DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/94

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

Part 15: Sample 90-10 443

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Abstract

The report presents the results of mineralogical investigations of the sample 90-10 443. This is the top part of Pd5 level in core 90-10 from near the western margin of the Skaergaard intrusion. Assays give 2787 ppb Pd, 282 ppb Au, and 137 ppb Pt for this interval.

The 750g sample was crushed in small portions using a shatter box with small cavities (200 ml) during short periods (0.3-0.5 min) and sieved to remove the fine fraction (sieve -70 µm) after each crushing session. The residual coarse fraction >70 µm was re-crusher until the entire sample has attained the desired maximum grain size. After complete crushing the material sieved under water into the following fractions: 1) <40µm, 2) 40-70µm, and 3) >70 µm. All fractions were subsequently subjected to wet magnetic separation. All magnetic fractions proved not to contain grains of precious metals.

The non-magnetic parts of every fraction were then hydroseparated using the computer controlled hydroseparator CNT-HS-11.From each heavy mineral fraction monolayer polished sections were produced. These polished sections and one of a chip from the core were investigated under the scanning electron microprobe.

The gabbro in the sample 90-10 443 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. Another characteristic is the presence of hydrous silicates. Olivine is replaced by H_2O-bearing phase (talc group?) and H_2O-bearing minerals occur in very small amounts in intergrowths with Cu-Fe-sulphides and PGMs.

The HS-concentrates contain numerous sulphide grains identified as sulphide droplets. They are composed of one or two Cu-Fe-sulphides, including bornite and chalcopyrite, and more rarely pentlandite, chalcosine and pyrrhotite. Some of these droplets and grains of sulphide contain inclusions of PGMs and (Au,Cu,Pd) alloys.

One zircon and one monazite grains were spotted in the heavy mineral HS concentrate. They can be used for specific geochronological investigations for age-dating of the studied ore horizon.

Grains of bornite and chalcopyrite, including irregular shaped particles, form droplet-like microglobules. These microglobules show characteristic exsolution textures with chalcopyrite lamellae in bornite and may document a primary high-temperature nature of the sulphides.

A representative selection of 52 particles containing precious metal minerals were studied in detail. The precious metal minerals represent 4 different groups: 1) Pd sulphides – vysotskite (Pd,Ni,Cu,Fe)S (22.5 %) and vasilite $(Pd,Cu,Fe)_{16}S_7$ (20.1 %); 2) Pd arsenides – guanglinite $(Pd,Pt,Cu)_3(As,Sn,Te)$ (24.8 %); 3) several types of (Au,Cu,Pd,Ag) alloys including tetra-auricupride (Au,Pd,Pt)(Cu,Fe) (4.4 %), unnamed $(Au,Pd)_3(Cu,Fe)$ (12.1 %); (Au,Pd,Cu,Ag) alloys of variable compositions (5.2 %); and 4) Pd-intermetallic alloys with

Sn, Te and Pb including atokite $(Pd,Pt,Au)_3(Sn,Pb,As)$ (5 %), keithconnite $Pd_{3-x}(Te,Pb)$ (4.5 %) and zvyagintsevite $(Pd,Pt)_3(Pb,Te,Sn)$ (1.8 %). The grain sizes of the precious metal minerals (ECD) varies between 4.5 and 61.3 µm with an average of 20 µm.

Three groups of precious metal dominate and are described in some detail. They includee: 1) Pd sulphides (vysotskite and vasilite), 2) Pd arsenides (guanglinite) and 3) gold minerals relatively poor in Au and Ag but rich in Pd and Cu such as tetra-auricupride, unnamed mineral Au_3Cu and Au-Cu-Pd alloys.

The observations of inter-grain relations suggest that all the precious metal minerals and phases and the Cu-rich sulphides form a have paragenesis.

The relatively Au-Ag-poor and Pd-Cu-rich compositions, including the unnamed mineral $AuPdCu_2$ and other (Au,Cu,Pd) alloys characterize the sample.

Introduction

The report describes the mineralogy of sample 90-10 443 from the top of Pd5 level in the “Platinova Reef” of the Skaergaard intrusion. The mineralogical report is based on a study of concentrates of PGMs produced using a new patented model of Hydroseparator CNT-HS-11 and a the polished section of a chip from the drill core. Mounts with concentrates and the polished section of the gabbro were studied under the electron microscope and analysed (Camscan-4DV, Link AN-10 000). The report gives details on the grain characteristics, the parageneses and the compositional variation of the identified groups of minerals of the host, the sulphides, and the precious metal minerals and alloys.

The investigation was carried out in 2010.

Sample 90-10 443

Sample 90-10 443 was collected from BQ drill core # 90-10 between 442.8 and 444.0 m and represents the upper part of Pd5 level - the main palladium resource in the Skaergaard mineralisation (Andersen et al., 1998; Nielsen et al, 2005). The core has previously been sampled for other purposes. The 750g sample collects 1/3 of the diameter of the preserved core. Assays give 2787 ppb Pd, 282 ppb Au, and 137 ppb Pt for this interval

Analytical techniques

Analytical techniques are described in Nielsen et al. (2003). The heavy mineral HS-concentrates enriched by precious metal minerals were obtained using a new patented model of computer controlled Hydroseparator CNT-HS-11 and newly patented glass separation tube (GST) (Rudashevsky and Rudashevsky 2006 and 2007). One polished section was prepared from a drill core fragment (Plate 1).

The remaining core was crushed to –70 μm. After complete grinding, the sample was passed through standard sieves with water (wet-sieving) and split into the following grain size fractions: 1) <40 μm (426 g), 2) 40-70 μm (204 g), and 3) >70 μm (59 g, no studied).

After wet magnetic separation, the <40 μm and 40-70 μm grain size fractions were processed through the hydroseparator. The obtained concentrates were used for monolayer polished sections (Plate 2).

Results

Rock forming minerals and sulphides

Silicates and FeTi-oxides

The silicates and FeTi-oxides related to sulphides and precious metal phases include: 1) *plagioclase*, $An_{46-50,}$ average An_{48} (Table 1, analyses 1-6); 2) monoclinic ferrous *pyroxene*, Mg# = 0.574-0.612 , average Mg# = 0.59 (Table 1, analyses 7-12), 3) orthorhombic ferrous *pyroxene*, Mg# = 0.49-0.51, average Mg# = 0.50 (Table 1, analyses 13-17) and Fe-Ti oxides including 4) *ilmenite* (Table 1, analyses 24-29), and 5) *titaniferous magnetite*, TiO_2 12.8-16.1 wt. %, average 14.5 % (Table 1, analyses 18-23). Monoclinic and orthorhombic pyroxenes form typical exsolution texture (Plate 1, #*3, 5, 7, 8*).

The Fe-Ti-oxides occur as aggregates of 1-3 mm, anhedral grains. They fill the space between grains of plagioclase and pyroxenes (Plate 1, #*1-4*). Some fine grains of Fe-Ti oxides (<20 µm) have the form of droplets. They occur as inclusions in pyroxenes, as well as in plagioclase.nOne zircon and one monazite grain (Plate 3) was found in the heavy mineral HS concentrates. They can be used for further geochronological and isotopic investigations.

Gabbro of the studied polished section from the sample 90-10 443 does not have characteristic structures of reactionary relationships of cumulus and inter cumulus phases i.e. rims at the boundaries between accumulated grains of Fe-Ti-oxides and two-pyroxenes (Holness et al., 2011) The place of olivine seems taken by H_2O-bearing phase (talc group?). H_2O-bearing minerals occur in small amounts as intergrowths with Cu-Fe-sulphides and PGMs.

Sulphides

Several grains of chalcopyrite (<20 µm) were found in the studied polished sections. They form as inclusions at the boundaries between aggregates of Fe-Ti oxides and pyroxenes (Plate 1, #*7*) and inside grains composed of two pyroxenes (Plate 1, #*8*).

The non-magnetic heavy mineral HS-concentrates are ilmenite-rich products (> 90 %). enriched in base metal sulphides and precious metal minerals (Plate 2). The dominating sulphide grain type is composed of bornite or bornite and chalcopyrite, less commonly of chalcopyrite, only. Besides, rare grains are composed of bornite, chalcosine, pentlandite and pyrrhotite (Plates 4 and 5). The relative proportion of the base metal sulphides in the sample 90-10 443 is evaluated in selection of 163 random grains in the concentrates with grain sizes <70 µm:

Minerals in grain	Number of grains	%
Bornite	105	64.4
Bornite+halcopyrite	44	27.0
Chalcopyrite	7	4.3
Pentlandite	4	2.5
Pyrrhotite	2	1.2
Bornite+chalcosine	1	0.6
Total	163	100

The sulphides grains include droplet-like microglobules of bornite (Plate 4, # *1-3, 5* etc.) and bornite+chalcopyrite (Plate 5, #*1-5*) and irregular shaped grains (see Plates 4 and 5). Bornite and chalcopyrite show classical exsolution withf chalcopyrite lamellae in bornite (Plate 5, #*3, 5-8* etc.).

The compositions of bornite (Table 2, analyses 1-14), chalcopyrite (Table 2, analyses 15-19), and chalcosine (Table 2, analysis 20) are all close to be stoikiometric. The composition of pentlandite (Table 2, analyses 21-25,) corresponds to formula $(Ni_{4.68}Fe_{4.25}Co_{0.07})_{7.00}S_{8.01}$. Pyrrhotite compositions (Plate 2, analyses 26, 27) are close to the formula $(Fe,Ni)_7S_8$ which is a characteristic of monoclinic pyrrhotite.

PGMs and Au-minerals: recovery, grain size and relations to host rock

Recovery

None of precious metal mineral grains were found in the polished section of gabbro (90-10 443).

The heavy mineral HS-concentrates gave 52 particles of PGMs and Au-minerals. At least 10 different PGMs and Au-minerals were recovered:

1. *vysotskite* (Pd,Ni,Cu,Fe)S – in 17 particles;
2. *vasilite* $(Pd,Cu,Fe)_{16}S_7$ - in 11 particles;
3. *guanglinite* $(Pd,Pt,Cu)_3(As,Sn,Te)$ – in 7 particles;
4. *atokite* $(Pd,Pt,Au)_3(Sn,Pb,As)$ - in 10 particles;
5. *keithconnite* $Pd_{3-x}(Te,Pb)$ – in 7 particles;
6. *zvyagintsevite* $(Pd,Pt)_3(Pb,Te,Sn,As)$ – 2 particles;
7. *tetra-auricupride* (Au,Pd,Pt)(Cu,Fe) – in 5 particles;
8. *unnamed* $(Au,Pd)_3(Cu,Fe)$ – in 7 particles;
9. *(Au,Cu,Pd) alloy* – in 2 particles;
10. *(Au,Ag,Cu,Pd) alloy* – in one particle;
11. *(Pd,Cu,Au,Pt) alloy* - in one particle.

The area proportions are calculated from the area of grains of these minerals (Tables 3, 4 and Fig. 1).

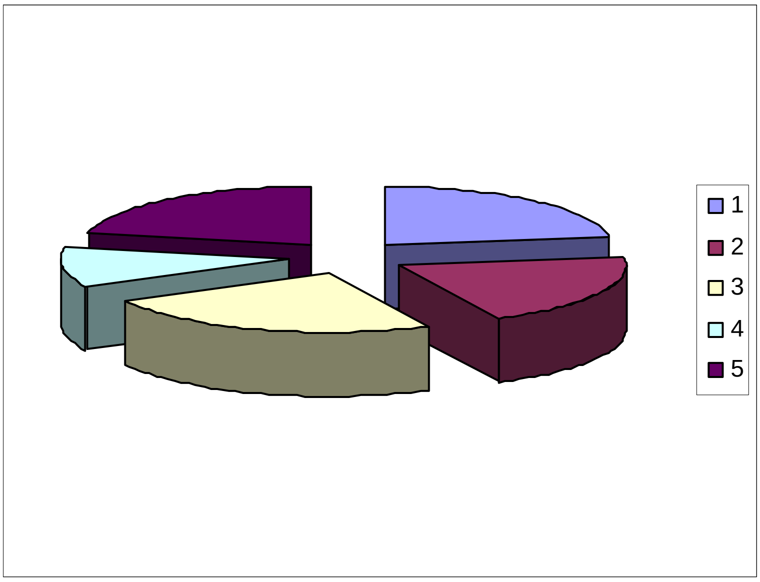

Fig.1. Proportions among precious metal minerals in the heavy mineral HS concentrates of the sample 90-10 443 (see Table 3). 1) vysotskite (22.5 %); 2) vasilite (20.1 %); 3) guanglinite (24.8 %); 4) atokite, kethconnite and zvyagintsevite (10.8 %); 5) variety of (Au,Cu,Pd,Ag) alloys (21.7 %).

Grain size

The grain size was measured as the effective diameter (ECD) of the grains using the "imageJ" ® software. It varies from 4.5 to 61 µm with an average of 20 µm (Tables 3, 4; Fig. 2). The histogram (Fig. 2) of the grain size of the precious metal mineral reflects an almost normal distribution for this 52 grains. As shown in the histogram, the grain size of the precious metal minerals distributes as follows:

Grain size, µm	Number of grains
0-10	6
10-20	21
20-30	21
30-40	3
40-50	0
50-60	0
60-70	1
Total	52

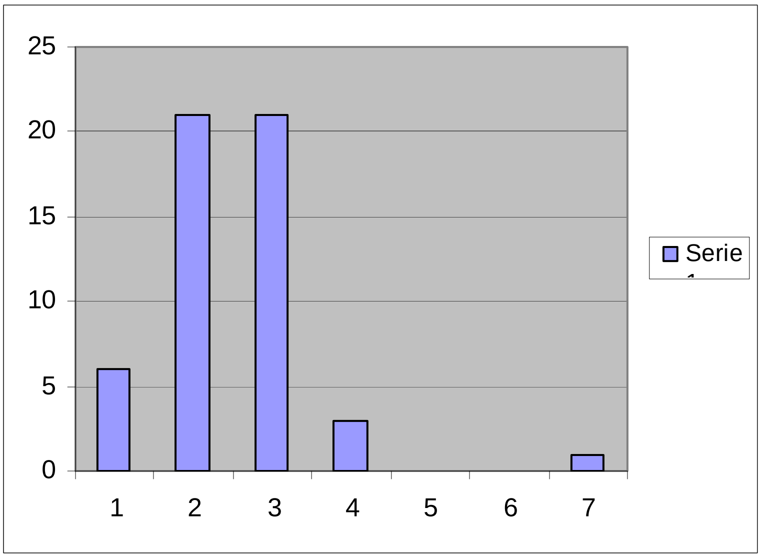

Fig 2.Size of grains (52) of precious metal minerals in the heavy concentrates of the sample 90-10 443.

