DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/47

Platinum, palladium and gold in the Layered Series of the Skaergaard intrusion

Implications for Pt, Pd and Au bulk composition, fractionation and mineralisation

T. F. D. Nielsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/47

Platinum, palladium and gold in the Layered Series of the Skaergaard intrusion

Implications for Pt, Pd and Au bulk composition, fractionation and mineralisation

T. F. D. Nielsen

Confidential report

Copy No.

22

To be released 01.04.2006

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

Contents

Summary

Based on a compilation of the stratigraphic variation in concentrations and elemental ratios of platinum, palladium and gold in the Skaergaard intrusion, a mass balance model for the distribution of platinum, palladium and gold, and the characteristics of the known mineralisation in the intrusion it is suggested that:

1: Reef-like structures enriched in PGE and with Pd/Pt ratios of 3-4 may exist in the gabbros below the known mineralisation The grades these reefs may carry can not be estimated from the available data.

2: The suggested reefs would be located in the central part of Middle Zone in a section characterised by macrorythmic layers. This part of Middle Zone has not yet been subjected to detailed exploration.

3: The suggested reefs would most likely be located in the base of leucogabbro layers and in mesogabbros below, similar to the Pd5 to Pd2 reefs in the known mineralisation.

4: The bulk composition of the intrusion and the known distribution of gold indicate that additional gold mineralisation may be found in the south-central part of the intrusion at stratigraphic levels above the known mineralisation. This part of the intrusion has not yet been subjected to exploration.

A cautionary note: The interpretations and suggestions in this report are based on a compilation of data from several sources. It can not be excluded, and it is indeed likely, that new and more detailed data would lead to revision of the models developed in this report and possibly of the suggestions based on these models.

Introduction

In a report on the Skaergaard PGE-Au mineralisation Nielsen (2001) included a short paragraph suggesting the possibilities for additional PGE reefs in the intrusion. The suggestion was based on an anomalous sample with c. 0.7 g/t PGE and a Pd/Pt ratio of 3.45 collected from gabbros *c.* 80m below the level of the known mineralisation.

Skaergaard Minerals Corporation has approached the Geological Survey of Denmark and Greenland and asked for further information, the data background and the rationale behind the suggested potential for further PGE reefs in the intrusion. This report elaborates on the suggested potential for additional, undetected, PGE reefs in the Skaergaard intrusion.

It is believed that a basic understanding of the distribution of PGE and Au, their behaviour during the solidification of the intrusion and the mineralisation processes are fundamental to the evaluation of the potential for additional PGE-reefs in the intrusion. An introduction to the Skaergaard intrusion and its mineralisation is followed by a compilation of the available data on PGE and Au in the Layered Series of the intrusion. The report compiles data from several laboratories and much of the data is also more than 10 years old. The data, the conclusions and the suggestions shall accordingly be treated with some caution.

The data is combined with a mass balance model to give estimates for the bulk composition of the intrusion and the bulk compositions of stratigraphic sections (zones and subzones) in the Layered Series. The data illustrates the behaviour of PGE and gold during the differentiation of the Skaergaard magma and is applied to mineralisation models.

The second part of the report describes the anomalous sample that could suggest the presence of undetected reefs. The composition is scrutinised to try to avoid misinterpretations and followed by a discussion on its suggested origin from a, possibly, undetected reef structure. The compiled data on the distribution of gold is discussed and a potential for additional gold mineralisation in the intrusion is suggested.

The last section of the report contains recommendations for further exploration.

Disclaimer: The Geological Survey of Denmark and Greenland and its employees can not be made responsible for costs for exploration or other company activities inspired by the evaluations and suggestions set forth in this report.

The Skaergaard intrusion

Geological introduction

It is beyond the scope of this report to give a detailed introduction to the Skaergaard intrusions. Detailed descriptions and overviews are published by Wager and Brown (1968), McBirney (1996), Irvine et al. (1998) and Nielsen (2004). The following crude description only sets the scene for the data presentation, the evaluations and the suggestions in this report.

The Skaergaard intrusion is a classic layered gabbro complex. The first description by Wager and Deer (1939) is an all time classic and a significant number of publications and petrogenetic models are the result of scientific investigations conducted since the 1930´es. The intrusion is about 55 million years old and formed in the developing volcanic rifted margin of the early North Atlantic.

Traditionally the intrusion is seen a funnel shaped intrusion filled with layered gabbros. Later, Blank and Gettings (1973) suggested a lacolith type intrusion. They suggested the intrusion formed as a vertically expanded sill. Irvine and co-workers (e. g., Irvine *et* al., 1998) suggested at least some of the margins of the intrusion to be fault controlled. Most recently Nielsen (2004) has modelled the intrusion as a fault-controlled box like magma chamber bounded by sub-vertical faults and roof and floor parallel with the bedding in the host sediments and basalts. The volume is estimated to 300 km^3. Nielsen (2004) sees the internal structure as onion shaped and a gradual concentration of the remaining liquid in the upper and central part of the intrusion.

The bulk composition of the intrusion has ever since the first descriptions by Wager and Deer (1939) been debated. Hoover (1989) investigated chilled margin samples and concluded that the parental magma of the intrusion was evolved and tholeiitic. The conclusion is supported by Nielsen (2004), who on the basis of a mass balance model suggests the parental magma to be similar to a specific suite of contemporaneous flood basalts. The suggestion is in agreement with bulk and trace element composition, time of emplacement and the depth of emplacement. The Mg# of the parental melt is suggested to be 0.45, the total FeO (Fe_2O_3 recalculated to FeO) to be 15-15.5 wt % and the TiO2/FeO* ratio to be ca. 0.2. As described below, even the bulk Pd, Pt and Au composition appears to compare to contemporaneous magmas in lavas and intrusions.

The modal layering in the Skaergaard gabbros, the phase layering and the cryptic variation in the chemistry of the rock-forming minerals have made the intrusion famous. They form the basis for the modelling of the differentiation of the parental melt. Many models have been developed over the years. Despite the often-agitated discussions on the genesis of the gabbros, all researchers seem to agree that the layering in the intrusion and the processes influenced by the layering holds the key to the understanding of the differentiation of the magma and the formation of the PGE-Au reefs.

The mineralisation

The mineralisation is described in significant detail in Bird et al. (1991), Andersen et al. (1998) and Nielsen (2001). The Skaergaard mineralisation, often referred to as the Platinova Reef, consists of five well-defined levels of palladium concentration in the Triple Group of the upper 100m of the Middle Zone. The name of the Triple Group refers to three major leucogabbro layers that form the top of macrorythmic units.

The structure is interpreted to be comparable to a succession of co-axial saucers (Nielsen, 2001). The individual palladium levels are from 2 to 10 meters thick. The internal stratigraphic height between the peak concentrations in the palladium horizons is ca. 10m. The mineralised levels are perfectly concordant with the magmatic layering and can be correlated throughout the intrusion. The systematics in the mineralisation, including density, mineralogy and geochemistry of the gabbros, suggest that the lower Pd-horizons (Pd5 to Pd2) all are located in the lower part of leucogabbro layers and the uppermost mesocratic gabbros of the macrorythmic layers. Details of the mineralogy of the lowest of five Pd-levels in the mineralisation (Pd5) can be found in Nielsen et al. (2003a, b, c, d, and e).

The sulphides and PGMs are found in the rims of and between the rock-forming minerals. This strongly suggests that the formation of immiscible sulphide liquid in concentrations of intercumulus melt. The intercumulus melt is suggested concentrated and trapped in the macrorythmic units below the partially impermeable roof of leucogabbros. Sulphur saturation was reached in the trapped melt and the PGE and Au concentrated in the sulphide melt. The processes took place at temperatures of at least 900^{o}C, as indicated by the phase relations in the Pd-Cu-S system (Karup-Møller and Makovicky, 1999).

The uppermost Pd-horizon (Pd1) has a different origin. Pd1 is located in mela- to mesogabbros above the leucocratic gabbro L2. In this level are found euhedral primocrysts of ilmenite with sulphide melt inclusions. This suggests that S-saturation in the main magma had been reached by the time the Pd1 formed. The Pd5 to Pd2 sequence seems thus to record the stage in the evolution of the Skaergaard magma just prior to S-saturation in the remaining magma.

Throughout the mineralised interval from Pd5 to Pd1, the Pd/Pt ratio remains high (10 or higher) compared to much lower ratios (1-5) in all other part of the intrusion. Based on the bulk considerations (see below) it is suggested that the Pd-enrichment in the mineralisation is due to preferential enrichment in palladium by a process that has scavenged Pd from the magma that remained at the time the mineralisation formed.

The process appears to have preferred palladium over platinum as indicated by the elevated Pd/Pt of the Pd5-Pd1 the mineralisation interval. The responsible process would probably not be S-saturation, which would concentrate palladium as well as platinum. It could be suggested – even though no experimental distribution coefficients can confirm the model - that Fe-Ti–rich, immiscible, and dense melts extracted palladium from the remaining magma and by gravity transported it down to the level in the magma chamber where the mineralisation is now found. The onset of the formation of immiscible Fe-Ti rich melts seems recorded in the estimated compositions of the melt from which uppermost Middle Zone and Upper Zone crystallised (McBirney and Nakamura, 1974). The onset of the formation of immiscible Fe-Ti oxide-rich melts in the main magma is shown by a mixing line between the compositions of the fractionating Skaergaard melt and the composition of immiscible Fe-rich melts (see figure 84 in McBirney and Nakamura, 1974).

PGE systematics in the layered series

In order to have a first impression of the Pd, Pt and Au distribution in the intrusion, data has been collected from exploration reports and profiles collected for petrogenetic studies. It should be noted that all the data, except some of the compilations for the anomalous zone and the mineralisation are from grab samples and do not give a complete picture of the variation in Pt, Pd and Au. It should also be noted that the analytical data originates from several batches of analyses and from several laboratories. Some of the data is quite old and can not be re-calibrated. It can not be excluded that some variations and anomalies are caused by differences between laboratories and analytical methods.

