DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/91

Gold, PGE and sulfide phases of the precious metal mineralization of the Skaergaard intrusion

Part 12: Sample 90-18 1001

Nikolay S. Rudashevsky, Vladimir N. Rudashevsky
& Troels F. D. Nielsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/91

Gold, PGE and sulfide phases of the precious metal mineralization of the Skaergaard intrusion

Part 12: Sample 90-18 1001

Nikolay S. Rudashevsky, Vladimir N. Rudashevsky
& Troels F. D. Nielsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND BUILDING

G E U S

Abstract

The report presents the results of mineralogical investigations of the sample 90-18 1001 from the Platinova Reef of the Skaergaard intrusion. The sample covers the interval between 1001 and 1002 m in diamond drill hole 90-18.The sample collects the Pd4 level (lower part) of the mineralisation. Assays give 668 ppb Pd, 59 ppb Au, and 74 ppb Pt for this interval.

The sample (1188 g) was crushed in small portions using a shatter box with small cavities (200 ml) for short periods (0.3-0.5 min) and sieved to remove the fine fraction (sieving -100 µm) after each crushing session. The residual coarse fraction >100 µm was re-crushed until the entire sample attained the desired maximum grain size.

After complete crushing, the material was passed with water through the following sieves (wet-sieving): 1) <40, 2) 40-50, 3) 50-70, and 4) 70-100 µm. All fractions were subsequently subjected to wet magnetic separation. All magnetic fractions showed not contain grains of precious metal grains.

The non-magnetic parts of every grain size fraction from the sample 90-18, 1001 were then passed through hydroseparaion using the computer controlled CNT HS-11 apparatus. Monolayer polished sections were produced from the heavy mineral HS-concentrates- one for each grain size fraction. The polished sections (and one of the whole rock) were investigated under the scanning electron microprobe.

The gabbro in the sample 90-18 1001 does not show the otherwise characteristic reaction relationships between cumulus and inter-cumulus phases, such as rims of olivine at the boundaries between Fe-Ti-oxides and pyroxenes. In general, the sample is “dry” with H_2O-bearing minerals occurring only locally in very insignificant amounts in intergrowths with Cu-Fe-sulphides.

The HS-concentrates contain numerous sulphide grains identified as sulphide droplets. They are formed by one or more Cu-sulphides – bornite (90 %), more rarely by bornite+chalcopyrite (5 %), bornite+chalcosine (3 %), or chalcopyrite, chalcosine and digenite. Several of these droplets and sulphide grains contain inclusions of PGMs. Besides, liberated (free) precious metal mineral grains were also recovered.

Base on microprobe investigations of the heavy mineral HS concentrates, a representative selection of PGMs in 20 particles (25 PGM grains in total) was studied in detail. The main precious metal minerals are skaergaardite PdCu (46.1 area %), vysotskite (Pd,Ni)S (20.5 area %) and vasilite $(Pd,Cu)_{16}S_7$ (20.3 area %). These minerals are followed by 5 minor minerals of minor importance (totalling ~13 % by area of all precious metal minerals in the sample) They include: zvyagintsevite $(Pd,Pt,Au)_3(Pb,Sn)$ (6.2 area %), (Au,Cu) alloy (6.1 area %), keithconnite $(Pd,Cu)_3(Te,Pb)$ (0.2 area %), (Pt,Fe,Cu) alloy (0.2 area %) and unnamed $(Pd,Ag,Cu)_5S$ (0.3 area %).

The grain size of the precious metal minerals (ECD) vary from 1 to 35 μm with an average grain size of 12 μm.

Average composition of skaergaardite (from 7 analyses) is (wt. %): Pd 60.0, Pt 1.7, Au 1.5, Cu 28.7, Fe 4.7, Zn 2.3, Te 0.5 Total 99.4; Giving the formula:

$$(Pd_{0.97}Pt_{0.02}Au_{0.01})_{1.00}(Cu_{0.78}Fe_{0.15}Zn_{0.06}Te_{0.01})_{1.00}$$

The estimated bulk composition of the sample (assay of whole rock in brackets) is (ppb): Pd 685 (668), Au 103 (59), Pt 13 (74). Pd is concentrated in skaergaardite (49%), Pd - sulphides (38 %), and other Pd-PGMs (13%). Pt is distributed between skaergaardite (74 %) and Pt- minerals (~17%, (Fe-Pt)-alloy). Au is concentrated in (Au,Cu) alloy (91%) and skaergaardite (8%). Most of the identified precious metal minerals form a single paragenesis together with Cu-Fe sulphides.

The identification of Au and Pt minerals in the sample with such low bulk Pt and Au concentrations (assay: 74 ppb Pt and 59 ppb Au) illustrates the sensitivity of HS technology for mineralogical investigations. Large errors on Pt and Au reflect nugget effects and the very low elemental concentrations.

Introduction

The report describes the mineralogy of sample 90-18 1001 from the Pd4 level in the "Platinova Reef" of the Skaergaard intrusion (Andersen et al., 1998 and Nielsen et al, 2007). The report is based on data from concentrates obtained using a new patented model of Hydroseparator CNT HS-11 and one polished thin section of the host gabbro. Monolayer polished sections of HS concentrate and the polished section of the gabbro were studied using electron microscopy and electron microprobe analysis (Camscan-4DV, Link AN-10000). The report gives description of the grain characteristics, the parageneses and the compositional variations within the identified groups of minerals, alloys, sulphide droplets (melts) and the host gabbro.

The investigation was carried out in 2009.

Sample 90-18 1001

Sample 90-18, 1001 was collected from BQ drill core #90-18 in the 1001-1002m interval at the Pd4 level of the Skaergaard mineralisation (Nielsen et al. 2005). Assays give 668 ppb Pd, 59 ppb Au, and 74 ppb Pt for this interval. The core has previously been sampled for other purposes and the sample collects 1/3 of the diameter of the preserved core.Details of the drilling campaign can be found in Watts, Griffis & MCOuat (1991).

Analytical techniques

Analytical techniques are described in Nielsen et al. (2003) In addition to the monolayer samples, one polished section was prepared from a fragment of the bulk sample (Plate 1). The heavy mineral HS concentrates, enriched in precious metal minerals and sulphides (Plate 2) were obtained using a new patented model of the computer controlled Hydroseparator CNT HS-11 and newly patented glass separation tube (GST) (Rudashevsky & Rudashevsky, 2006 and 2007).

Apart from the fragment used for a thin section all the core material was crushed to <100 μm. After complete grinding, the sample was passed through standard sieves with water (wet sieving, recoveries in brackets): <40 μm (474.8 g) , 40-50 μm (70 g), 50-70 μm (202 g), 70-100 μm (342.1 g).

After wet magnetic separation, the powdered fractions <40 μm, 40-50 μm, 50-70 μm, 70-100 μm were passed through hydroseparator CNT HS-11 to produce heavy mineral concentrates. Monolayer polished sections were produced from all heavy mineral HS-concentrates.

Results

Rock forming minerals and sulphide mineralogy

Silicates and oxides

The silicates and oxides related to sulphides are: monoclinic ferrous pyroxene, Mg# = 0.62-0.63 (Table 1, analyses 1-3); orthorhombic ferrous pyroxene, Mg# = 0.51-0.55 (Table 1, analyses 4-6); plagioclase, An_{49} (Table 1, analyses 7 and Fe-Ti oxides including ilmenite (Table 1, analyses 9-11) and titaniferous magnetite (Table 1, analyses 12-14). Monoclinic and orthorhombic pyroxenes form typical exsolution textures (Plate 1, #2-5).

The Fe-Ti-oxides occur as aggregates of 1-3 mm anhedral grains. They fill space between grains of plagioclase and pyroxenes (see Plate 1, #1). The studied fragment of the gabbro of sample 90-18 1001 does not show the otherwise characteristic reaction relationships with olivine rims between cumulus and inter-cumulus phases (e.g., Holness et al, 2011). No olivine rims are observed between grains of Fe-Ti-oxides and pyroxenes in the studies fragment (Plate 1, #1).

Several grains (~40 µm) of baddeleyite were identified In the heavy mineral HS concentrate (Plate 3). Potentially, they can be used for dating of the Pd4 ore horizon.

Sulphides

The host gabbro is poor in sulphide. In the polished thin section (Plate 1, #5), only a few rare grains of bornite were identified in intergrowths of pyroxenes. The ilmenite-rich (>97 % ilm.) non-magnetic heavy mineral HS concentrates are, however, enriched in grains of sulphide and PGMs (see Plate 2). The sulphide grains are represented by droplet-like microglobules of bornite (Plate 4, #1-14 etc) or bornite and chalcopyrite (Plate 4, #25-28 etc), and irregular grains of bornite (Plate 4, #15-24 etc), bornite and chalcopyrite (Plate 4, #29, 30 etc), chalcosine (Plate 4, #31), bornite and chalcosine (Plate 4, #32), chalcopyrite, or digenite (Plate 4, #33). The droplets and grains are up to 100 µm in size.

The majority (~90 %) of sulphide grains are composed of bornite, with only few of bornite+chalcopyrite (5%), or bornite+chalcosine (3%), sometimes chalcopyrite, chalcosine or just digenite. Bornite and chalcopyrite, or bornite and chalcosine form exsolution textures inside sulphide micro globules and grains (see Plate 4, #25, 30 and 32).

Chemical compositions of bornite (Table 2, analyses 1-18, the average analysis 19), chalcopyrite (Table 2, analyses 20-24, the average analysis 25), chalcosine (Table 2, analyses 26-28) and digenite (Table 2, analysis 29) are all close to being stoikiometric. One grain of cobalt-pentlandite (Plate 5, #4; Table 2, analysis 30) was found in the heavy mineral HS concentrates.

Silicate and FeTi-oxide minerals that can be found in the marginal parts of sulphide grains or PGM grains include: ilmenite (Plate 4, #15), chlorite (Plate 4, 18, 31), hornblende (Plate 4, #16) and actinolite (Plate 4, #17).

Precious metal minerals: recovery, grain size and relations to host rock

An almost perfect separation of accessory minerals has been achieved by gentle crushing/disintegration of the studied sample. The method of disintegration allows to preserve primary grain size and recover the most important information on the mineral genesis. The concentrates can provide all the information needed for the reconstruction of the primary shapes and sizes of accessory minerals, together with their mineral paragenesises and relationships with the minerals of the matrix rock.

Recovery

No PGM grains were located during SEM investigation of a polished section of the bulk rock. Despite the low bulk rock elemental concentrations the heavy mineral HS concentrates yielded a suite of precious metal grains. A selection of 20 fine particles from the <40 µm fraction of the heavy mineral HS concentrates is believed to be representative for the precious metal mineral paragenesis and is studied in detail. In total, 8 different PGE and Au-bearing minerals are documented in the sample. They include (Table 3):

1) skaergaardite (Pd,Pt,Au)(Cu,Fe,Zn,Te)
2) vysotskite (Pd,Ni,Cu)S
3) vasilite $(Pd,Cu)_{16}S_7$
4) zvyagintsevite $(Pd,Pt,Au)_3$ (Pb,Sn)
5) (Au,Cu) alloy (Au,Cu,Pd)
6) keithconnite Pd_{3-x}(Te,Pb)
7) (Pt,Fe) alloy (Pt,Fe,Cu)
8) unnamed $(Pd,Ag,Cu)_5S$

The volumetric proportions of these minerals (area %) are shown in Fig. 1 and table 3.

