

A Study on the efficiency of organic activator application to process refractory hard-to-beneficiate raw materials

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Received May 28th 2024; Revised August 05th 2024; Accepted August 24th 2024



Cite this <https://doi.org/10.24036/jptk.v7i3.38323>

Abstract: Polymetallic ores with complex mineralogical compositions pose significant challenges in flotation beneficiation, often resulting in suboptimal separation and recovery of valuable minerals. This study aims to analyse the effectiveness of alkyl benzene sulfonic acid (ABSA) as a frothing activator in improving the flotation performance and mineral recovery of polymetallic ore. It presents the results of flotation beneficiation experiments for polymetallic ore of complex mineralogical composition. Experiments were conducted on polymetallic ore samples using ABSA as the frothing activator in the flotation process. The performance was evaluated based on recovery rates and separation efficiency, comparing the results with standard floating frothing agents. The findings showed the highest efficiency of ABSA application for samples of mixed-type ores in increasing the recovery of gold, copper, zinc and lead in the collective concentrates of flotation beneficiation. ABSA activator promotes additional cleaning of fragments containing valuable metals from oxide films and coatings and the transfer of valuable metals' microparticles due to the organics' adsorption properties and the formation of metal-carbon bonds. Another effect of using this reagent is there was an increase in concentrate mass yield while maintaining the quality parameters. A similar effect was observed for beneficiation of copper ore with complex composition - copper recovery in the main concentrate increased. Selective flotation with the development of gold concentrate from hard-to-beneficiate polymetallic ore also showed a significant increase in gold recovery with ABSA pretreatment.

Keywords: Hard-to-beneficiate raw materials; Flotation polymetallic ore; Alkyl benzene sulfonic acid; Industry, innovation, and infrastructure

1. Introduction

The growing need to process refractory and complex ores has driven studies in precious and non-ferrous metal production for mixed-type ores that contain oxidised and sulfide mineral forms. There are various methods to selectively separate valuable elements of multi-component mineral raw materials in metallurgical practice. Some methods may include the treatment of enrichment products at high temperatures ([V. N. Volodin et al., 2018](#); [Zeng et al., 2024](#)) and low pressure ([Trebukhov et al., 2022](#); [V. Volodin et al., 2024](#); [V. N. Volodin et al., 2018, 2024](#)), based on different physical and chemical properties of minerals during flotation ([Feng et al., 2024](#); [Q. Zhang et al., 2024](#)). High selectivity can be achieved by treatment of ultrafine particles as exemplified by high-intensity flotation within Concorde chambers ([Yáñez et al., 2024](#)). Current studies have also established the effect of amino polymers on the selective gold recovery in concentrate ([Wang et al.,](#)

2023), as well as the separation of pyrite from arsenic-containing minerals using specifically modified Isopropyl Ethyl Thionocarbamate (IPETC) (Forson et al., 2023). The use of thiocarbamide activators of selective gold recovery (Forson et al., 2021; Matveeva et al., 2023) or a mixture of diisobutyl dithiophosphate (DTP) with AERO 7249 (mixture of diisobutyl monothiophosphate (MTP) and diisobutyl dithiophosphate (DTP) (W. Liu et al., 2022) is envisioned most commonly.

Hydrometallurgical technologies such as cyanide and sulfuric acid leaching are the main processing methods for oxidised ores. These methods make it possible to extract valuable components from oxidised minerals efficiently. However, standard flotation methods are used for sulfide ores which sometimes alternate insufficiently effective for ores with complex composition, especially when it needs to extract several types of minerals simultaneously. Mixed-type ores are difficult, as they require a combination of different processing technologies to extract all valuable components efficiently. This leads to additional technological operations and optimises existing enrichment methods. For example, standard flotation methods may not be sufficient to process such ores and additional reagents or process modifications may be required to ensure effective separation of minerals.

Flotation efficiency is usually assessed using two parameters - collection capacity and selectivity (W. Zhang et al., 2023). One of the previous studies found an increase in the size, number and stability of nanobubbles, with a decrease in their zeta potential after adding a surfactant such as sodium oleate (Y. Wang et al., 2023). The addition of a surfactant to the flotation process also affects the hydrophobicity of mineral particles, in particular during contact with a foaming agent (Nazari et al., 2023). Besides, the use of various types of polyethoxylated surfactants at different pH values significantly affects the selective and collective properties of the flotation process (Skorzewska et al., 2023).

Flotation beneficiation studies include comparative variants of the standard method of flotation beneficiation, as well as flotation after ore raw material grinding in the presence of alkyl benzene sulfonic acid (ABSA). This compound refers to surfactants having the aromatic hydrocarbon benzene in combination with isomers of sodium salts alkylbenzenesulfonic acids as a base composition, with the general formula $R_2-C_6H_4O_3S^-$, where R - radicals, corresponding to the general formula C_nH_{2n+1} , where $n=14-18$ (Figure 1).

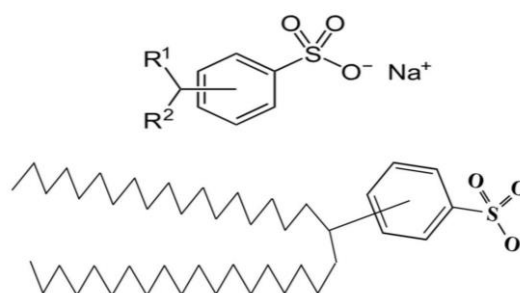


Figure 1. Structure of alkylbenzenesulfonic acid (ABSA)

ABSA can have a cleansing effect on oxide films and other mineral coatings of waste rock during the interaction process with mineral slurry. This effect promotes the release of valuable components. Besides, gold nanoparticles (AuNPs) can bind to organic compounds for example polymers and phospholipids (Cardellini et al., 2024). The formation properties of chemical compounds of various metals with aromatic hydrocarbons to produce dibenzoles were studied in detail in the 70s of the

XX century (Zeinstra & De Boer, 1973). The formation mechanisms of bonds between different metals, benzene rings and other metal-carbon bonds were described in research works (Baker et al., 2024; Ikariya et al., 2005; Kumar et al., 2023). The nature of organometallic compound formation and metallocenes largely depends on the physicochemical properties of these compounds, including such factors as the Stone-Wales defect (P.-B. Liu et al., 2023). Thus, the mechanism of reactions between ABSA and the valuable mineral metals themselves can proceed through the sulfate group (Equation 1), as adsorption of nanoparticles (MeNPs), as well as through the formation of bonds with the carbon of benzene rings (Figure 2).