The SEIs (scanning electron images, Plates 6-10) show that the majority of PGM grains are well preserved and have kept their primary shape and size. Most of the grains of precious metal minerals have not been damaged during the production of the concentrates. The largest proportion of precious metal grains is in the <40 µm fraction.

Petrographic observations

The almost perfect separation of accessory minerals from the host rock was achieved by gentle crushing. The method of disintegration preserves grains and allows recovery of most of the important information on the origin of the minerals. The heavy mineral HS-concentrates provide the information needed for the reconstruction of primary shapes and sizes of accessory minerals, together with their paragenesises and the relationships the minerals of the host rock.

In sample 90-10 443 the grains of the precious metal minerals occur in the associations shown in figure 3 (data in table 5 and 6).

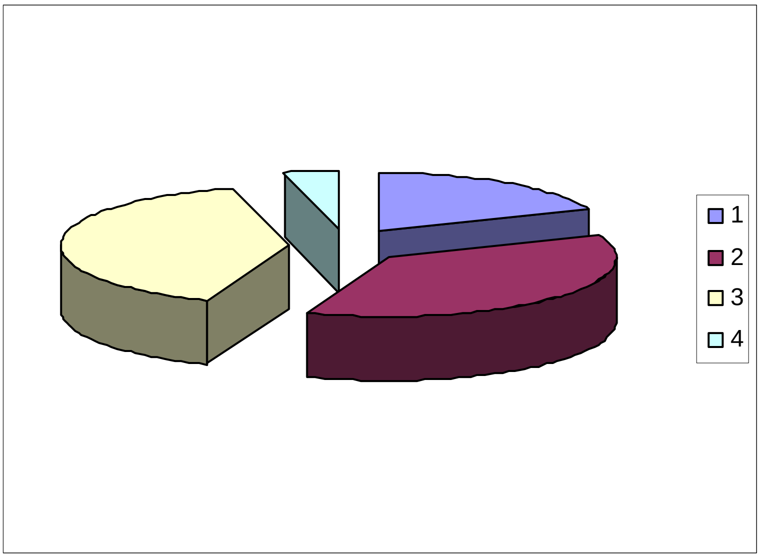

Fig. 3. - Groups of associations of precious metal minerals of the sample 90-10 443.
1) **L** association (19.0 %); 2) **Lp** association (36.7 %); 3) **bms+bms-L** association (40.5 %), 4) **ag** association (3.8 %)..

Based on SEIs, the identified precious metal minerals in the heavy mineral HS-concentrates include divided in different groups:

1. vysotskite - (Plate 6);
2. vasilite - (Plate 7);
3. guanglinite – (Plate 8).
4. atokite, zvyagintsevite and (Pd,Cu,Au,Pt) alloy (Plate 9).
5. different (Au,Cu,Pd,Ag) alloys and associated with gold mineral keithconnite (Plate 10).

Description and chemistry of PGMs and Au-minerals

Vysotskite (Pd,Ni,Cu,Fe)S

Description
Vysotskite is one of the main Pd minerals of the heavy mineral HS-concentrates of sample 90-10 443 (22.5 area %). Besides occurring as liberated grains (Plate 6, #*12-14*) it is also found in intergrowths with Cu-Fe sulphides (bornite and chalcopyrite) - (Plate 6; Plate 9, #*1, 2, 8*). Vysotskite is also associated to other PGMs such as atokite (Plate 9, #*1, 2*), guanglinite (Plate 9, #*2*) and (Pd,Cu,Au,Pt) alloy (Plate 9, #*8*).

As a rule, vysotskite-bearing sulphide grains are irregular-shaped aggregates (see Plate 8; Plate 9, #*1, 2, 8*), except for one grain which is a droplet-like bornite-chalcopyrite globule

(Plate 8, #*1*). Commonly, enclosed vysotskite grains are located at the margins of the sulphide hosts.

Vysotskite grains occur as:

1. euhedral crystals or partially euhedral grains (Plate 6, #*2-5, 10*);
2. irregular shaped aggregates (Plate 6, #*6-9, 11-14*);
3. rare isometric droplet-like grains with the rounded outlines (Plate 6, #*1*).

The grain sizes of vysotskite varies between 3 and 33.5 µm with an average of 16.5 µm (Table 3).

Mineral chemistry
The composition of vysotskite is constrained by 13 analyses in 13 particles (Table 7). The average composition of vysotskite (Table 7, analysis 14) is (wt. %): Pd 69.8, Ni 4.0, Cu 1.1, Fe 0.9, S 24.2, Total 100.0. The composition corresponds to the formula:

$$(Pd_{0.87}Ni_{0.09}Cu_{0.02}Fe_{0.02})_{1.00}S_{1.00}.$$

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

Description
Vasilite is the second most important Pd sulphide in the heavy mineral HS-concentrates of sample 90-10 443 (20.1 area %). Besides liberated grains (Plate 7, #*7, 9*) and one grain-integrowth of vasilite and chlorite (Plate 7, #*11*), it usually occurs in intergrowths with Cu-Fe sulphides (bornite and chalcopyrite) - (Plate 7; #*1-6, 8, 10*). Vasilite is also associated with other precious metal minerals including keithconnite (Plate 7, #*7, 8*) and atokite (Plate 7, #*9*), as well as tetra-auricupride (Plate 7, #*10*).

Vysotskite-bearing Cu-sulphide grains usually form irregular aggregates (see Plate 7) with vysotskite grains located at their margins.The vysotskite grains occur as:

1. euhedral or subhedral crystals (Plate 7, #*1, 3-6, 8*);
2. irregular shaped aggregates and grains (Plate 7, #*2, 6, 7, 9-11*).

The grain sizes of vasilite varies between 14 and 28.4 µm with an average of 20.6 µm (Table 3).

Mineral chemistry
The chemical composition of vasilite is constrained by 11 analyses in 11 particles (Table 8). The average composition of vasilite (Table 8, analysis 12) is (wt. %): Pd 73.0, Cu 13.5, Fe 0.5, S 12.7, Total 99.7. The composition corresponds to the following formula:

$(Pd_{12.12}Cu_{3.74}Fe_{0.13})_{12.99}S_{7.00}$.

Guanglinite $(Pd,Pt,Cu)_3(As,Sn,Te)$

Description

Together with vysotskite and vasilite guanglinite is the third main Pd mineral of the heavy mineral HS-concentrates of sample 90-10 443 (24.8 area .%). It occurs in intergrowths with Cu-Fe sulphides (bornite and chalcopyrite) - (Plate 8, #*1, 2*; Plate 9, #*3*) and as liberated grains (Plate 8, #*3-5*). Guanglinite is often associated with to PGMs (atokite – Plate 8, #*1, 2*; Plate 9, #*3*; and vysotskite – Plate 9, #*3*) as well as to gold minerals (Plate 8, #*4, 5*).

Guanglinite-bearing sulphide grains are irregular aggregates (Plate 8, #*1,2*; Plate 9, #*3*). Guanglinite may occur as irregular grains (Plate 8; #*1, 2*; Plate 9, #*3*) or rounded grains with isometric outlines (Plate 8, #*3-6*).

The grain sizes of guanglinite varies between 5 and 58.7 µm with an average of 25.3 µm (Table 3).

Mineral chemistry

The composition of guanglinite is constrained by 5 analyses in 5 particles (Table 9, analyses 1-5, the average analysis 6). Typical substitutions in guanglinite are: Pt up to 3.5 % (Table 9, analysis 3), Cu up to 1.4 % (Table 9, analysis 4), Sn 3.1-.7.7 %, Te up to 7.9 % (Table 9, analysis 4), Pb up to 1.6 % (Table 9, analysis 4).

(Au,Cu,Pd,Ag,Pt) alloys

Description

Gold minerals - (Au,Cu,Pd,Ag,Pt) alloys of different compositions represent app. 1/5 of all the precious metal minerals (21.5 area % from all precious metal minerals) in the heavy mineral HS-concentrates of sample 90-10 443. The alloys occur as tetra-auricupride AuCu and unnamed Au_3Cu and as disordered (Au,Cu,Pd,Ag,Pt) alloys (Table 3).

The tetra-auricupride ((Au,Pd,Pt)(Cu,Fe), 4.4 area %) occurs in the concentrates as inclusions in bornite and chalcopyrite (Plate 7, #*10*; Plate 10, #*1, 2*) and as liberated particles (Plate 10, #*3, 4*). It is associated with keithconnite, vasilite and unnamed Au_3Cu (Plate 7, #*10*; Plate 10, #*4*).

$(Au,Pd)_3Cu$ (12.1 area %) usually occurs in the form of liberated particles (Plate 8, #*4*; Plate 10, #*4-9*) as well as in association with rock-forming clinopyroxene (Plate 10, #*7*). It is also found to be associated with keithconnite (Plate 10, #*4-9*), guanglinite (Plate 8, #*4*) and tetra-auricupride (Plate10, #*4*).

Disordered ((Au,Cu,Pd,Ag), 5 area %) alloy occurs in the concentrates as liberated particles (Plate 8, #*5*; Plate 10, #*10, 11*), sometimes associated with guanglinite and atokite (Plate 8, #*5*).

One euhedral crystal of unnamed Au_3Cu was found to be an inclusion in guanglinite (Plate 8, #*4*). The size of Au-mineral grains is from 6 to 30.7 μm with an average of 17 μm (Table 3).

Mineral chemistry

The compositions of Au-minerals are shown in the Table 10:

1. tetra-auricupride – analyses 1-3, the average analysis 5;
2. unnamed $(Au,Pd)_3Cu$ – analyses 6-10, the average analysis 11;
3. (Au,Cu,Pd) alloy – analyses 12-15;
4. (Au,Ag,Pd,Cu) alloy – analysis 16.

It should be noted that that dominating compositions of (Au,Cu,Pd) are usually poor in Au and rich in Pd and Cu reaching compositions $AuPdCu_2$ a composition often encountered in the concentrates from the Skaergaard mineralization and probably an unnamed mineral (Table 10, analysis 4). Gold minerals contain have Pt substitutions of up to 3.9 % in tetra-auricupride (Table 10, analysis 1), and up to 3.6 % in (Au,Cu,Pd) alloy (Plate 10, analysis 12). It should be also noted that Ag-bearing Au alloys are relatively in the sample (see Plate 8, #*5*; Table 10, analysis 16).

Atokite $(Pd,Pt,Au)_3(Sn,Pb,As)$

Description

Atokite $(Pd,Pt,Au)_3(Sn,Pb,As)$ is found in 10 PGM-bearing particles (5.0 area % of all precious metal minerals). It occurs as inclusions in guanglinite (Plate 8, #*1-3, 5*) and vasilite grains (Plate 7, #*9*). In addition, atokite was found with vysotskite and guanglinite as inclusions in bornite and chalcopyrite (Plate 9, #*1-3*), as well as completely liberated grains (Plate 9, #*4, 5*).

Atokite grains may occur as:

1. euhedral crystals or partially euhedral grains (Plate 9, #*4, 5*);
2. irregular shaped aggregates and grains (Plate 7, #*9*; Plate 8, #*1-3, 5*; Plate 9, #*1-3).*

The grain size of atokite varies between 1 and 20.6 μm with an average of 9.8 μm (Table 3).

Mineral chemistry

The composition of atokite is constrained by 6 analyses in 6 particles (Table 9, analyses 7-12, the average analysis 13). Typical substitutions in atokite are: Pt up to 16.6 % (Table 9, analysis 10), Au up to 3.8 % (Table 9, analysis 7), Pb up to 15.7 % (Table 9, analysis 11), As up to 7.3 % (Table 9, analysis 10).

Keithconnite $Pd_{3-x}(Te,Pb)$

Description

Keithconnite $Pd_{3-x}(Te,Pb)$ (4.0 area % of all precious metal minerals) was found in 7 precious metal mineral grains. It has a close association with gold minerals (tetra-auricupride and unnamed Cu_3Au – Plate10, #*4-8*). Besides, keithconnite is associated with vasilite and bornite, chalcopyrite (Plate 7, #*7, 8*).

The keithconnite-containing grains and keithconnite itself have irregular shapes. The size of keithconnite grains varies between 3.9 and 19.1 µm, with an average of 10.5 µm.

Mineral chemistry

The composition of keithconnite is constrained by 4 analyses in 4 particles (Table 9, analyses 14-17). The average composition of keithconnite (Table 10, analysis 18) is (wt. %):
Pd: 69.8, Te: 30.0, Pb: 0.7, Total 99.6. The composition corresponds to the formula:

$$Pd_{2.93}(Te_{1.06}Pb_{0.01})_{1.07}.$$

Zvyagintsevite $(Pd,Pt)_3(Pb,Te,Sn,As)$

Zvyagintsevite $(Pd,Pt)_3(Pb,Te,Sn,As)$ (1.8 area % from all precious metal minerals) is found in two liberated grains (Plate 9, #*6, 7*). Zvyagintsevite occur as euhedral crystals or sub-euhedral grains, 13.7-15.7 µm in size. The compositions of the grains are shown in Table 9, analyses 19-21.

(Pd,Cu,Au,Pt) alloy

One fine grain of (Pd,Cu,Au,Pt) alloy (app. 7 µm, 0.2 area %) was found as an inclusion in bornite, together with vysotskite (Plate 9, #*8*; Table 10, analysis 17).

Discussion

Bornite and chalcopyrite are the main sulphides in the studied gabbro (~96 %). These sulphides form inclusions in cumulus two-pyroxenes aggregates (Plate 1, # *8*), as well as in reaction rims of H_2O-bearing silicate (after olivine?) between Fe-Ti aggregates and pyroxenes (Plate 1, # *7*) and in intercumulus plagioclase.

Bornite and chalcopyrite grains in the heavy mineral concentrates and their irregular particles form characteristic droplet-like microglobules (see Plate 4, #*1-3, 5* etc.; Plate 5, # *1-5* etc.). The microglobules show the characteristic exsolution texture with chalcopyrite lamellae in a bornite matrix (Plate 5, #*3, 5-8* etc.).which testifies to their high-temperature nature.

Three groups of precious metal minerals dominate (see Table 3): 1) Pd sulphides (vysotskite and vasilite), 2) Pd arsenides (guanglinite) and 3) gold minerals relatively poor in Au and Ag but rich in Pd and Cu (tetra-auricucupride, unnamed Au_3Cu mineral phase and alloys of Au, Cu and Pd).

The bornite and chalcopyrite paragenesis relate to both the (Au,Cu,Pd) alloys and the PGM paragenesis. All observations of inter-grain relations suggest that main part of precious metal minerals forms a single paragenesis with the Cu-Fe sulphides.