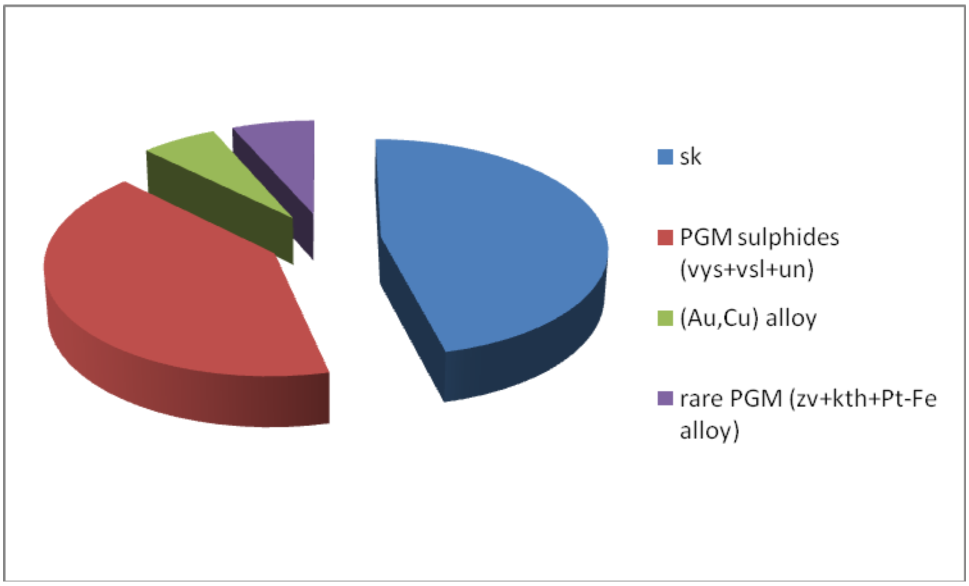


Fig. 1. Precious metal minerals (area %) from the heavy mineral HS concentrates of sample 90-18 1001: sk – skaergaardite, vys – vysotskite, vsl – vasilite, zv – zvyagintsevite, kth – keithconnite, un – unnamed $(Pd,Ag)_5S$.

Grain size

The size of recovered grains is given as the effective diameters (ECD) and found using the software ”imageJ” ®. The size varies from 1 to 35 µm with an average of 12 µm (Table 4; Fig. 2).

The grain size distribution is:

Grain size, µm	Number of grains
0-10	14
10-20	3
20-30	7
30-40	1
Total	25

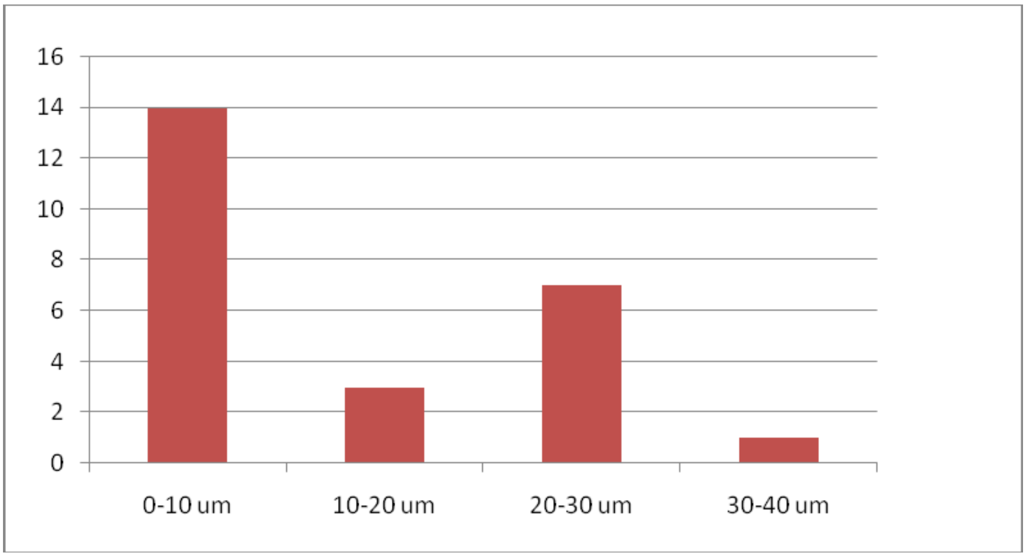


Figure 2. The number of grains of precious metal minerals from sample 90-18 1001 distributed according to size (n=25, ECD avg = 12.3 µm).

The histogram (Fig. 2) shows two maxima for the statistical selection (n=25) at 0-10 µm which represent PGM inclusions in sulphides and 20-30 µm in free PGMs and grains with >90% exposed PGM.

The SEIs (scanning electron images) show that majority of precious metal mineral grains are well preserved and have kept their primary shape and size (Plates 4-8). Grains have not been broken during production of the concentrates. The largest proportion of PGM grains appears to have been or be as inclusions in Cu-Fe sulphide globules and grains.

Associations

In the heavy mineral concentrates of the sample 90-18 1001 (n=25 grains) the precious metal mineral grains occur in the following mineral associations (Fig. 3; Table 5).

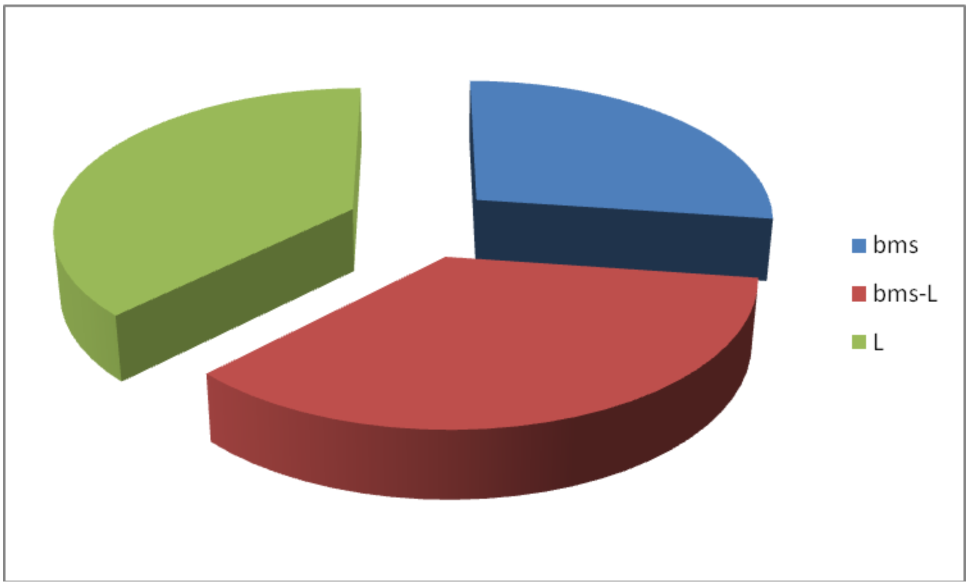


Figure. 3. Distribution of liberation for PGE- and gold minerals from the heavy mineral HS concentrates of the sample 90-18, 1001; bms - precious metal minerals attached to base metal sulphides; bms-L - >90% exposed precious metal minerals attached to bms; L – liberated (free) precious metal minerals.

Description and composition of precious metal minerals

Skaergaardite (Pd,Pt,Au)(Cu,Fe,Zn,Te)

The type locality of skaergaardite (PdCu) is in core 90-24 between 1057 and 1058 m in the Skaergaard mineralisation (Rudashevsky *et* al., 2004).

Description

In sample 90-18 1001 skaergaardite is the main precious metal mineral and constitutes by area 46.1 % of all precious metal minerals. It is found in intergrowths with the base metal sulphides bornite, chalcopyrite and cobalt-pentlandite (Plate 5, #1-6). Occasionally skaergaardite contains inclusions of other PGM, e.g., keithconnite (Plate 8, #3).

Grains of skaergaardite may be euhedral, subhedral or irregular. Irregular grains may cluster into aggregates (Plate 5). The grain size of skaergaardite (9 grains) is from 2 to 29 µm with an average of 15 µm (Table 3).

Mineral chemistry

Analyses of skaergaardite were obtained from 7 grains (Table 6, analyses 1-7). The average composition (analysis 8) is (wt. %): Pd 60.0, Pt 1.7, Au 1.5, Cu 28.7, Fe 4.7, Zn 2.3, Te 0.5. The total is 99.4% and the composition corresponds to the formula:

$$(Pd_{0.97}Pt_{0.02}Au_{0.01})_{1.00}(Cu_{0.78}Fe_{0.15}Zn_{0.06}Te_{0.01})_{1.00}$$

Typical substitutions in skaergaardite are: Pt up to 5.9 % and Au up to 9.3 % for Pd and Fe 2.3-8.9 %, Zn up to 7.3 % and Te up to 1.8 % for Cu

Vysotskite (Pd,Ni,Cu)S

Description

After skaergaardite vysotskite and vasilite are the second most important PGMs. Vysotskite constitutes 20.5 area % of all PGMs and gold minerals. Vysotskite occurs as inclusion in bornite globules (Plate 6, #1), as intergrowths with small bornite grain, or as liberated particles (Plate 6, #2, 3). Vysotskite grains mostly have irregular shapes (see Plate 6). The size of the grains (3 grains) varies from 2 to 29 µm with an average of 18 µm (Table 3).

Mineral chemistry

The chemical composition of the three vysotskite grains is shown in table 6 (analyses 9-11). The average composition (Table 6, analysis 12) is (wt.%): Pd 68,5, Cu 0.6, Fe 0.5, Ni 6.2, S 24.6. The total is100.4% and the composition corresponds to the formula:

$$(Pd_{0.84}Ni_{0.14}Cu_{0.02}Fe_{0.01})_{1.01}S_{1.00}.$$

Typical substitutions in vysotskite are: Ni 4.1-8.2 %, Cu up to 1.2 % and Fe up to 0.6 %, substituting Pd.

Vasilite $(Pd,Cu)_{16}S_7$

Description

Vasiite is as important as vysotskite with 20.3 area % of all PGMs and gold minerals. Vasilite is found as inclusion in sulphide globules (bornite, chalcopyrite) (Plate 6, #4-6) and as liberated grain (Plate 6, #7). Vasilite occur as globules (Plate 6 #4, 7), and as irregular shape grains (Plate 6, #5, 6). The size of vasilite grains is 1-35 µm with an average of 10.5 µm (see Table 3).

Mineral chemistry

The chemical composition of vasilite from 3 grains (Table 6, analyses 13-15) suggests the following average composition (Table 6, analysis 16, wt.%): Pd 70.6, Cu 13.5, S 12.7. The total is 99.8% and the composition corresponds to the formula:

$$(Pd_{12.24}Cu_{3.76})_{16.00}S_{7.00} .$$

Zvyagintsevite $(Pd,Pt,Au)_3(Pb,Sn)$

Description

Zvyagintsevite constitutes 6.2 % by area of all PGMs and gold minerals. It occurs as inclusion in bornite (Plate 7, #1-3), as intergrowth with (Pt,Fe) alloy and bornite (Plate 7, #4), and as liberated grains (Plate 7, #5). Zvyagintsevite forms small (2-17µm, avg. 6 µm) irregular grains (Plate 7, Table 3).

