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The Technology of Upward Capillary Formation of Waste for Creating a Deposit before Land Reclamation

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Abstract

Mineral resources in the subsoil are classified as exhaustible. One of the ways to potentially replenish the sources of mineral resources is presented in the materials of these studies. In this article, we studied the natural formation in the bowels of the array of zones of high concentrations of compounds of useful components. We aimed to develop the technological methods of mass transfer and directed deposition of useful components. The technological transition of mineral resource extraction from the "gathering" paradigm to the "growing" paradigm is commonly performed by fluid filtration mass transfer in the near-surface region through the capillary system in the subsoil. In this article, we proposed a new technique for the upward capillary movement and extraction of useful components based on the framework of the new paradigm of "deposit growing". This new approach focused on lifting useful components to the surface of the massif. The experiments and the associated results concerning the mass transfer of water-soluble compounds are presented here. Experiments were conducted on the kinetics and concentrations of fluids and sediments at physical and geochemical barriers. Natural materials of non-ferrous metal enrichment waste and artificial water-soluble compounds of non-ferrous metals were used. The results suggested the viability of the new methods proposed for the ascending filtration capillary rise of useful components present in the fluids. The technological methods presented in this article might help to expand the mineral resource base and increase the efficiency of the process. New processes for the development of new ore bodies on the surface of objects on the evaporation and geochemical barriers were experimentally validated in this article. Additionally, new technological solutions were proposed in the framework of the formation of new ore bodies before surface reclamation.

Keywords
Capillary; upward fluid; ore occurrence; waste massif; sedimentation

1. Introduction

Geological processes do not create mineral deposits that are suitable and effective for development. Most natural processes lead to dissipation. The accumulation of useful components in a deposit occurs due to a combination of several conditions. Many deposits are formed and re-formed over a long time, and certain geological processes occur relatively fast, leading to the accumulation of useful components in the subsoil. For technological methods of "growing" deposits in the first stage of transition to a new paradigm, fast geological processes are suitable. Filtration is a fast-flowing geological process. Geochemical and physical barriers reliably lead to the accumulation of sediments during fluid mass transfer. The most attractive physical barrier is the evaporation barrier on the day surface of the massif. The mass transfer of useful components in the subsoil and the geological processes associated with the concentration of the compounds of useful components at the site of occurrence with the formation of local concentration zones in natural and new technogenic mineral formations have been studied [1, 2]. However, the processes are not well-understood [3]. Fluid mass transfer in the subsoil is used in technological methods for extracting minerals, for example, uranium and copper. [1, 3]. Technogenic objects are very important and accessible research objects and include enrichment wastes and areas of non-coding ore deposits. Sometimes they contain considerable reserves of useful components, but their extraction is unprofitable. After their reclamation, the extraction of these reserves becomes impossible. Using the approach for the application of the directed geological process of fluid mass transfer and concentration on the evaporation barrier might lead to a thorough extraction of useful components and increase the safety of the subsoil [3-5].

For certain minerals, leaching is the only method for extracting components. These are low-quality and refractory ores of metals [6]. Leaching is the most efficient extraction process for the selective extraction of valuable components from ores [7]. The US, Australia, and South Africa are the world leaders in the gold mining industry because they use highly efficient leaching techniques. Various leaching methods are currently being improved. The processing volumes and the speed of the associated processes with which the leaching process is optimized have increased considerably over the past decade [8, 9]. Several studies have investigated the effect of particle surface characteristics and mineralogy on the heap leaching process. The mineralogical composition of the ore and the properties of the leaching agent influence the kinetics of the exchange of useful substances between the solid and liquid phases, highlighting the applicability and effectiveness of leaching under certain conditions [10]. Bioleaching methods are used extensively [11]. The modern era of bioleaching began in the mid-1940s with the discovery of the bacterium *Thiobacillus ferrooxidans* (*Acidithiobacillus ferrooxidans*) and its role in copper recovery. In the mid-1950s, Kennecott Mining patented the use of *Thiobacillus ferrooxidans* to extract copper from low-grade copper ores from the Bingham Canyon Mine (Utah, USA). Biomining is widely used around the world, as the technique increases the recovery of gold from ore and concentrates. This method allows the extraction of useful components from secondary ores. Leaching metals from dumps is time-consuming due to low solution filtration, oxygen saturation, and microbial activity [12]. Leaching methods are cost-effective when the initial contents of useful components are low. The leaching methods mentioned above can be applied to the new technique of ascending capillary leaching with the formation of zones of high concentration in the near-surface aeration zone.