Note should be taken of the close association between gold minerals and Pd-tellurides (keithconnite – see Plate 10, #*4-8*) and Pd-arsenides (guanglinite – Plate 8, #*4, 5*). Taking into account that many grains of gold minerals occur as liberated grains (**L** and **Lp** – see Table 6) and as irregular formed grains, we suggest that the crystallization of the preciouss metal minerals and phases took place contemporaneously with the rock-forming minerals crystallized from a metal-rich melt/fluid (see for example Plate10, #7 – **ag** association of unnamed Au_3Cu mineral phase and keithconnite with monoclinic pyroxene).

Summary

1. Bornite and chalcopyrite dominate the sulphide paragenesis of the studied sample (app. 96 %). Bornite and chalcopyrite form characteristically droplet-like microglobules. The microglobules have characteristic exsolution textures with chalcopyrite lamellae in a bornite host, a texture preserved from high temperature.

2. A representative set of fiftytwo grains of precious metal minerals and phases was selected for detailed studies from the HS-concentrates of sample 90-10 443 (750g). The precious metal minerals represent four groups: 1) Pd sulphides – vysotskite (Pd,Ni,Cu,Fe)S (22.5 %) and vasilite $(Pd,Cu,Fe)_{16}S_7$ (20.1 %); 2) Pd arsenides – guanglinite $(Pd,Pt,Cu)_3(As,Sn,Te)$ (24.8 %); 3) different (Au,Cu,Pd,Ag) alloys – tetra-auricupride (Au,Pd,Pt)(Cu,Fe) (4.4 %), unnamed $(Au,Pd)_3(Cu,Fe)$ (12.1 %); (Au,Pd,Cu,Ag) alloys of different compositions (5.2 %); 4) Pd-intermetallides of Sn, Te and Pb – atokite $(Pd,Pt,Au)_3(Sn,Pb,As)$ (5 %), keithconnite $Pd_{3-x}(Te,Pb)$ (4 %) and zvyagintsevite $(Pd,Pt)_3(Pb,Te,Sn)$ (1.8 %). The size of the grains of the precious metal minerals (ECD) varies between 4.5 and 61.3 μm with an average of 20 μm.

3. The bulk of the precious metal balance is made by three groups of minerals: 1) Pd sulphides (vysotskite and vasilite), 2) Pd arsenides (guanglinite) and 3) gold minerals - relatively poor in Au and Ag but rich in Pd and Cu (tetra-auricucupride, unnamed Au_3Cu mineral phase and Au-Cu-Pd alloys).

4. The base metal sulphides (bornite and chalcopyrite) and PGMs, as well as (Au,Cu,Pd) alloys appear to belong to one and the same paragenesis.

5. The close association of gold minerals with Pd-tellurides (keithconnite) and Pd-arsenides (guanglinite), and the fact that gold minerals mostly occur in the heavy mineral concentrates as liberated associations (**L** and **Lp**) as well as their irregular shape suggested that their shae is determined by the rock-forming minerals and that they crystallized from a a metal-rich melt/fluid in the intersticies in the host.

6. one zircon and one monazite grain was identified. They can be used for the geochronological and isotopic investigations of the ore horizon.

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Appendix

Abbreviations used in Figures, Tables and in the text of report

Rock-forming minerals

pl – plagioclase
cpx – monoclinic pyroxene
opx – orthorhombic pyroxene
ilm – ilmenite
mt - magnetite
timt – titaniferous magnetite
chl – chlorite
tlc - talc
pyr (exs) – exsolution texture of monoclinic and orthorhombic pyroxenes
zrn – zircon
mnz – monazite

Sulphides

bn - bornite
cp – chalcopyrite
pn – pentlandite
po –pyrrhotite
chal – chalcosine

Precious metal minerals

gng – guanglinite
vys – vysotskite
vsl - vasilite
kth - keithconnite
at – atokite
zv - zvyagintsevite
(Au,Cu,Pd,Ag,Pt) - alloys of Au, Cu, Pd, Ag and Pt
(Pd,Cu,Au,Pt) – alloy of Pd,Cu,Au and Pt
Au_3Cu – unnamed mineral phase

TABLES

Table 1. Chemical composition and formuli of silicates and FeTi-oxides, sample 90-10 443

	Plagioclase						Monoclinic pyroxene						Orthorhombic pyroxene					Titaniferous magnetite						ilmenite					
Analysis	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
(wt%)						**avr.**						**avr.**					**avr.**						**avr.**						**avr.**
SiO_2	55.2	54.9	51.2	55.7	55.7	55.5	49.9	51.0	51.0	50.1	50.7	50.5	50.7	50.4	50.3	50.9	50.6	-	-	-	-	-	-	-	-	-	-	-	-
TiO_2	-	-	-	-	-	-	0.6	0.6	0.3	0.4	0.3	0.4	-	0.5	-	0.3	0.2	13.5	15.6	14.3	12.8	16.1	14.5	49.1	49.2	49.5	49.2	49.4	49.3
Al_2O_3	27.8	27.9	27.5	27.3	27.3	27.6	1.2	1.6	0.8	1.5	1.0	1.2	-	-	0.8	-	0.2	2.9	2.5	2.6	3.6	3.4	3.0	-	-	-	-	-	-
V_2O_3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.3	1.2	1.3	1.3	1.4	1.3	-	0.5	-	0.6	0.6	0.3
Fe_2O_3	0.4	0.4	0.3	0.4	0.4	0.4	-	-	-	-	-	-	-	-	-	-	-	37.9	34.9	36.8	38.4	32.0	36.0	6.2	5.6	5.4	5.1	4.9	5.4
FeO	-	-	-	-	-	-	16.2	14.8	14.0	15.8	15.5	15.3	28.9	28.5	27.9	28.4	28.4	42.7	44.7	44.5	43.1	46.0	44.2	43.3	43.3	44.0	43.5	43.9	43.6
MnO	-	-	-	-	-	-	0.5	0.3	0.3	0.4	0.5	0.4	0.5	0.6	0.8	0.7	0.7	-	-	0.3	0.3	0.3	0.2	0.8	0.9	0.5	0.7	0.5	0.7
MgO	-	-	-	-	-	-	12.1	12.8	12.9	12.4	12.6	12.6	16.1	16.5	16.5	15.6	16.2	0.8	0.8	-	-	-	0.3	-	-	-	-	-	-
CaO	9.8	10.2	9.2	9.9	9.5	9.7	18.8	18.0	19.7	18.9	18.8	18.8	3.0	2.9	3.3	3.4	3.2	-	-	-	-	-	-	-	-	-	-	-	-
Na_2O	5.7	5.5	6.1	5.6	5.9	5.8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
K_2O	0.5	0.4	0.4	0.4	0.5	0.4	-	-	-	-	-	-	-	-	-	-	-												
Total	99.4	99.3	99.7	99.3	99.3	99.4	99.3	99.1	99.0	99.5	99.4	99.3	99.2	99.4	99.6	99.3	99.5	99.1	99.7	99.8	99.5	99.2	99.5	99.4	99.5	99.4	99.1	99.3	99.3
Cations																													
Si	2.50	2.49	2.54	2.53	2.53	2.52	1.93	1.95	1.96	1.93	1.95	1.94	1.99	1.97	1.96	1.99	1.98	-	-	-	-	-	-	-	-	-	-	-	-
Ti	-	-	-	-	-	-	0.02	0.02	0.01	0.01	0.01	0.01	-	0.01	-	0.01	0.01	0.38	0.44	0.40	0.36	0.45	0.41	0.94	0.94	0.95	0.94	0.95	0.94
Al	1.49	1.49	1.46	1.46	1.46	1.47	0.06	0.07	0.04	0.07	0.05	0.06	-	-	0.04	-	0.01	0.13	0.11	0.11	0.16	0.15	0.13	-	-	-	-	-	-
V	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	0.04	0.04	0.04	0.04	0.04	-	0.02	-	0.01	0.01	0.01
Fe3+	0.01	0.01	0.01	0.01	0.01	0.01	-	-	-	-	-	-	-	-	-	-	-	1.07	0.98	1.04	1.08	0.90	1.01	0.12	0.11	0.10	0.10	0.09	0.10
Fe2+	-	-	-	-	-	-	0.52	0.47	0.45	0.51	0.50	0.49	0.95	0.93	0.91	0.93	0.93	1.34	1.39	1.39	1.35	1.44	1.38	0.92	0.92	0.94	0.93	0.94	0.93
Mn	-	-	-	-	-	-	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.03	0.02	0.02	-	-	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.01	0.02
Mg	-	-	-	-	-	-	0.70	0.73	0.74	0.71	0.72	0.72	0.94	0.96	0.96	0.91	0.94	0.04	0.05	-	-	-	0.02	-	-	-	-	-	-
Ca	0.48	0.49	0.45	0.48	0.46	0.47	0.78	0.74	0.81	0.78	0.78	0.78	0.13	0.12	0.14	0.14	0.13	-	-	-	-	-	-	-	-	-	-	-	-
Na	0.50	0.49	0.53	0.49	0.52	0.51	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
K_2O	0.03	0.02	0.02	0.02	0.03	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
O-basis	8	8	8	8	8	8	6	6	6	6	6	6	6	6	6	6	6	-	-	-	-	-	-	-	-	-	-	-	-
Cation basis	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	3	3	3	3	3	2	2	2	2	2	2

Table 2. Chemical composition of base metal sulphides, sample 90-10 443

	Bornite													
Object	40,#7a	40-2,#1	40-2,#2	70,#2	70,#2b	40,#s1	40,#s2	40,# s3	40,# s4	40,# s6	40, #s7	40, #p1	40,# p2	Average
Association	bn	vsl+kth +bn	vys+bn	vys+bn+ (Pd,Cu,Au,Pt)	bn+cp	bn	bn	bn	bn	bn	bn	bn	bn	
Ananlysis #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
(wt%)														
Fe	12.1	12.1	11.5	11.5	11.9	11.6	11.1	11.4	11.7	11.8	11.6	11.7	11.4	11.6
Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cu	61.9	61.9	62.2	63.1	62.1	62.7	62.8	63.4	62.4	63.2	63.2	62.6	63.4	62.7
S	25.3	25.6	25.4	25.4	25.6	25.5	25.3	25.4	25.5	25.5	25.7	25.5	25.8	25.5
Total	99.3	99.6	99.1	100.0	99.6	99.8	99.2	100.2	99.6	100.5	100.5	99.8	100.6	99.9
Proportions														
Fe	1.09	1.09	1.04	1.03	1.07	1.04	1.01	1.02	1.05	1.05	1.04	1.05	1.02	1.05
Co	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cu	4.92	4.90	4.95	4.99	4.91	4.96	5.00	5.00	4.94	4.97	4.96	4.95	4.97	4.96
S	3.99	4.01	4.01	3.98	4.02	4.00	3.99	3.98	4.00	3.98	4.00	4.00	4.01	4.00
sum	10	10	10	10	10	10	10	10	10	10	10	10	10	10

	Chalcopyrite					Chalcosine	Pentlandite					Pyrrhotite	
Object	40,#5	40,# 5s	40,# 10s	40, #p4	Average	40,# p7	40, #14s	40,# 19s	40,# 22s	40,# p13	Average	40, #25s	40, #p18
Association	vsl+cp	cp	cp	cp		chal+bn	pn	pn	pn	pn		po	po
Analysis #	15	16	17	18	19	20	21	22	23	24	25	26	27
(wt%)													
Fe	30.5	30.4	30.6	30.8	30.6	1.7	30.6	30.6	30.5	30.9	30.7	60.2	60.4
Co	-	-	-	-	-	-	0.5	0.5	0.4	0.7	0.5	-	-
Ni	-	-	-	-	-	-	35.9	35.3	35.4	35.4	35.5	-	-
Cu	34.0	34.5	34.5	34.4	34.4	78.0	-	-	-	-	-	-	-
S	34.8	34.9	35.2	35.4	35.1	20.9	33.2	33.0	33.2	33.5	33.2	39.5	39.7
Total	99.3	99.8	100.3	100.6	100.1	100.6	100.2	99.4	99.5	100.5	99.9	99.7	100.1
Proportions													
Fe	1.01	1.00	1.00	1.00	1.00	0.05	4.23	4.26	4.24	4.25	4.25	7.80	6.99
Co	-	-	-	-	-	-	0.07	0.06	0.05	0.09	0.07	-	-
Ni	-	-	-	-	-	-	4.72	4.68	4.68	4.63	4.68	-	-
Cu	0.99	1.00	0.99	0.99	0.99	1.93	-	-	-	-	-	-	-
S	2.00	2.00	2.01	2.01	2.01	1.02	7.99	8.00	8.03	8.03	8.01	8.00	8.01
sum	4	4	4	4	4	3	17	17	17	17	17	15	15

Abbreviations: bn: bornite; cp: chalcopyrite; chal: chalcosine; vsl: vasilite; kth: keithconnite; (PdCu,Au,Pt): alloy; pn: pentlandite and po: pyrrhotite.