Mineral chemistry

The composition of zvyagintsevite is given by 3 analyses from 3 grains (Table 6, analyses 11-19). The average composition (Table 6, analysis 20) is (wt.%): Pd 60.2, Pt 1.3, Au 0.8, Fe 0.9, Sn 3.2, Pb 32.9. The total is 99.3% and the composition corresponds to the formula:

$$(Pd_{2.90}Fe_{0.09}Pt_{0.04}Au_{0.02})_{3.05}(Pb_{0.83}Sn_{0.13})_{0.96}$$

Alloy (Au,Cu)

One liberated (free) grain of (Au,Cu) alloy was found in the HS concentrates (Plate 8, #1; Table 6, analysis 22). It is irregular in shape, 20 µm in size, and constitutes 6.1 areal % of all precious metal minerals.

Keithconnite (Pd,Cu)3(Te,Pb)

Only one small, irregular grain of keithconnite grain was found. It is 4 µm in size and constitutes 0.2 areal % of all PGE and gold minerals (Table 3). The grain is enclosed in skaergaardite (Plate 8, #3; Table 6, analysis 21).

(Pt,Fe) alloy

As the last precious metal phase one grain of (Pt,Fe) alloy was found in the heavy mineral HS concentrates (Table 3). The small grain (identified by semi-quantitative microprobe analysis, ~ 4 µm and, 0.2 areal % of all precious metal minerals) is enclosed in zvyagintsevite (Plate 7, #4).

Bulk composition of PGMs of the sample 90-18, 1001

The relative concentrations of Pd, Au and Pt of the sample 90-18 1001 can be calculated from the total concentrations of precious metals (assay), the determined recovery, the modal proportions, the chemical compositions (Tables 3 and 6) and ideal densities of precious metal minerals. The estimated bulk composition of the sample (assays of whole rock in brackets) is (ppb): Pd 685 (668), Au 103 (59), Pt 13 (74). Pd is concentrated in skaergaardite (339 ppb, ~50 %) and Pd sulphides (261 ppb, ~30 %): vysotskite, vasilite and unnamed $(Pd,Ag)_5S$. Pt is also distributed between skaergaardite (~77 %) and (Pt,Fe) alloy. Au is concentrated in (Au,Cu) alloys (93%) and its less amount is in skaergaardite. The large errors on Pt and Au reflect nugget effects and the low bulk concentrations.

Discussion

PGM-paragenesis

The investigation documents that the main PGM in the studied sample is skaergaardite (46.1 area. %) followed by the Pd-sulphides vysotskite (20.5 area %) and vasilite (20.3 area %). All the observations and the inter-grain relations (Plates 5-8) suggest that all PGMs are parts of a single paragenesis together with Cu-Fe sulphides. The Cu-Fe sulphides and precious metal minerals are synchronous. The droplets would have formed while silicate liquid was still present and the formation of the sulphide droplet occurred near the liquidus temperature.

References

Andersen, J.C.; Rasmussen, H.; Nielsen, T.F.D. & Rønsbo, J.G. (1998). The Triple Group and the Platinova gold and palladium reefs in the Skaergaard intrusion. Stratigraphy and petrographic relations. Econ. Geol. **93**, 488-509.

Holness, M.B., Stripp, G., Humphreys, M.C.S., Veksler, I.V., Nielsen, T.F.D. & Tegner, C. (2011). Silicate liquid immiscibility within the crystal mush: Late-stage magmatic microstructures in the Skaergaard intrusion, East Greenland. Journal of Petrology **52(1)**, 175-222.

Nielsen, T.F.D., Andersen, J.C.Ø & Brooks, C.K. (2005). The Platinova Reef of the Skaergaard intrusion. Mineralogical Association of Canada Short Course **35**, 431-455.

Nielsen, T.F.D., Rasmussen, H., Rudashevsky, N.S., Kretser, Yu.L., Rudashevsky, V.N. 2003. PGE and sulphide phases of the precious metal mineralisation of the Skaergaard intrusion. Part 2: sample 90-24, 1057.Geol. Surv. Denmark & Greenland report **2003/48**; 20 pp.

Rudashevsky, N.S., MacDonalds, A.M., Cabri, L.J., Nielsen, T.D.F., Stanley, C.J., Kretzer, Yu.L., Rudashevsky, V.N., Skaergaardite, PdCu, a new platinum group intermetallic mineral from the Skaergaard intrusion, Greenland. Mineralogical Magazine, 2004, vol. **68** (4), 615-632.

Rudashevsky, N.S., Rudashevsky, V.N. Patent of Russian Federation #2281808, invention “Hydraulic Classifier”, Moscow, August 20, 2006.

Rudashevsky, N.S., Rudashevsky, V.N. Patent of Russian Federation #69418, industrial (utility) model, “Device for separation of solid particles”, Moscow, December 27, 2007.

Watts, Griffis & MCOuat (1991). 1990 Skaergaard project, Platinova/Corona concession, East Greenland. Exploration report, 55 pp. andappendixes (in archive of the Geological Surveyof Denmark and Greenland, GRF no. 20848.

TABLES

Table 1. Chemical compositions (wt%) and formuli of silicates and Fe-Ti oxides of Skaergaard gabbro (sample 90-18 1001)

	Clinopyroxene			Orthopyroxene			Plagioclase		Ilmenite			Titaniferous magnetite		
Analysis #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	49.25	49.46	49.89	51.18	51.61	50.11	56.10	55.67	nd	nd	nd	nd	nd	nd
TiO_2	0.67	0.67	0.50	0.17	nd	0.33	nd	nd	51.59	51.25	51.09	11.83	10.53	8.43
Al_2O_3	1.89	1.89	1.51	1.13	1.15	1.02	27.41	27.98	nd	nd	nd	2.02	2.93	2.84
FeO	14.28	13.26	13.51	26.63	27.80	29.34	0.26	0.00	42.15	42.41	43.01	42.48	41.45	40.81
Fe_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	3.06	3.63	3.53	42.32	43.47	48.42
V_2O_3	nd	nd	nd	nd	nd	nd	nd	nd	0.44	0.74	0.59	1.57	1.85	1.57
MnO	0.39	0.39	0.37	0.78	0.80	0.76	nd	nd	0.65	0.39	0.52	nd	nd	nd
MgO	12.60	12.44	12.77	18.41	17.41	17.25	nd	nd	1.99	1.82	1.33	nd	nd	nd
CaO	20.28	20.98	21.26	1.26	1.12	1.26	10.07	9.93	nd	nd	nd	nd	nd	nd
Na_2O	nd	nd	nd	nd	nd	nd	5.66	5.53	nd	nd	nd	nd	nd	nd
K_2O	nd	nd	nd	nd	nd	nd	0.36	0.48	nd	nd	nd	nd	nd	nd
Sum	99.36	99.09	100.26	99.56	99.89	100.07	99.86	99.59	99.87	100.23	100.06	100.23	100.23	100.80
Cation proportions														
Si	1.90	1.91	1.91	1.96	1.98	1.94	2.53	2.52	-	-	-	-	-	-
Ti	0.02	0.02	0.01	0.00	-	0.01	-	-	0.97	0.96	0.96	2.67	2.37	1.89
Al	0.09	0.09	0.07	0.05	0.05	0.05	1.46	1.49	-	-	-	0.71	1.03	0.97
Fe^{3+}	-	-	-	-	-	-	-	-	0.06	0.07	0.07	9.57	9.78	10.88
Fe^{2+}	0.46	0.43	0.43	0.85	0.89	0.95	0.01	0.00	0.88	0.88	0.90	10.67	10.37	9.89
V	-	-	-	-	-	-	-	-	0.01	0.01	0.01	0.38	0.45	0.38
Mn	0.01	0.01	0.01	0.03	0.03	0.02	-	-	0.01	0.01	0.01	-	-	-
Mg	0.72	0.71	0.73	1.05	1.00	1.00	-	-	0.07	0.07	0.05	-	-	-
Ca	0.84	0.87	0.87	0.05	0.05	0.05	0.49	0.48	-	-	-	-	-	-
Na	-	-	-	-	-	-	0.50	0.48	-	-	-	-	-	-
K	-	-	-	-	-	-	0.02	0.03	-	-	-	-	-	-
O-basis	6.00	6.00	6.00	6.00	6.00	6.00	-	-	-	-	-	-	-	-
Cation basis	-	-	-	-	-	-	5.01	5.00	2	2	2	24	24	24
Mg#	0.61	0.62	0.62	0.54	0.52	0.51	-	-	-	-	-	-	-	-
An%	-	-	-	-	-	-	48.5	48.5	-	-	-	-	-	-

Table 2. Chemical compositions and formuli of base metal sulphides in heavy mineral concentrates, sample 90-18 1001.

Grain#	**40-1a**	**40-1b**	**40-1d**	**40-1f**	**40-1h**	**40-2a**	**40-3a**	**40-6a**	**40-8**	**40-10**	**40-12**	**40-12b**	**40-12c**	**40-13a**	**40-16**
Association	bn-cp	bn	bn-cp	bn	bn	bn	cp-bn-chl	bn	vsl-bn-cp	sk-bn	$(Pd,Ag)_5S$	bn	bn	bn	sk-bn-cp
Min.	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite	bornite
Analysis #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cu	62.9	62.7	63.0	62.4	63.0	62.6	63.6	62.8	62.8	63.0	63.5	62.7	62.7	62.5	62.7
Fe	11.5	11.6	11.3	11.4	11.3	11.2	11.2	11.2	11.4	11.3	11.5	11.3	11.4	11.2	11.3
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	25.9	25.9	26.0	25.5	25.7	25.5	25.7	25.5	25.4	25.5	25.9	25.5	25.4	25.3	25.4
sum	100.3	100.2	100.3	99.3	100.0	99.3	100.5	99.5	99.6	99.8	100.9	99.5	99.5	99.0	99.4
cations															
Cu	4.94	4.92	4.95	4.96	4.97	4.97	4.99	4.98	4.98	4.94	4.96	4.97	4.98	4.98	4.98
Fe	1.03	1.04	1.01	1.03	1.01	1.01	1.00	1.01	1.03	1.02	1.02	1.02	1.03	1.02	1.02
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S	4.03	4.04	4.05	4.01	4.02	4.01	4.01	4.00	3.99	3.99	4.01	4.01	4.00	4.00	4.00
sum	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00

Grain#	**40-17**	**40-20c**	**70-1**	**average**	**40-3a**	**40-3b**	**40-8**	**40-16**	**70-1**	**average**	**40-12a**	**40-20b**	**average**	**40-2b**	**40-9**
Association	zv-bn	bn	vsl-bn-cp		cp-bn-chl	cp-bn	vsl-bn-cp	sk-bn-cp	vsl-bn-cp			chc-chl		dgn	sk-copn-cp
Min.	bornite	bornite	bornite	**bornite**	chalcop.	chalcop.	chalcop.	chalcop.	chalcop.	**chalcop.**	chalcoc.	chalcoc.	**chalcoc.**	digenite	Co-pentl.
Analysis #	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Cu	62.7	62.7	63.2	62.9	34.5	34.9	35.2	34.8	35.0	34.9	78.0	77.1	77.6	76.1	0.7
Fe	11.2	11.1	11.4	11.3	30.4	29.8	29.9	30.2	30.3	30.1	1.4	1.7	1.6	1.4	17.1
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-	16.6
Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-	32.1
S	25.3	25.3	25.6	25.6	34.7	34.7	34.8	34.8	34.7	34.7	20.1	20.2	20.2	21.6	32.7
sum	99.2	99.1	100.2	99.8	99.5	99.4	99.9	99.8	100.0	99.7	99.5	99.6	99.6	99.1	99.2
cations															
Cu	5.00	5.00	4.98	4.97	1.00	1.01	1.02	1.01	1.01	1.01	1.96	1.95	1.96	8.84	0.09
Fe	1.01	1.01	1.02	1.02	1.00	0.99	0.98	0.99	1.00	0.99	0.04	0.05	0.05	0.19	2.4
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.22
Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4.28
S	3.99	4.00	4.00	4.01	2.00	2.00	2.00	2.00	1.99	2.00	1.00	1.00	1.00	4.97	8.01
sum	10.00	10.00	10.00	-	4.00	4.00	4.00	4.00	4.00	-	3.00	3.00	-	14.00	17

Phase abreviations: bn: bornite; cp and chalcop.: chalcopyrite; chl: chlorite; vsl: vasilite; sk: skaergaardite; zv: zviagintsevite; chc and chalcoc: chalcocine; dgn: digenite; Co-pent: coboltian pentlandite.