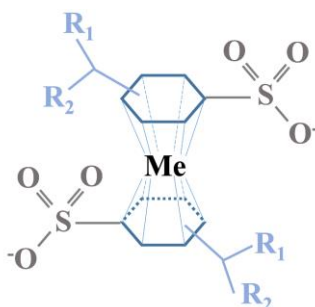


Figure 2. Formation of metal-carbon bonds in the ABSA structure

This study direction has been chosen due to the growing need to involve refractory and difficult-to-beneficiate ores in the production of precious and non-ferrous metals (Y. Liu et al., 2024). These study developments are especially relevant for mixed-type ores that have both oxidised and sulfide forms of minerals containing valuable components. The main processing methods are hydrometallurgical leaching (cyanide, sulfuric acid) for ores represented by oxidised forms and standard flotation methods of beneficiation are used for sulfide ore types. At the same time, some enterprises need to process mixed-type ores which in turn requires additional technological operations. Therefore, an in-depth study was conducted to develop innovative technologies to expand the raw material production base for noble and non-ferrous metals with the help of additional reagents and methods involving activation treatment for valuable components extraction from resistant mineral raw materials.

2. Material and Methods

Polymetallic ore of the Ridder beneficiation plant was chosen during the flotation beneficiation experiments for noble and non-ferrous metals as an object of study. The main valuable components of this ore are such metals as gold, copper, zinc and lead. The chemical composition of the ore sample is presented in Table 1.

Table 1. Chemical composition of polymetallic ore from the ridder beneficiation plant

Au, g/t	Cu, %	Zn, %	Pb, %	Fe, %	S, %	Ca, %	Ti, %	Al, %	Mg, %
2.2-2.3	0.2-0.25	0.2-0.5	0.3-0.4	1.93	0.63	0.97	0.215	4.86	1.57

The procedure of this study is presented in Figure 3 within the production diagram for selective gold-containing concentrate from polymetallic ore.

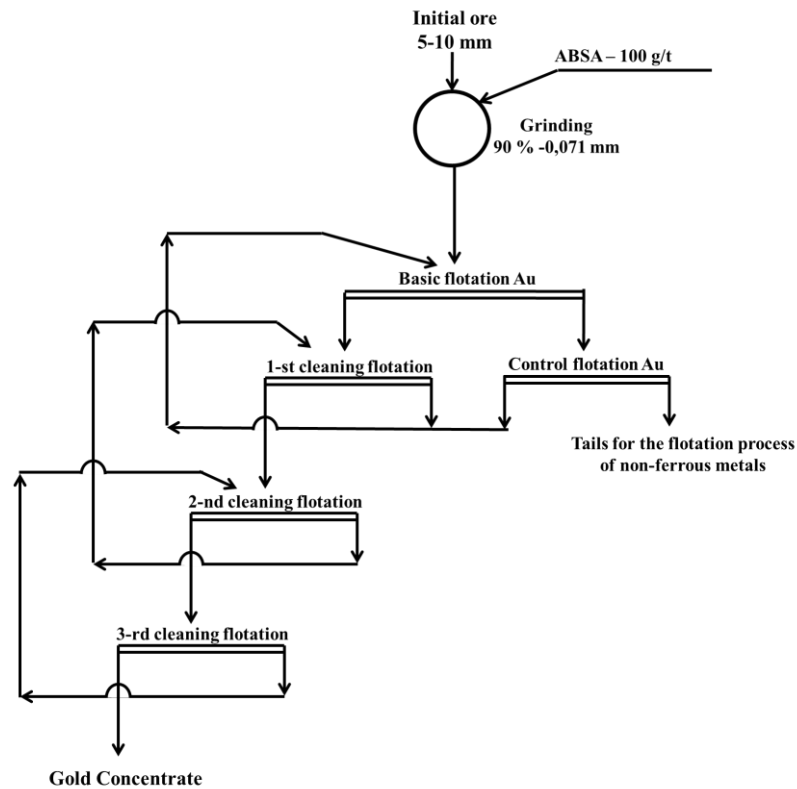


Figure 3. Production diagram for selective gold-containing concentrate from polymetallic ore

The production of selective gold-bearing flotation concentrates from polymetallic ore included main and control flotation. The concentrate of the main flotation was subjected to three cleanings, with the final gold concentrate. Control gold flotation tailings can be further considered raw materials obtaining copper, zinc and lead concentrates. Experiments were performed with the machinery chain consisting of 4 flotation machines and chambers with volumes of 8.0, 4.0, 1.0 and 0.5 litres (Figure 4).



Figure 4. Flotation machines in the experiment to produce gold concentrate

The gold concentrate production experiments also included two flotation options, standard and ABSA treated. The mode and reagent feed were same as previously described for the flotation conditions. Copper, zinc and lead depressor reagents were added additionally. The weight of each variant sample was 10 kg. The final gold concentrate, intermediate products (all residual tailings of re-treatments) and tailings of control gold flotation were analyzed as the final products of the experiment.

ABSA was added when the mineral-raw material was ground in a ball mill at a rate of not more than 100 g/t. It was found that a further increase in ABSA is inexpedient and causes excessive foaming. Two collective concentrates were produced as experimental options with standard and ABSA flotation. No addition of foaming agent was required in the variant with the addition of ABSA, at the grinding stage in a ball mill to a size class of minus 0.071 mm 90 %, at further flotation beneficiation. Standard flotation experiments were performed in parallel to utilize ABSA efficiently. Copper ore with a complex composition of *Kepcham* deposit and gold ore of sulfide type were used as additional objects of study.

Flotation beneficiation

The weight of the experimental suspension of each variant was 1000 g. The weights of standard flotation beneficiation concentrates were main concentrate - 139.3 g, control concentrate - 768.2 g; the weight of main concentrate during flotation with ABSA was 286.9 g, control concentrate - 128.5 g. The obtained beneficiation products were weighed analysed for the valuable components. The gold component was determined by atomic adsorption method and the main non-ferrous metals were by X-ray fluorescence analysis. The reagent regimes of the experiments are following these parameters:

Standard flotation

Main flotation: xanthate - 100 g/t, Na₂S -10 g/t, foaming agent C7 - 50 g/t, pH -9.5, time 10 minutes; Control flotation: xanthate - 50 g/t, foaming agent C7 - 25 g/t, pH -9.5, time 5 minutes.

Flotation after alkyl benzene sulfonic acid (ABSA) treatment

Main flotation: alkyl benzene sulfonic acid - 100 g/t, xanthogenate - 100 g/t, Na₂S -10 g/t, foaming agent C7 - not added, pH -9.5, time 10 minutes; Control flotation: xanthogenate - 50 g/t, foaming agent C7 - not added, pH -9.5, time 5 minutes.

3. Results and discussion

Phase composition of ore from the ridder beneficiation plant

The phase composition results are presented in Table 2. The mineralogical analysis found that the main component of the product is the ore-hosting gangue (feldspars of various classifications, quartzites, calcium carbonate, micas (sericite, muscovite, biotite), chlorite and, to a lesser extent, such dark-coloured minerals as apatite, olivine, plagioclases). A detailed study of the sulfide forms of minerals in the groundmass found arsenopyrite (FeAsS), pyrite (FeS₂), and chalcopyrite (CuFeS₂). Lead and zinc sulfide minerals occurred predominantly in galena and sphalerite (Figure 5).