The directed geological process of filtration mass transfer in the massif leads to the development of a non-equilibrium state in a selected area of the subsoil and leads to material and structural transformations [13]. Several studies have investigated fluid filtration in rocks and technogenic objects and the resulting transformations of minerals [14-16]. These studies have found that the natural concentrations of the compounds of useful components are confined to the zones of geochemical and physical barriers in the subsoil massifs, such as the evaporative barrier. Technologically, it is attractive due to the vertical rise of fluids to the surface and the precipitation of salts in the aeration zone of the massif. The solutions rise due to the hydrostatic supply pressure, the surface tension in the capillaries of the array, and a drop in the pressure during evaporation. Evaporation pulls solutions to the surface. Humidity in the aeration zone ranges from 100% at the level of the “mirror” of the aquifer to the value of atmospheric humidity on the day surface of the array. In the aeration zone, as water evaporates, the salt concentration increases to the limit value, causing precipitation. When the concentration exceeds the solubility limit, useful compounds precipitate. This occurs throughout the height of the aeration zone. Different mineral compounds have different concentration limits of aqueous solutions, and thus, the compounds can be selectively deposited at different massif heights in the aeration zone. The regularities in the selectivity of the deposition of both simple and complex solutions in the evaporative barrier layer are particularly interesting; the temperature and humidity of the air affect the kinetics and zoning of deposition. The critical conditions for the capillary rise to the surface include the hydrostatic pressure, atmospheric air humidity, groundwater level, and salt concentration in the fluid. During movement, the solutions pass through the zone of near-surface aeration. In the aeration zone of the massif, the concentration of salts increases since only water evaporates. Evaporation “draws” solutions from all new portions of the aquifer to replace the lost solution. This process occurs continuously [17] as long as evaporation takes place. The evaporation barrier can form zones of high concentration on the massif surface, up to 100% salt crust. Capillary rise is an additional powerful natural mechanism that moves solutions through the layer of the array [18]. It helps to move large volumes of solutions from the pores of the rock mass to the day surface with the evaporation of water. The evaporation of water in the aeration zone and directly from the surface forms the pressure gradient necessary for the upward transport of solutions. This mechanism also controls the kinetics of the upward flow of fluids [19, 20]. The aeration zone is a natural barrier to evaporation. Due to different values of the limiting salt concentration, selective accumulation might occur at different levels of the aeration zone of the massif. The salinization of agricultural soils is an important problem in surface nature management. A detailed investigation of the formation of salt deposits and their prevention is presented in other studies [21]. Based on these studies, a series of experiments were conducted on the formation of concentration zones on evaporation barriers.

Natural geological processes suggest options for artificially implementing directed concentration at the site of occurrence. In situ enrichment in a massif might be a slower process than the use of concentrators, and this approach might be used as an additional process in preparing deposits for development. The possibility and applicability of this approach should be confirmed experimentally. Such experimental studies should be conducted on a poor material of enrichment tailings to assess the technological profitability. Considering the universality and high prevalence of the process of fluid mass transfer of matter in porous massifs, detailed studies should be conducted in this area. Selective enrichment of different minerals can be achieved by aeration zones with the rise of solutions through capillaries. During the upward movement of fluids in the mass, the mass transfer parameters must be optimized to ensure that extraction is completed and a new ore body is formed.

2. Materials and Methods

The fluid in the capillaries rose in the experimental column (Figure 1). In the experimental setup, a polycarbonate column (1.5 m high and 110 mm in diameter) was used.