Table 3. **Precious metal minerals of the heavy mineral HS concentrates, sample 90-10 443**

Mineral	General formula	abbreviated	Number of grains	area, µm2	n%	area%	Grain size, ECD, µm min	average	max
Guanglinite	$(Pd,Pt,Cu)_3(As,Sn,Te)$	gng	7	4796	10.0	24.8	5.0	25.3	58.7
Vysotskite	(Pd,Ni,Cu,Fe)S	vys	17	4347	24.3	22.5	3.2	16.5	33.5
Vasilite	$(Pd,Cu,Fe)_{16}S_7$	vsl	11	3887	15.7	20.1	14.0	20.6	28.4
Atokite	$(Pd,Pt,Au)_3(Sn,Pb,As)$	at	10	972	14.3	5.0	1.0	9.8	20.6
Keithconnite	$Pd_{3-x}(Te,Pb)$	kth	7	777	10.0	4.0	3.9	10.5	19.1
Zvyagintsevite	$(Pd,Pt)_3(Pb,Te,Sn)$	zv	2	341	2.9	1.8	13.7	14.7	15.7
Tetra-auricupride	(Au,Pd,Pt)(Cu,Fe)	AuCu	5	844	7.1	4.4	6.0	13.1	21.7
Unnamed Au3Cu	$(Au,Pd)_3(Cu,Fe)$	Au3Cu	7	2337	10.0	12.1	10.8	19.9	30.7
(Au,Cu,Pd) alloy	(Au,Cu,Pd)	(Au,Cu.Pd)	2	913	2.9	4.7	19.3	20.1	23.7
(Au,Ag,Cu,Pd) alloy	(Au,Ag,Cu,Pd)	(Au,Ag,Cu,Pd)	1	58	1.4	0.3	-	8.6	-
(Pd,Cu,Au,Pt) alloy	(Pd,Cu,Au,Pt)	(Pd,Cu,Au,Pt)	1	40	1.4	0.2	-	7.1	-
	Total		70	19312	100.0	100.0			

Table 4. Grain size of precious metal mineral, sample 90-10 443

N	Grain#	Association	Type	Mineral	Area, μm^2	ECD, μm
1	40,#1	vys-gng-at-bn-cp	bms	Total	225	16.9
2	40,#1	vys-gng-at-bn-cp	bms	vys	185	15.4
3	40,#1	vys-gng-at-bn-cp	bms	gng	20	5.0
4	40,#1	vys-gng-at-bn-cp	bms	at	20	5.0
5	40,#2	Au_3Cu-kth-cpx	ag	Total	103	11.5
6	40,#2	Au_3Cu-kth-cpx	ag	Au_3Cu	91	10.8
7	40,#2	Au_3Cu-kth-cpx	ag	kth	12	3.9
8	40,#3	vys-cp-bn	bms	vys	149	13.8
9	40,#4	(Au,Cu,Pd)	L	(Au,Cu,Pd)	292	19.3
10	40,#5	vsl-cp	bms	vsl	154	14.0
11	40,#6	vys	L	vys	490	25.0
12	40,#7	vys-bn-cp	bms	vys	58	8.6
13	40,#8	Au_3Cu-kth	Lp	Total	590	27.4
14	40,#8	Au_3Cu-kth	Lp	Au_3Cu	304	19.7
15	40,#8	Au_3Cu-kth	Lp	kth	286	19.1
16	40,#9	vsl-chl	ag	vsl	633	28.4
17	40,#10	vsl-bn-cp	bms	vsl	422	23.2
18	40,#11	at	L	at	334	20.6
19	40,#12	vys	L	vys	330	20.5
20	40,#13	gng-at--bn	bms	Total	531	26.0
21	40,#13	gng-at--bn	bms	gng	436	23.6
22	40,#13	gng-at--bn	bms	at	195	15.8
23	40,#14	zv	L	zv	194	15.7
24	40,#15	Au_3Cu-kth	Lp	Total	345	21.0
25	40,#15	Au_3Cu-kth	Lp	Au_3Cu	315	20.0
26	40,#15	Au_3Cu-kth	Lp	kth	30	6.2
27	40,#16	(Au,Cu,Pd)	L	(Au,Cu,Pd)	621	28.1
28	40,#17	vsl-at	Lp	Total	409	22.8
29	40,#17	vsl-at	Lp	vsl	377	21.9
30	40,#17	vsl-at	Lp	at	32	6.4
31	40,#18	vsl-kth	Lp	Total	300	19.5
32	40,#18	vsl-kth	Lp	vsl	174	14.9
33	40,#18	vsl-kth	Lp	kth	126	12.7
34	40,#19	vys	L	vys	175	14.9
35	40,#20	vys-bn	bms	vys	342	20.9
36	40,#21	at	L	at	168	14.6
37	40,#22	vys-bn-cp	bms	vys	380	22.0
38	40,#23	gng-at	Lp	Total	725	30.4
39	40,#23	gng-at	Lp	gng	698	29.8
40	40,#23	gng-at	Lp	at	27	5.9
41	40,#24	Au_3Cu-kth	LP	Total	841	32.7
42	40,#24	Au_3Cu-kth	LP	Au_3Cu	741	30.7
43	40,#24	Au_3Cu-kth	LP	kth	100	11.3
44	40,#25	AuCu-cp	bms-L	AuCu	370	21.7
45	40,#26	vsl-bn	bms	vsl	554	26.6
46	40,#27	vys-cp	bms	vys	157	14.1
47	40,#28	at-vys-cp	bms	Total	114	12.1

Table 4 continued

N	Grain	Association	Type	Mineral	Area, μm^2	ECD, µm
48	40,#28	at-vys-cp	bms	at	106	11.6
49	40,#28	at-vys-cp	bms	vys	8	3.2
50	40,#29	vys-bn-cp	bms	vys	256	18.1
51	40,#30	gng	L	gng	354	21.2
52	40,#31	vys-bn	bms	vys	355	21.3
53	40,#32	vys-bn	bms	vys	280	18.9
54	40,#33	gng-at-(Au,Ag,Cu,Pd)	Lp	Total	362	21.5
55	40,#33	gng-at-(Au,Ag,Cu,Pd)	Lp	gng	278	18.8
56	40,#33	gng-at-(Au,Ag,Cu,Pd)	Lp	(Au,Ag,Cu,Pd)	58	8.6
57	40,#33	gng-at-(Au,Ag,Cu,Pd)	Lp	at	26	5.8
58	40,#34	AuCu	L	AuCu	313	20.0
59	40,#35	vys-bn-cp	bms	vys	29	6.1
60	40,#36	Au_3Cu	L	Au_3Cu	305	19.7
61	40,#37	AuCu-bn-cp	bms	AuCu	33	6.5
62	40,#38	kth-AuCu-Au_3Cu	Lp	Total	663	29.1
63	40,#38	kth-AuCu-Au_3Cu	Lp	kth	210	16.4
64	40,#38	kth-AuCu-Au_3Cu	Lp	Au_3Cu	353	21.2
65	40,#38	kth-AuCu-Au_3Cu	Lp	AuCu	100	11.3
66	40,#39	vsl-bn	bms	vsl	425	23.3
67	40,#40	zv	L	zv	147	13.7
68	40,#41	vsl-cp	bms	vsl	233	17.2
69	40-2,#1	vsl-kth-bn-cp	bms	Total	236	17.3
70	40-2,#1	vsl-kth-bn-cp	bms	vsl	223	16.9
71	40-2,#1	vsl-kth-bn-cp	bms	kth	13	4.1
72	40-2,#2	vys-bn	bms	vys	60	8.7
73	40-2,#3	vsl-AuCu-cp-bn	bms	Total	183	15.3
74	40-2,#3	vsl-AuCu-cp-bn	bms	vsl	155	14.1
75	40-2,#3	vsl-AuCu-cp-bn	bms	AuCu	28	6.0
76	40-2,#4	gng-at-cp-bn	bms	Total	352	21.2
77	40-2,#4	gng-at-cp-bn	bms	gng	304	19.7
78	40-2,#4	gng-at-cp-bn	bms	at	48	7.8
79	40-2,#5	vsl-cp	bms	vsl	537	26.2
80	70,#1	vys-bn	bms	vys	880	33.5
81	70,#2	vys-(Pd,Cu)-bn	bms	Total	253	18.0
82	70,#2	vys-(Pd,Cu)-bn	bms	vys	213	16.5
83	70,#2	vys-(Pd,Cu)-bn	bms	(Pd,Cu)	40	7.1
84	70,#3	at-bn	bms	at	16	4.5
85	70,#4	gng-Au_3Cu	Lp	Total	2934	61.1
86	70,#4	gng-Au_3Cu	Lp	gng	2706	58.7
87	70,#4	gng-Au_3Cu	Lp	Au_3Cu	228	17.0

Abbreviations:

Alloys:	(Pd,Cu); (Au,Cu,Pd) and (Au,Ag,Cu,Pd)
Gold minerals:	Auricupride: Au_3Cu; tetra-auricupride AuCu
PGMs:vys	vys: vysotskite; gng: guanglinite; at: atokite; kth: keithconnite; zv: zvyagintsevite; vsl: vasilite.
Base metal sulphides:	bn: bornite; cp: chalcopyrite
Silicates:	chl: chlorite

Table 5. Precious metal Mineral associations in grains of different groups of precious metal minerals, sample 90-10 443

Association	Number of grains	Area, μm^2	n%	Area%	ECD, µm		
					min	average	max
L	12	3723	23.1	19.0	13.7	19.5	28.1
Lp	9	7188	17.3	36.7	19.5	29.5	61.3
bms	28	7566	53.8	38.6	4.5	17.2	33.5
bms-L	1	370	1.9	1.9		21.7	
ag	2	736	3.8	3.8	11.5	19.9	28.4
Total	52	19583	100.0	100.0			

Abbreviations:

L.	completely liberated (free) particles of precious metal minerals
Lp:	two or more precious metal minerals completely liberated (free) particles
bms:	intergrowths of precious metal minerals with base metal sulphides
bms-L:	liberated particles of precious metal minerals with <10 % attached base metal sulphides
sag:	sulphide and gangue attached to precious metal minerals
ag:	precious metal minerals attached to gangue

Table 6 Groups of precious metal minerals and their associations; sample 90-10 443

Association	PGMs, area % (15 grains)	(Au,Cu,Pd) alloys, area % (15 grains)
L	10.3	36.9
Lp	33.4	50.6
bms+bms-L	51.5	10.4
ag	4.8	2.2
Total	100	100

L - completely liberated (free) particles; Lp – two or more precious metals completely liberated (free) particles; bms - intergrowths with base metal sulphides (bornite and chalcopyrite); bms-L - liberated particles with <10 % attached base metal sulphides; ag – precious metal minerals attached to gangue (clinopyroxene, chlorite).

Table 7. Chemical composition of vysotskite fin the heavy mineral HS-concentrates from sample 90-10 443.

Object	40,#3	40,#6	40,#7	40,#12	40,#19	40,#20	40,#22	40,#27	40,#29	40,#35	40-2,#2	70,#1	70,#2	Average
Association	vys+bn +cp	vys	vsl+bn +cp	vys	vys	vys+bn	vys+bn +cp	vys+cp	vys+bn +cp	vys+bn +cp	vys+bn	vys+bn +cp	vys+bn+ (Pd,Cu,Au,Pt)	vys
Analysis (wt%)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fe	1.1	0.7	1.0	0.5	0.6	0.6	0.6	1.2	0.6	2.5	2.1	-	0.7	0.9
Ni	6.0	2.7	-	-	1.8	-	7.1	7.4	4.6	4.5	2.2	8.3	7.0	4.0
Cu	1.6	-	1.1	-	-	-	0.7	0.6	-	2.3	2.8	-	5.1	1.1
S	24.7	23.7	23.7	23.1	23.5	23.0	24.6	25.1	23.6	24.7	24.3	25.0	25.0	24.2
Pd	66.1	72.6	74.1	75.6	73.5	76.0	66.5	65.9	71.1	66.3	68.0	66.8	61.5	69.8
Total	99.5	99.7	99.9	99.2	99.4	99.6	99.5	100.2	99.9	100.3	99.4	100.1	99.3	100.0
proportions														
Fe	0.03	0.02	0.02	0.01	0.02	0.01	0.01	0.03	0.01	0.06	0.05	-	0.02	0.02
Ni	0.13	0.06	-	-	0.04	-	0.16	0.16	0.10	0.10	0.05	0.18	0.15	0.09
Cu	0.03	-	0.02	-	-	-	0.01	0.01	-	0.05	0.06	-	0.10	0.02
S	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.01	0.99	0.99	1.00	1.01	0.99	1.00
Pd	0.81	0.92	0.95	0.99	0.94	0.99	0.81	0.79	0.89	0.80	0.84	0.81	0.74	0.87
sum	2.00	2.00	2.00	2.00	2.00	2.00	1.99	2.00	1.99	2.00	2.00	2.00	2.00	2.00

Abbreviations

Alloys:	(Pd,Cu,Au,Pt)
PGMs:	vys: vysotskite; vsl: vasilite.
	kth: keithconnite; zv: zvyagintsevite;
Base metal sulphides:	bn: bornite; cp: chalcopyrite

Table 8 . **Chemical composition of vasilite in PGM-grains in the heavy mineral HS-concentrates of sample 90-10 443**

Object	40,#5	40,#9	40,#10	40,#17	40,#18	40,#26	40,#39	40,#41	40-2,#1	40-2,#3	40-2,#4	Average
Association	vsl+cp	vsl+chl	vsl+bn+cp	vsl+at	vsl+kth	vsl+bn	vsl+bn	vsl+cp	vsl+kth+bn	vsl+cp+bn +(Au,Pd)Cu	vsl+cp	vsl
Analysis (wt%)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Fe	0.7	-	-	0.5	0.7	-	0.5	0.6	1.0	1.1	-	0.5
Cu	13.8	13.4	13.5	13.4	12.7	13.5	13.8	13.8	13.8	13.9	13.4	13.5
S	12.7	12.7	12.6	12.7	12.7	12.6	12.8	12.6	12.7	12.9	12.6	12.7
Pd	72.3	73.5	73.0	72.9	73.3	73.4	73.2	72.5	72.7	72.6	73.2	73.0
Total	99.5	99.6	99.1	99.5	99.4	99.5	100.3	99.5	100.2	100.5	99.2	99.7
Proportions												
Fe	0.21	-	-	0.15	0.22	-	0.17	0.19	0.30	0.33	-	0.13
Cu	3.82	3.73	3.78	3.72	3.54	3.77	3.80	3.83	3.79	3.80	3.75	3.74
S	6.99	7.02	7.01	7.00	7.02	6.99	6.99	6.95	6.94	6.99	7.01	7.00
Pd	11.98	12.25	12.20	12.12	12.21	12.23	12.04	12.04	11.97	11.88	12.24	12.12
sum	23	23	23	23	23	23	23	23	23	23	23	23

Abbreviations:

PGE alloys:	(Au,Pd)Cu
PGMs:	vsl: vasilite; at: atokite; kth: keithconnite
Base metal sulphides:	cp: chalcopyrite; bn: bornite;

Table 9. Chemical compositions of guanglinite, atokite, keithconnite and zvyagintsevite in PGM-grains in heavy mineral HS-concentrates, sample 90-10 443.