Table 2. Phase composition of ore from the ridder beneficiation plant

Name	Formula	%
Quartz	SiO ₂	79.5
Muscovite-1M, syn	KAl ₂ Si ₃ AlO ₁₀ (OH) ₂	6.1
Dolomite	CaMg _{0,77} Fe _{0,23} (CO ₃) ₂	4.6
Clinochlor-1MII	(Mg,Fe) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	3.9
Potassium aluminium silicate	K(AlSiO ₄)	3.0
Calcite	CaCO ₃	2.9

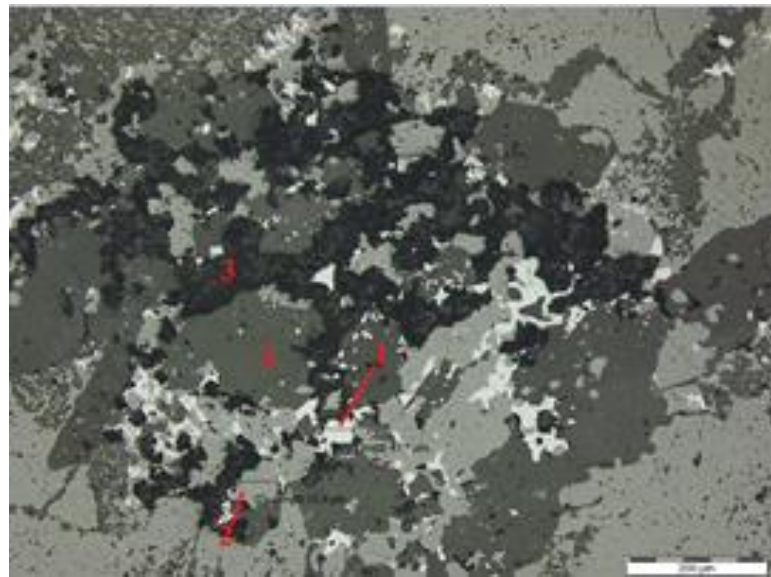


Figure 5. Sample of Ridder polymetallic ore magnification 100: Galena with a size of 47.1 microns (1), sphalerite with a size of 55.9 microns (2), non-metallic mass (3)

The oxidised forms of mixed polymetallic ore minerals were mainly represented by cerussite (PbCO_3), smithsonite (ZnCO_3), and malachite ($(\text{CuOH})_2\text{CO}_3$). Fragments of sulfates were also found. The presence of sulfide and mixed minerals in the composition of the polymetallic ore sample fully confirmed the mixed type of this raw material. It was also found during the analysis of the gold forms that part of the metal has inclusions in pyrite-type sulfide minerals, and there are also small gold veinlets in the quartz rock. Mineralogical inclusions are common for refractory gold-bearing ores (Kenzhaliyev et al., 2024). Part of the gold was fixed as free particles with coatings in oxidised films. Axio Scope.A1 optical microscope images of gold inclusions and free forms are presented in Figure 6.

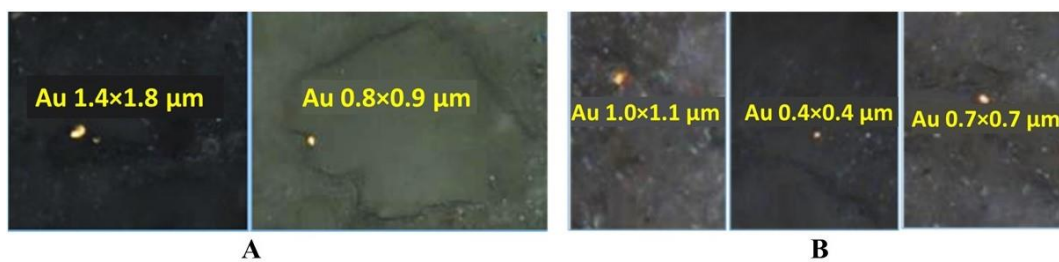


Figure 6. Micrographs of gold particles in polymetallic ore: (A) Gold in the accretions of the host waste rock, and (B) Free gold particles coated with oxidised films

Detailed electron scanning analysis of the ore enabled the finding of the gold fragments embedded in sulfide minerals. The gold spectra among the spectra of iron and sulfur (characteristic of pyrite) are shown in images from a JXA-8230 JEOL scanning electron microscope in Figure 7.

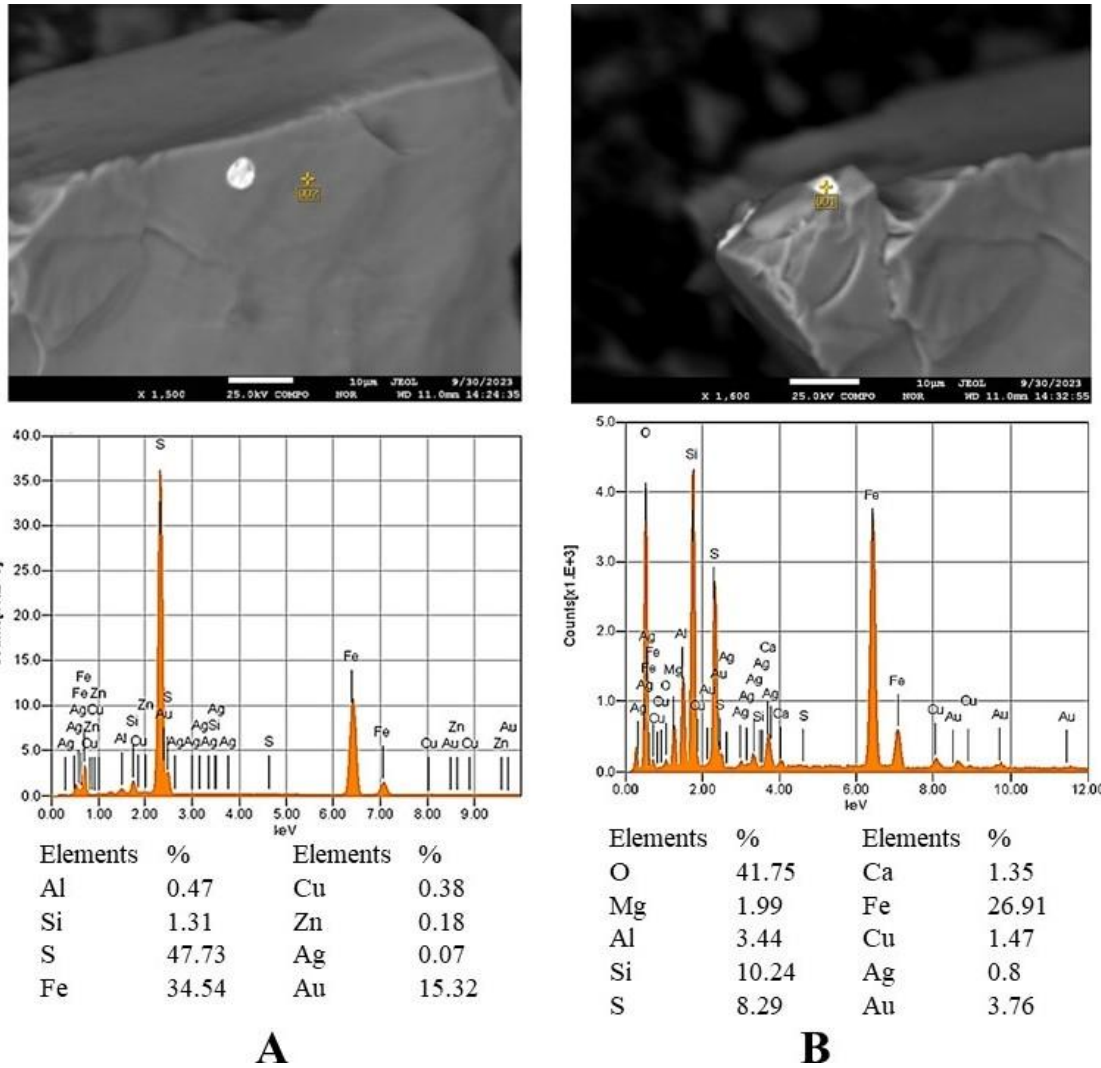


Figure 7. Electronic raster images of gold particles disseminated in pyrite-type sulfide minerals: (A) Pure pyrite, and (B) Pyrite in silicate fragments