Table 3. Platinum group and gold minerals with ECD (µm) from the heavy mineral HS concentrates of sample 90-18 1001

	Mineral	General formula	n	Area	# %	Area %	ECD min	ECD avg	ECD max
1	Skaergaardite	(Pd,Au,Pt)(Cu,Fe,Zn,Te)	9	2405	32.1	46.1	2.3	15.1	29.4
2	Vysotskite	(Pd,Ni)S	3	1071	10.7	20.5	2.3	18	28.6
3	Vasilite	$(Pd,Cu)_{16}S_7$	5	1059	17.9	20.3	1.1	10.5	34.9
4	Zvyagintsevite	$Pd_3(Pb,Sn)$	7	324	25	6.2	1.6	5.9	16.9
5	(Au,Cu)	(Au,Cu,Pd)	1	320	3.6	6.1		20.2	
6	Keithconnite	$Pd_{3-x}(Te,Pb)$	1	10	3.6	0.2		3.6	
7	(Pt,Fe) alloy	(Pt,Fe,Cu)	1	11	3.6	0.2		3.7	
8	Unnamed	$(Pd,Ag,Cu)_5S$	1	17	3.6	0.3		4.7	
	Total		28	5217	100	100			

Table 4. Sizes of precious metal mineral grains in heavy mineral HS concentrates, sample 90-18 1001.

#	Grain	Association	Type	Mineral	Area, μm^2	ECD, μm
1	40-1	sk-zv-bn	bms	sk	631.0	28.4
2	40-1	sk-zv-bn	bms	zv	2.0	1.6
3	40-1	sk-zv-bn	bms	sk	629.0	28.3
4	40-10	sk-bn	bms	sk	14.0	4.2
5	40-11	sk-bn	bms	sk	214.0	16.5
6	40-12	$(Pd,Ag)_5S$-bn	bms	$(Pd,Ag)_5S$	17.0	4.7
7	40-13	sk-kth-cp	bms-L	Total	690.0	29.6
8	40-13	sk-kth-cp	bms-L	kth	10.0	3.6
9	40-13	sk-kth-cp	bms-L	sk	680.0	29.4
10	40-14	vys-bn	bms-L	vys	426.0	23.3
11	40-15	zv-(Pt,Fe)-bn	bms-L	Total	234.0	17.3
12	40-15	zv-(Pt,Fe)-bn	bms-L	zv	223.0	16.9
13	40-15	zv-(Pt,Fe)-bn	bms-L	(Pt,Fe)	11.0	3.7
14	40-16	sk-cp-bn	bms	sk	31.0	6.3
15	40-16	sk-cp-bn	bms	sk	7.0	3.0
16	40-16	sk-cp-bn	bms	sk	4.0	2.3
17	40-17	zv-bn	bms	zv	10.0	3.6
18	40-17	zv-bn	bms	zv	3.0	2.0
19	40-18	zv-bn	bms	zv	8.0	3.2
20	40-19	(Au,Cu)	L	(Au,Cu)	320.0	20.2
21	40-20	vys-bn	bms	vys	4.0	2.3
22	40-3	zv	L	zv	43.0	7.4
23	40-4	zv-bn	bms	zv	35.0	6.7
24	40-5	vys	L	vys	641.0	28.6
25	40-6	sk-bn	bms-L	sk	489.0	25.0
26	40-7	vsl	L	vsl	954.0	34.9
27	40-8	vsl-bn-cp	bms	vsl	89.0	10.6
28	40-8	vsl-bn-cp	bms	vsl	3.0	2.0
29	40-9	sk-copn	bms	sk	337.0	20.7
30	70-1	vsl-bn-cp	bms	vsl	12.0	3.9
31	70-1	vsl-bn-cp	bms	vsl	1.0	1.1

Table 5. Associations of PGE- and gold minerals with ECD (µm) from the heavy mineral HS concentrates, sample 90-18 1001

	Association	n	area, μm^2	# %	Area %	ECD min	ECD avg	ECD max
1	bms	17	1420	68	27.2	1.1	7.1	28.4
2	bms-L	4	1839	16	35.3	17.3	23.8	29.6
3	L	4	1958	16	37.5	7.4	22.8	34.9
	Total	25	5217	100	100			

Bms - intergrowths with base metal sulphides (bornite, chalcopyrite, cobalt-pentlandite);
bms-L - liberated particles with <10 % attached base metal sulphides; L - completely liberated (free) particles

Table 6. Chemical compositions (wt.%) and formulas of precious metal minerals, sample 90-18 1001

Grain#	40-1	40-6	40-9	40-10	40-11	40-13	40-16	Avg	40-5	40-14	Avg
Assoc.	sk-zv-bn	sk-bn	sk-copn-cp	sk-bn	sk-bn	sk-kth-cp	sk-bn-cp		vys	vys-bn	
mineral	Skaerg.	Skaerg.	Skaerg.	Skaerg.	Skaerg.	Skaerg.	Skaerg.	Skaerg.	vysots.	vysots.	vysots.
Anal. #	1	2	3	4	5	6	7	8	9	11	12
Pd	61.3	57.2	62.6	63.7	52.1	62.7	60.5	60	69.7	67.2	68.5
Pt	1.7	5.9	0	0	2.1	0	2.4	1.7	nd	nd	nd
Au	0	1.4	0	0	9.3	0	0	1.5	nd	nd	nd
Ag	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cu	28.1	28.2	27.4	26.9	29.9	30.9	29.5	28.7	1.2	0	0.6
Fe	2.3	6.3	2.3	8.9	4	4.8	4.4	4.7	0.4	0.6	0.5
Zn	4.9	0.4	7.3	0	0	0.9	2.6	2.3	nd	nd	nd
Ni	nd	nd	nd	nd	nd	nd	nd	nd	4.1	8.2	6.2
Sn	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Te	0.9	0.7	0	0	1.8	0	0	0.5	nd	nd	nd
Pb	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
S	nd	nd	nd	nd	nd	nd	nd	nd	24.3	24.8	24.6
sum	99.3	100.1	99.6	99.5	99.2	99.3	99.4	99.4	99.7	100.8	100.4
Atomic proportions											
Pd	1	0.94	1	1.01	0.89	1	0.98	0.97	0.87	0.81	0.84
Pt	0.02	0.05	0	0	0.02	0	0.02	0.02	-	-	-
Au	0	0.01	0	0	0.09	0	0	0.01	-	-	-
Ag	-	-	-	-	-	-	-	-	-	-	-
Cu	0.77	0.78	0.74	0.72	0.85	0.83	0.8	0.78	0.03	0	0.02
Fe	0.07	0.2	0.07	0.27	0.13	0.15	0.14	0.15	0.01	0.01	0.01
Zn	0.13	0.01	0.19	0	0	0.02	0.07	0.06	-	-	-
Ni	-	-	-	-	-	-	-	-	0.09	0.18	0.14
Sn	-	-	-	-	-	-	-	-	-	-	-
Te	0.01	0.01	0	0	0.03	0	0	0.01	-	-	-
Pb	-	-	-	-	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-	-	1	0.99	1
Total	2	2	2	2	2	2	2	2	2	2	2

Grain#	40-7	40-8	70-1	Avg	40-3	40-4	40-15	Avg	40-13	40-19	40-12
Assoc.	vsl	vsl-bn-cp	vsl-bn-cp	vasilite	zv	zv-bn	zv-bn-(Pt,Fe)	zvyag.	sk-kth-cp	(Au,Cu)	(Pd,Ag)5S
mineral	vasilite	vasilite	vasilite		zvyag.	zvyag.	zvyag.		keithc.	alloy	no-n
Anal. #	13	14	15	16	17	18	19	20	21	22	23
Pd	73.5	73.9	73.5	73.6	66	59.3	55.2	60.2	63.9	17.9	54.3
Pt	nd	nd	nd	nd	0	2	2	1.3	nd	nd	nd
Au	nd	nd	nd	nd	0	0	2.3	0.8	nd	74.2	nd
Ag	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	32.4
Cu	13.8	13.1	13.6	13.5	nd	nd	nd	nd	3	6.8	5.7
Fe	nd	nd	nd	nd	1.3	0.5	1	0.9	0.8	0.7	1.5
Zn	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ni	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sn	nd	nd	nd	nd	9.5	0	0	3.2	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd	nd	nd	29.1	nd	nd
Pb	nd	nd	nd	nd	22.2	37.4	39.2	32.9	3	nd	nd
S	12.8	12.6	12.6	12.7	nd	nd	nd	nd	nd	nd	6
sum	100.1	99.7	99.6	99.8	99	99.2	99.7	99.3	99.8	99.6	99.9
Atomic proportions											
Pd	12.15	12.34	12.24	12.24	2.99	2.94	2.77	2.9	2.66	0.25	2.75
Pt	-	-	-	-	0	0.05	0.06	0.04	-	-	-
Au	-	-	-	-	0	0	0.06	0.02	-	0.57	-
Ag	-	-	-	-	-	-	-	-	-	-	1.62
Cu	3.82	3.67	3.79	3.76	-	-	-	-	0.21	0.16	0.48
Fe	-	-	-	-	0.11	0.05	0.1	0.09	0.06	0.02	0.15
Zn	-	-	-	-	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-
Sn	-	-	-	-	0.39	0	0	0.13	-	-	-
Te	-	-	-	-	-	-	-	-	1.01	-	-
Pb	-	-	-	-	0.52	0.95	1.01	0.83	0.06	-	-
S	7.02	6.99	6.98	7	-	-	-	-	-	-	-
Total	23	23	23	23	4	4	4	4	4	1	6

Abbreviations: Sk and skaerg.: skaergaardite; zv and zvyag.: zvyagintsevite; bn: bornite; copn: coboltian pentlandite; kth and keithc.: keithconnite; cp: chalcopyrite; vys and vysots.: vysotskite; vsl: vasilite; (Pt,Fe): alloy; $(Pd,Ag)_5S$: un-named mineral

PLATES

Plate 1

The relationship of rock-forming minerals, Fe-Ti oxides and sulphides in the tholeitic gabbros of sample 90-18 1001 (1-5), polished section, SEM images (BIE); abbreviations used: pl – plagioclase, cpx – clinopyroxene, opx – orthopyroxene, cpx-opx exs – clinopyroxene-orthopyroxene exsolution texture, ilm - ilmenite, timt – titaniferous magnetite, bn – bornite.