	Guanglinite						Atokite						
Object	40,#23	40,#30	40,#33	40-2,#4	70,#4	avr.	40,#11	40,#13	40,#21	40,#33	40,#28	40-2,#4	avr.
Association	gng+at	gng	gng+at+ (Au,Ag,Pd)	gng+at+ cp+bn	gng+ (Au,Pd,Cu)	gng	at	gng+at +bn	at	gng+at+ (Au,Ag,Pd)	at+vys +cp	gng+at+ cp+bn	at
Analysis #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Wt%													
Fe			0.6	0.6		0.2		0.7				0.7	0.2
Cu				1.4		0.3							
S	0.9					0.2							
Pt			4.6			0.9	2.1		3.0	16.6			3.6
Pd	79.7	79.7	74.7	72.5	78.4	77.0	66.2	67.3	70.7	61.7	67.5	65.8	66.5
Au							3.8		2.1				1.0
Pb				1.6		0.5	3.3	13.3	2.1		15.7	19.8	9.0
As	12.2	15.3	16.4	8.7	13.6	13.2			6.4	7.3			2.3
Te				7.9		1.6							
Sn	6.8	5.5	3.1	7.0	7.7	6.0	24.1	18.5	15.5	14.2	15.8	13.1	16.9
Total	99.6	100.5	99.4	99.7	99.7	99.9	99.5	99.8	99.8	99.8	99.0	99.4	99.5
Proportions													
Fe			0.04	0.04		0.02		0.06				0.06	0.02
Cu				0.09		0.02							
S	0.12					0.02							
Pt			0.10			0.02	0.05		0.07	0.39			0.08
Pd	3.00	3.00	2.86	2.84	3.00	2.94	2.86	2.92	2.90	2.63	3.01	2.96	2.88
Au							0.09		0.05				0.02
Pb				0.03		0.01	0.07	0.30	0.04		0.36	0.46	0.21
As	0.65	0.82	0.89	0.48	0.74	0.72			0.37	0.44			0.14
Te				0.26		0.05							
Sn	0.23	0.18	0.11	0.25	0.26	0.23	0.93	0.72	0.57	0.54	0.63	0.53	0.65
sum	4	4	4	4	4	4	4	4	4	4	4	4	4

Abbreviations:	Alloys:	(Au,Ag,Pd); (Au,Pd,Cu); (Au,Cu,Pd): $(Au,Pd)_3Cu$
	Gold minerals:	unnamed (Au,Pd)Cu
	PGMs:vys	vys: vysotskite; gng: guanglinite; at: atokite; kth: keithconnite; zv: zvyagintsevite; vsl: vasilite.
	Base metal sulphides:	bn: bornite; cp: chalcopyrite

Table 9 continued

	Keithconnite					Zvyagintsevite			
Object	40,#8	40,#15	40,#38	40-2,#1	avr.	40,#14	40,#14	40,#40	avr.
Association	$(Au,Pd)_3Cu$ +kth	(Au,Cu,Pd) +kth	$(Au,Pd)_3Cu$ +(Au,Pd)Cu +kth	vsl+kth +bn	kth	zv-1,2	zv-1,2	zv	zv
Analysis	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Wt%									
Fe						0.6			0.2
Cu									
S									
Pt							3.1	2.7	2.9
Pd	67.1	68.2	69.8	70.6	68.9	67.7	59.4	60.7	62.6
Au									
Pb				2.8	0.7	17.8	35.9	30.6	28.1
As						4.0			1.3
Te	32.5	31.2	30.0	26.1	30.0	9.1			3.0
Sn							1.9	5.1	2.3
Total	99.6	99.4	99.8	99.5	99.6	99.2	100.3	99.1	99.4
Proportions									
Fe						0.04			0.01
Cu									
S									
Pt							0.08	0.07	0.05
Pd	2.85	2.90	2.94	3.01	2.93	2.97	2.93	2.94	2.95
Au									
Pb				0.06	0.01	0.40	0.91	0.76	0.69
As						0.25			0.08
Te	1.15	1.10	1.06	0.93	1.06	0.33			0.11
Sn							0.08	0.22	0.10
sum	4	4	4	4	4	4	4	4	4

Abbreviations:

Alloys:	(Au,Ag,Pd); (Au,Pd,Cu); (Au,Cu,Pd): $(Au,Pd)_3Cu$
Gold minerals:	unnamed (Au,Pd)Cu
PGMs:vys	vys: vysotskite; gng: guanglinite; at: atokite;
	kth: keithconnite; zv: zvyagintsevite; vsl: vasilite.
Base metal sulphides:	bn: bornite; cp: chalcopyrite

Table 10. Chemical composition of gold minerals from the heavy mineral HS concentrates of the sample 90-10 443

	Tetra-auricupride					Unnamed $(Au,Pd)_3Cu$					
Object	40,#25	40,#34	40,#37	40-2,#3	Average	40,#2	40,#8	40,#24	40,#36	40,#38	Average
Association	(Au,Pd)Cu	(Au,Pd)Cu	(Au,Pd)Cu +cp+bn	(Au,Pd)Cu +cp+bn +vsl	(Au,Pd)Cu	$(Au,Pd)_3Cu$ +kth+cpx	$(Au,Pd)_3Cu$ +kth	Au_3Cu +kth	Au_3Cu	$(Au,Pd)_3Cu$ +(Au,Pd)Cu +kth	$(Au,Pd)_3Cu$
Analysis #	1	2	3	4	5	6	7	8	9	10	11
wt%											
Fe	1.4	0.7	0.6	2.7	1.4	0.9	-	-	0.6	-	0.3
Cu	26.6	24.3	25.2	25.2	25.3	10.5	10.1	9.0	10.3	10.0	10.0
Pt	3.9	-	-	-	1.0	-	-	-	-	-	-
Pd	16.3	16.6	20.2	25.7	19.7	25.4	19.1	4.9	19.5	17.0	17.2
Au	51.3	58.1	53.0	46.1	52.1	62.4	70.2	85.6	69.3	72.4	72.0
Ag	-	-	-	-	-	-	-	-	-	-	-
Total	99.5	99.7	99.0	99.7	99.5	99.2	99.4	99.5	99.7	99.4	99.5
Proportions											
Fe	0.06	0.03	0.03	0.11	0.06	0.09	-	-	0.06	-	0.03
Cu	0.95	-	-	-	0.91	0.90	0.92	0.91	0.92	0.92	0.91
Pt	0.05	-	-	-	0.01	-	-	-	-	-	-
Pd	0.35	0.37	0.44	0.52	0.42	1.30	1.03	0.20	1.04	0.93	0.90
Au	0.59	0.70	0.62	0.51	0.61	1.72	2.05	2.79	1.99	2.15	2.14
Ag	-	-	-	-	-	-	-	-	-	-	-
Total	2	2	2	2	2	4	4	4	4	4	4

Abbreviations:

Gold minerals:	(Au,Pd)Cu: tetra-auricupride; (Au,Pd)3Cu: unnamed mineral; Au3Cu: unnamed mineral
PGMs:	vsl: vasilite; kth: keithconnite; ; gng: guanglinite; at: atokite; vys: vysotskite
Unnamed alloys:	(Au,Pd)Cu; (Au,Cu,Pd); (Au,Ag,Pd); (Pd,Cu,Au,Pt)
Base metal sulphides:	bn: bornite; cp: chalcopyrite;
Silicates:	cpx<. Clinopyroxene;

Table 10. Continued

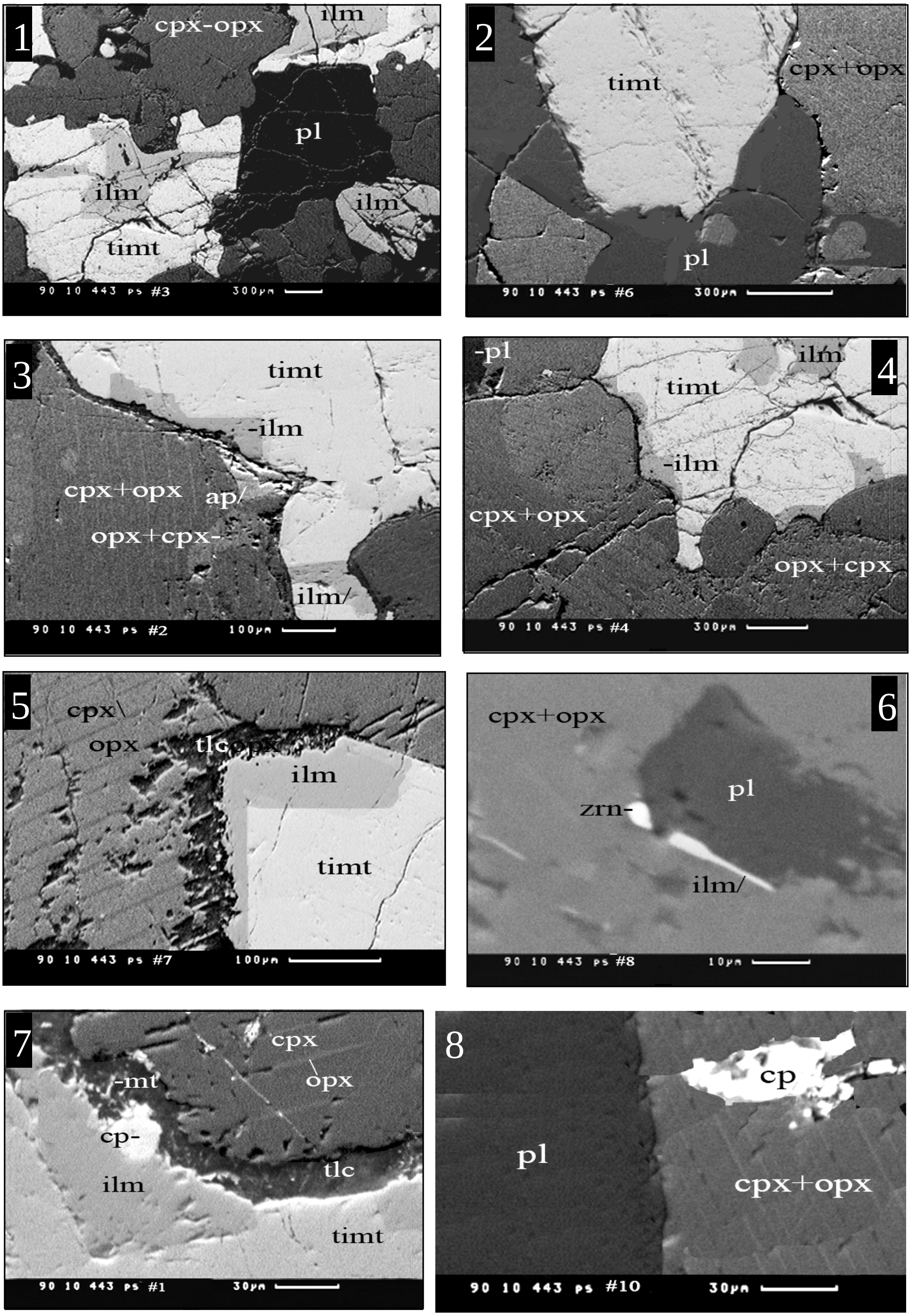
	Alloys (Au,Cu,Pd)				Alloy (Au,Ag,Pd)	Alloy (Pd,Cu,Au,Pt)
Object	40,#4	40,#15	40,#16	70,#4	40,#33	70,#2
Association	(Au,Cu,Pd)	(Au,Pd,Cu) +kth	(Au,Cu,Pd)	gng+ (Au,Pd,Cu)	gng+at+ (Au,Ag,Pd)	vys+ (Pd,Cu,Au,Pt) +bn
Analysis #	12	13	14	15	16	17
wt%						
Fe	1.0	0.6	-	-	-	3.1
Cu	19.0	7.1	16.7	5.5	1.0	11.3
Pt	3.6	-	2.9	-	-	15.9
Pd	14.7	12.1	17.2	14.9	4.2	44.8
Au	61.3	80.6	62.8	79.0	84,6	24.6
Ag	-	-	-	-	9,4	-
Total	99.6	100.4	99.6	99.4	99.2	99.7
Proportions						
Fe	0.02	0.02	-	-	-	0.06
Cu	0.38	0.17	0.35	0.14	0,03	0.21
Pt	0.02	-	0.02	-	-	0.09
Pd	0.18	0.18	0.21	0.22	0,07	0.49
Au	0.40	0.63	0.42	0.64	0,75	0.14
Ag	-	-	-	-	0,15	-
Total	1	1	1	1	1	1

Abbreviations:

Gold minerals:	(Au,Pd)Cu: tetra-auricupride; (Au,Pd)3Cu: unnamed mineral; Au3Cu: unnamed mineral
PGMs:	vsl: vasilite; kth: keithconnite; ; gng: guanglinite; at: atokite; vys: vysotskite
Unnamed alloys:	(Au,Pd)Cu; (Au,Cu,Pd); (Au,Ag,Pd); (Pd,Cu,Au,Pt)
Base metal sulphides:	bn: bornite; cp: chalcopyrite;
Silicates:	cpx<. Clinopyroxene;

PLATES

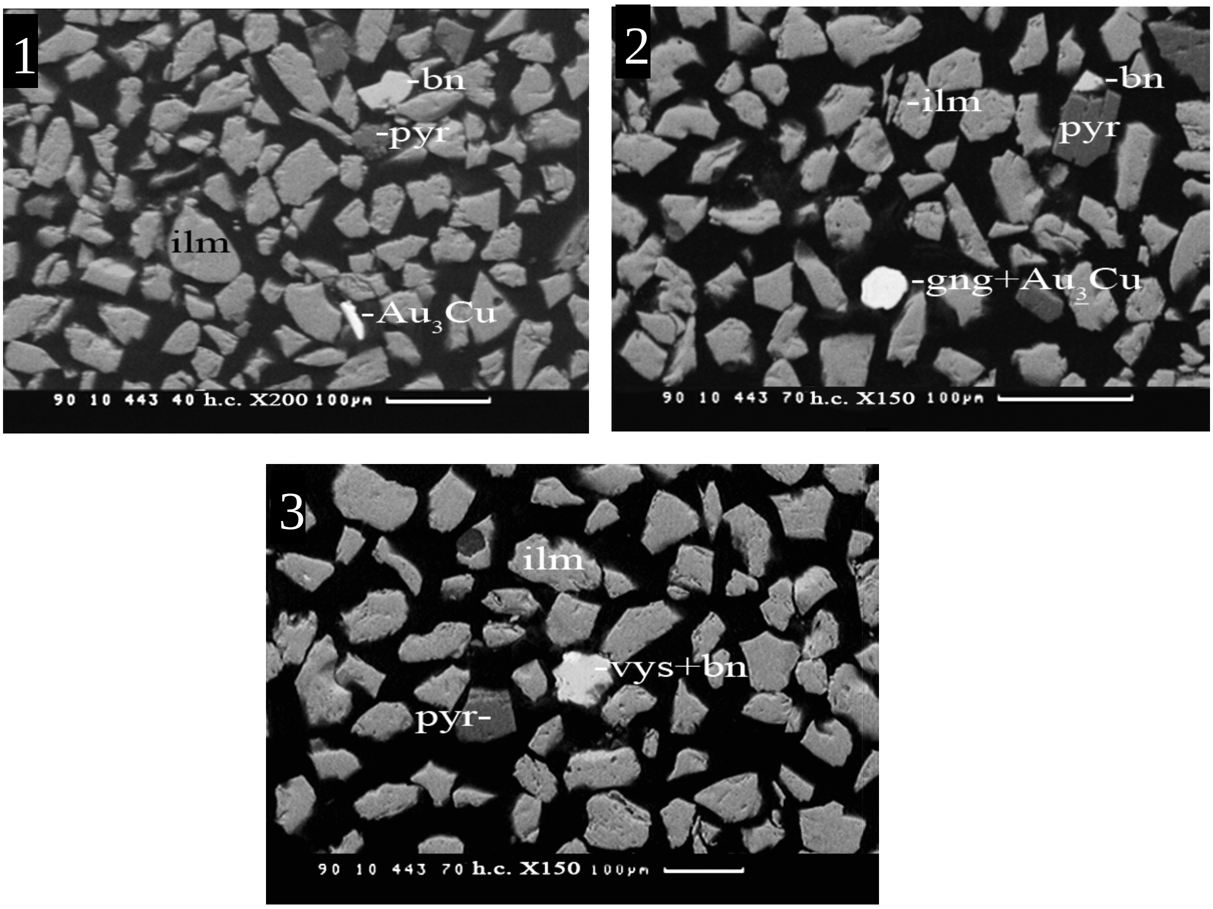
Plate 1



Relationships of rock-forming minerals and Fe-Ti oxides, sample 90-10 443, polished section; SEM-images (BIE).