Thus, the presence of gold mainly in a mixed form of polymetallic ore was confirmed. It was supported by a rational analysis that found 47% of the gold was associated with sulfides, and the remaining 53% was free or finely disseminated form in gangue material minerals. Scanning electron microscope images also found oxidised and sulfide mineral formations of lead. A detailed analysis of lead-containing minerals showed spectra characteristic of cerussite ($PbCO_3$) and galena (PbS). The spectra of lead among the spectra of carbon and oxygen most likely indicated the mineral cerussite, while the spectra of lead and sulfur were characteristic of galena. Sulfide and oxidised lead minerals obtained on a JXA-8230 JEOL microscope are presented in Figure 8.

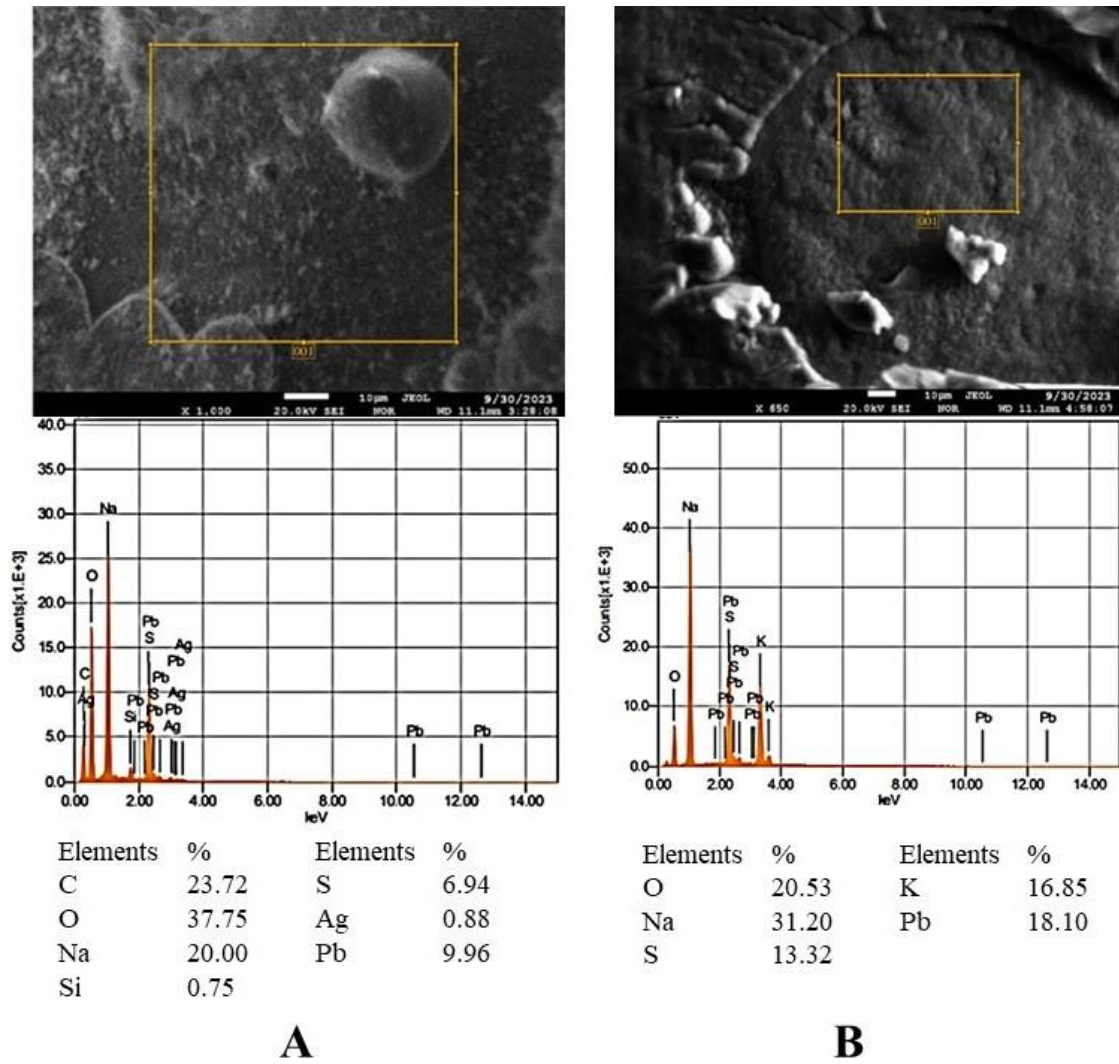


Figure 8. Electron raster images of oxidised and sulfide lead minerals: (A) Spectra characteristic of cerussite, and (B) Spectra characteristic of galena

Copper and zinc spectra were not found in certain forms of mineral dissemination. The distribution of elements in the polymetallic ore sample was characterised by fine-grained mineral formations dispersed. Electron raster images of zinc and copper ore fragments are presented in Figure 9. These metals can often significantly complicate flotation beneficiation of mineral raw materials by standard methods (A. K. Koizhanova et al., 2024; Pankratjev et al., 2023). Some types of disseminations occurred in microparticles and coated with oxide films do not allow effective treatment of mineral pulp in the flotation process and achieve maximum recovery of valuable metals in concentrates with the use of standard reagents, such as collectors - xanthogenates, sulfidizers, etc.

