	-	-	-	79,5
36-5	Tverrfjell	8350	4850S	0	Norite	-	-	-	79,5
36-6	Tverrfjell	8340	4910S	0	Peridotite	81,7	0,094	739	
36-7	Tverrfjell	8340	4910S	0	Peridotite	81,9	0,090	707	
31-7	Kvanåkertind	3920	4060S	0	Peridotite	71,9	0,242	1902	
32-1	Kvanåkertind	4070	4000S	0	Peridotite	79,6	0,167	1312	82,3
32-2	Nordbotn	3000	3150S	0	Peridotite	80,3	0,088	692	80,7
37-5	Rånkjeipen	9080	1350	0	Quartz norite	-	-	-	56,4
37-6	Rødfjell	11700	1700	0	Quartz norite	-	-	-	55,8
29-5	Arneshesten	4010	2475	0	Micronorite	-	-	-	59,1
19-3	Råndal	5260	3640	0	Gabbronorite	-	-	-	73,3
19-6	Råndal	5260	3640	0	Micronorite dyke	-	-	-	67,0
19-7	Råndal	5260	3640	0	Micronorite dyke	-	-	-	54,4
20-3	Råndal	5261	3440	0	Pyroxenite	-	-	-	79,5
20-6	Råndal	5261	3440	0	Norite	-	-	-	72,4

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