The samples

Platinova profiles

The sample profiles collected by Plationova Resources Ltd. in 1988 cover the Lower and Upper zones of the intrusion (Turner and Mosher, 1989). The Lower Zone profile was collected from the NW corner of the intrusion and climbing up the ridge toward Wager Top. The profile ends at the top of Lower Zone c. The Upper Zone profile was collected from the shore of Uttental Sund and up the north-west and north sides of Basistoppen (see geological map published by A.R. McBirney in1996 for localities).

Bollingberg profiles

The Bollingberg profile collected by K. Bollingberg for her Masters Thesis. It follows the shore of Kraemer Ø along Uttental Sund from the contact at Strømstedet to the SE tip of Kraemer Ø. It continues to Lille Ivnamiut and jumps over to the areas around Hjemsted Bugt and continues up the west face of Basistoppen (Maps can be obtained on request).

The anomalous zone

The anomalous zone is defined as the c. 110 m upper most part of Middle Zone and includes the known mineralisation. The lower Pd5 horizon in the mineralisation (see, e. g., Nielsen 2001) is located ca. 100m below the MZ/UZ boundary.

The samples available from this part of the Layered Series are grab samples collected by the author 1988 and 1989 and the cores drilled by Platinova Resources Ltd. in 1989 and 1990. The entire section from below Pd5 to the MZ/UZ boundary in core DDH 89-09 has been analysed for Pt, Pd and Au by Platinova Resources Ltd. A series of grab samples from the anomalous zone collected by T.F.D. Nielsen have also been analysed. The drill core data are used in the compilation of the bulk Pt, Pd and Au composition of the anomalous zone.

Analytical techniques

The analytical data for the samples analysed by Platinova Resources Ltd can be found in Turner and Mosher (1989) and Watts, Grifffis and McOuat (1991). Samples collected by all other groups have been analysed by ACME analytical laboratories using 10-g samples. The method is Pb fire assay with ICP finish. Details on the methods can be found in Nielsen and Brooks (1995).

The Platinova resources Ltd. data can be found in Turner and Mosher (1989). The data collected by the author is compiled in Appendix 1.

The elemental variation

The analytical data for Pt, Pd and Au are shown in Figs. 1 and 2. The known mineralisation stands out. Common to all three elements is that the concentrations are low in Lower Zone and in Upper Zone. Palladium seems to increase slightly in the Lower Zone and Middle Zone sections characterised by cumulus magnetite and possibly in zones characterised by many gabbroic and basaltic inclusions. A general and slow increase in Pd/Pt with stratigraphic height is in accordance with the behaviour of these elements during fractionation (e. g., Momme et al., 2002).

Apart from the known mineralisation notable deviations from a generally low concentration of PGE and Au are observed in the Layered Series. They occur in Middle Zone below the known mineralisation. Most notable is a single sample (GGU 394913, see section below) collected ca. 80m below the Pd5 horizon of the known mineralisation. Another anomalous sample (GGU 394904) collected further down into Middle zone also shows an elevated palladium concentration (153 ppb). The origin of anomalous concentrations of Pt and Pd in samples from the deeper parts of Middle Zone is not known with certainty, but could be explained by local enrichments due to auto-contamination processes caused by reactions with large gabbroic inclusions. Alternatively they could represent enrichments in reef-like structures. The latter is of major interest as it could increase the economic potential of the Skaergaard intrusion.

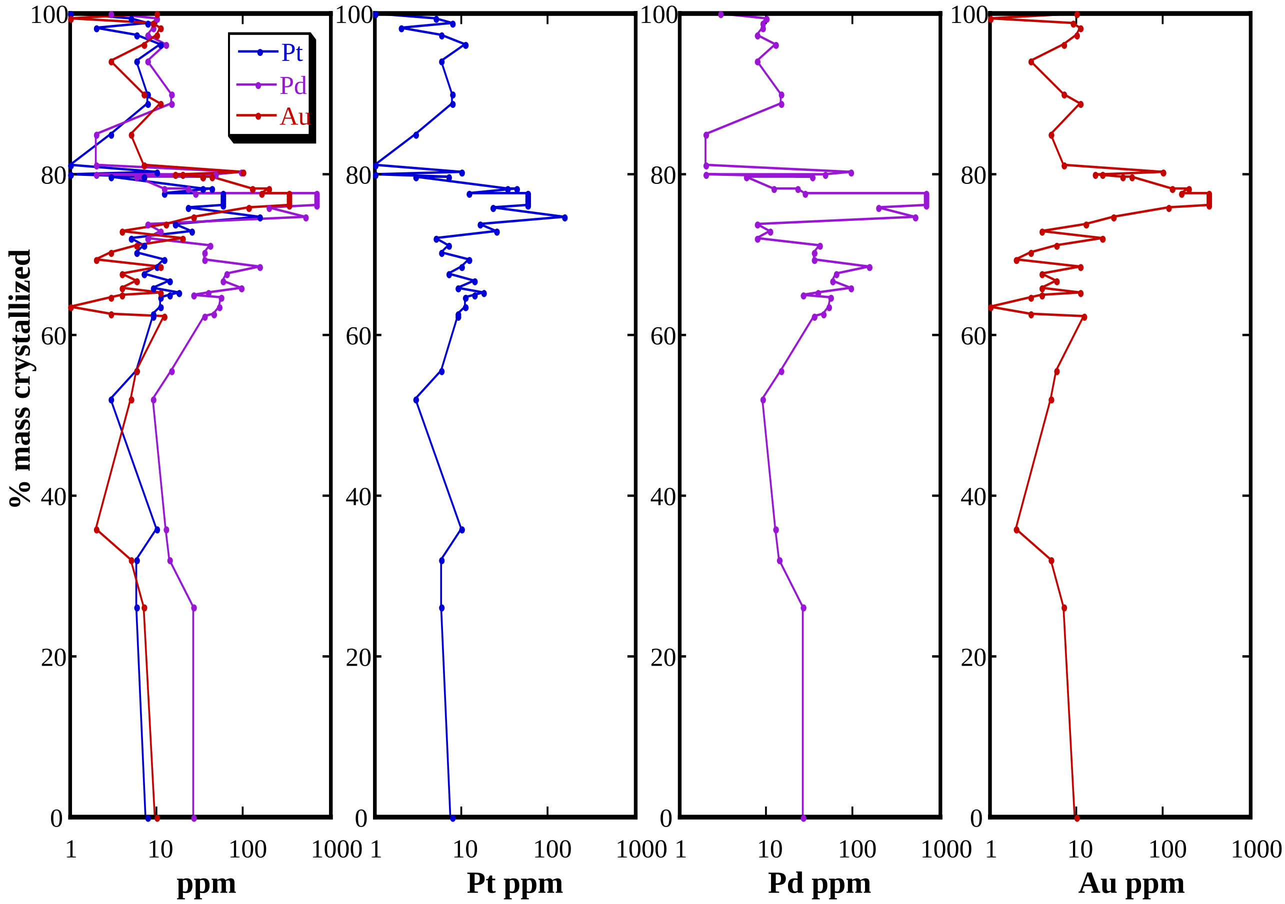

Figure 1. *Pt, Pd and Au variation up through the Layered Series of the Skaergaard intrusion as shown in a grab sample profile. The elemental values are plotted against the calculated percentage of crystallisation (see electronic file: "Au+PGE profile SMC.xls"). The known mineralisation is app. 40m thick. The average value for the 40m is plotted. Note the anomalous sample (GGU 394913) just below the known mineralisation and the bulge of Pt and Pd values between 60 and 70% crystallised. The details of the mineralisation are illustrated in Fig. 2.*

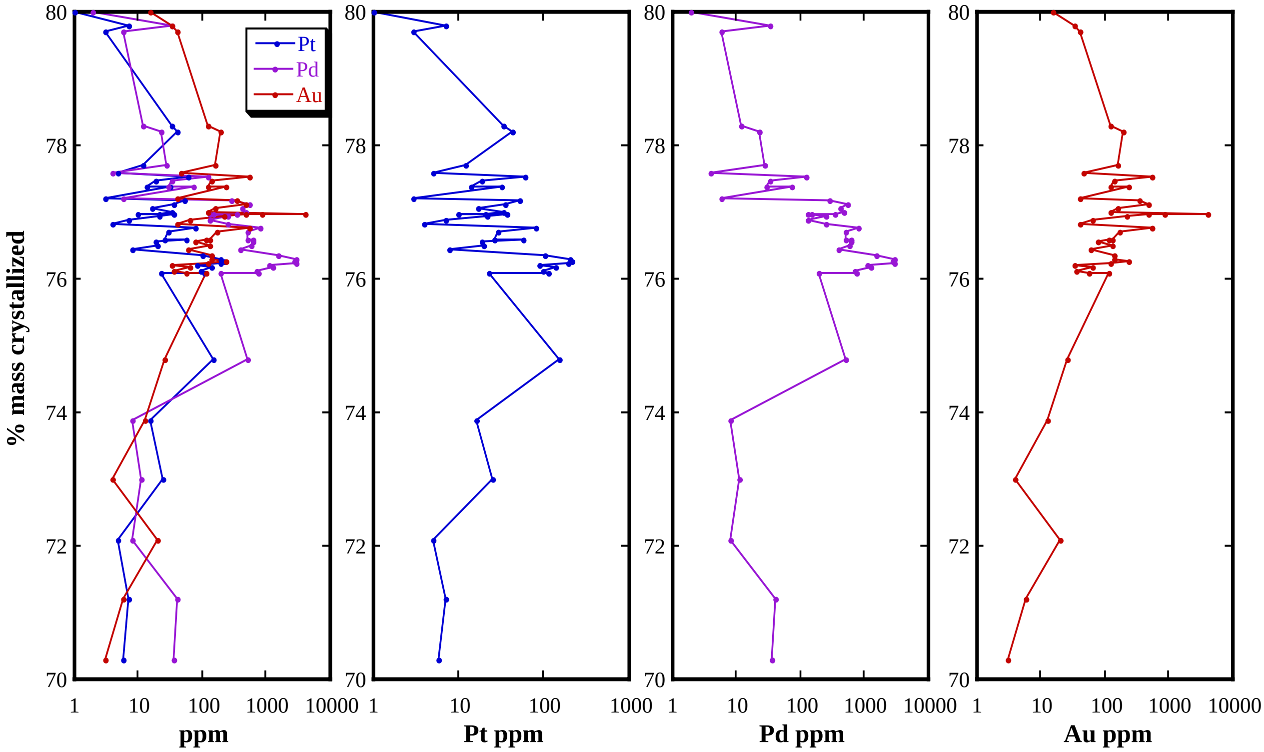

Figure 2. *Pt, Pd Au versus % mass crystallised for the upper part of MZ as shown by grab samples. The elemental values are plotted against the calculated percentage of crystallisation (see electronic file: "Au+PGE profile SMC.xls"). The interval 70-80% crystallised is equivalent to the upper 250m of Middle Zone and includes the anomalous sample (GGU 394913) 80m below the known mineralisation at ca. 75% crystallised.*