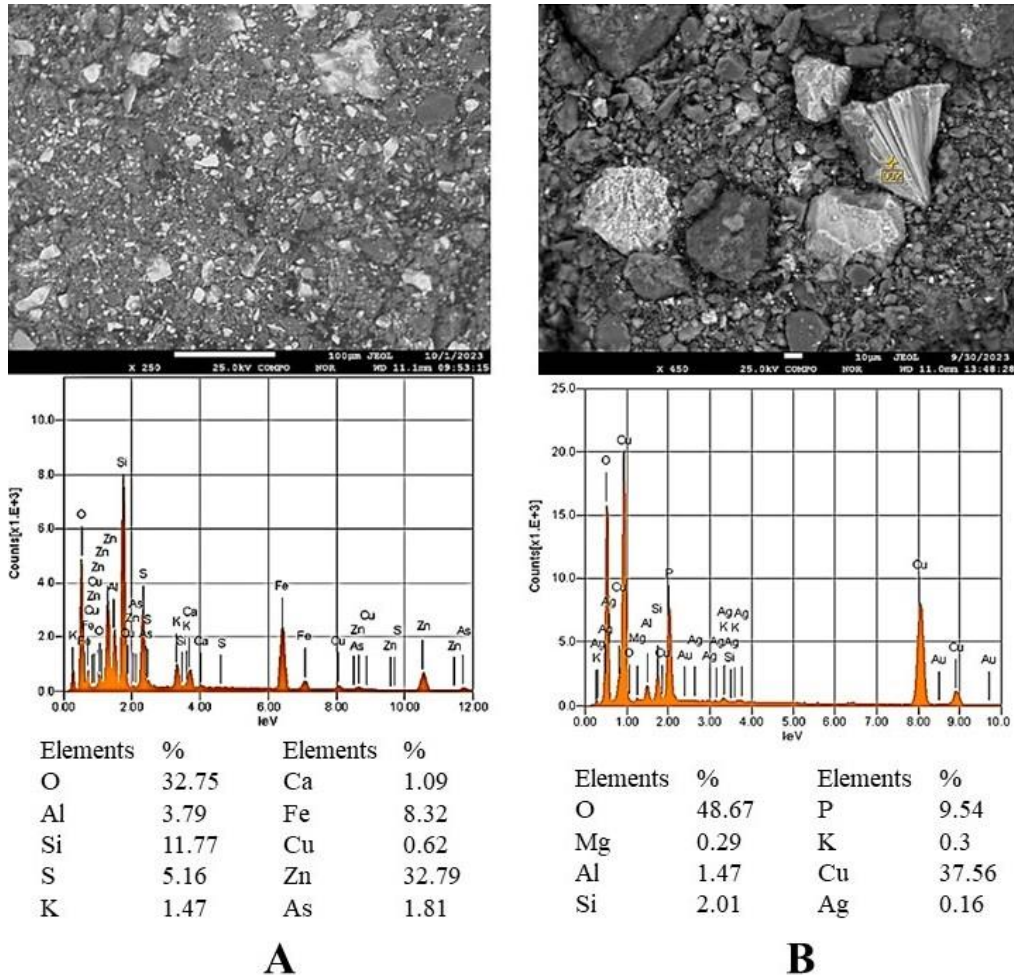


Figure 9. Electron-slice images of zinc (A) and copper (B) mineral fragments

Flotation beneficiation

The balance of each valuable metal was calculated based on the weight of the beneficiation products and the results of the analyses. The beneficiation balance for gold is shown in Table 3.

Table 3. Results of flotation concentration, calculation of gold balance

Standard flotation				
Product	weight, g	mass yield,%	Au, g/t	E Au, %
Basic concentrate	139.3	13.93	7.60	46.81
Cont. concentrate	92.5	9.25	4.7	19.22
Tailings	768.2	76.82	1.0	33.97
Total	1000.0	100.00	2.26	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	mass yield,%	Au, g/t	E Au, %
Basic concentrate	286.9	28.69	7.80	97.06
Contact concentrate	128.5	12.85	0.3	1.67
Tailings	584.6	58.46	0.05	1.27
Total	1000.0	100.00	2.31	100.00

It is obvious from the data in Table 3 that 46.81 % of gold was recovered in the main concentrate of 7.6 g/t in standard flotation, 19.22% was recovered in the control concentrate 4.7 g/t, and 3.97% of the gold in the flotation tailings concentrate 1.0 g/t. There is a twofold increase in the mass yield of concentrate during flotation beneficiation with pretreatment with ABSA, and the quality of concentration with a gold content of 7.8 g/t is not inferior to that of standard flotation. Thus, 97.06% of gold occurs in the main concentrate and the remaining 1.67 % in the subsequent control concentrate. Only 1.27 % of gold remains at a residual grade of 0.05 g/t in the spent tailings of flotation concentration with ABSA. These beneficiation products were analyzed for base metal content after gold assays. The results of the metal balance for copper content are presented in Table 4.

Table 4. Results of flotation beneficiation, calculation of balance for copper

Standard flotation				
Product	weight, g	mass yield,%	Cu, %	E Cu, %
Basic concentrate	139.3	13.93	1.02	67.50
Cont. concentrate	92.5	9.25	0.44	19.35
Tailings	768.2	76.82	0.036	13.15
Total	1000.0	100.00	0.21	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	mass yield,%	Cu, %	E Cu, %
Basic concentrate	286.9	28.69	0.71	90.80
Contact concentrate	128.5	12.85	0.061	3.48
Tailings	584.6	58.46	0.022	5.72
Total	1000.0	100.00	0.225	100.00

The balance of copper distribution in the concentrates showed some reduction in grade from 1.02% to 0.71% with ABSA. However, copper recovery in the main concentrate was 90.8 % compared to 67.5 % for standard flotation due to the higher mass yield. Similarly to gold, the recovery of copper occurred to a greater extent in the main concentrate with ABSA. For example, standard flotation recovered 19.35 % to the control concentrate, while ABSA pretreatment resulted in a residual recovery of 3.48 % to the control concentrate. The lowest residual copper grade of 0.022 % was also observed in the final flotation tailings from ABSA flotation. In the case of zinc recovery, the effect of ABSA application on the quality of the main concentrate for this metal was already observed. Data on zinc content and the balance of its distribution in the beneficiation products are presented in Table 5.

It is obvious from the results and zinc balance calculation that the total zinc recovery was 57.46% (main concentrate - 22.04%, control concentrate - 35.42%) during standard flotation. The control concentrate shows better zinc content - 0.726 % compared to the main concentrate - 0.3 %. The total zinc recovery in flotation with ABSA was 72.37 % (58.81 % in the main concentrate, and 13.55 % in the control concentrate). As in the case of copper, higher zinc recovery was achieved due to higher mass yields. However, the residual amount of zinc in the final flotation tailings with ABSA at 0.095 % was 27.63 %, while 42.54 % remained in the standard flotation tailings at 0.105 %.

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Table 5. Results of flotation beneficiation, calculation of zinc balance

Standard flotation				
Product	weight, g	mass yield,%	Zn, %	E Zn, %
Basic concentrate	139.3	13.93	0.30	22.04
Cont. concentrate	92.5	9.25	0.726	35.42
Tailings	768.2	76.82	0.105	42.54
Total	1000.0	100.00	0.190	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	mass yield,%	Zn, %	E Zn, %
Basic concentrate	286.9	28.69	0.41	58.81
Contact concentrate	128.5	12.85	0.212	13.55
Tailings	584.6	58.46	0.095	27.63
Total	1000.0	100.00	0.201	100.00

The lead balance also showed significant recovery to the main concentrate. The detailed lead content and recovery balance are summarised in Table 6.