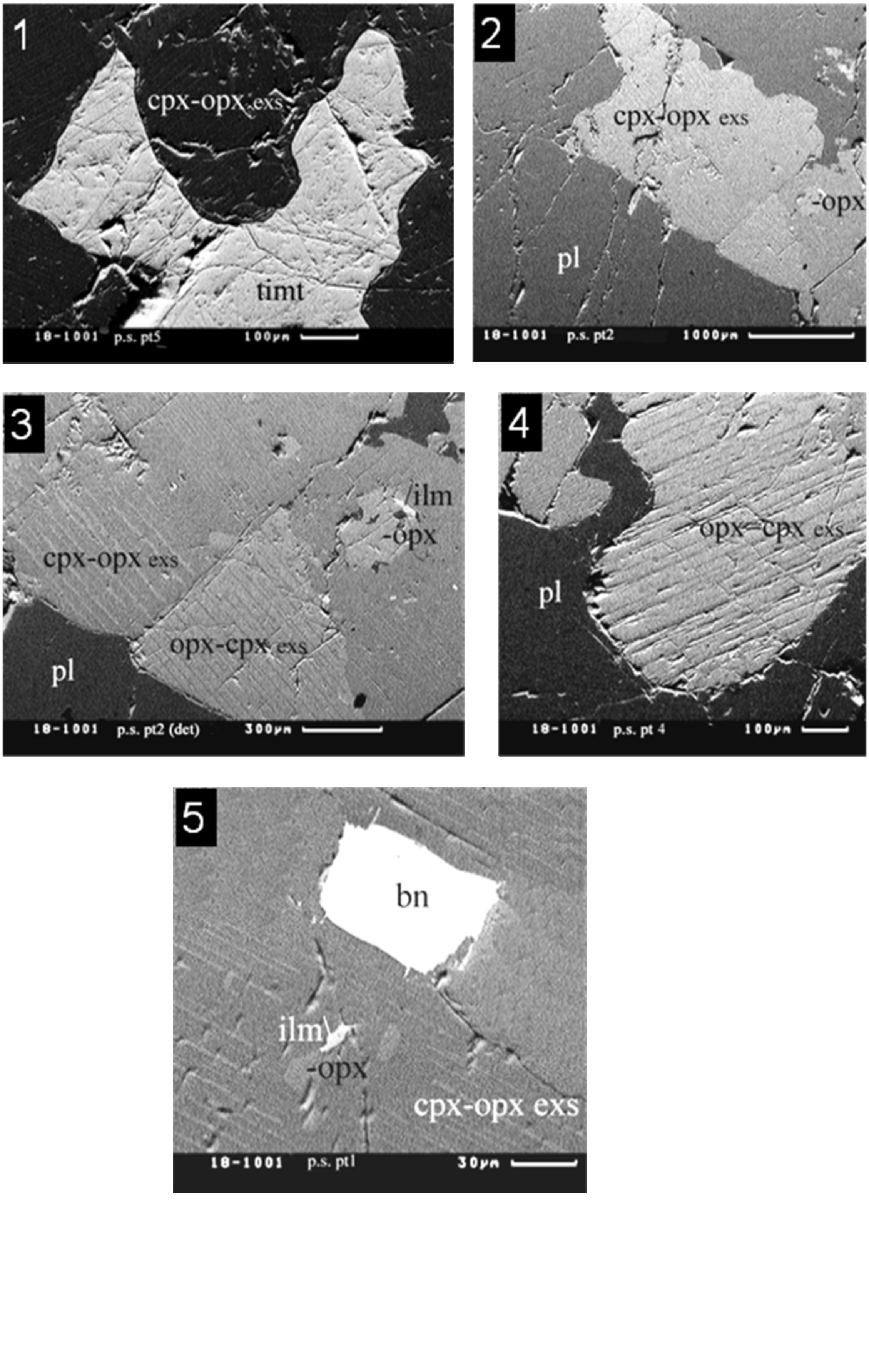

1
cpx-opx exs
timt
18-1001 p.s. pt5 100μm
2
cpx-opx exs
-opx
pl
18-1001 p.s. pt2 1000μm
3
/ilm
-opx
cpx-opx exs
opx-cpx exs
pl
18-1001 p.s. pt2 (det) 300μm
4
opx-cpx exs
pl
18-1001 p.s. pt 4 100μm
5
bn
ilm
-opx
cpx-opx exs
18-1001 p.s. pt1 30μm

Plate 2

Polished sections of the heavy mineral HS concentrate (1 -fraction <40 µm; 2 – 50-70 µm, 3 – 70-100 µm, sample 90-18 1001), SEM-images (BIE); abbreviations used: ilm – ilmenite, sk – skaergaardite, vsl – vasilite, bn – bornite, cp – chalcopyrite, cpx – clinopyroxene.

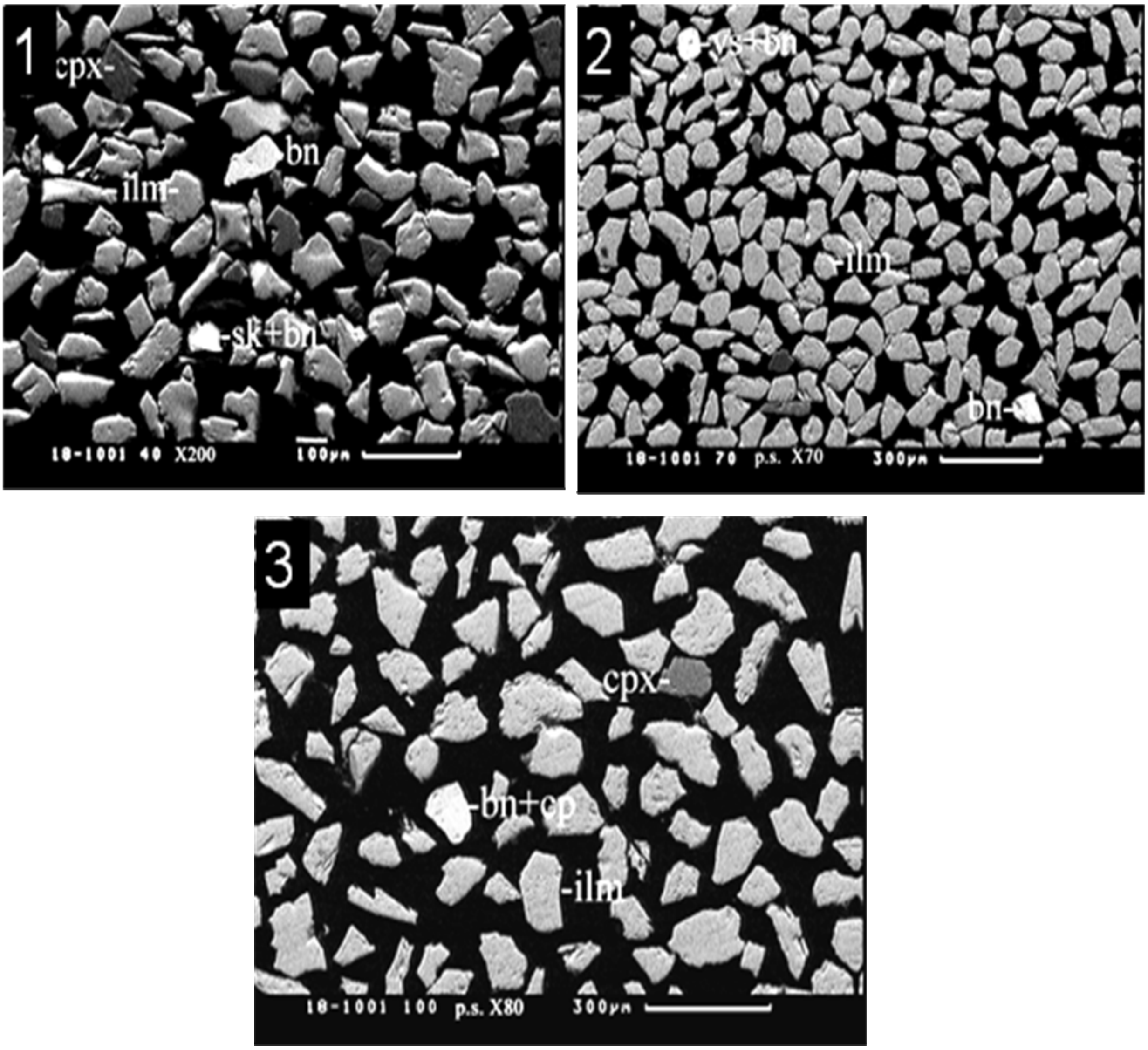

1
cpx-
bn
ilm-
-sk+bn
10-1001 40 X200
100μm
2
-vs+bn
-ilm
bn-
10-1001 70 p.s. X70
300μm
3
cpx-
-bn+cp
-ilm
10-1001 100 p.s. X80
300μm

Plate 3

Baddeleyite grains (for age dating), extracted in the heavy mineral HS concentrate of the sample 90-18, 1001 (1-6); polished section, SEM-image (BIE); bdl – baddellyite, ilm – ilmenite.