Bulk composition and mass balance for platinum, palladium and gold.

Average compositions of zones and subzones

The uncertainty caused by the low concentrations of PGE and the not entirely systematic sampling are significant. In order to minimise the uncertainties average compositions have been calculated for the Layered Series. Averages are calculated for all zones and zubzones including Lower Zone (LZa to LZc) and Middle Zone (MZ) below the known mineralisation, the mineralisation, the top of MZ above the mineralisation and Upper Zone (UZa to UZc). The calculations are based on the data in Appendix 1.

Zone or subzone	Mass prop.	Pt	Pd	Au	Pd/Pt	Au/Pd	Au/Pt
Upper Zone c	2.2	5	9	7	1.8	0.8	1.4
Upper Zone b	8.0	8	11	7	1.4	0.6	0.9
Upper Zone a*****	9.8	4	6	8	1.5	1.3	2.0
Upper Zone a	9.8	6	28	31	4.7	1.1	5.2
MZ above the mineralisation	2.0	13	32	44	2.5	1.4	3.4
The mineralisation	1.1	47	549	156	11.7	0.3	3.3
MZ below the mineralisation	10.3	21	85	13	4.1	0.2	0.6
Lower Zone c	7.3	8	25	9	3.1	0.4	1.1
Lower Zone b	23.9	6	9	5	1.5	0.6	0.8
Lower Zone a and Hidden Zone	35.4	7	20	6	3.3	0.3	0.9

Table 1. *Average Pt, Pd and Au concentrations (ppb) in zones, subzones and sections of the Skaergaard intrusion. All concentrations in ppb. Upper Zone a*: excludes the anomalous sample (GGU 348832) from the base of UZa. This sample with elevated PGE (100 ppb level) and Au may be a local and thin layer enriched in PGE and Au. It is not clear if it should be included when the average composition of UZa is calculated.*

Bulk composition of the Skaergaard intrusion.

Nielsen (2004) presents a model for the calculation of the major and trace element bulk composition of the Skaergaard intrusion. The suggested composition of the parental magma appears to be similar to evolved, high-Ti, plateau basalts in the Giekie Plateau Formation of the contemporaneous East Greenland flood basalts. The parental magma was evolved with Mg# = 0.45. Based on the same model the bulk Pt, Pd and Au composition of the intrusion can be calculated using the average data in the table above. The result shown in Table 2 together with compositions of so-called Skaergaard-like dykes, the chilled margin of the contemporaneous Kraemers Island macrodyke and plateau basalts.

Formation	Sample #	Pt	Pd	Au	Pd/Pt	Au/Pd
SK bulk	this work	**8**	**26**	**10**	**3.3**	**0.4**
SK-like dyke	GM 27700-2	13	13	4	1.0	0.3
SK-like dyke	GM 40533	11	15	21	1.4	1.4
SK-like dyke	GM 40536	10	20	18	2.0	0.9
SK-like dyke	GGU 361043	10	18	22	1.8	1.2
SK-like dyke	GGU 361027	6	2	13	0.3	6.5
SK-like dyke A	GGU 361033	9	20	26	2.2	1.3
SK-like dyke A	GGU 361034	12	15	38	1.3	2.5
SK-like dyke A	GGU 361035	14	18	11	1.3	0.6
SK-like dyke A	GGU 361036	16	27	16	1.7	0.6
SK-like dyke A	GGU 361037	11	17	11	1.5	0.6
SK-like dyke A	GGU 361038	8	10	15	1.3	1.5
SK-like dyke A	GGU 361039	10	19	11	1.9	0.6
SK-like dyke A	GGU 361040	6	23	52	3.8	2.3
Average dyke A		**10.8**	**18.6**	**22.5**	**1.7**	**1.2**
SK-like dyke E	GGU 361045	10	27	21	2.7	0.8
SK-like dyke E	GGU 361046	10	34	20	3.4	0.6
SK-like dyke E	GGU 361049	9	22	15	2.4	0.7
Average dyke E		**9.7**	**27.7**	**18.7**	**2.9**	**0.7**
SK-like dyke B	GGU 361051	12	15	15	1.3	1.0
SK-like dyke B	GGU 361052	26	16	11	0.6	0.7
SK-like dyke B	GGU 361053	9	22	16	2.4	0.7
SK-like dyke B	GGU 361054	24	19	16	0.8	0.8
SK-like dyke B	GGU 361055	9	20	24	2.2	1.2
Average dyke B		**16**	**18.4**	**16.4**	**1.2**	**0.9**
KØ Macrodyke	KIM CM	5	25	7	5.0	0.3
KØ Macrodyke	KIM CM	5	27	6	5.4	0.2
Average KIM CM	KIM CM	**5**	**26**	**7**	**5.2**	**0.3**
Plateau basalt	High Ti	4	10	12	2.5	1.2
Plateau basalt	High Ti	4	13	8	3.3	0.6

Table 2. *Calculated bulk Pt, Pd and Au composition (ppb) of the Skaergaard intrusion and comparisons. Data from Kraemer Ø macrodyke and plateau basalts from Momme (2002). All other data from Nielsen and Brooks (1995). Note should be taken that the differences between analytical methods do not allow direct comparison between data from Momme (2002) and Nielsen and Brooks (1995). The very variable Au concentrations in SK-like dykes may be caused by contact alteration. SK-like dyke E shows the closest compari-*

son to the bulk Skaergaard composition in major as well as trace elements. The comparatively low Au in the Skaergaard bulk compared to the average of SK-like dyke E may be real and caused by undiscovered Au in the Skaergaard intrusion (see below).

Despite the obvious differences between the shown compositions of skaergaard-like dykes, macrodykes and plateau basalts it is suggested that the Skaergaard gabbros crystallised from magma similar to those of contemporaneous dyke and lava. The similarity between Skaergaard-like dyke E and the calculated bulk composition of Skaergaard is believed to reflect a cogenetic relationship (see also Brooks & Nielsen, 1978 and 1990).

Average composition below and above the mineralisation

Several models can be suggested for the origin of the Skaergaard mineralisation and its reef structure. Two fundamentally different models are often advocated. So-called “downer” processes refer to classic gravitational accumulation due to S-saturation and the formation of dense droplets of heavy sulphides. They would sink and be deposit as layers concordant with the igneous layering in the gabbros. So-called “upper” processes, as proposed by Boudreau and Meurer (1999) envisage upwards transportation of PGEs, etc, in intercumulus melt or fluid from the deeper parts of the cumulus pile of the intrusion. PGE could be deposited in specific levels due to reaction with, e.g., Fe-oxide rich layers.

If the known mineralisation is the result of a “downer” process, the bulk composition of the mineralisation and all melt that remained at the time of the formation of the mineralisation should be similar to the composition of an evolved basaltic melt. Concentrations of Pt, Pd and Au and the elemental ratios should be comparable to those of evolved basaltic melt. No strong fractionation between PGEs would be expected.

A comparison between the average Pt, Pd and Au concentrations and the elemental ratios in the Layered Series below the mineralisation and in the remaining part of the intrusion (including the mineralisation and the remaining part of the Layered Series above the known mineralisation) should give an indication of the process responsible for the concentrations of the PGE and Au in the known mineralisation.

Section	Pt	Pd	Au	Pd/Pt	Au/Pd	Au/Pt
From base of mineralisation to Sandwich Horizon	8	36	13	4.5	0.4	1.6
From floor of intrusion to base of mineralisation	8	25	7	3.1	0.3	0.9
Bulk Skaergaard	8	26	10	3.3	0.4	1.3

Table 3. *Average Pt, Pd and Au composition (ppb) of the Layered Series gabbros below and above the base of the known mineralisation. Data from Appendix 2.*

The PGE and Au concentrations in the lower part of the Layered Series are low and their ratios are comparable to those of the estimated bulk Skaergaard composition. No obvious fractionation appears to have taken place, maybe except from a relative depletion in Au. The interpretation is that the average concentrations through the Layered Series to the base of the known mineralisation reflect the concentration of trapped intercumulus melt. Pd and Au are in this part of the intrusion incompatible element, whereas a minor increase in the Pd/Pt ratio up through the Layered Series (see Table 1) seems to suggest that Pt might be slightly less incompatible than Pd and Au during silicate-dominated fractionation. These observations are in agreement with the known behaviour of PGE and Au in basaltic systems that have not been subjected to S-saturation and immiscibility.