Table 6. Results of flotation beneficiation, calculation of lead balance

Standard flotation				
Product	weight, g	mass yield,%	Pb, %	E Pb, %
Basic concentrate	139.3	13.93	1.18	42.11
Cont. concentrate	92.5	9.25	0.45	10.66
Tailings	768.2	76.82	0.240	47.23
Total	1000.0	100.00	0.39	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	mass yield,%	Pb, %	E Pb, %
Basic concentrate	286.9	28.69	1.23	92.54
Contact concentrate	128.5	12.85	0.085	2.86
Tailings	584.6	58.46	0.03	4.60
Total	1000.0	100.00	0.381	100.00

Table 6 shows that 92.54 % of lead was recovered in the collective concentrate of the main flotation as a result of flotation beneficiation after ABSA treatment. A small amount of lead was recovered in the control concentrate - 2.86 %, and residual lead in the flotation tailings amounted to 4.6 %. Lead recovery rates in standard flotation showed 42.11 % in the main concentrate and 10.66 % in the control concentrate, with 47.23 % remaining in the flotation tailings.

The obtained main flotation concentrate using ABSA was characterised by a lower concentration of copper compared to standard flotation. The high recovery in the copper balance was provided by the increase in the mass yield, taking into account the factor of small initial copper content in the studied polymetallic ore of Ridder deposit. However, the application of ABSA also showed better recovery in the copper balance. A copper ore sample from the *Kepcham* deposit characterised with higher initial metal content (0.4-0.5 %) and mixed type of mineralogy, i.e. the content of oxidised and sulfide forms of copper-bearing minerals was approximately equally distributed, to test ABSA in the flotation beneficiation processes of copper. The flotation of copper ore involved similar

experimental approaches to those previously used for polymetallic ore. The results of flotation beneficiation experiments with *Kepcham* copper ore are presented in Table 7.

Table 7. Results of flotation beneficiation of *Kepcham* copper ore, calculation of copper balance

Standard flotation				
Product	weight, g	yield, %	Cu, %	E Cu, %
Main concentrate	86.3	8.63	1.708	33.51
Control concentrate	53.5	5.35	1.446	17.59
Tailings	860.2	86.02	0.25	48.90
Total	1000.0	100.0	0.440	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	yield, %	Cu, %	E Cu, %
Main concentrate	229.8	22.98	1.69	87.61
Control concentrate	43.4	4.34	0.211	2.07
Tailings	726.8	72.68	0.063	10.33
Total	1000.0	100.0	0.443	100.00

It is obvious from the balance under the data in Table 7 that the standard flotation beneficiation extracted 51.1% of copper, of which 33.51% in the main concentrate, and 15.59% in the control concentrate. Metal remains at 48.9% in the tailings of standard flotation beneficiation of copper ore. Adding ABSA at the grinding stage increased the copper recovery rate in the main concentrate to 87.61 %, while increasing the mass yield and maintaining the quality of the main concentrate (1.708 % - standard, 1.69 % - ABSA). The high level of copper recovery in the main concentrate with ABSA allows for bypassing the control flotation stage, where the residual copper recovery is 2.07%. Express analysis of the main flotation tailings entering the control flotation stage established copper content in the range of 0.07-0.075 %, and this indicator amounted to 0.063 % in the final tailings. The results of the Altyntas ore beneficiation experiments are presented in Table 8.

Table 8. Results of flotation beneficiation of gold-bearing ore *Altyntas*, gold balance calculation

Standard flotation				
Product	weight, g	Yield, %	Au, g/t	E Au, %
Main concentrate	511.4	25.57	3.0	82.07
Control concentrate	167.1	8.355	0.739	6.61
Tailings	1321.5	66.075	0.16	11.32
Feedstock (ore)	2000.0	100.00	0.934	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	Yield, %	Au, g/t	E Au, %
Main concentrate	553.3	27.665	3.08	88.55
Control concentrate	112.3	5.615	0.821	4.79
Tailings	1334.4	66.72	0.096	6.66
Feedstock (ore)	2000.0	100.00	0.962	100.00

Experiments were also conducted to beneficiate sulfide gold-bearing ore of *Altyntas* deposit to test the effect of ABSA application. The mineralogical composition consists primarily of sulfide minerals that contain gold. Gold recovery by the standard flotation method of this ore is not less than 80%.

The taken sample was a poor ore sample with gold content at 0.9-1.0 g/t. The experiments involved two comparative tests - standard flotation and a variant with ABSA pretreatment.

A slight increase in the gold recovery in concentrates was noted as ABSA application for the sulfide-type gold-bearing ore compared to the standard flotation method. Thus, the gold content had an insignificant difference (3.0 - 3.08 g/t) in the main concentrates of both variants of flotation. The mass yield of the main concentrate of the ABSA flotation was about 2% higher than the standard flotation. Relatively, small differences were observed in the control concentrates. The final gold recovery was 88.68 % (82.07 % + 6.61 %) in standard flotation and 93.34 % (88.55 % + 4.79 %) in flotation with ABSA treatment. Thus, the effect of an increase in 4.6% gold recovery was also noted in the case of ABSA reagent use for gold-bearing ore that is not classified as difficult to beneficiate.

Comparison between standard flotation and ABSA flotation in the polymetallic ore beneficiation

A large-scale flotation beneficiation test of ABSA was conducted for a polymetallic ore sample as the final stage of the experimental part to obtain a selective gold-bearing concentrate (Figure 10).

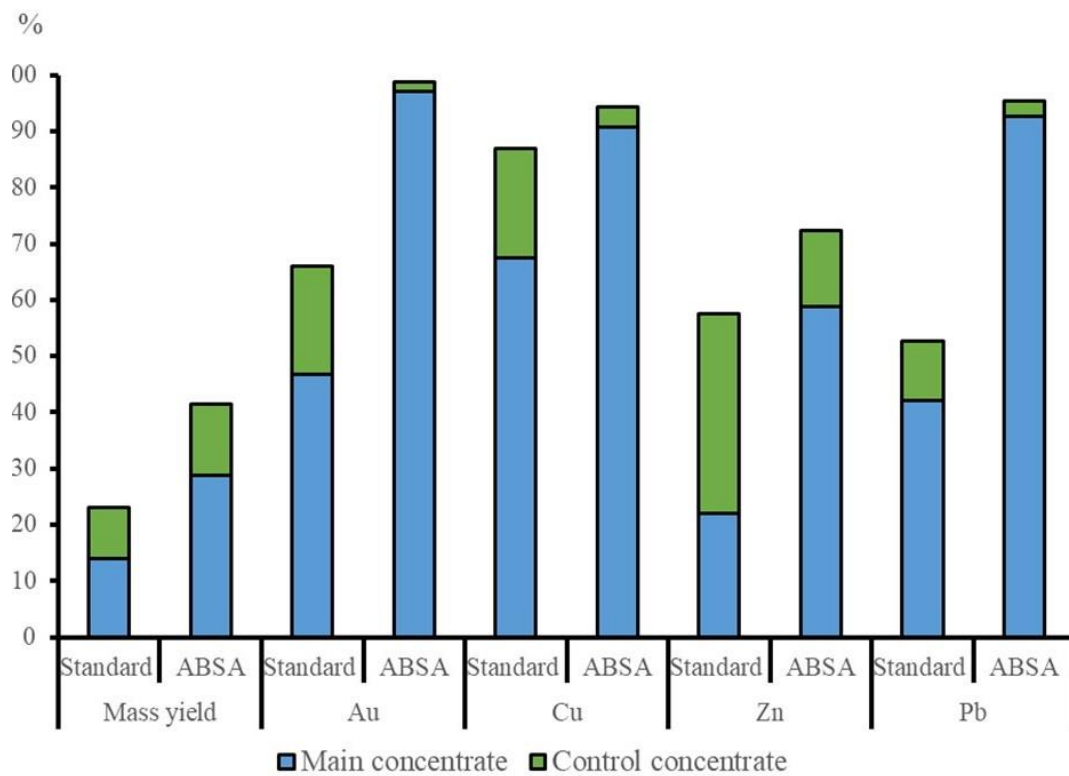


Figure 10. Comparison of recovery rates in the collective concentrate of standard flotation and ABSA flotation in the polymetallic ore beneficiation