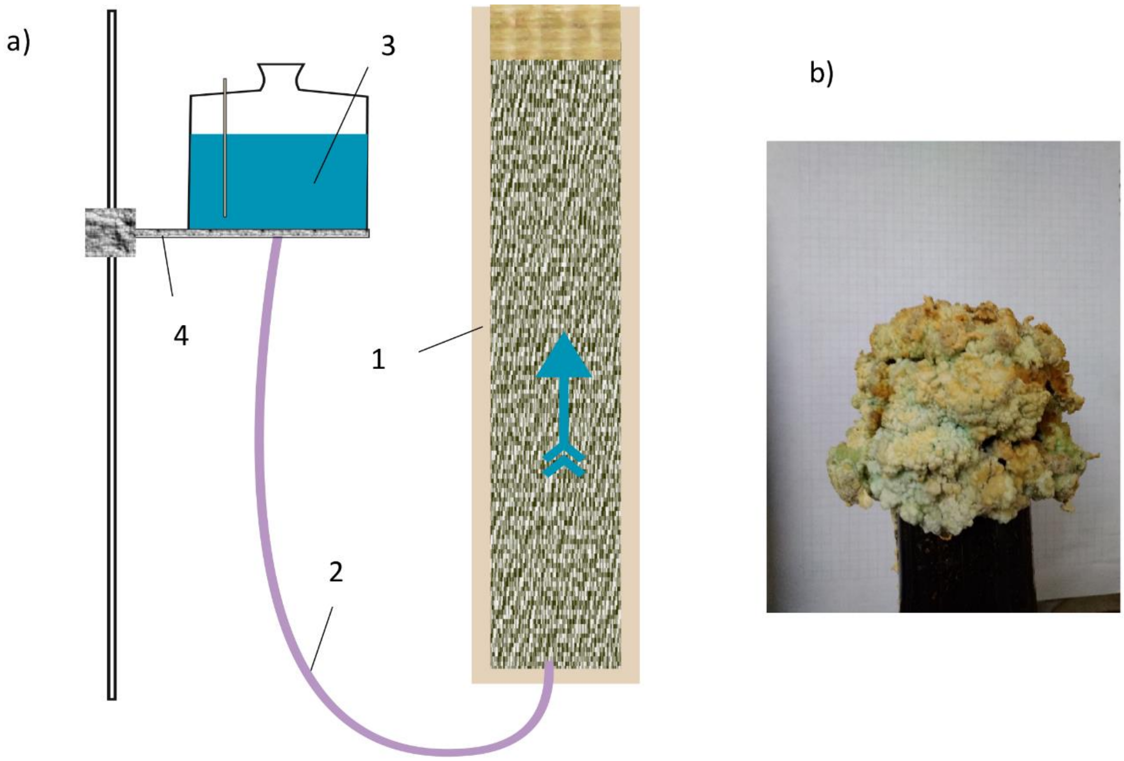

Figure 1 The laboratory setup that was used for the upward capillary leaching experiments is shown. a) A schematic representation of the laboratory setup; b) The surface of the column at the end of the experimental cycle. 1: polycarbonate column, 2: flexible feeding tube, 3: capacitance, and 4: movable platform.

To supply the solution to the experimental massif in the center column, its bottom was connected to a tank using a flexible pipe. In the pilot experiment of the continuous upward flow system, the column was loaded with flotation tailings from the Norilsk industrial hub. These flotation tailings consisted of finely crushed ore, where the particles were mostly 0.05–1.2 mm. Drinking mineralization water was used for conducting experiments in studies on mass exchange. Water is the best natural solvent. Hydrogen peroxide (10%) was used as a leaching agent. The peroxide solution was supplied from the tank to the bottom of the massif at a constant rate. The feed rate was controlled by the level of the solution in the Mariotte bottle, which was set to the height of the material surface in the column. The speed and the temporal variation of the directed rise of aqueous solutions in the capillary were obtained for the dispersed materials of enrichment waste. The kinetics of the formation of water-soluble salts of nonferrous and noble metals was evaluated for the tailing dump. This process is necessary for the water leaching of enrichment waste. The mineral content of the initial working solution was similar to that of mineralized drinking water at pH 7.0. This solution flowed through the capillaries in the material to the surface, where it was collected for testing. The useful contents of the flotation tailings in the column were monitored by performing serial geochemical analysis during the experiment using the method described in another study [22]. The results showed that the exchangeable fraction consisted of water-soluble compounds (Figure 2). Throughout the experiment, which was conducted for several months, the water remained at the same level. A Mariotte vessel was used to evaluate fluid capillary kinetics over time. To assess the distribution of sediment in the surface zone of the massif, core samples were taken from the entire aeration zone. The distribution was controlled by copper sulfate.

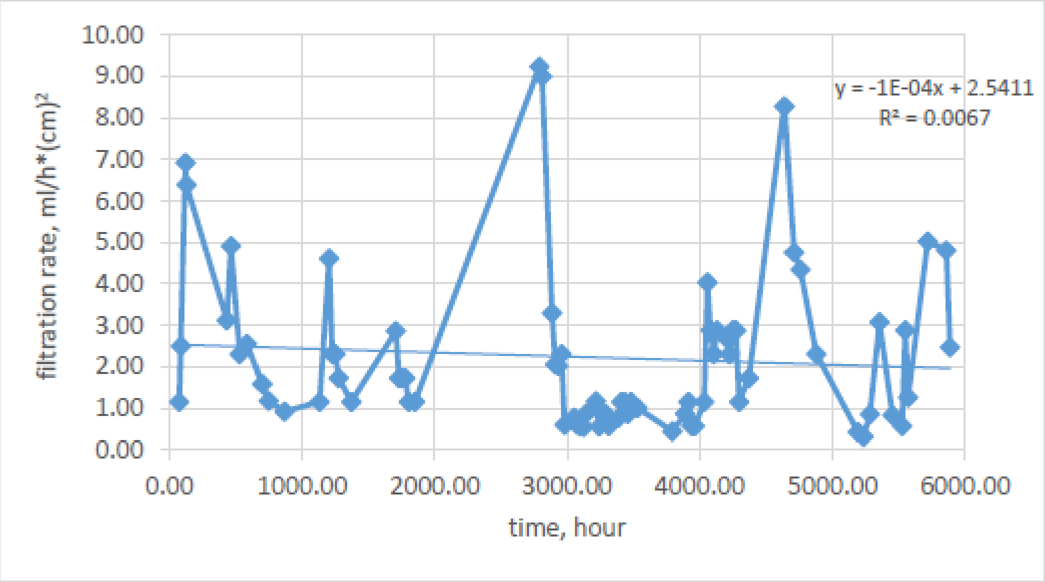

Figure 2 The rate of upward filtration.