The remaining part of the intrusion from the base of the mineralisation to the Sandwich Horizon also shows average elemental concentrations and elemental ratios in agreement with the general behaviour of the PGE and Au in basaltic liquids that have yet not been influenced by processes like S-saturation and the formation of immiscibility sulphide liquids.

Based on these observations it seems likely that the Pt, Pd and Au found in the mineralisation originate from the melt that at the time of the formation of the mineralisation occupied the volume from the base of the mineralisation to the contemporaneous solidification front under the roof of the intrusion.

With the present data, and especially the very high Pd/Pt ratio in the known mineralisation it seems unavoidable to suggest the known mineralisation formed by a “downer” process that concentrated Pt, Au and preferentially Pd (plus other elements) in the melt just above the solidification front in upper Middle Zone.

Fractionation and concentration of Pt, Pd and Au

Above the base of the mineralisation the fractionation is significant. The lowest part of the section comprises the up to 60m thick mineralised section. It is strongly enriched in Pd with a ratio close to 10 and in some parts much higher, probably due to mineralogical effects (the composition of the liquidus PGM). The change from ratios of 3-4 just below the mineralisation to 10 occurs over a stratigraphic height of <50m (see Appendix 1).

Zone or subzone	Pt	Pd	Au	Pd/Pt	Au/Pd	Au/Pt
Uzc	5	9	7	1.8	0.8	1.4
Uzb	8	11	7	1.4	0.6	0.9
Uza*	4	6	8	1.5	1.3	2.0
Top MZ	13	32	44	2.5	1.4	3.4
Mineralisation	47	549	156	11.6	0.3	3.3
Average above the base of the mineralisation	8	36	13	4.5	0.4	1.6

Table 4. *Pt, Pd and Au average compositions (ppb) in subzones and subsections in the upper part of the Skaergaard intrusion starting at the base of the known mineralisation. UZa*: excludes anomalous sample GGU 348832 at base of UZa.*

In the top part of Middle Zone above the mineralisation (Top MZ) the concentrations decrease and the Pd/Pt ratio drops to less than 3. The same applies to Upper Zone as a whole.

The concentrations and the Pd/Pt ratios suggest that the mineralisation is preferentially enriched in Pd, and that Pt, Pd and Au in the mineralisation was scavenged from the magma column from the base of the mineralisation to the crystallisation front below the roof of the intrusion. The rationale for this suggestion is that the bulk average for this part of the Layered Series is close to the composition that would be expected for a fractionating S-undersaturated magma. The increase in Pd in the mineralisation seems counter-balanced by a lower Pd/Pt in the gabbros above the mineralisation. Based on this, it is suggested that the key factor for the formation of the known and very Pd-rich mineralisation in the Skaergaard intrusion is not anomalous PGE contents, but a process that scavenges PGE and Au and preferentially Pd from the column of remaining magma at the time the mineralisation formed.

It is surprising that the “downer” process preferentially scavenge Pd. This could suggest that the mineralisation process was not due to S-saturation in the magma that remained at the time of mineralisation. An alternative could be the formation of immiscible Fe-Ti-rich melts. Such melts are well known in experimental systems and have now also been observed in the gabbros of the Skaergaard intrusion (Jakobsen et al. In press). No distribution coefficients are known for PGE and Au between evolved basaltic melts and coexisting, immiscible, Fe-rich melts and the preferential scavenging of Pd can not be modelled.

Some information on the possible effects of immiscible Fe-rich liquids are available in the studies of the liquid line of descent in the Layered Series (McBirney and Nakamura, 1974) and studies of immiscible Fe-rich melts (e.g., Naslund, 1976). The line of liquid descent proposed by McBirney and Nakamura (1974) shows a clear break toward Fe-rich compositions at a stage equivalent to upper Middle Zone. McBirney and Nakamura interpreted the break as the point where the melt hit the two liquid field (Few-rich silicate melt and granophyric melt) in the experimental system. Here, the break is interpreted to be the stage at which immiscible Fe-rich melts from the cooler upper parts of the magma chamber survive all the way to the crystallisation front of the floor cumulates.

They would add Fe (and all the elements concentrated in the immiscible Fe-rich melts) to the melt at the crystallisation front. The combined effects of fractional crystallisation and the addition of Fe-rich material from the upper part of the intrusion would gradually pull the liquid composition toward that of the immiscible Fe-rich. The line of liquid descent from top Middle Zone to the last crystallising melt in the Sandwich Horizon (see McBirney and Nakamura, 1974) could be interpreted as a mixing line between the fractionating main silicate melt and an increasing proportion of immiscible, Fe-rich, melt.

Effects on the bulk composition of an undetected reef

The Pt, Pd and Au distribution in the Skaergaard intrusion shows that between 7% of all the Pt, 23% of all the Pd and 17% of all the Au in the entire volume of the intrusion are found in the known mineralisation. The contribution of the different zones, subzones and sections of the intrusion to the calculated bulk composition are shown in Table 5. As shown in the table, the known mineralisation accounts for 0.5 ppb Pt, 6 ppb Pd and 1.7 ppb Au of the bulk composition.

Zone or subzone	**Pt contrib.**	**Pd contrib.**	**Au contrib.**	**Pd/Pt**	**Au/Pd**	**Au/Pt**
Uzc	0.11	0.20	0.15	1.80	0.78	1.3
Uzb	0.64	0.88	0.56	1.38	0.64	0.9
Uza	0.39	0.59	0.78	1.51	1.32	2.0
Top MZ (89-09)	0.26	0.64	0.88	2.46	1.38	3.4
Mineralisation (89-09)	0.52	6.04	1.72	11.68	0.28	3.3
Lower MZ	2.16	8.76	1.34	4.05	0.15	0.6
LZc	0.58	1.83	0.66	3.13	0.36	1.1
LZb	1.43	2.15	1.20	1.50	0.56	0.8
HZ+LZa	2.12	7.08	2.12	3.33	0.30	1.0
Skaergaard bulk	**8**	**26**	**10**	**3.3**	**0.4**	**1.3**

Table 5. *Contribution of zones, subzones and sections to the bulk concentrations of Pt, Pd and Au of the Skaergaard intrusion in ppb. From Appendix 2.*

The mass balance model for the intrusion allows the calculation of the effects on the bulk composition of an undetected Pt-rich reef. The calculations (see Appendix 3) indicates that a 2m thick reef with 3 g/t platinum only would contribute 1 ppb to the bulk. A similar reef with 3 g/t platinum and 10 g/t palladium (Pd/Pt = 3.45) would contribute 1 ppb platinum and 4 ppb palladium to the bulk composition. These are quite small numbers. In view of the variability in the compositions of the melts shown in Table 2 it is suggested that bulk considerations can not be used as evidence for – or against – the existence of undetected reefs.

The anomalous sample GGU 394913

The present discussion, pro et contra the occurrence of undetected reefs in the Skaerggard intrusion more Pt-rich than the already known mineralisation, is based on the occurrence of the anomalous sample (GGU 394913) and excursions in PGE concentration in gabbros of central and lower Middle Zone.

Sample GGU 394913 belongs to a profile (GGU 394901-907 and 394909 to 394914; Table 6) from the SE corner of Kraemer Ø. It was sampled by the author in 1989. For unknown reasons Platinova Resources Ltd. had not covered Middle Zone in their systematic profiles. When asked, Platinova Resources Ltd. always claimed that they did cover Middle Zone, but no detailed data have been found. Only the upper 200m of Middle Zone are covered in drill cores and chip lines.

The combined grab sample profile from Middle Zone consists of the Bollingberg and Kraemer Ø profiles. The more detailed Kraemer Ø profile reaches about 2/3 down trough Middle Zone.

The composition of gabbros from the Kraemer Ø profile

The compositions of the samples from the Kraemer Ø profile collected below Pd5 are shown in Table 6. The profile consists of grab samples and as such they do not give a complete picture of the geochemical variation.

The gabbros in the profile are typical Middle Zone compositions. The basic characteristics seem to be an enrichment in ilmenite and magnetite in sample GGU 394902 and 903 and again in sample GGU 394911 and an increase in the clinopyroxene component in the upper part of the profile in samples GGU 394912 to 914.

From an economic point of view the most important observation is that both concentrations of Pt, Pd and Au as well as the elemental ratios vary in the Kraemer Ø profile. This is in contrast to the calculated bulk composition of the intrusion below the known mineralisation. The calculated bulk composition of gabbros below the known mineralisation (Table 3) is as would be expected from fractionated basaltic liquids. These observations strongly suggest that the PGEs and Au have been subjected to fractional processes before the known mineralisation had formed. The timing of these processes seems to be after the establishment of the layered structure of the gabbros, but prior to solidification, i. e. during intercumulus crystallisation. In other words PGE and Au are suggested to have been redistributed, fractionated and possibly concentrated during the solidification of the gabbros.