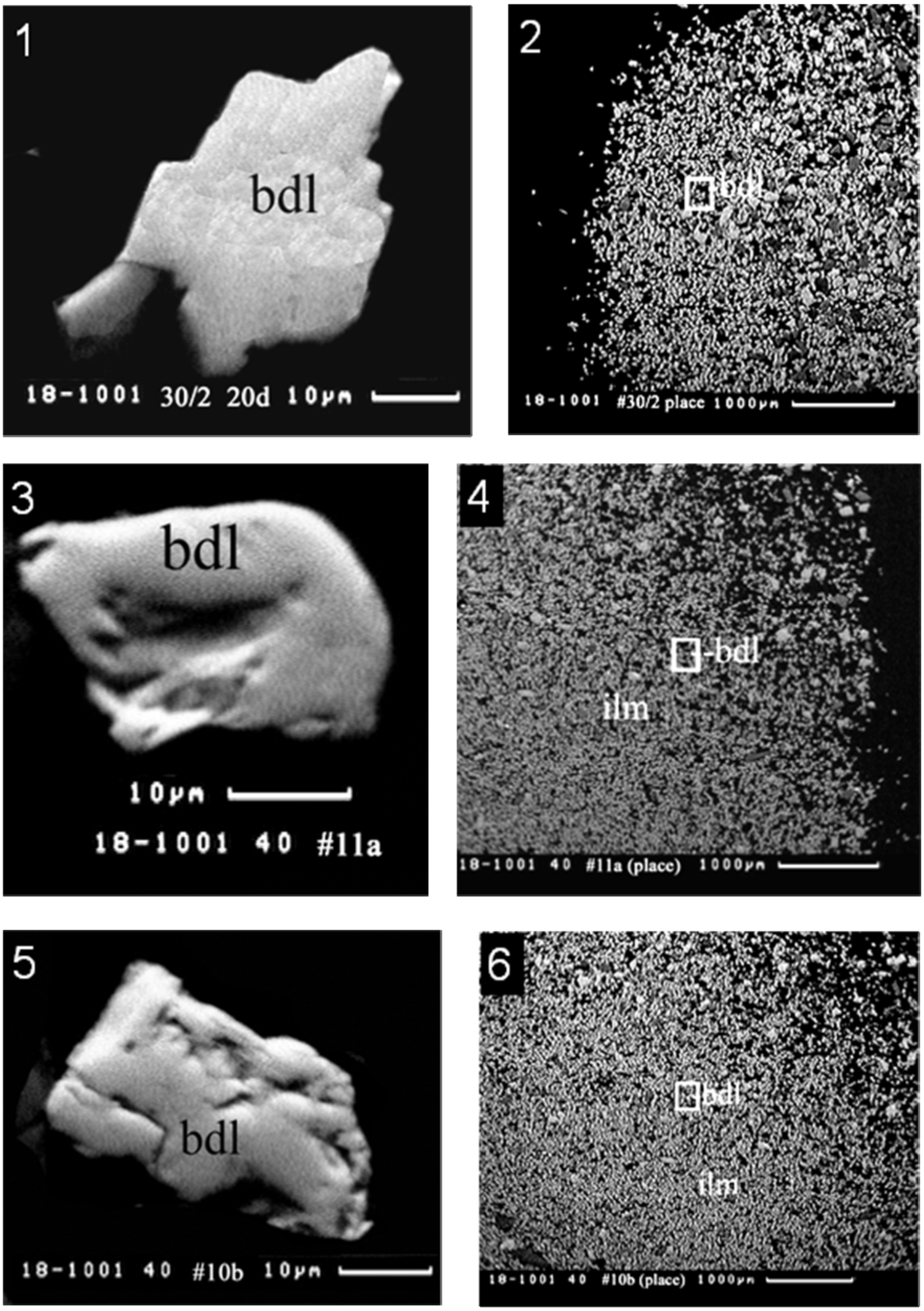
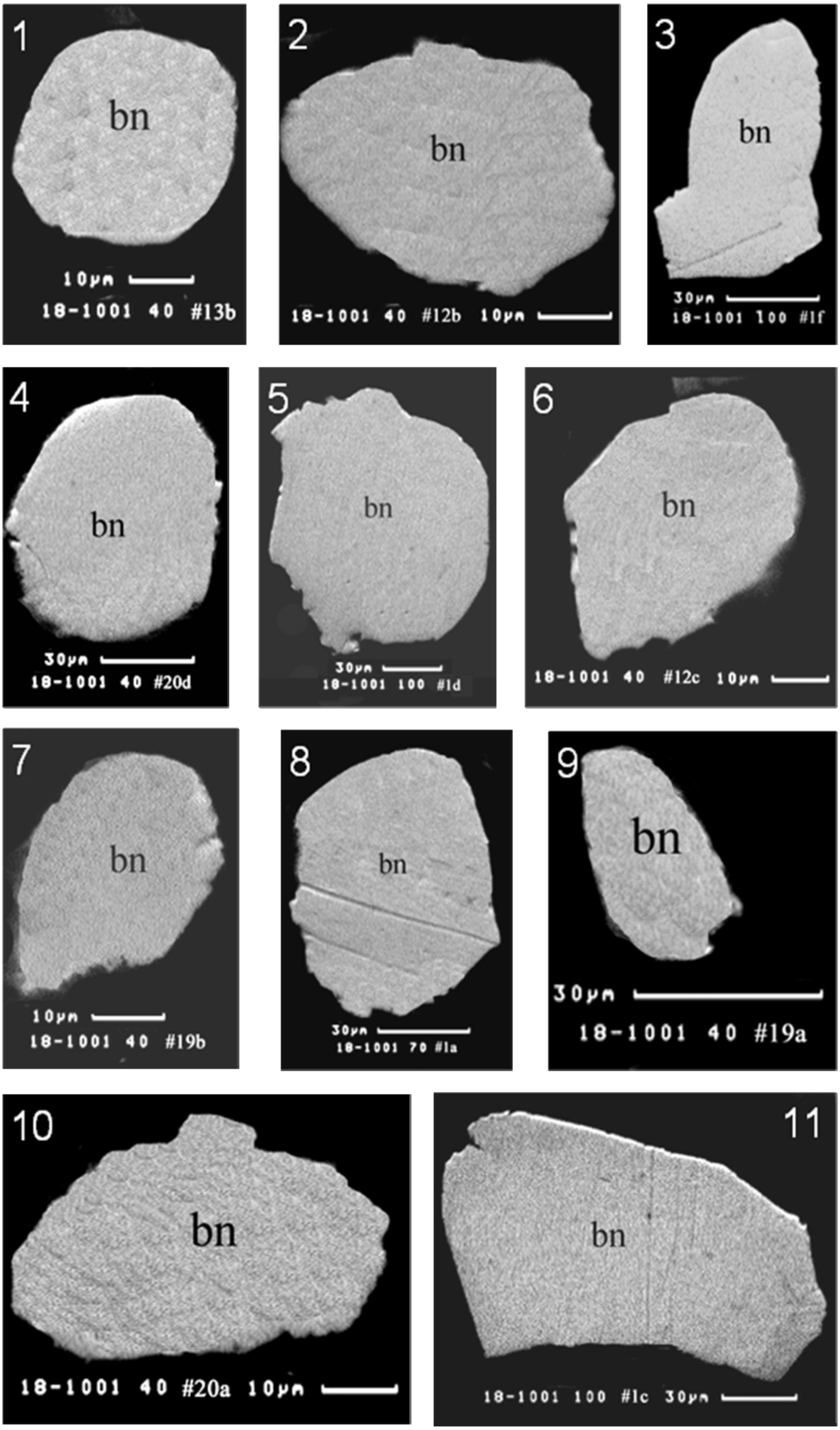
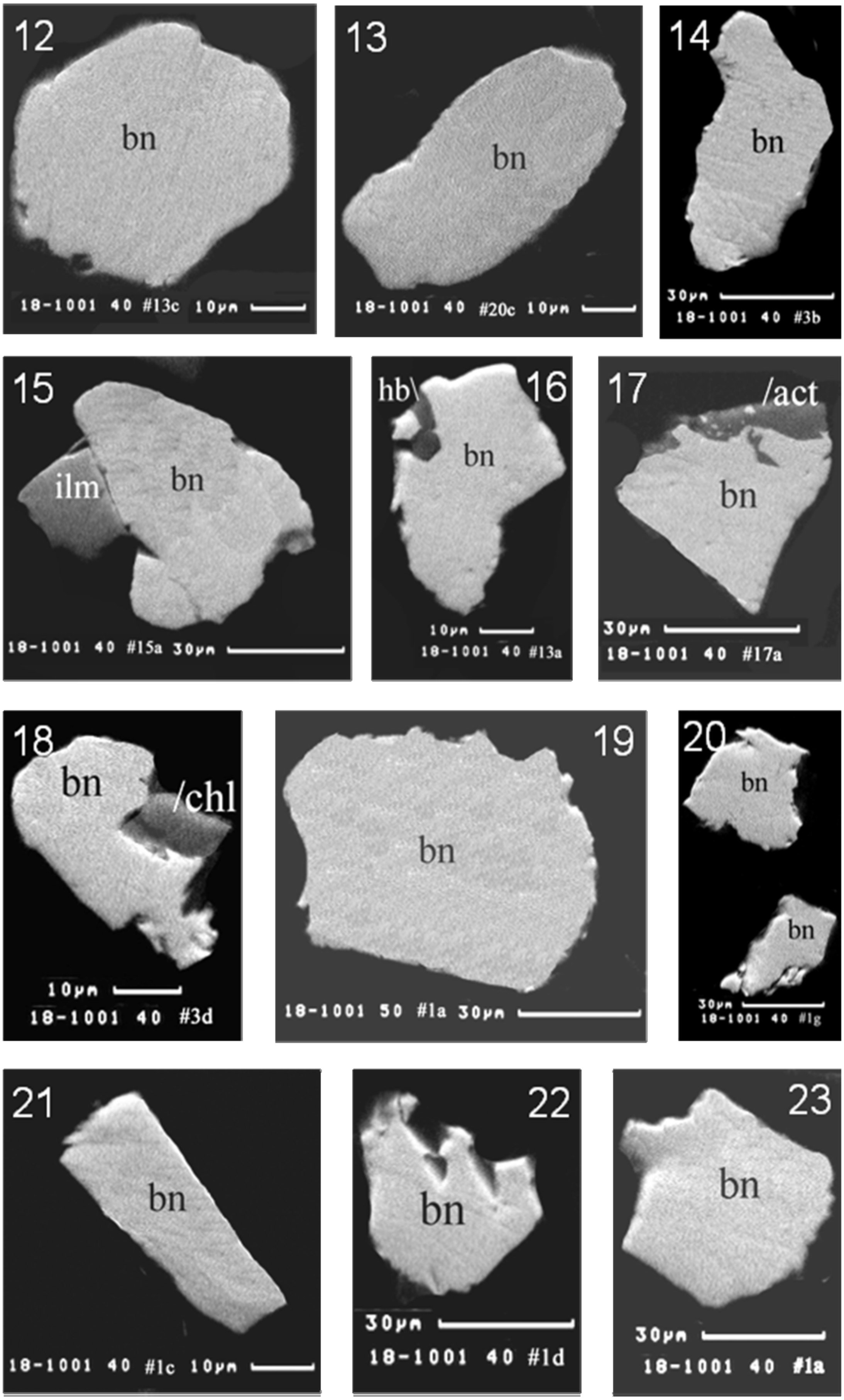

1
bdl
18-1001 30/2 20d 10μm
2
bdl
18-1001 #30/2 place 1000μm
3
bdl
10μm
18-1001 40 #11a
4
bdl
ilm
18-1001 40 #11a (place) 1000μm
5
bdl
18-1001 40 #10b 10μm
6
bdl
ilm
18-1001 40 #10b (place) 1000μm

Plate 4

Sulphide mineralisationglobules and grains of oxide rich tholeitic gabbros, the sample 90-18 1001 91-33); polished sections; SEM-images (BIE); abbreviations used: bn – bornite, cp – chalcopyrite, chc – chalcocine, dgn – digenite, ilm – ilmenite, hb – hornblende, act – actinolite, chl – chlorite.