Abbreviations: Pl: plagioclase; cpx-opx: pyroxene with exsolutions; ilm: ilmenite; timt: titanomagnetite; ap: apatite; tlc: talc; zrn: zirkon; cp: chalcopyrite

Plate 2

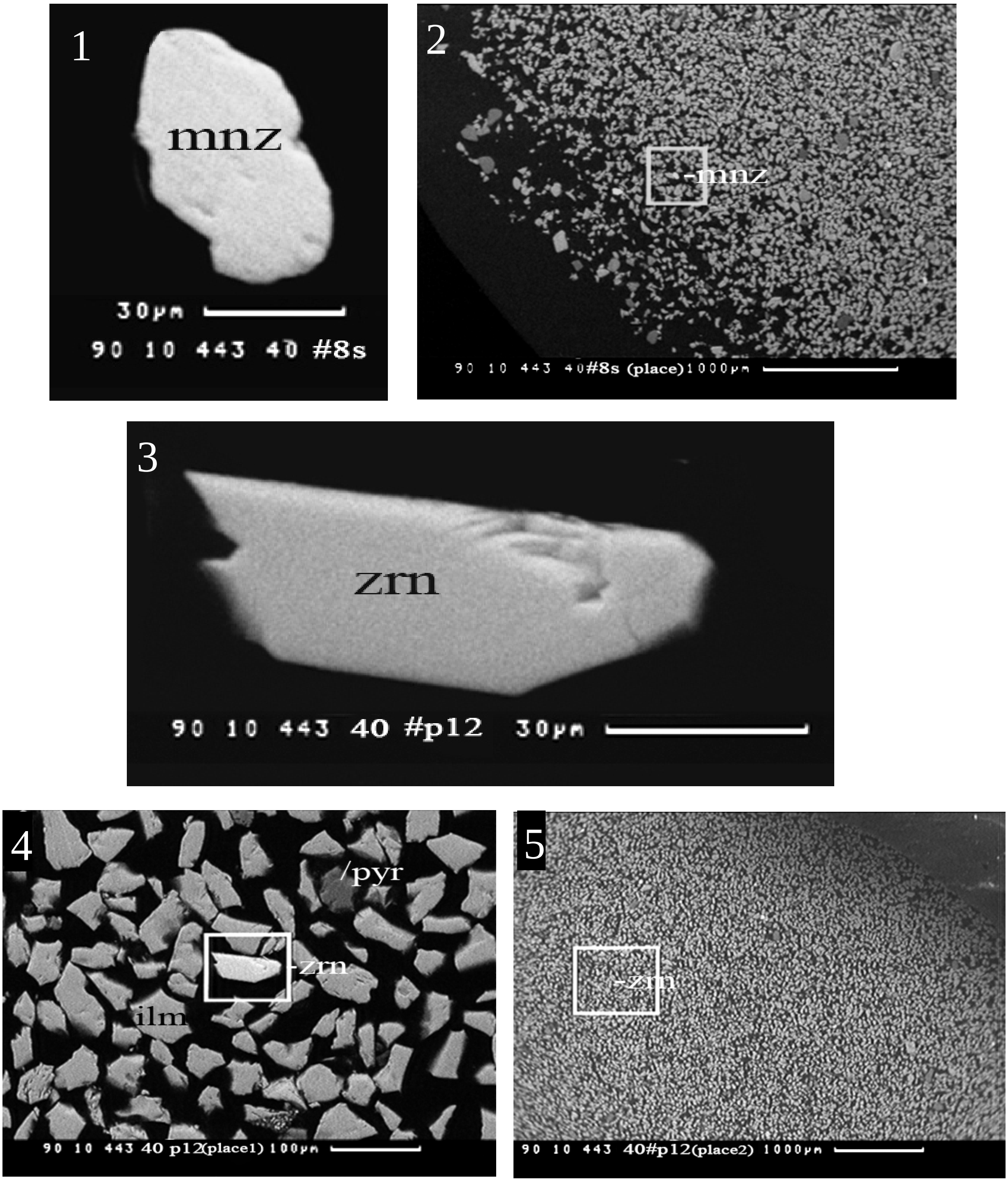


Polished sections of heavy mineral HS-concentrates, sample 90-10 443,
SEM-images (BIE): 1) <40 µm fraction, and 2 and 3) 40-70µm fraction

Abbreviations:

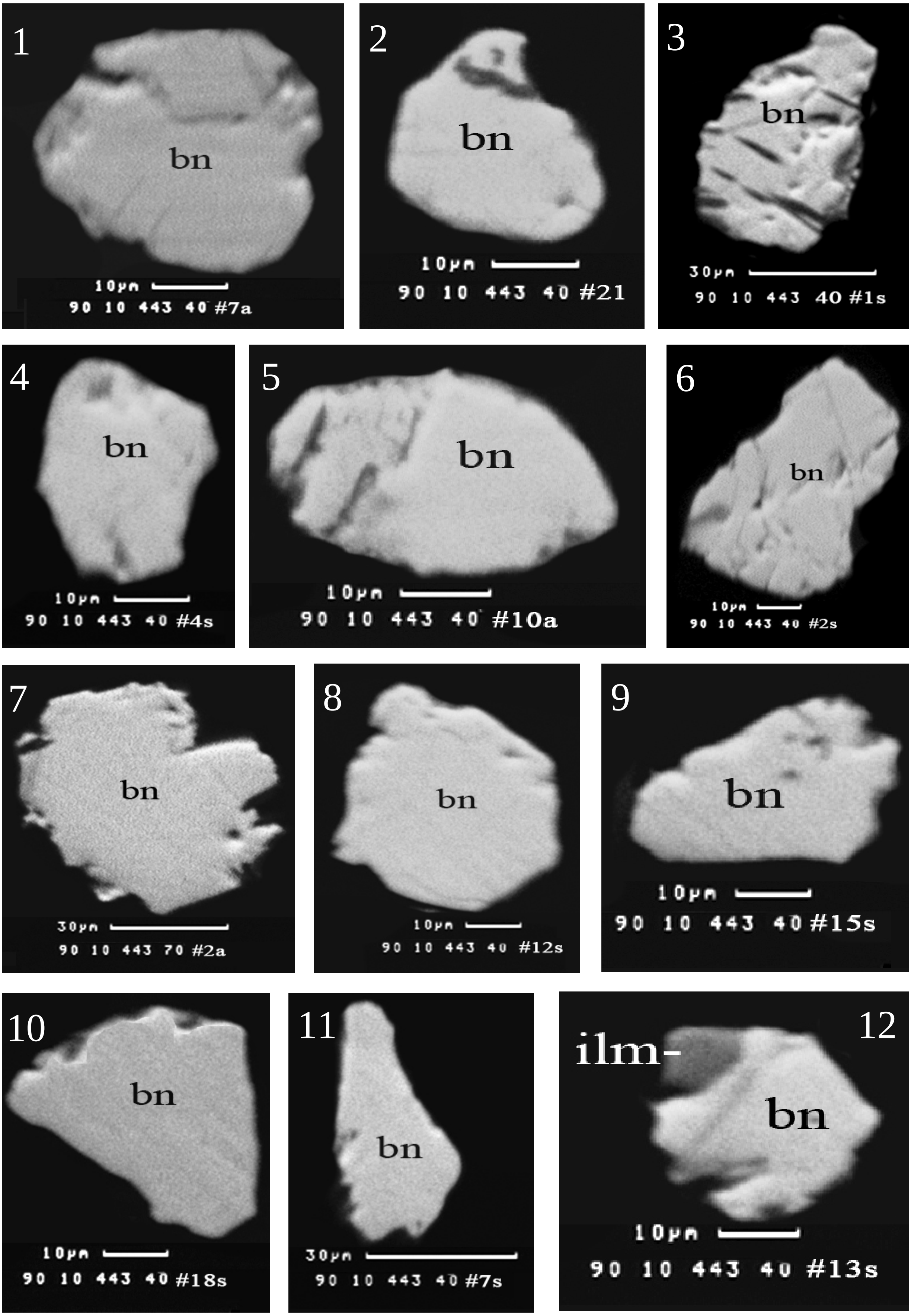
Precious metal phases:	vys: vysotskite; gng: ganglinite; alloy Au3Cu, alloy
Base metal sulphides:	bn: bornite
Other phases:	pyr: pyroxene, ilm: ilmenite; timt: titanomagnetite

Plate 3



Grains of monazite (mnz) and zircon (zrn) in the heavy mineral HS-concentrates of sample 90-10 443.The grains are suited for isotope investigation. Polished monolayer samples, SEM-images (BIE).

Plate 4

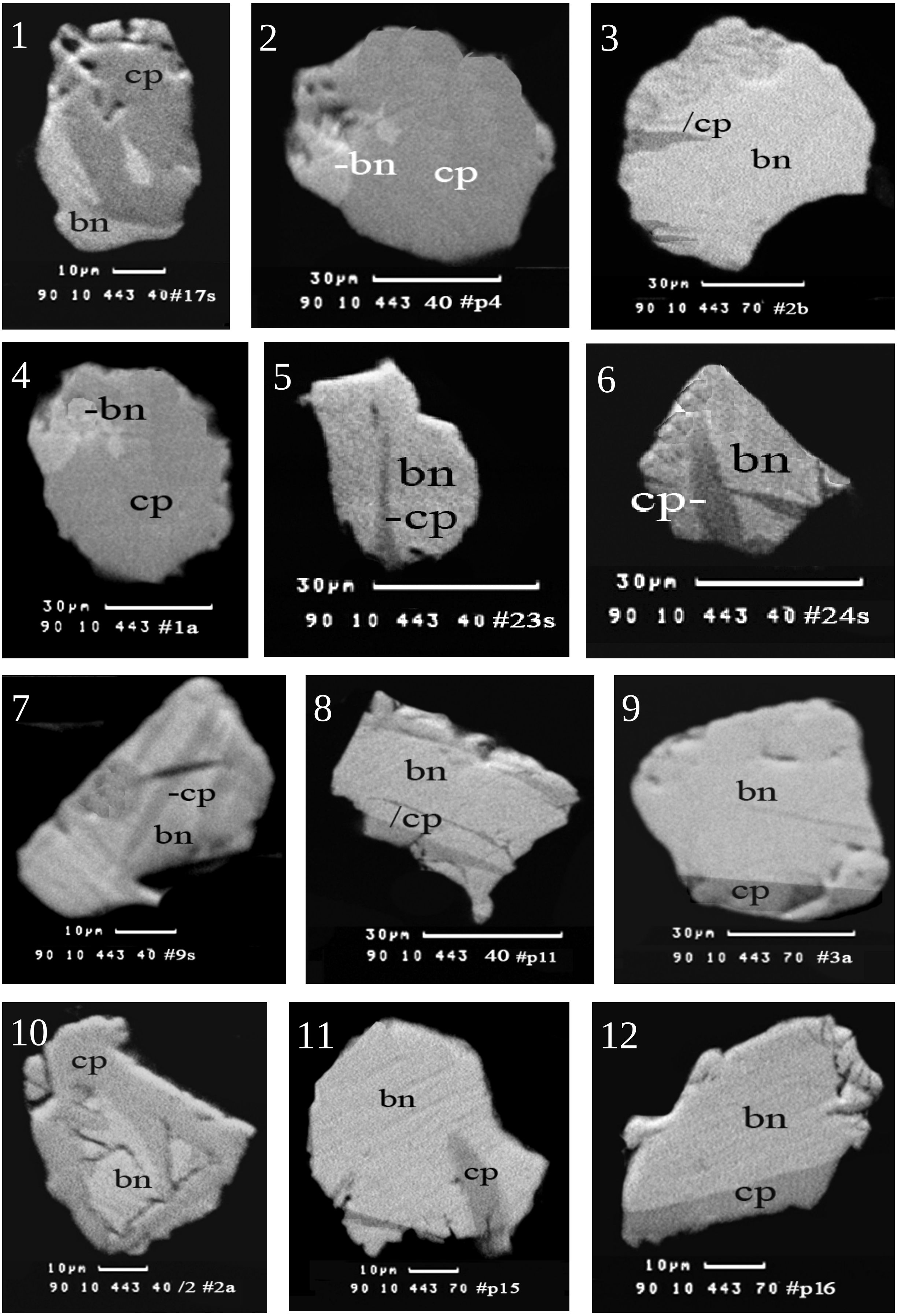


Grains of bornite (bn) in the heavy concentrates of sample 90-10 443 (1-12); polished polished sections; SEM-images (BIE). Abbreviations: bn: bornite; ilm: ilmenite

Plate 5

Copper sulphide globules and grains in heavy mineral HS-concentrates of sample 90-10 443, polished sections; SEM-images (BIE): Image 1-12: bornite and chalcppyrite , image 13-15: chalcopyrite; image 16-17: pentlandite; image 18-19: pyrrhotite; image 20: bornite and chalcosine.

Abbreviations: cp: chalcopyrite; bn: bornite; pn: pentlandite; po: pyrrhotite; chalc: chalcosine and chl: chlorite.