The objective of the gold concentrate experiment was to establish the feasibility of selective flotation with the use of ABSA while achieving minimum gold values in the flotation tailings. The gold grades in this initial polymetallic ore are of the greatest industrial interest, while the copper, zinc and lead grades are of lesser value.

Selective flotation of ridder polymetallic ore

The gold concentrate production experiments also included two flotation options, standard and ABSA treated. The mode and reagent feed were same as previously described for the flotation conditions. Copper, zinc and lead depressor reagents were added additionally. The weight of each variant sample was 10 kg. The final gold concentrate, intermediate products (all residual tailings of re-treatments) and tailings of control gold flotation were analysed as the final products of the experiment. The results of the analyses and the balance calculation are presented in Table 9.

Table 9. Results of selective flotation of Ridder polymetallic ore, calculation of the gold balance

Standard flotation				
Product	weight, g	yield, %	Au content, g/t	Au recovery, %
Gold concentrate	275.0	2.75	49.5	60.41
Intermediate products	1120.0	11.2	1.05	5.22
Final tailings	8605.0	86.05	0.9	34.37
Feedstock (ore)	10,000.0	100.0	2.25	100.00
Flotation with alkyl benzene sulfonic acid (ABSA)				
Product	weight, g	yield, %	Au content, g/t	Au recovery, %
Gold concentrate	354.5	3.545	58.3	90.24
Intermediate products	1135.0	11.35	1.07	5.30
Final tailings	8510.5	85.105	0.12	4.46
Feedstock (ore)	10,000.0	100.0	2.29	100.00

The high efficiency of ABSA pretreatment has been demonstrated through the selective extraction of gold concentrate from complex polymetallic ore. This approach ultimately achieves a maximum gold recovery of 90.24%, with only 4.46% remaining in the flotation tailings, corresponding to 0.12 g/t. The standard flotation method recovered only 60.41% of the gold in the gold concentrate, leaving 34.37% in the final tailings at 0.9 g/t. Approximately 5.2-5.3 % remained in the balance of intermediate products represented by retreatment tailings in both variants.

The content of non-ferrous metals such as copper, zinc and lead in the obtained concentrates did not exceed the permissible indicators. The main amount of these elements remains in the gold flotation tailings. The possibility of further processing of these tailings to obtain selective concentrates of non-ferrous metals will require a separate series of studies. The obtained concentrates were analyzed by electron scanning microscope. Spectra characteristics of host gold sulfide mineral fragments such as pyrite were recorded in the concentrate particles for both flotation beneficiation variants. Images of sulfide gold-bearing mineral particles of concentrates obtained from electron-slit microscope JXA-8230 JEOL are presented in Figure 11.