Sample #	394 901	394 907	394 902	394 903	394 904	394 905	394 906*	394 911	394 912	394 913	394 914
Major elements in wt% by XRF (GEUS, 1992)											
SiO2	39.22	35.06	32.53	31.92	40.78	40.50	37.97	34.37	44.31	43.10	41.23
TiO2	9.25	10.50	13.57	14.44	8.42	9.82	10.29	13.53	6.78	6.87	8.70
Al2O3	11.51	9.61	5.75	8.43	10.60	11.89	8.03	14.50	12.06	10.37	8.00
Fe2O3	6.43	6.01	3.32	9.17	5.76	4.82	-3.11	7.04	3.50	4.56	3.92
FeO	15.17	20.00	25.30	18.90	14.59	14.19	26.71	15.99	13.63	15.66	17.9
MnO	0.24	0.27	0.31	0.28	0.25	0.24	0.32	0.21	0.25	0.28	0.32
MgO	5.91	6.98	7.69	5.87	6.64	5.97	8.28	2.43	6.06	6.52	7.39
CaO	9.75	8.96	9.61	8.85	10.72	9.90	8.60	6.73	10.37	9.96	9.91
Na2O	2.11	1.63	0.94	1.45	1.97	2.36	1.61	2.98	2.45	2.09	1.67
K2O	0.14	0.10	0.06	0.09	0.13	0.17	0.10	0.21	0.16	0.18	0.16
P2O5	0.02	0.02	0.14	0.02	0.02	0.04	0.02	0.04	0.03	0.05	0.05
LOI	0.56	0.59	1.24	0.77	0.52	0.47	1.37	0.26	0.71	0.62	0.87
Sum	100.31	100.25	100.23	100.19	100.40	100.38	100.46	100.08	100.32	100.26	100.12
FeO*	20.96	25.41	28.29	27.15	19.77	18.53	23.91	22.32	16.78	19.76	21.43
Reconnaissance trace elements in ppm by XRF on glass discs (GEUS, 1992)											
V	1806	1818	2570	2475	1484	1110	1067	1500	709	805	771
Cu	158	92	97	80	115	106	97	118	93	96	96
Ni	112	148	132	129	91	81	90	72	46	43	45
Ba	283	386	312	212	365	275	289	223	302	351	374
Pt, Pd and Au in ppb by Pb fire assay with ICP finish (ACME, 1992)											
Pt	11	14	9	7	10	6	7	25	16	149	23
Pd	56	27	92	64	153	36	41	11	8	514	191
Au	3	4	4	4	11	3	6	4	13	26	114
Pd/Pt	5.1	1. 9	10.2	9.1	15.3	6.0	5.9	0.4	0.5	3.4	8.3

Table 6. *Major and trace element analyses including Pt, Pd and Au for samples from profile below known mineralisation. The profile covers app. 300 meters of stratigraphy; no detailed calculation of the stratigraphic depth has been attempted.*

Sample 394906: Negative Fe2O3 is suggested caused by local sulphides due to alteration

Sample GGU 394913

The anomalous sample, located on the Skaergaard 1:20 000 map published by McBirney 1989 to 68^{0}10'22.5''N and 31^{o}44'54.7''W, is estimated to be located ca. 80m below the Pd5 horizon of the known mineralisation. As shown in Plate 6 in Wager and Deer (1939, 1962 re-issue) the sample would be located in the top part of a section in the central part of Middle Zone characterised by macrorythmic layers.

Sample GGU 394913 contains 149 ppb Pt, 549 ppb Pd and 26 ppb Au (Table 6). The sample has only been analysed once. The first observation is that the combined PGE and Au concentration is close to 0.7 g/t. This is anomalous for anywhere below the known mineralisation. The second observation is that the Pd/Pt ratio is 3.45. This ratio is quite different from that of the known mineralisation. The Pt concentration is as high as in Pd5 samples with 2 g/t Pd. These characteristics make a relationship between the anomalous sample and the type of mineralisation known from the Pd5-Pd1 levels quite difficult. The Au/Pd ratio is, as in the known mineralisation low (0.05).

Several explanations for the anomalous sample can be suggested. The first two suggestions question the validity of the sample for evaluation of a potential for undetected reefs.

1) The analysis is in error. The sample is only analysed once and should be re-analysed. There is, however, no indication in the data set that an error should have occurred. All other samples have concentration within the expected range.
2) The second possibility is that the sample could in fact be related to the lower part of the Pd5 horizon. This could be caused by repetition of the stratigraphy due to faulting. As noted above the PGE concentration and the Pd/Pt ratio does not suggest that the anomalous sample relates to the lower part of Pd5. No faults of significance are recorded in the profile.

Based on all available data it is thus likely that the anomalous sample does represent an anomalous concentration of PGE well below the known mineralisation.

The GGU 394913 level in drill cores DDH 90-10 and DDH 90-14.

Two explanations can be suggested for the concentrations of PGE in anomalous sample GGU 394913.

1) Middle Zone contains a large number of inclusions of roof rocks. These inclusions have by many researchers been suggested to add volatiles to the magma. The anomalous sample could be suggested to represent a local enrichment in PGE due to S-saturation caused by oxidation and local Fe-depletion during interaction of the inclusion and the host high-temperature gabbro mush or magma.
2) The anomalous sample originates from an undetected reef.

The known reefs in the intrusion are genetically related to macrorythmic layering. It is already known that macrorythmic layers are well developed at the appropriate depth below the known mineralisation. A study of the drill core sections that were drilled into the gabbros below the known mineralisation could give hints to the potential for other reefs. Two of the drill cores, DDH 90-10 and DDH 90-14, reach stratigraphic levels 80m below Pd5.

Leucogabbro layers

The logs for core DDH 90-10 and DDH 90-14 are not all that detailed. Descriptions are not available and the following comments are based on the logs in Watts, Griffis and McOuat (1991). The descriptions start from the peak Pd-concentration in Pd5 at 444m in DDH 90-10 and at 194m in DDH 90-14. The levels equivalent to sample GGU 394913 would be around 524m in core DDH 90-10 and around 274m in core DDH 90-14. Note should be taken that the calculated depth of sample 394913 relative to Pd5 (80m) is not precise.

DDH 90-10: Core DDH 90-10 was the first core logged in 1990. The details are restricted. Nearly all the gabbros are described as mesocratic to leucocratic gabbros with marked oxide-rich layers. Apart from dykes the only exception is a leucogabbro layer from 511 to 518m followed by mesocratic gabbros. This leucogabbro layer could well be similar to those of the Triple Group hosting the Platinova Reef.

DDH 90-14: The core log records mesocratic and melanocratic gabbro, some well layered and some with oxide-rich layers down to 264m. Leucocratic gabbros are recorded from 264 to 270m and again from 278m to "End of Hole" at 285m. A closer look at Plate 6 in Wager and Deer (1939, 1962 re-issue) shows both the oxide-rich layers and the two leucogabbro layers. The latter seem to form the top of the section in the central parts of Middle Zone characterised by well-developed macrorythmic units.

The upper of the two recorded leucogabbro layers are in drill cores DDH 90-10 and DDH 90-14 met at 67(+/- 1) m and 70(+/-1) m below the Pd5 peak in 90-10 and 90-14. The leucogabbro layers in core DDH 90-14 is also easily identified in density logs (unpublished). Based on the well-established continuity of the magmatic layering it is suggested that the leucogabbro layers 67 and 70 m below the Pd5 peak in cores DDH 90-10 and DDH 90-14 in fact is the same stratigraphic level and that they represent a plagioclase-rich top-layer in the macrorythmic section in the central part of Middle Zone.

One thin-section of the upper leucogabbro layer in DDH 90-10 is available. The leucogabbro is in petrography very similar to the leucogabbro layers in the known mineralisation, and composed of densely packed plagioclase primocrysts that have only been subjected to limited adcumulus growth.

Composition of sample GGU 394913

The bulk composition of GGU 394913 is shown in Table 7 together with the composition of samples from the peak Pd concentration in Pd5 (GGU 361009-911, surface profile on "Toe of Forbindelse"). They are very similar types of gabbro and by analogy, sample GGU 394913 is suggested to be a gabbro with a comparatively high proportion of the rock-forming minerals crystallised from intercumulus melt (cpx and Ti-magnetite).

The similarities are such that it seems more than likely that all these samples are formed by the same processes. On the assumption that the three samples from the Pd5 horizon represent concentrations of trapped liquid, it seems more than likely that the anomalous sample with elevated PGE concentrations also represents a concentration of trapped liquid.

With reference to the observed plagioclase-rich layers in the drill core logs and the variation in concentration and elemental ratios in the Kraemer Ø profile it seems more that likely that reefs of intercumulus melts are formed. PGE and possibly Au would conceivably be trapped in these reefs. What concentrations PGE and Au could have reached in these reefs is not known.

Sample #	394913	361009	361010	361011
Major elements as above				
SiO2	43.10	43.97	46.56	44.26
TiO2	6.87	6.54	4.26	6.74
Al2O3	10.37	12.53	11.31	12.89
Fe2O3	4.56	4.31	2.96	4.47
FeO	15.66	14.00	12.82	13.34
MnO	0.28	0.26	0.27	0.25
MgO	6.52	5.83	6.95	5.58
CaO	9.96	9.62	10.99	9.77
Na2O	2.09	2.59	2.40	2.57
K2O	0.18	0.16	0.16	0.19
P2O5	0.05	0.03	0.04	0.04
LOI	0.62	0.61	0.80	0.61
Sum	100.26	100.45	99.53	100.44
FeO*	19.76	17.88	15.48	17.36
Trace elements as above				
V	805	1058	657	1035
Cu	96	55	18	59
Ni	43	44	45	43
Ba	351	No data	No data	No data
Pt, Pd and Au as above				
Pt	149	192	217	200
Pd	514	2932	2795	3022
Au	26	121	235	138
Pd/Pt	3.4	15.3	12.9	15.1

Table 7. *Anomalous sample GGU 394913 compared to samples GGU 361009 -11 from the peak of Pd5 at "Toe of Forbindelse".*

The relevance of this is that leucogabbro layers very similar to those of the Triple Group (L0, L1 and L2) exist in the gabbros below the known mineralisation. As in the known mineralisation in Triple Group, the leucogabbro layers deeper in Middle Zone could also have acted as traps for intercumulus melt with PGE and Au and caused the formation of PGE reefs.

Assays at the GGU 394913 level in cores DDH 90-10 and DDH 90-14

DDH 90-10

Drill core DDH 90-10 barely reaches the level 80m below Pd5. The lowermost sample from 533.50 to 534.15m records 11 ppb Pd and 28 ppb Pt and a Pd/Pt ratio of 0.4. The analysis could be in error and the content of 28 ppb Pt does not seem much, but the sample has at least twice the Pt concentration of any other 90-10 sample from below the Pd5 horizon. To the Pd5 horizon is here include a 10m section below the peak value in Pd5 with slowly decreasing Pd concentrations. It is probably over-optimistic to suggest that the relative increase in Pt is a first sign of a zone with selective enrichment in Pt. Unfortunately, a dyke is intercepted at depth and no further data can be obtained from core DDH 90-10.