1
cp
bn
10µm
90 10 443 40#17s
2
-bn
cp
30µm
90 10 443 40 #p4
3
/cp
bn
30µm
90 10 443 70 #2b
4
-bn
cp
30µm
90 10 443 #1a
5
bn
-cp
30µm
90 10 443 40 #23s
6
bn
cp-
30µm
90 10 443 40 #24s
7
-cp
bn
10µm
90 10 443 40 #9s
8
bn
/cp
30µm
90 10 443 40 #p11
9
bn
cp
30µm
90 10 443 70 #3a
10
cp
bn
10µm
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12
bn
cp
10µm
90 10 443 70 #p16

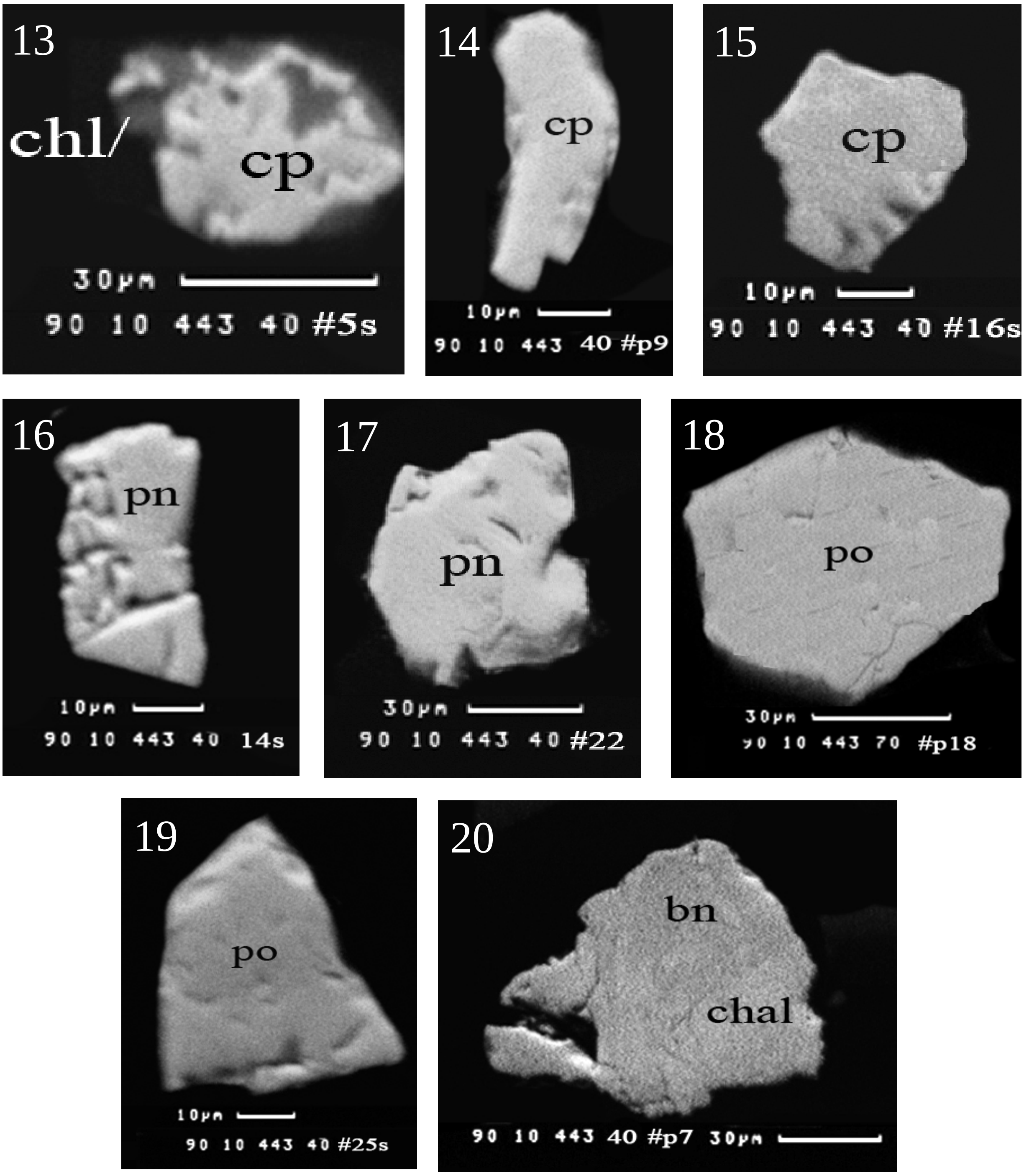
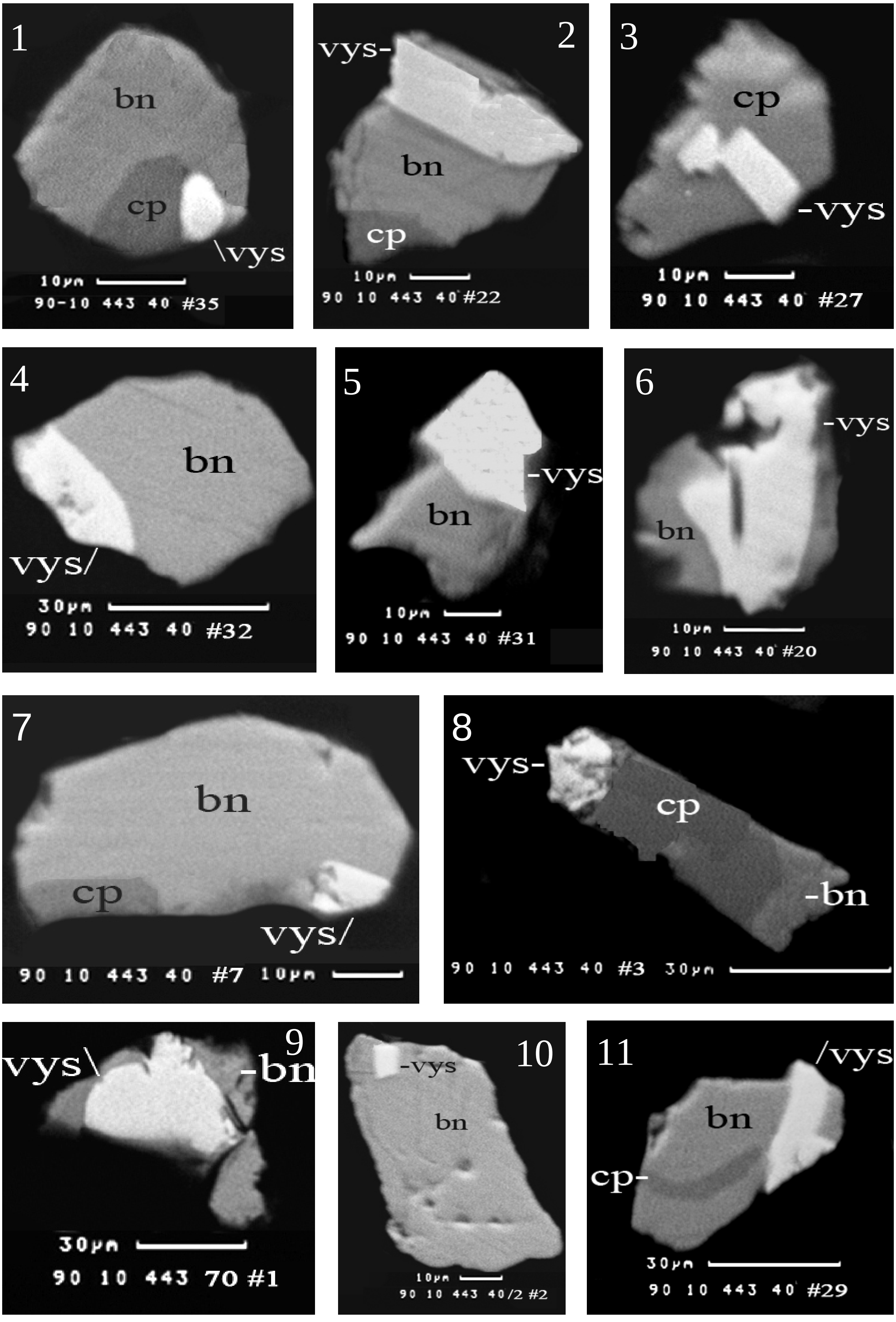
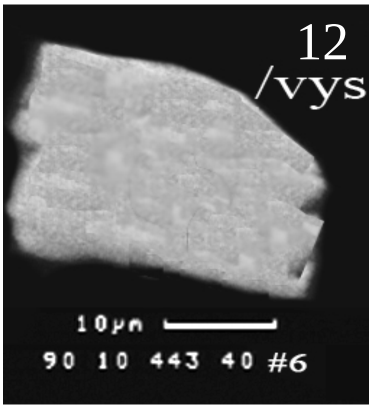

13
chl/
cp
30μm
90 10 443 40 #5s
14
cp
10μm
90 10 443 40 #p9
15
cp
10μm
90 10 443 40 #16s
16
pn
10μm
90 10 443 40 14s
17
pn
30μm
90 10 443 40 #22
18
po
30μm
90 10 443 70 #p18
19
po
10μm
90 10 443 40 #25s
20
bn
chal
90 10 443 40 #p7 30μm

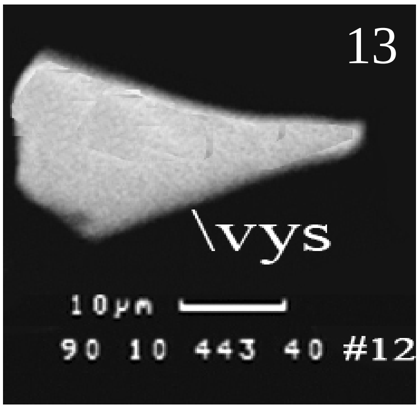
Plate 6

Grains of vysotskite in the heavy mineral HS concentrate of sample 90-10 443; polished sections; SEM-images (BIE).

Abbreviations: vys: vysotskite; bn: bornite; cp: chalcopyrite.


1
bn
cp
\vys
10μm
90-10 443 40 #35
2
vys-
bn
cp
10μm
90 10 443 40 #22
3
cp
-vys
10μm
90 10 443 40 #27
4
bn
vys/
30μm
90 10 443 40 #32
5
-vys
bn
10μm
90 10 443 40 #31
6
-vys
bn
10μm
90 10 443 40 #20
7
bn
cp
vys/
90 10 443 40 #7 10μm
8
vys-
cp
-bn
90 10 443 40 #3 30μm
9
vys\
-bn
30μm
90 10 443 70 #1
10
-vys
bn
10μm
90 10 443 40/2 #2
11
/vys
bn
cp-
30μm
90 10 443 40 #29


12
/vys
10µm
90 10 443 40 #6


13
\vys
10µm
90 10 443 40 #12

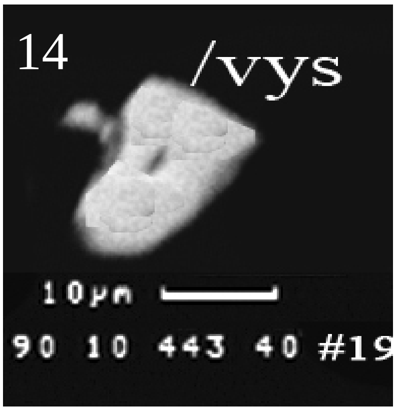
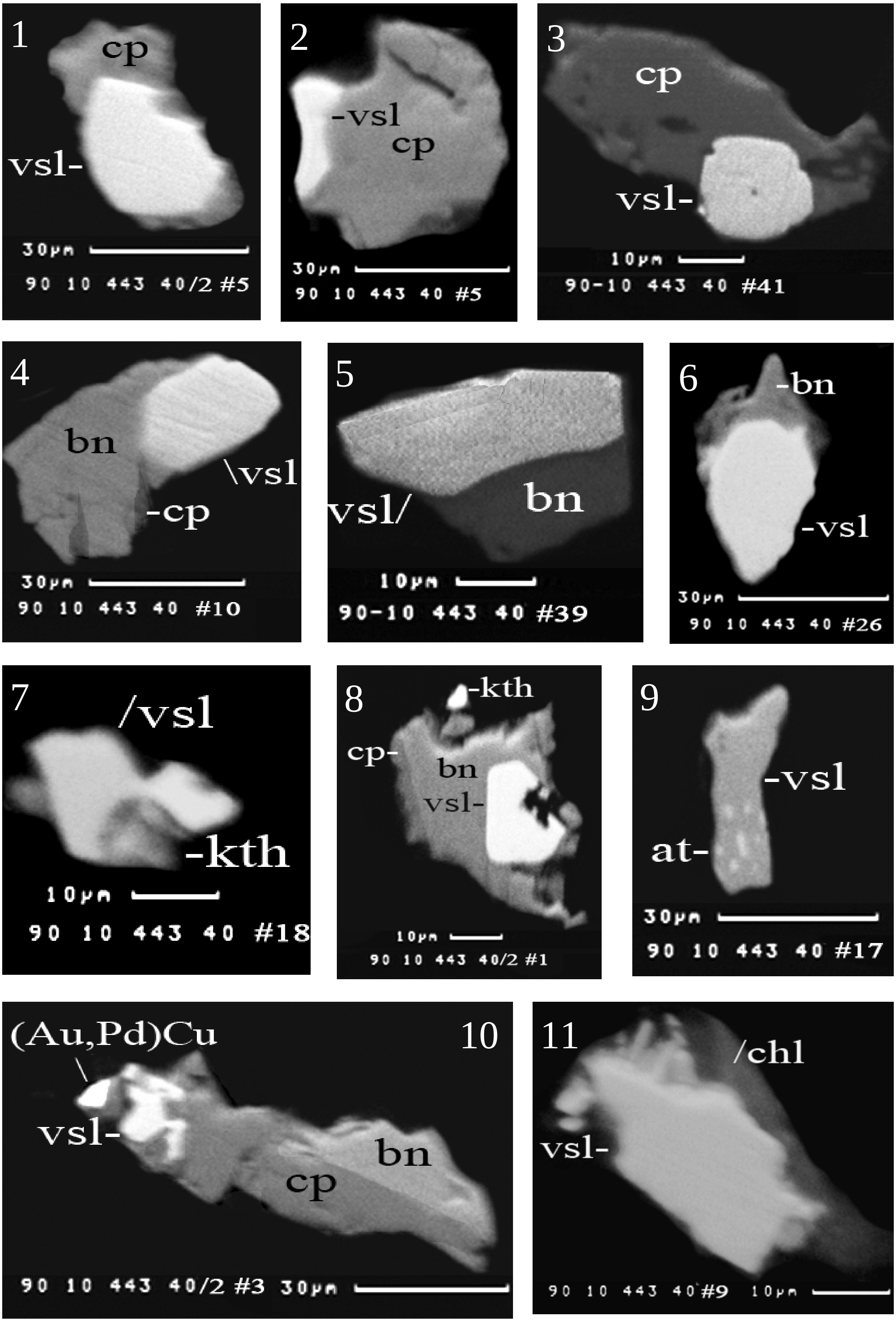