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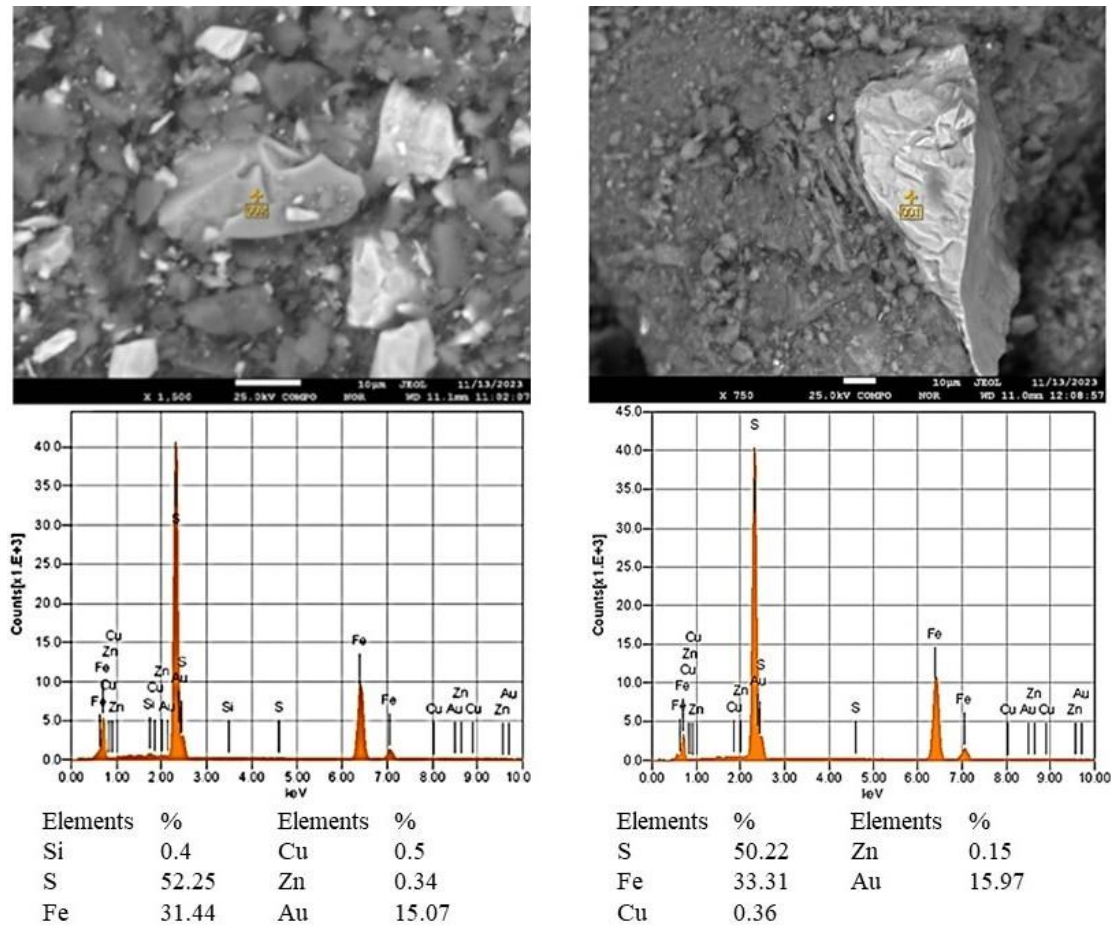
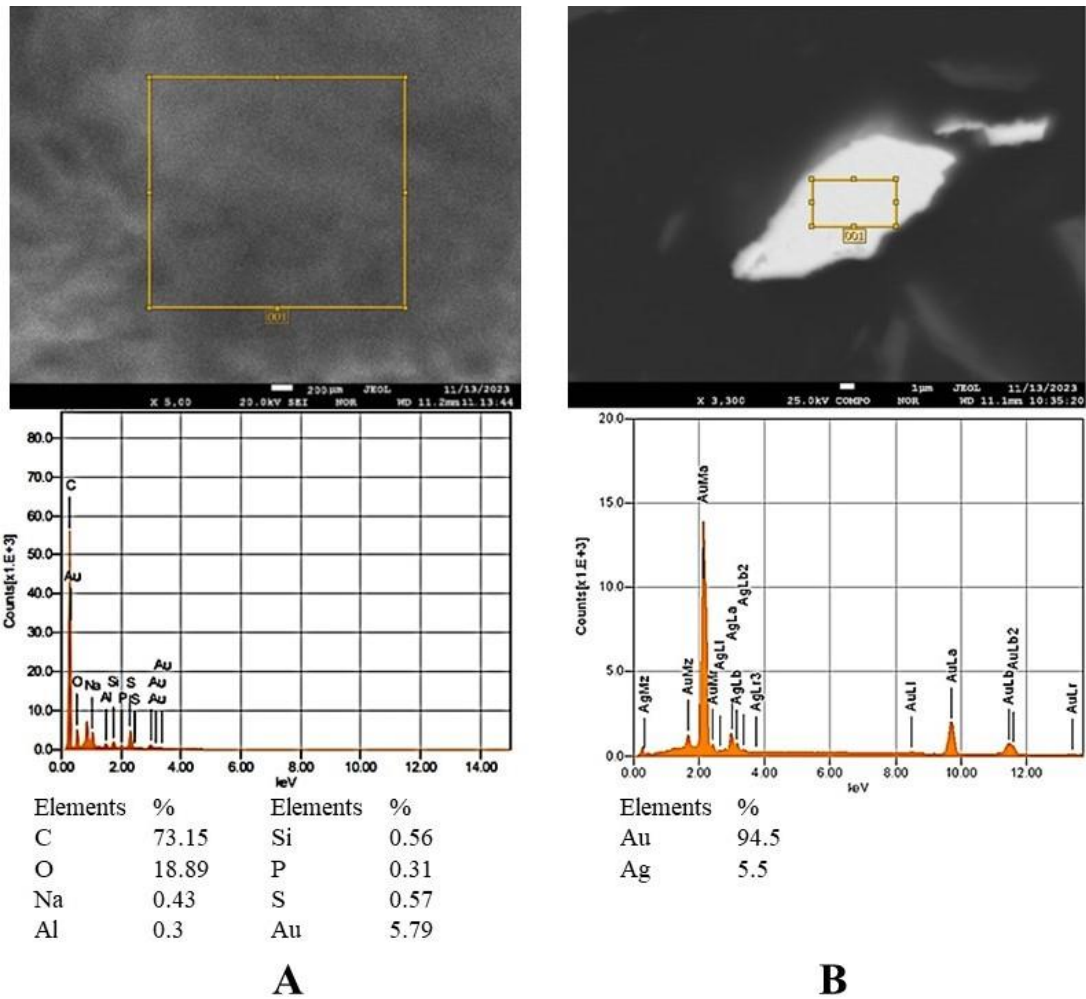


Figure 11. Electron scanning images of sulfide gold-bearing mineral particles in flotation concentrates

The concentrate from the ABSA treatment of ore showed gold particles in clusters with distinct organic spectra. Thus, the spectra of carbon, oxygen, and sulfur are typical for organic compounds of ABSA type, detailed analysis of the spectra of metal particles in clusters indicated the presence of noble metals - Au - 94.5 %, Ag - 5.5 % (Figure 12). It confirms the binding mechanism for gold microparticles with the organic structure of ABSA including the formation of metal-carbon bonds. Mainly quartz formations, including also some types of micro-silica (Sangulova et al., 2022), iron-containing minerals, calcites, etc. were observed from the waste rock elements (Figure 12). In some cases, a significant amount of arsenic-containing minerals accumulates in gold concentrates, which requires the use of innovative, effective and environmental methods of purification from this element (Ilmaliyev et al., 2022; A. Koizhanova et al., 2023; Sheriyev et al., 2016; Surkova et al., 2022; Trebukhov et al., 2023). However, the arsenic content was insignificant in the obtained concentrates of flotation variants.



A - Spectra characteristic of organic compound ABSA (carbon, oxygen, sulfur) with gold particles inclusions; B - detailed analysis of gold particles

Figure 12. Electron scanning images of gold-bearing fragments in flotation concentrates with ABSA

4. Conclusion

The study of the polymetallic ore composition of the Ridder deposit showed a fairly diverse chemical and mineralogical composition. It was found that this ore belongs to the mixed type and has sulfide and oxidized mineral forms of copper, zinc and lead in its composition. The gold in the ore exists both as sulfide-bound particles and as free grains covered with oxide films. The ABSA treatment effectively removes these oxide films and coatings from valuable metal fragments, enhancing their separation. Additionally, ABSA promotes foaming, eliminating the need for external foaming agents. Due to its polymer-like structure and aromatic hydrocarbons, ABSA can extract fine particles of valuable metals which is typically not recovered by standard xanthate flotation. Thus, there is an increase in the mass yield of the concentrate while maintaining the quality parameters. Experiments on selective flotation of polymetallic ore by obtaining a gold concentrate, showed that ABSA treatment provides the most complete recovery of gold in the concentrate compared to the standard method. Non-ferrous metals which are part of polymetallic ore, mainly remain in the gold flotation beneficiation tailings. The results of the conducted studies have shown that the use of alkyl benzene sulfonic acid (ABSA) significantly increases the efficiency of flotation enrichment of complex hard-to-enrich polymetallic ores, which manifests itself in an

increase in the extraction of valuable components in the concentrate. However, further studies are required to understand ABSA as a frothing activator comprehensively and its application in different settings. In particular, some recommendations for future studies are testing ABSA on other types of ores, optimizing the use of ABSA, and testing interaction of ABSA with the other reagents.

Author contribution

Kenzhaliyev Bagdaulet Kenzhalievich: Conceptualization, Methodology, and Software. Koizhanova Aigul Kairgeldiyevna: Data curation and Writing- Original draft preparation. Magomedov David Rasimovich: Visualization and Investigation. Yerdenova Mariya Beisenbekovna: Visualization and Investigation. Bakrayeva Akbota Nurdildakyzy: Supervision. Smailov Kenzhegali Mamanovich: Software and Validation. Abdyldayev Nurgali Nurlanovich: Software and Validation.

Funding statement

This study has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21882140).

Acknowledgements

The authors would like to thank the research team at the Institute of Metallurgy and Ore Beneficiation, Satbayev University, Kazakhstan for their support in this study.

Conflict of interest

There are no competing interests for all authors.

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