DDH 90-14

Core DDH 90-14 was drilled close to the margin of the intrusion on Lille Ivnamiut. As such the core is not representative for the more central parts of the intrusion. Never the less the core reaches a level about 90m below (at 285.3m) the Pd peak in Pd5 (at 194m). The core has only been assayed down to 226m. The core is located in Soedalen in Miki Fjord and could be analysed in the search for a PGE anomaly.

Pt, Pd and Au in sample GGU 394913 compared to Pd5

For stratigraphic levels well below Pd5 the Pd/Pt ratio remains <4. At the level of ca. 500 ppb Pd the lower part of the Pd5 horizon has in general a Pd/Pt ratio of ca. 5 or even higher closer to the margin of the intrusion. Ratios similar to that of sample GGU 394913 (3.45) are normally first reached when the Pd concentration is below 50-100 ppb Pd.

The composition of sample 394913 can apparently not be related to any of the compositions in the cores in the lower part of the Pd5 horizon. Assuming it is not an analytical error, sample GGU 394913 has an anomalous PGE composition, which in its Pd/Pt ratio relates to intercumulus melt below the known mineralisation and the sample appears to represent a PGE concentration unrelated to the known mineralisation.

Conclusion on the origin of sample GGU 394913

On the assumption that the analysis is correct and that the structural reconstruction of the depth of sample GGU 394913 relative to the Pd5 horizon of 80m is correct, reasons are found to suggest that the sample collects PGE-enriched gabbro unrelated to the known mineralisation. The sample would be from a concentration of intercumulus melt in which PGMs crystallised and settled.

In many respects the anomalous sample can be suggested to have been formed by processes known from the Pd-horizons Pd5 to Pd2 in the known mineralisation. Although very little evidence is at hand it is conceivable that the middle and lower parts of Middle Zone, as the upper part hosting the Triple Group, is subdivided into cells that trapped intercumulus melt. The trapping of intercumulus melt below top layers of densely packed plagioclase primocrysts could in some cases lead to S-saturation and the deposition of PGEs in reef structures similar to those of the known mineralisation. It would be expected, as also seen in the anomalous sample, that the Pd/Pt ratio would be between 3 and 4.

The models are not yet sufficiently developed to evaluate the concentrations of PGE that could have been developed in MZ below the known mineralisation. However, concentrations of 50-100 ppb Pd and 15-35 ppb Pt in the bulk melt at the Middle Zone stage can easily be envisaged. In the hypothetical situation that intercumulus melt is trapped within a 15m thick macrorythmic unit, a 1m thick reef like zone under the top leucogabbro layer of the macrorythmic unit could potentially reach concentrations of 0.7-1.5 g/t Pd and 0.2-0.5 g/t Pt. Any further speculation seems inappropriate.

A comment on the distribution of gold.

As may have been noticed in Table 2 and the comments to the table, the concentration of Au in the Skaergaard-like dykes are elevated compared to the calculated bulk concentrations in the parental magma of the intrusion.

Up to now no chilled margin analyses have been presented for the intrusion. Some analyses exist, but sulphides are quite often observed in these rocks. This may be caused by contamination at the contact. The contamination could have led to the formation of sulphides and trapping of PGE and Au in concentrations well above those of the melt.

Sample #		**Pt**	**Pd**	**Au**	**Pd/Pt**	**Au/Pd**	**Au/Pt**
366912	Ni FA, BC	23	53	45	2.3	0.8	2.0
366912	Pb FA, ACME	10	49	57	4.9	1.2	5.7
366912	Ni FA, Laur.	9	34	37	3.8	1.1	4.1
Average		14	45	46	3.2	1.0	3.3
SK-like dyke E	Pb FA, ACME	10	28	19	2.8	0.7	1.9
SK bulk	Pb FA ACME	8	27	11	3.4	0.4	1.4

Table 8. *Chilled margin composition from the Skaergaard intrusion analysed by Ni fire assay by Bondar Clegg, lead fire assay by ACME and and by Momme (2000) by Ni fire assay at Laurentian University.*

The concentrations of chilled margin samples may not represent the parental melt, but they all seem to show a Pd/Au ratio well above that suggested for the intrusion. This is not readily understood. It could be suggested that the marginal rocks were selectively enriched in Au due to the contamination process. However, relatively elevated Au/Pd ratios seem also common among the Skaergaard-like dykes, although less marked. Significant uncertainty remains as to the absolute concentrations, but the ratios seem to identify a deficit in Au in the calculated bulk composition for the intrusion. This could suggest that not all gold had been located. The following observations could support this view:

(a) the recorded increase in total Au in the known mineralisation towards a centre in the southern part of the intrusion (trend surface analyses by Platinova Resources Ltd.; see also Bird et al., 1991)
(b) the existence of a gold mineralised zone (Au+1) above Pd1 in core DDH-90-18,
(c) the small (2m) upwards displacement of Au in Pd1 of, e. g., DDH 90-22
(d) the observation of small but well defined additional levels of Au concentration (100 ppb level) in core DDH-89-09 above the known mineralisation (see Nielsen, 2001).

.

In the mineralogical reports (Nielsen *et* al., 2003 a-e) it is noticed that Au is related to hydrous phases. It seems conceivable that Au remained mobile long after Pd and Pt had been deposited. This may also be indicated by the increased relative concentration of Au in the MZ section above the known mineralisation (Table 4).

It is only a suggestion, but it could be envisaged that late volatile-rich melt or fluid could have led to concentrations of gold in the south-central part of the intrusion, at stratighraphic levels above the Pd5-Pd1 structure.

Conclusions

1. The investigation of the distribution of Pt, Pd and Au in the Skaergaard intrusion shows that the characteristics of the zones, subzones and mineralised section of the intrusion can be explained by simple processes at temperatures above solidi of the gabbros.

2. The anomalous sample (GGU 394913) with elevated Pt and Pd and high Pt/Pd from a stratigraphic level ca. 80m below the known mineralisation is believed to represent a true concentration of PGE. No data suggests that it originates from any part of the known mineralisation.

3. The conditions, which could lead to the formation of reefs at stratigraphic levels below the known mineralisation appear to have been present.

4. The Pt, Pd and Au contribution of undetected reefs to bulk composition of the intrusion would be limited and not lead to unexpected or unreasonable bulk compositions for differentiated basaltic magma.

5. The distribution of gold does seem to suggest the possibility for undetected gold concentrations. They are suggestibly located in the not yet drilled south-central part of the intrusion.

Recommendations

Pt-enriched reefs

It is found likely that mineralisation processes similar to those that have formed the Pd5 to Pd2 Pd-levels in the known mineralisation have taken place in the macrorythmic section in the central part of Middle Zone. It is also found likely that the Pd/Pt ratio that such mineralisations would have is between 3 and 4. No concentrations of PGE can be calculated for the suggested mineralisation. The following activities could be suggested if exploration for additional reefs in the Skaergaard intrusion is to be undertaken.

1. Sampling from core DDH 90-14 of the interval around the leucogabbro layers from 264m to EOH. In accordance with the developed mineralisation model systematic assaying may show elevated levels of PGE. The core is located in the core depot in Soedalen, Miki Fjord.

2. Surface sampling of the macrorythmic section in the central part of MZ on the west-facing walls of Pukugagryggen. A very tight sampling (approaching chip line sampling) would be able to show whether additional reefs exist. The concentrations may not be economical, but could tentatively increase towards a center in the southern or south-western part of the intrusion.

3. Drlling to levels of at least 200m below the peak in the Pd5 anomaly in the area around the western end of Forbindelsesgletscher. Systematic assays may show concentrations in PGE in gabbros at the lower contact of leucogabbro layers.

Gold

The suggested deficit in gold in the bulk estimate of the parental melt of the Skaergaard intrusion could suggest concentration of gold at stratigraphic levels above the Pd5-Pd1 mineralisation in the south-central part of the intrusion. Grades of such Au mineralisation(s) can not be estimated. The following action can be suggested if exploration for this hypothetical gold mineralisation is to be undertaken.

1. A deep drill hole to depth of 1500m or more in the south-central part of the intrusion in the Kobbernunatak area. Further refinement of the structural model is needed to give an estimate of the depth of the hypothetical concentration of gold. The stratigraphic control for this part of the intrusion is very limited.

References

Bird, D. K., Brooks, C. K., Gannicott, R. A. & Turner, P. A. 1991: A gold-bearing horizon in the Skaergaard intrusion, East Greenland. Economic Geology **86**, 1083-1092.

Blank, H. R. & Gettins, M. E. 1973: Subsurface form and extend of the Skaergaard intrusion, East Greenland. (abs.). Transactions of the American Geophysical Union **54**, 507 only.

Brooks, C. K. & Nielsen, T. F. D. 1978: Early stages of the Skaergaard magma as revealed by a closely related suite of dike rocks. Lithos **11**, 1-14.

Brooks, C. K. & Nielsen, T. F. D. 1990: The differentiation of the Skaergaard intrusion. A discussion of R. H. Hunter & R. S. J. Sparks (Contrib. Mineral. Petrol. 95:451-461). Contributions to Mineralogy and Petrology **104**, 244-247.

Boudreau, A. E. & Meurer, W. P. 1999: Chromatographic separation of Platinum-group elements, gold, base metals and sulphur during degassing of a compacting and solidifying igneous crystal pile. Contributions to Mineralogy and Petrology **134**, 174-185

Hoover, J. D. 1989: The chilled margin gabbro and other contact rocks of the Skaergaard intrusion. Journal of Petrology **30**, 441-476.