14
/vys
10µm
90 10 443 40 #19

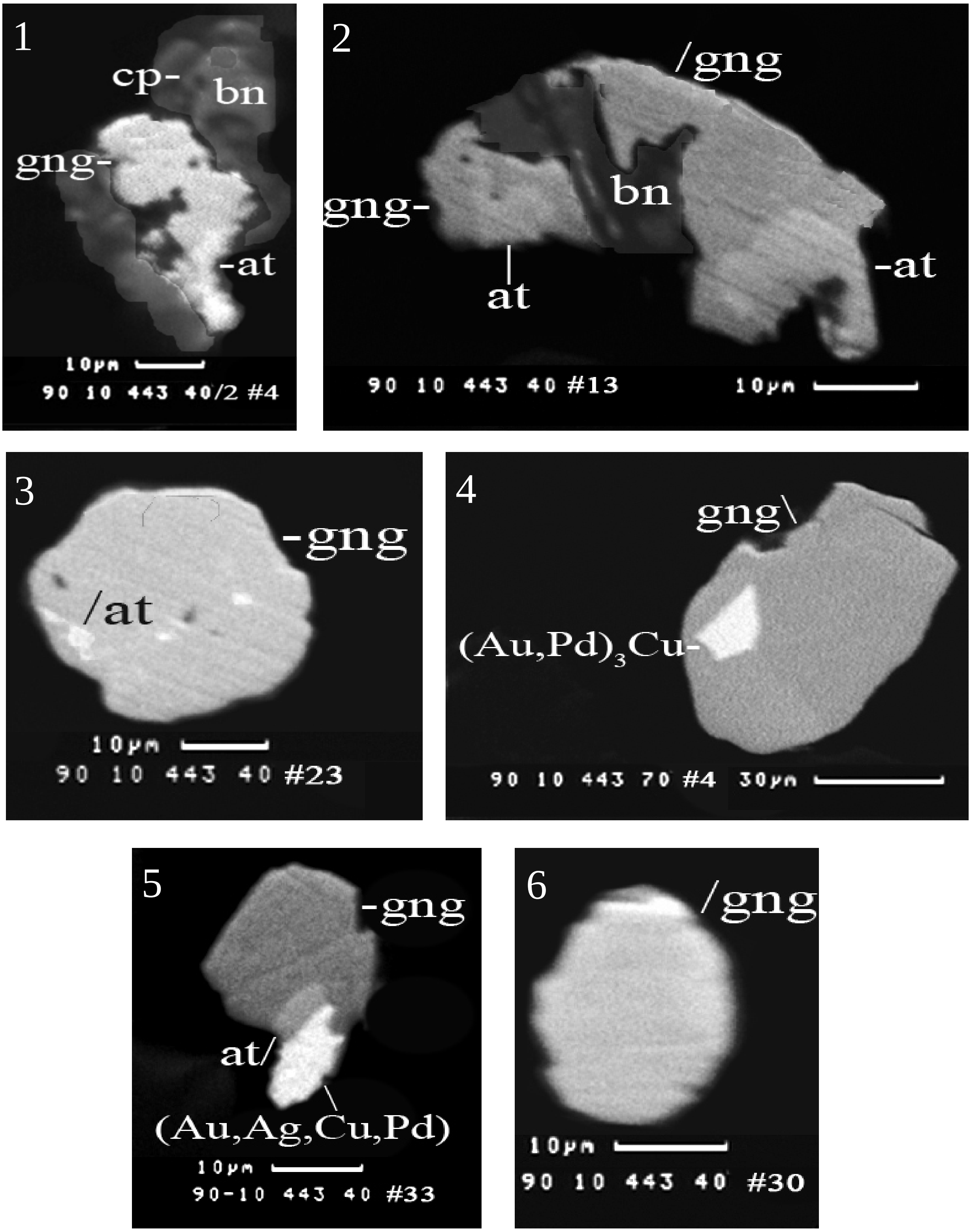
Plate 7



Grains of vasilite in the heavy mineral concentrates of sample 90-10 443; polished sections; SEM-images (BIE).

Abbreviations: vsl: vasilite; at: atokite; kth: keithconnite, (Au,Pd)Cu: unnamed mineral
cp: chalcopyrite; bn: bornite; chl: chlorite

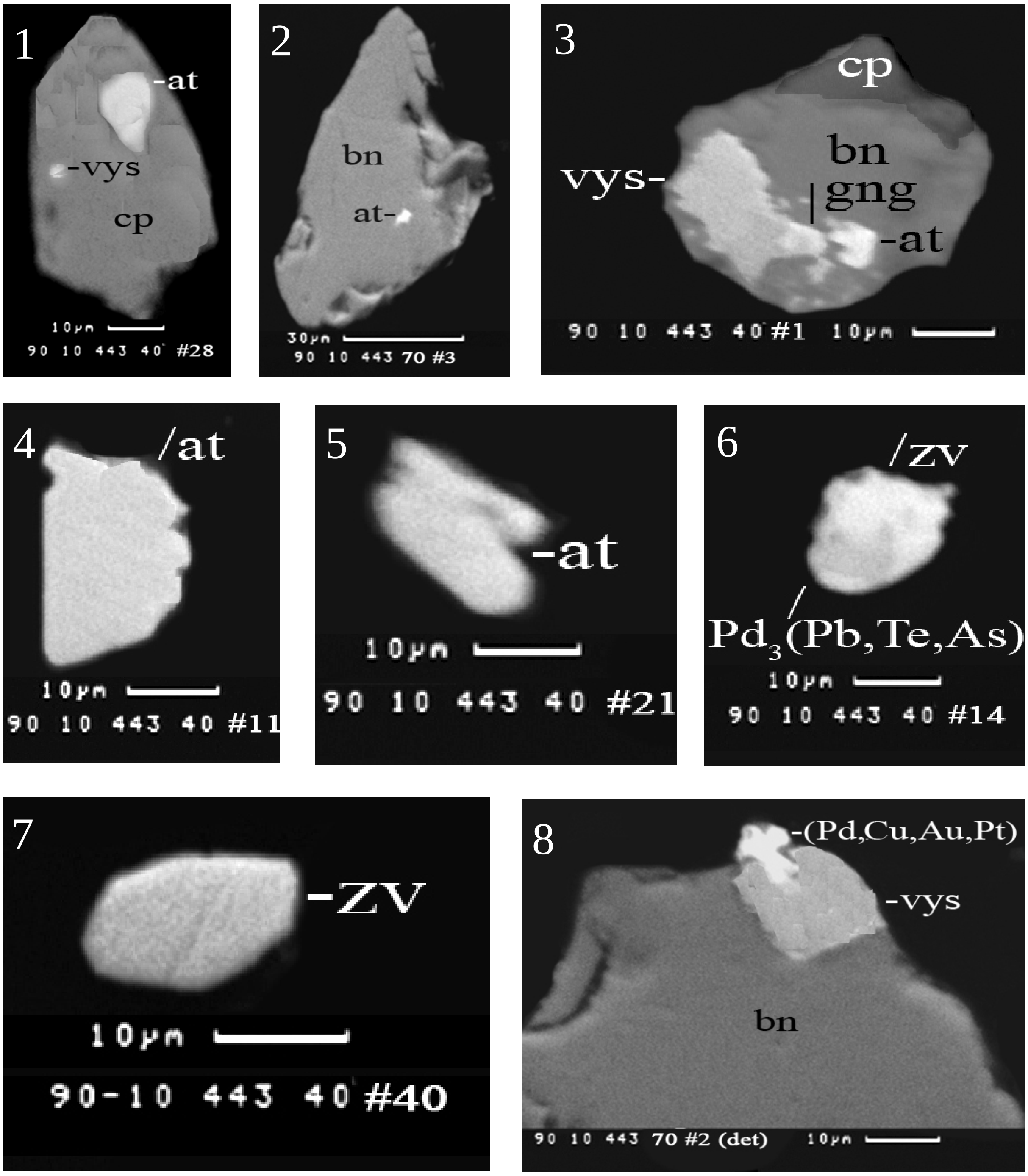
Plate 8



Grains of guanglinite in the heavy mineral HS-concentrates of sample 90-10 443; polished sections; SEM-images (BIE).

Abbreviations: gng: guanglinite; at: atokite; $(Au,Pd)_3Cu$ and (Au,Ag,Cu,Pd): unnamed mineral and alloy; cp: chalcopyrite and bn: bornite.

Plate 9



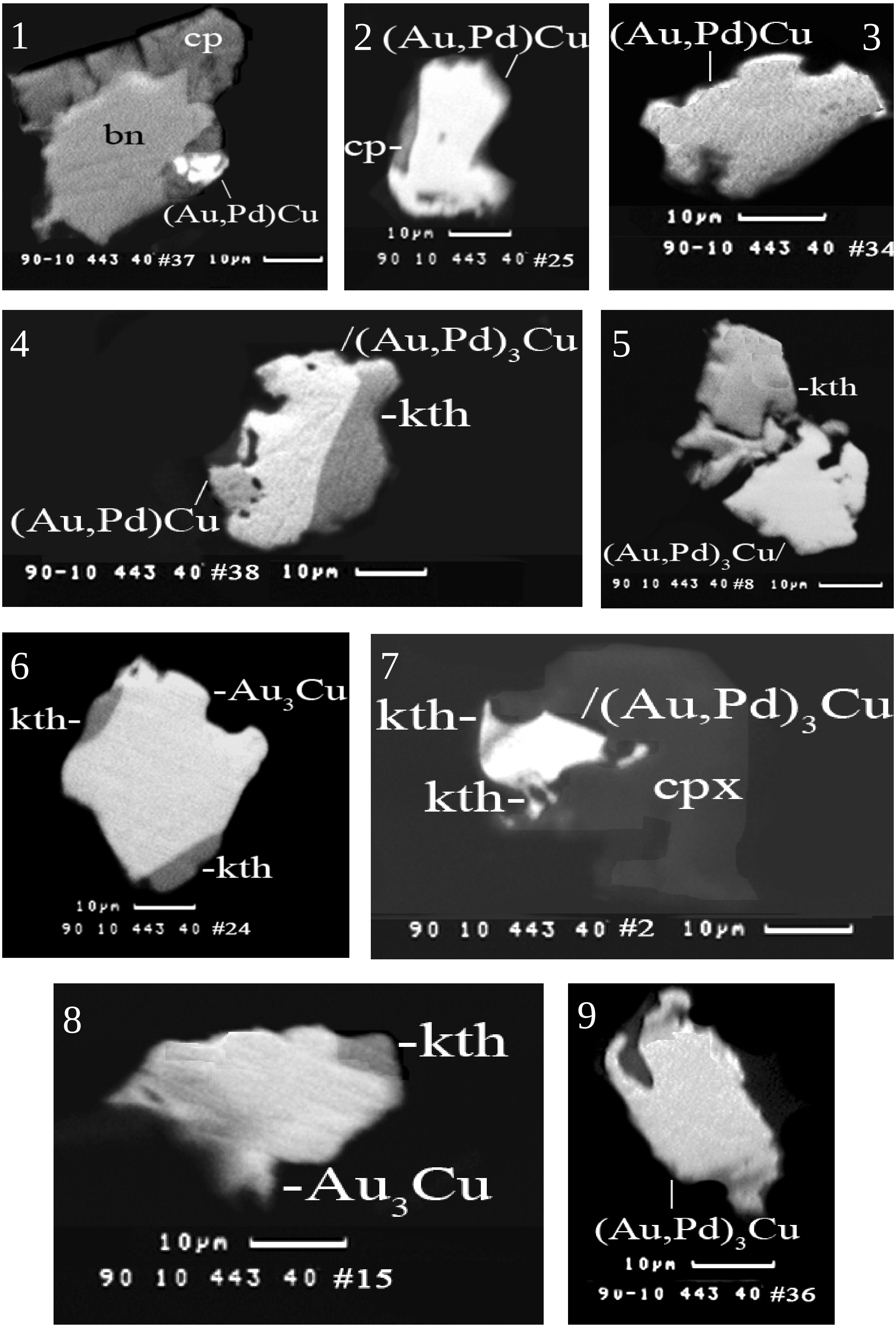
Grains of atokite (at), zvyagintsevite (zv) and (Pd,Cu,Au,Pt) alloy in the heavy mineral HS-concentrates of sample 90-10 443; polished sections; SEM-images (BIE).

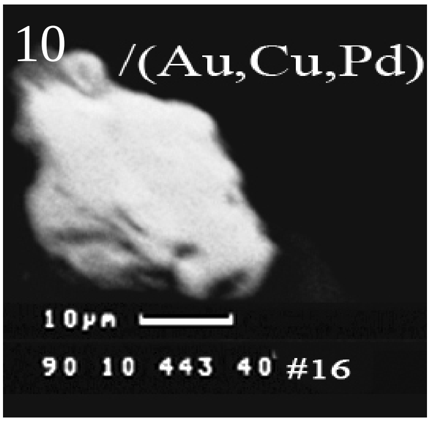
Abbreviations: vys: vysotskite; at: atokite; gng: guanglinite, Pd3(Pb,Te,As): unnamed; (Pd,Cu,Au,Pt) alloy; zv: zvyagintsevite; cp: chalcopyrite; bn: bornite;

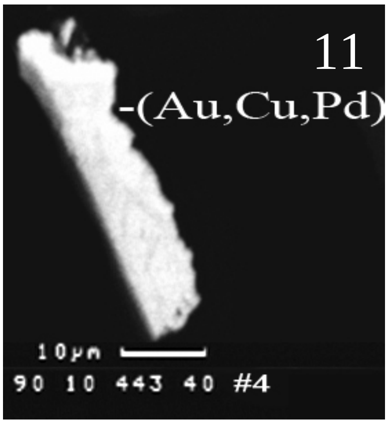
Plate 10

Grains of Au-minerals in the heavy mineral HS-concentrates of sample 90-10 443; polished sections; SEM-images (BIE).

Abbreviations: (Au,Pd)Cu: tetra-auricupride; $(Au,Pd)_3Cu$: unnamed mineral; Au_3Cu: unnamed mineral, kth: keithconnite; (Au,Cu,Pd) alloy; bn: bornite and cp: chalcopyrite.


1
cp
bn
(Au,Pd)Cu
90-10 443 40 #37 10μm
2 (Au,Pd)Cu
cp-
10μm
90 10 443 40 #25
(Au,Pd)Cu
3
10μm
90-10 443 40 #34
4
/(Au,Pd)$_3$Cu
-kth
(Au,Pd)Cu
90-10 443 40 #38 10μm
5
-kth
(Au,Pd)$_3$Cu/
90 10 443 40 #8 10μm
6
-Au$_3$Cu
kth-
-kth
10μm
90 10 443 40 #24
7
kth-
/(Au,Pd)$_3$Cu
kth-
cpx
90 10 443 40 #2 10μm
8
-kth
-Au$_3$Cu
10μm
90 10 443 40 #15
9
(Au,Pd)$_3$Cu
10μm
90-10 443 40 #36


10
/(Au,Cu,Pd)
10μm
90 10 443 40 #16


11
-(Au,Cu,Pd)
10μm
90 10 443 40 #4