1
bn
10μm
18-1001 40 #13b
2
bn
18-1001 40 #12b 10μm
3
bn
30μm
18-1001 100 #1f
4
bn
30μm
18-1001 40 #20d
5
bn
30μm
18-1001 100 #1d
6
bn
18-1001 40 #12c 10μm
7
bn
10μm
18-1001 40 #19b
8
bn
30μm
18-1001 70 #1a
9
bn
30μm
18-1001 40 #19a
10
bn
18-1001 40 #20a 10μm
11
bn
18-1001 100 #1c 30μm


12
bn
18-1001 40 #13c 10μm
13
bn
18-1001 40 #20c 10μm
14
bn
30μm
18-1001 40 #3b
15
ilm
bn
18-1001 40 #15a 30μm
hb\
16
bn
10μm
18-1001 40 #13a
17
/act
bn
30μm
18-1001 40 #17a
18
bn
/chl
10μm
18-1001 40 #3d
19
bn
18-1001 50 #1a 30μm
20
bn
bn
30μm
18-1001 40 #1g
21
bn
18-1001 40 #1c 10μm
22
bn
30μm
18-1001 40 #1d
23
bn
30μm
18-1001 40 #1a

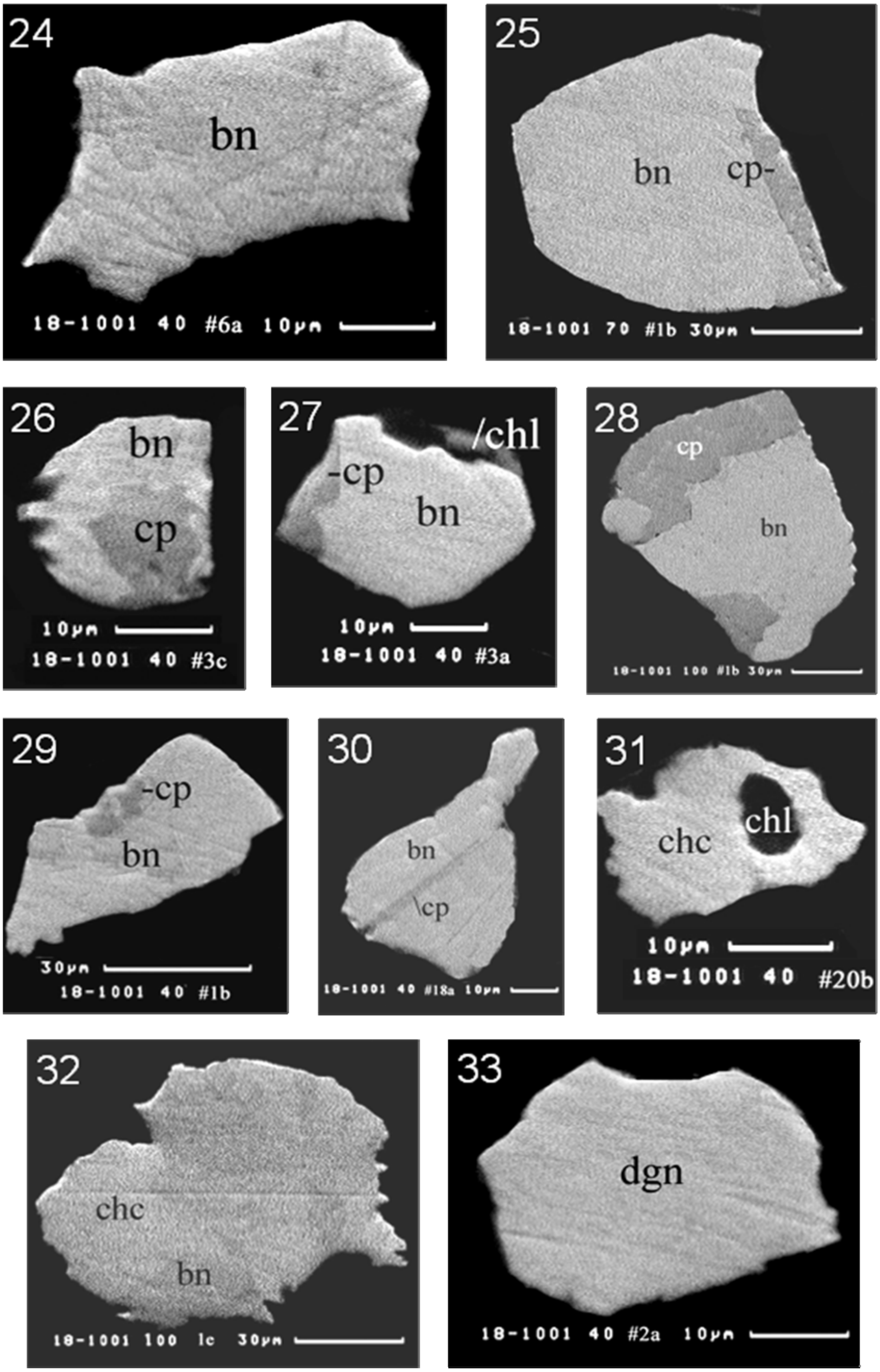

24
bn
18-1001 40 #6a 10μm
25
bn
cp-
18-1001 70 #1b 30μm
26
bn
cp
10μm
18-1001 40 #3c
27
/chl
-cp
bn
10μm
18-1001 40 #3a
28
cp
bn
18-1001 100 #1b 30μm
29
-cp
bn
30μm
18-1001 40 #1b
30
bn
\cp
18-1001 40 #18a 10μm
31
chc
chl
10μm
18-1001 40 #20b
32
chc
bn
18-1001 100 1c 30μm
33
dgn
18-1001 40 #2a 10μm

Plate 5

SEM-images (BIE) of skaergaardite (1-6) from the polished sections of the heavy mineral HS concentrates of the sample 90-18 1001; abbreviations used: sk – skaergaardite, bn – bornite, cp – chalcopyrite, copn – cobalt-pentlandite.

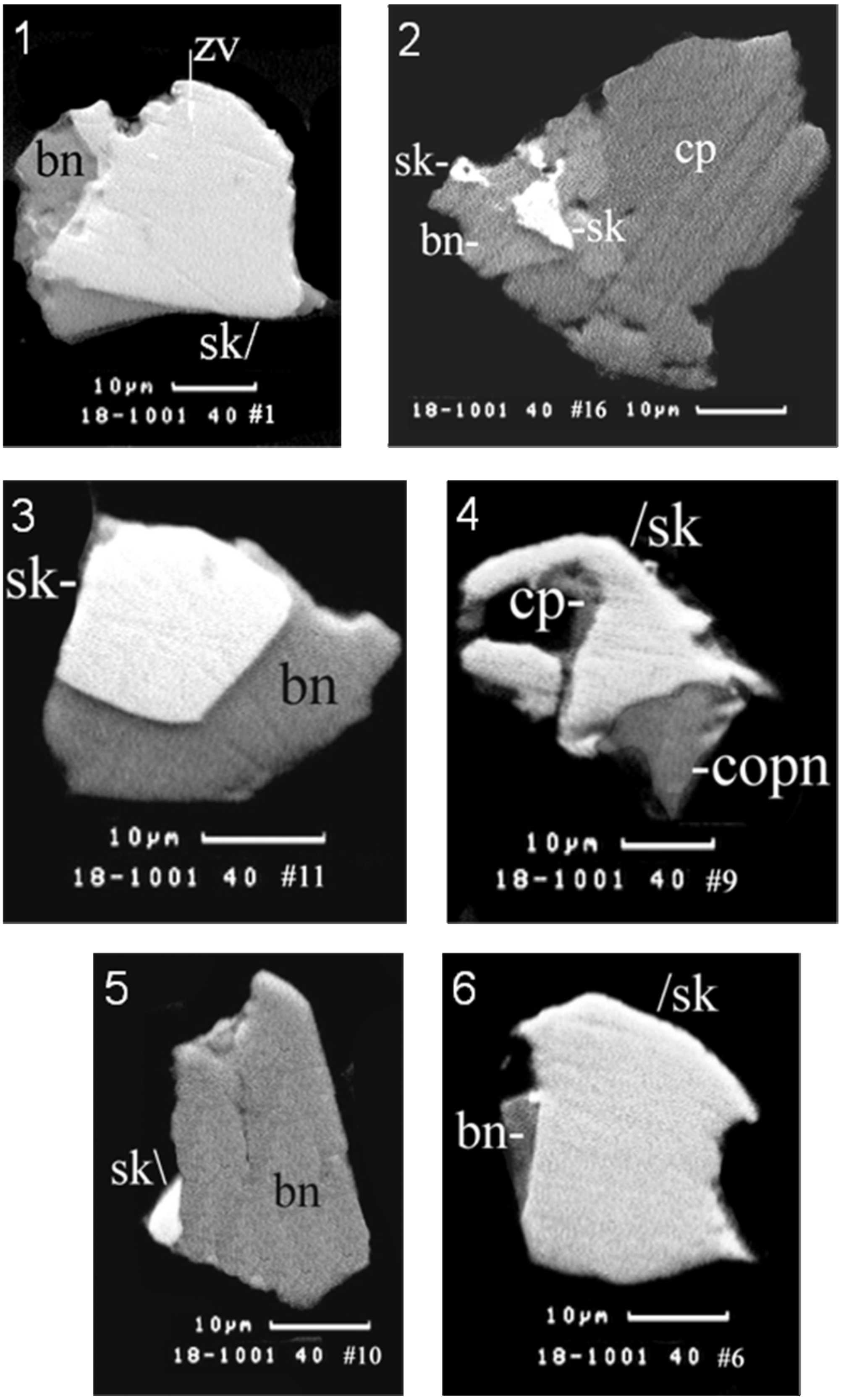

1
zv
bn
sk/
10μm
18-1001 40 #1
2
sk-
cp
bn-
-sk
18-1001 40 #16 10μm
3
sk-
bn
10μm
18-1001 40 #11
4
/sk
cp-
-copn
10μm
18-1001 40 #9
5
sk\
bn
10μm
18-1001 40 #10
6
/sk
bn-
10μm
18-1001 40 #6

Plate 6

SEM-images (BIE) of vysotskite (1-3) and vasilite (4-7) from the polished sections of the heavy mineral HS concentrates of the sample 90-18 1001; 6 is detail of 5; abbreviations used vys – vysotskite, vsl - vasilite, bn – bornite, cp – chalcopyrite.