Irvine, T. N., Andersen, J. C. Ø. & Brooks, C. K. 1998: Included blocks (and blocks within blocks) in the Skaergaard intrusion, East Greenland. Bulletin of the Geological Society of America **110 (11)**, 1398-1447.

Jakobsen, J. K., Veksler, I. V., Tegner, C. & Brooks, C. K. (in press): Extreme Fe enrichment and liquid immiscibility in Skaergaard: Evidence from apatite-hosted melt inclusions. Goldschmidt conference abstracts.

Karup-Møller, S. & Makovicky, E. 1999: The phase system Cu-Pd-S at 900 degrees, 725 degrees, 550 degrees, and 400 degrees C: Neues Jahrbuch Fur Mineralogie-Monatshefte **1999**, p. 551-567.

McBirney, A. R. 1989: Geological map of the Skaergaard intrusion, East Greenland. University of Oregon.

McBirney, A. R. 1996: The Skaergaard intrusion. In: Cawthorn, R. G. (ed.) Layered Intrusions. 147-180. Amsterdam: Elsevier.

McBirney, A. R. & Nakamura, Y 1974: Immiscibility in late-stage magmas of the Skaergaard intrusion. Carnegie Institution Year Book **73**, 348-352.

Momme, P., Tegner, C., Brooks, C. K. & Keays, R. R. 2002: The behaviour of platinum group elements in basalts from the east Greenland rifted margin. Contributions to Mineralogy and Petrology **143**, 133-153.

Naslund, H. R. 1976: Liquid immiscibility in the system $KAlSi_3O_8$-$NaAlSi_3O_8$-FeO-Fe_2O_3-SiO_2 and its application to natural magmas. Carnegie Institution Year Book **75**, 592-597

Nielsen, T. F. D. 2001: The palladium potential of the Skaergaard intrusion, South-East Greenland. Report GEUS **2001/23**, 38 pp.

Nielsen, T. F. D. 2004: The shape and volume of the Skaergaard intrusion, Greenland: Implications for mass balance and bulk composition. Journal of Petrology **45**, 507-530.

Nielsen, T. F. D. & Brooks, C. K. 1995: Precious metals in magmas of East Greenland: Factors important to the mineralisation in the Skaergaard intrusion. Economic Geology **90**, 1911-1917.

Nielsen, T. F. D., Rasmussen, H., Rudashevsky, N. S., Kretser, Y., L. & Rudashevsky, V. N., 2003a: PGE and sulphide phases of the precious metal mineralisation of the Skaergaard intrusion: Part 1: Sample 90-23A, 807: Danmarks og Grønlands Geologiske Undersøgelse Rapport, **2003/47**, 20 pp.

Nielsen, T. F. D., Rasmussen, H., Rudashevsky, N. S., Kretser, Y., L. & Rudashevsky, V. N., 2003b: PGE and sulphide phases of the precious metal mineralisation of the Skaergaard intrusion: Part 2: Sample 90-24, 1057: Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/48**, 20 pp.

Nielsen, T. F. D., Rasmussen, H., Rudashevsky, N. S., Kretser, Y., L., & Rudashevsky, V. N., 2003c: PGE and sulphide phases of the precious metal mineralisation of the Skaergaard intrusion: Part 3: Sample 90-18, 1010: Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/52**, 25 pp.

Nielsen, T. F. D., Rasmussen, H., Rudashevsky, N. S., Kretser, Y., L. & Rudashevsky, V. N., 2003d: PGE and sulphide phases of the precious metal mineralisation of the Skaergaard intrusion: Part 3: Sample 90-23A, 806: Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/53**, 18 pp.

Nielsen, T. F. D., Rasmussen, H., Rudashevsky, N. S., Kretser, Y., L. & Rudashevsky, V. N., 2003e: PGE and sulphide phases of the precious metal mineralisation of the Skaergaard intrusion: Part 3: Sample 90-23A, 808: Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/54**, 16 pp.

Turner, P. A. & Mosher, G. W. 1989: Report of the 1988 field season, Skærgaard concession and East Greenland prospecting license, 71 pp. Company report. Toronto: Platinova Resources Ltd. (in achive of Danmarks og Grønlands Geologiske Undersøgelse, GRF. no. 20845).

Wager, L. R. & Brown, G. M. (1968). Layered igneous rocks. Edinburgh and London: Oliver and Boyd.

Wager, L. R. & Deer, W. A. 1939 (1962 issue): Geological investigations in east Greenland. Part III. The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland. Meddelelser om Grønland **105 (4)**, 352 pp.

Watts, Griffis and McOuat 1991: 1990 Skaergaard project, Platinova/Corona concession, East Greenland. 3 volumes (In archives of the Geological Survey of Denmark and Greenland, GRF # 20848).

Appendixes

The report includes 3 appendixes. The data sheets are available in electronic form on request.

Appendix 1: File “Au+PGE profile SMC.xls” contains all the background data for the grab sample profile from the Skaergaard intrusion.

Appendix 2: File “SK bulk 2004.xls” contains the calculation of the bulk composition for the Skaergaard intrusion and the contribution of individual zones to the total PGE and Au budget.

Appendix 3: File “Reef contrib. 2004.xls” shows the results of the calculation of the PGE and Au contribution to the bulk composition of an un-detected reef.

Appendix 1

PGE and Au assay for the Skaergaard Layered Series

Stratigraphic height and % of mass crystallised are calibrated to the average stratigraphic thicknesses and mass proportions in Nielsen (2004).

GGU Sample #	Profile	Strat. height	% LS mass	comment	zone	peak	Pt	Pd	Au	Ir	Rh	Pd/Pt	Au/Pd	Au/Pt
Sandwich Horizon														
SH average	Bollingberg profile				SH		1	3	10			3.0	3.3	10.0
SH average		3310	100%				1	3	10			3.0	3.3	10.0
Upper Zone c														
348877	Bollingberg profile	3260	99.6		UZc		5	10	1			2.0	2.0	0.2
348882	Bollingberg profile	3220	99.0		UZc		8	9	9			1.1	1.1	1.1
348883	Bollingberg profile	3140	98.2		UZc		2	9	11			4.5	4.5	5.5
UZc average							5	9	7			2.5	2.5	1.4
Upper Zone b														
348884	Bollingberg profile	3100	97.4		UZb		6	8	10			1.3	1.3	1.7
348876	Bollingberg profile	3030	96.1		UZb		11	13	7			1.2	1.2	0.6
348878	Bollingberg profile	2930	94.1		UZb		6	8	3			1.3	1.3	0.5
348881	Bollingberg profile	2740	90.2		UZb		8	15	7			1.9	1.9	0.9
UZb average							8	11	7			1.4	1.4	0.9
Upper Zone a														
348880	Bollingberg profile	2680	88.9		UZa		8	15	11			1.9	1.9	1.4
348879	Bollingberg profile	2530	85.2		UZa		3	2	5			0.7	2.5	1.7
		Strat.	% LS											

GGU Sample #	Profile	height	mass	comment	zone	peak	Pt	Pd	Au	Ir	Rh	Pd/Pt	Au/Pd	Au/Pt
348869	Bollingberg profile	2400	81.2		UZa		1	2	7			2.0	3.5	7.0
348832	Puku profile	2330	80.3	Anomalous	UZa		10	93	99			9.3	1.1	9.9
UZa av. without 348832							4	6	8			1.5	1.3	2.0
UZa av. with 348832							6	28	31			3.5	2.2	5.5
Uppermost Middle Zone														
348833	Puku profile	2328	80.1		MZ		1	47	20			47.0	0.4	20.0
348866	Bollingberg profile	2326	80.0		MZ		1	2	16			2.0	8.0	16.0
348834	Puku profile	2320	79.8		MZ		7	34	33			4.9	1.0	4.7
348835	Puku profile	2319	79.7		MZ		3	6	42			2.0	7.0	14.0
384828	Puku profile	2281	78.3		MZ		33	12	126			0.4	10.5	3.8
348827	Puku profile	2278	78.2		MZ		42	23	198			0.5	8.6	4.7
348826	Puku profile	2260	77.7		MZ		12	28	161			2.3	5.8	13.4
Average MZ above Pd1							14	22	85			1.5	3.9	6.0
Mineralised zone														
348825	Puku profile	2256	77.60		MZ		5	4	48			0.8	12.0	9.6
348829	Puku profile	2254	77.54		MZ	Pd1	61	125	554			2.0	4.4	9.1
348824	Puku profile	2252	77.47		MZ		19	34	140			1.8	4.1	7.4
348831	Puku profile	2251	77.40		MZ		14	29	125			2.1	4.3	8.9
348830	Puku profile	2051	77.40		MZ		32	72	238			2.3	3.3	7.4
348840	Puku profile	2046	77.20		MZ		3	6	42			2.0	7.0	14.0
348839	Puku profile	2045	77.17		MZ	Pd2	53	286	348			5.4	1.2	6.6
348838	Puku profile	2044	77.13		MZ	Pd2	36	538	477			14.9	0.9	13.3
348836	Puku profile	2243	77.07		MZ		17	430	157			25.3	0.4	9.2
348837	Puku profile	2241	77.00		MZ		33	487	122			14.8	0.3	3.7
348816	Kraemer Ø TFN 1	2240	76.97		MZ	Pd3	21	352	4213			16.8	12.0	200.6
		Strat.	% LS											
GGU Sample #	Profile	height	mass	comment	zone	peak	Pt	Pd	Au	Ir	Rh	Pd/Pt	Au/Pd	Au/Pt

348816 repeat	Kraemer Ø TFN 1	2240	76.97	Ni FA	MZ	Pd3	600	870	4200			1.5	4.8	7.0
348870	Bollingberg profile	2240	76.97		MZ		10	153	845			15.3	5.5	84.5
361022	Toe of Forbindelse profile	2240	76.97		MZ		37	130	473			3.5	3.6	12.8
361021	Toe of Forbindelse profile	2239	76.94		MZ		22	259	230			11.8	0.9	10.5
361020	Toe of Forbindelse profile	2238	76.90		MZ		7	133	66			19.0	0.5	9.4
361019	Toe of Forbindelse profile	2236	76.84		MZ		4	253	41			63.3	0.2	10.3
361018	Toe of Forbindelse profile	2234	76.78		MZ	Pd4	81	827	559			10.2	0.7	6.9
361018 repeat	Toe of Forbindelse profile	2234	76.77	Ni FA	MZ	Pd4	0	1040	620			-	0.6	
361017	Toe of Forbindelse profile	2232	76.70		MZ		29	504	174			17.4	0.3	6.0
361016	Toe of Forbindelse profile	2230	76.60		MZ		26	501	135			19.3	0.3	5.2
361016 repeat	Toe of Forbindelse profile	2230	76.60	Ni FA	MZ		57	640	120	5.4	15.0	11.2	0.2	2.1
361015	Toe of Forbindelse profile	2228	76.55		MZ		19	622	77			32.7	0.1	4.1
361014	Toe of Forbindelse profile	2226	76.50		MZ		20	603	132			30.2	0.2	6.6
361013	Toe of Forbindelse profile	2224			MZ		8	404	61			50.5	0.2	7.6
361012	Toe of Forbindelse profile	2222			MZ		104	1590	145			15.3	0.1	1.4
361011	Toe of Forbindelse profile	2220			MZ	Pd5	200	3022	138			15.1	0.0	0.7
361011 repeat	Toe of Forbindelse profile	2220	76.30	Ni FA	MZ	Pd5	250	3800	125			15.2	0.0	0.5
361010	Toe of Forbindelse profile	2219			MZ	Pd5	217	2795	235			12.9	0.1	1.1
361009	Toe of Forbindelse profile	2218			MZ	Pd5	192	2932	121			15.3	0.0	0.6
361008	Toe of Forbindelse profile	2217	76.20		MZ		87	1137	33			13.1	0.0	0.4
361023	Toe of Forbindelse profile	2216			MZ		140	1242	64			8.9	0.1	0.5
361024	Toe of Forbindelse profile	2215			MZ		96	703	36			7.3	0.1	0.4
361025	Toe of Forbindelse profile	2214	76.10		MZ		112	757	56			6.8	0.1	0.5
Mineralised zone average							57	698	336			12.3	0.5	5.9
Lower Middle Zone														
394914	Kraemer Ø profile	2190	76.1		MZ		23	191	114			8.3	0.6	5.0
394913	Kraemer Ø profile	2140	74.8		MZ		149	514	26			3.4	0.1	0.2
		Strat.	% LS											
GGU Sample #	Profile	height	mass	comment	zone	peak	Pt	Pd	Au	Ir	Rh	Pd/Pt	Au/Pd	Au/Pt
394912	Kraemer Ø profile	2120	73.9		MZ		16	8	13			0.5	1.6	0.8

394911	Kraemer Ø profile	2100	73.0		MZ		25	11	4			0.4	0.4	0.2
348865	Bollingberg profile	2080	72.1		MZ		5	8	20			1.6	2.5	4.0
394906	Kraemer Ø profile	2060	71.2		MZ		7	41	6			5.9	0.1	0.9
394905	Kraemer Ø profile	2040	70.3		MZ		6	36	3			6.0	0.1	0.5
348867	Bollingberg profile	2020	69.4		MZ		12	35	2			2.9	0.1	0.2
394904	Kraemer Ø profile	2000	68.5		MZ		10	153	11			15.3	0.1	1.1
394903	Kraemer Ø profile	1980	67.6		MZ		7	64	4			9.1	0.1	0.6
348868	Bollingberg profile	1960	66.7		MZ		14	58	6			4.1	0.1	0.4
394902	Kraemer Ø profile	1940	65.8		MZ		9	92	4			10.2	0.0	0.4
348887repeat	Bollingberg profile	1930	65.3	NI FA	MZ		46	93	8	2.7		2.0	0.1	0.2
348887	Bollingberg profile	1930	65.3		MZ		18	39	11			2.2	0.3	0.6
394907	Kraemer Ø profile	1915	65.0		MZ		14	27	4			1.9	0.1	0.3
394901	Kraemer Ø profile	1910	64.8		MZ		11	56	3			5.1	0.1	0.3
348889	Bollingberg profile	1880	63.6		MZ		11	51	1			4.6	0.0	0.1
348886	Bollingberg profile	1860	62.7		MZ		9	46	3			5.1	0.1	0.3
Lower MZ average							18	79	13			4.5	0.2	0.8
Lower Zone c														
348872	Bollingberg profile	1840	62.5		LZc		9	35	12			3.9	0.3	1.3
348890	*Bollingberg profile*	*1700*	*59.0*	*Ni FA*	*LZc*		*20*	*40*	*12*			*2.0*	*0.3*	*0.6*
348888	Bollingberg profile	1610	55.6		LZc		6	15	6			2.5	0.4	1.0
LZc average (3)							12	30	10			2.8	0.3	0.9
LZc average (2)				without Ni FA			8	25	9			2.4	0.4	1.2
Lower Zone b														
348874	Bollingberg profile	1500	52.2		LZb		3	9	5			3.0	0.6	1.7
		Strat.	% LS											
GGU Sample #	Profile	height	mass	comment	zone	peak	Pt	Pd	Au	Ir	Rh	Pd/Pt	Au/Pd	Au/Pt
348873	*Bollingberg profile*	*1250*	*44.0*	*Ni FA*	*LZb*		*4*	*4*	*9*			*1.0*	*2.3*	*2.3*
348871	Bollingberg profile	1000	35.9		LZb		10	13	2			1.3	0.2	0.2

LZb average							6	9	5			1.8	0.6	0.9
Lower Zone a														
348863	Bollingberg profile	880	32.1		LZa		6	14	5			2.3	0.4	0.8
348862	*Bollingberg profile*	*800*	*29.1*	*Ni FA*	*LZa*		*21*	*10*	*9*			*2.0*	*0.5*	*0.4*
348864	Bollingberg profile	720	26.2		LZa		6	26	7			4.3	0.3	1.2
LZa + HZ average (3)							11	17	7			2.9	0.4	0.6
LZa + HZ average (2)				without Ni FA			6	20	6			3.1	0.4	1.0
Bulk		0	0.0				8	26	10			3.3	0.4	1.3

Appendix 2

Bulk composition of the Skaergaard intrusion												
Based on average compositions in file "Au+PGE profile SMC.xls". Average data for SK dykes from Nielsen and Brooks (1995).												
Zone or subzone	**mass propor- tion**	**ppb Pt TFN**	**ppb Pt Platin.**	**ppb Pd TFN**	**ppb Pd Platin.**	**ppb Au TFN**	**ppb Au Platin.**	**ppb Pt contr.**	**ppb Pd contr.**	**ppb Au contr.**	**Pd/Pt**	**Au/Pd**
Uzc	2.2	5	-	9	-	7	1	0.11	0.20	0.15	1.80	0.78
Uzb	8	8	-	11	3	7	1	0.64	0.88	0.56	1.38	0.64
Uza	9.8	4	-	6	3	8	5	0.39	0.59	0.78	1.50	1.33
Top MZ (profile)	2	14		20		84		0.28	0.40	1.68	1.43	4.20
Top MZ (from DDH 89-09)	2		13		32		44	0.26	0.64	0.88	2.46	1.38
Anomalous zone (profile)	1.1	57		698		336		0.63	7.68	3.70	12.25	0.48
Anomalous zone (DDH 89-09)	1.1		47		549		156	0.52	6.04	1.72	11.68	0.28
Lower MZ	10.3	18		79		13		1.85	8.14	1.34	4.39	0.16
LZc	7.3	8	8	25	25	9	2	0.58	1.83	0.66	3.13	0.36
LZb	23.9	6	6	9	13	5	1	1.43	2.15	1.20	1.50	0.56
HZ+Lza	35.4	6	7	20	8	6	1	2.12	7.08	2.12	3.33	0.30
Bulk LS from profiles		8		29		12					3.50	0.42
Bulk LS using DDH 89-09 data		8		27		9					3.75	0.32
average of estimates		8		29		11					3.63	0.38
UBS + MBS		7		18		7					2.57	0.39
Bulk SK w. estim. UBS +MBS		**8**		**26**		**10**					**3.34**	**0.38**
Bulk SK; no PGE+Au in MBS + UBS		6		20		8					3.33	0.38
Average UZ		6		8		7		1.1	1.7	1.5	1.46	0.90
Average anomalous to UZ		25		215		84		0.5	6.0	1.7	8.60	0.39
Av. anomalous and top of LS		8		36		13		1.7	7.7	3.2	0.87	0.65
Av. below anomalous zone		8		25		7		6.0	19.2	5.3	3.20	0.28

Appendix 3

Contribution to Pt, Pd and Au budget of hypothetical reef				
Hypothetical reef, 2m thick, with 3 ppm Pt, 10.35 ppm Pd and 1.58 ppm Au (ratios as in GGU 394913). Volume of 2m thick reef in upper MZ: 0.118 km3.				
Proportion of mass: 0.04%				
	Pt	**Pd**	**Au**	**Pd/Pt**
Bulk SK	8	26	10	3.3
Reef contribution	1	4	1	4.0
New bulk	9	30	11	3.3
Hypothetical reef, 2m thick, with 3 ppm Pt and 3 ppm Pd. Volume of 2 m thich reef in upper MZ: 0.118 km3. Proportion of mass: 0.04%.				
	Pt	**Pd**	**Au**	**Pd/Pt**
Bulk SK	8	26	10	3.3
Reef contribution	1	1	0	1.0
New bulk	9	27	10	3.0