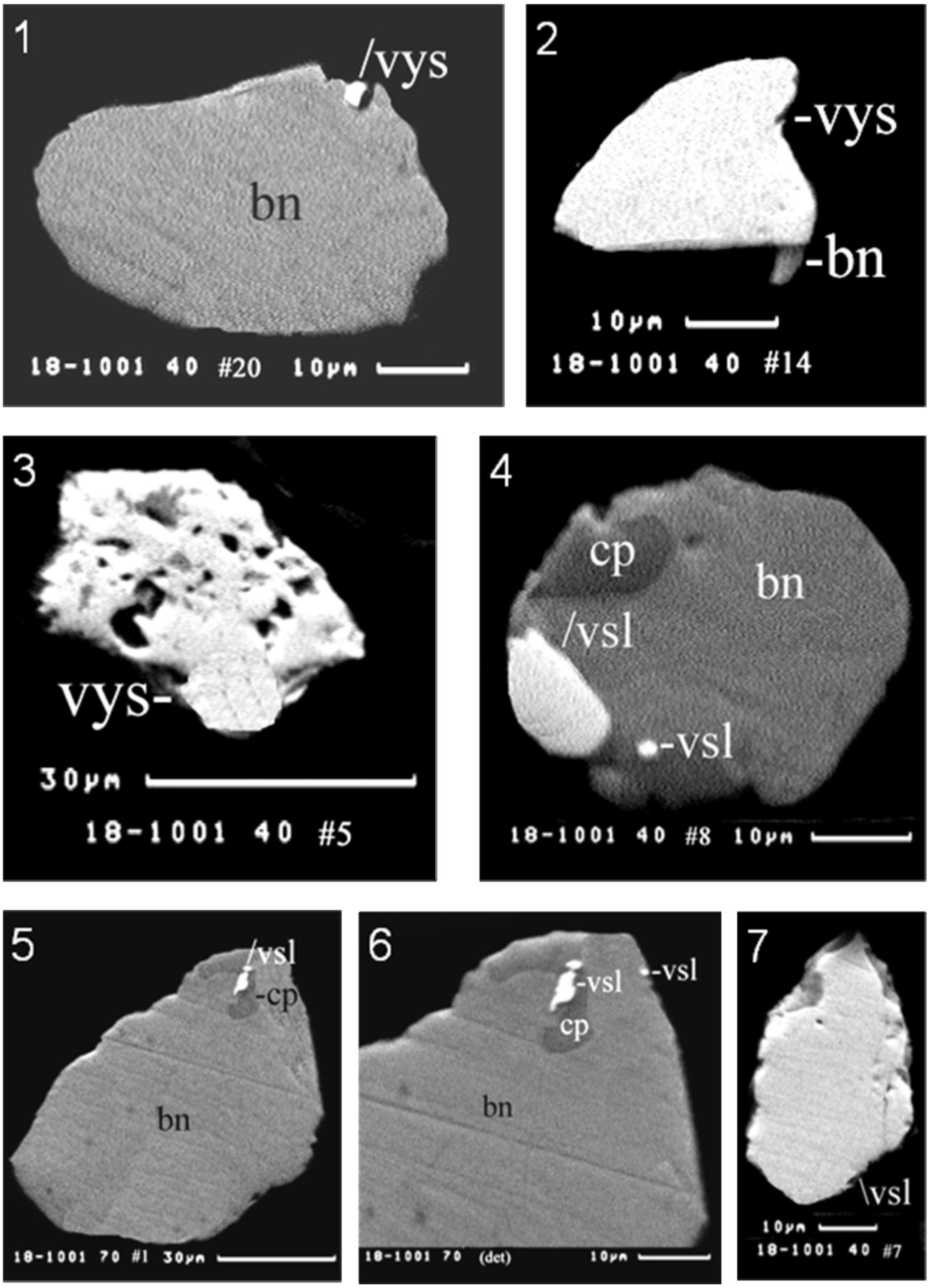

1
/vys
bn
18-1001 40 #20 10μm
2
-vys
-bn
10μm
18-1001 40 #14
3
vys-
30μm
18-1001 40 #5
4
cp
bn
/vsl
-vsl
18-1001 40 #8 10μm
5
/vsl
-cp
bn
18-1001 70 #1 30μm
6
-vsl
-vsl
cp
bn
18-1001 70 (det) 10μm
7
\vsl
10μm
18-1001 40 #7

Plate 7

SEM-images (BIE) of zvyagintsevite (1-5) and (Pt,Fe) alloy (4) from the polished sections of the heavy mineral HS concentrates of the sample 90-18 1001; abbreviations used: zv - zvyagintsevite, bn – bornite.

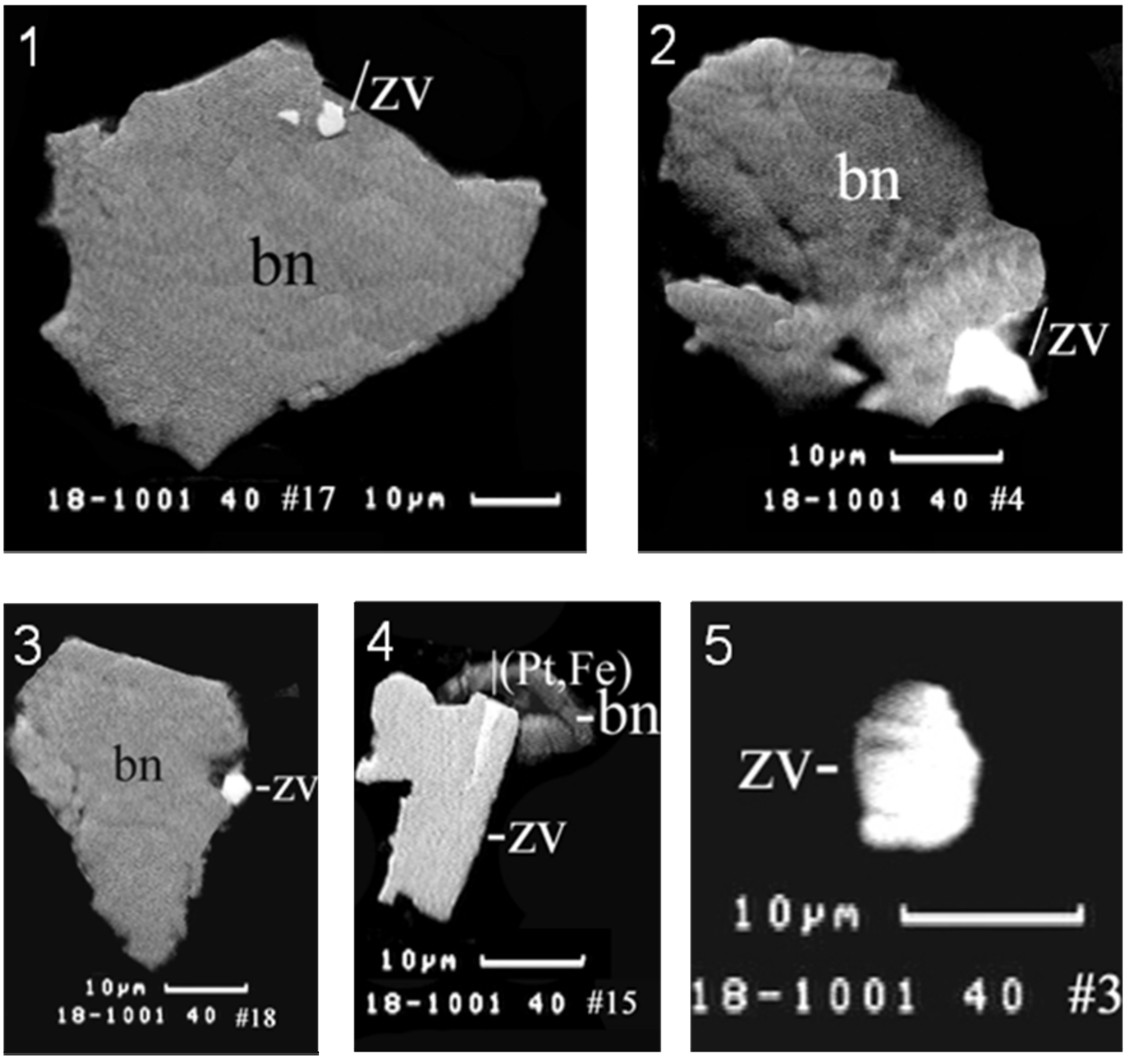
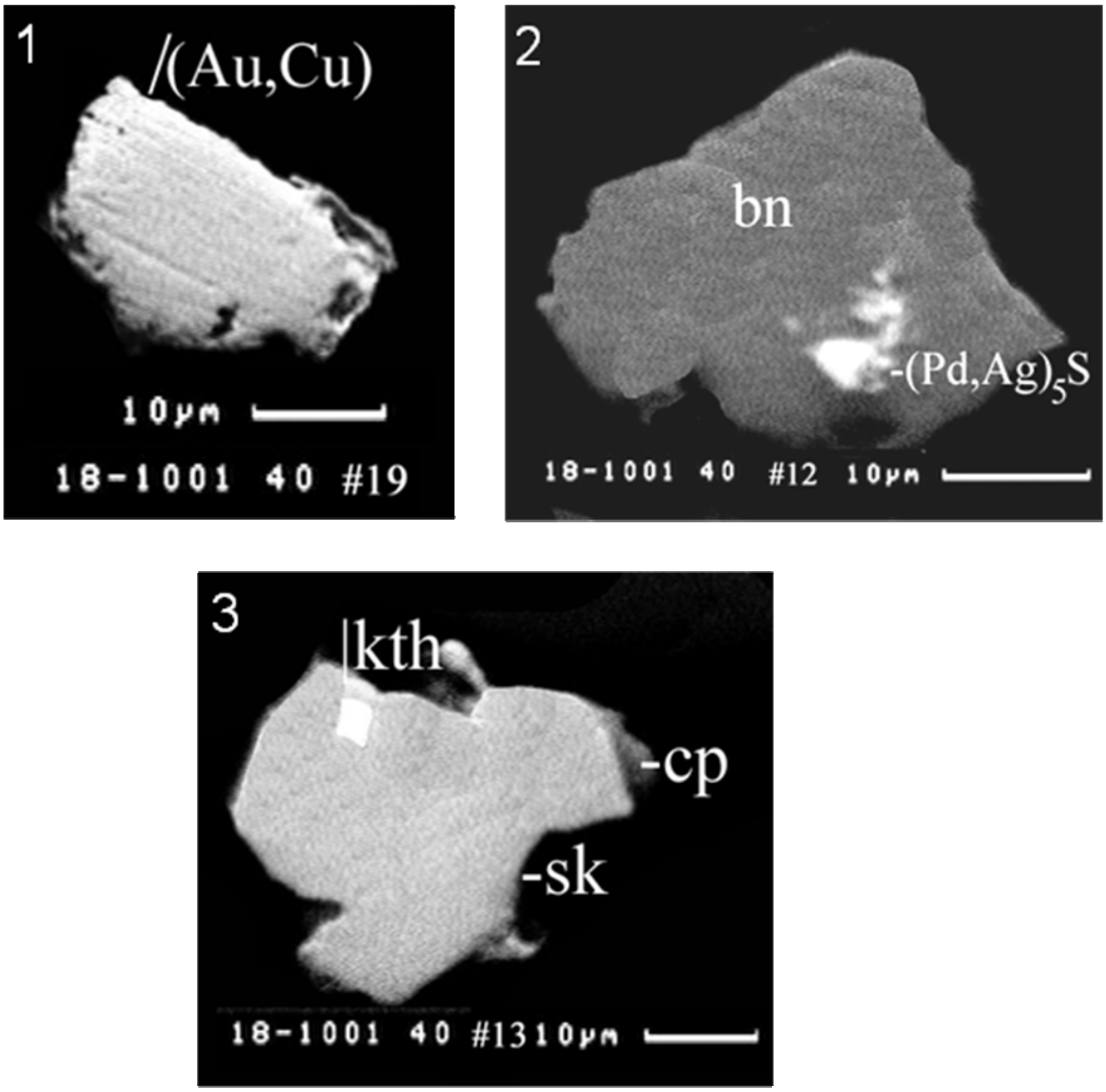

1
ZV
bn
18-1001 40 #17 10μm
2
bn
ZV
10μm
18-1001 40 #4
3
bn
-ZV
10μm
18-1001 40 #18
4
(Pt,Fe)
-bn
-ZV
10μm
18-1001 40 #15
5
ZV-
10μm
18-1001 40 #3

Plate 8

SEM-images (BIE) of (Au,Cu) alloy (1), unnamed $(Pd,Ag)_5S$ (2) and keithconnite (3) from the polished sections of the heavy mineral HS concentrates of the sample 90-18 1001; abbreviations used: kth – keithconnite, sk – skaergaardite, bn – bornite, cp – chalcopyrite.


1
/(Au,Cu)
10μm
18-1001 40 #19
2
bn
-(Pd,Ag)$_5$S
18-1001 40 #12 10μm
3
kth
-cp
-sk
18-1001 40 #1310μm