3. Results and Discussion

In the experiment, especially in the initial period, fluctuations in the filtration flow were unstable. The fluctuations were 2–4 times the average value. The solution supply level corresponded to the surface level. The calculated filtration flow in the initial period differed from the experimental one and was only half of it. Filtration instability of liquid flow through capillaries with such fluctuations from the average calculated value can be associated with a periodic local flow concentration through individual capillaries of larger sizes. Upon contact with water-soluble compounds, the solid phase turns into a liquid phase, which increases the size of the capillaries to the size of the channels and increases the rate of filtration of the array. The movement of the solution changes multiple times with an increase in porosity. This quickly increases the permeability locally, which in turn accelerates the leaching front. Areas with small capillaries are temporarily excluded from the process. During the reprecipitation of the mineral phase in the capillaries, the advancement of the reaction front disappears. The mineral phase precipitates partially and forms deposits, which do not exclude the complete overlap of the open section of the capillaries. A clogging effect is indicated by the episodic fluctuations in the filtration rate of solutions in the massif and changes in the level of mineralization of the solutions at different horizons of the massif. Our results showed that the average decrease in the rate of capillary flow of solutions was below 25%. At the beginning and the end of the experimental cycle, the nature of the change in the concentrations of elements in the solution differed across levels. In the initial section, the concentration decreased toward the surface. After a certain interval, all elements in the solution rose to the surface. This was due to the successive redeposition of salts as the solution moved up. In the experiment, initially, almost all the water-soluble parts of non-ferrous metals were extracted, and their proportion was estimated by the geochemical phase analysis before the start of the experiment. At the end of the experiment, the geochemical phase analysis was performed again, which showed that the proportion of water-soluble phases of non-ferrous metal elements decreased, but did not disappear, although the water-soluble volume (according to the calculations) passed into the sediment on the surface of the column throughout the experimental cycle. This indicated that the water-soluble forms of non-ferrous metals under hypergenesis conditions were replenished at the expense of crystalline oxides and sulfides.

Among the parameters studied in the experiments, the most important parameters were selected for a more detailed study, such as the filtration rate and the content of the main elements in the solution at different levels. The rate of capillary filtration of liquid showed high variation from 0.5 to 10 mL/cm^2·h. Thus, validating the regularity of the obtained experimental data was difficult (Figure 2). The regularities of filtration kinetics did not correspond to the generally accepted approaches used to assess the filtration movement of the fluids. Darcy’s filtering law was suitable for the filtration process throughout the observation period and when the values were smoothed. Within short periods, such as from 1 h to 1 day, the regularity based on Darcy’s law did not match completely. A slight decrease in the filtration rate was found throughout the observation period. The reasons for the sharp fluctuations in the filtration rate up to several times, showing an increase and then a decrease in the middle and at the end of the experimental cycle, were difficult to determine. The fluctuations in the speed of movement might be associated with the chemical activity during intermediate precipitation from the solution in the capillaries of the array, followed by a transition into solution or continuation of movement. The kalmatation of the capillaries in the porous state of the array was not observed. No other reasons were found for such significant fluctuations since, during these periods, there were no external changes in the temperature, pressure, and pH of the solution.

To study the kinetics of ascending filtration, regime tests were performed in an experimental column (Figure 1) of enrichment tailings with a lifting height of 1.5 m. The changes in the filtration rate are shown in Figure 2. The filtration rate showed high variation and decreased slightly over time. With a non-pressure supply, the average filtration rate decreased; in the initial period (the first 40 days), it was 4.9 mL/cm^2·h, while in the end, it was 2.4 mL/cm^2·h. The decrease in the filtration rate over time might be explained by rock compaction and possible clogging of the pores in the rock mass. To determine the dynamics of fluid movement in the massif, the physical and reservoir properties of the rock need to be considered. These properties are determined from the known dependencies [23], which include the effective diameter of the particles that constitute the porous medium. In addition, one of the parameter that affected the capillary rise above the level of the main water mirror in the array was water saturation in the aeration zone. The height of the capillary rise of the solution was determined following the method described in another study [23]. The calculated indicators of the filtration parameters of the experimental array were consistent with the data. The estimated reservoir properties of the material used are shown below.

Weighted average grain diameter: 0.238 mm
Effective particle diameter: 0.220 mm
Hydraulic radius: 3.100 µm
Permeability: 0.480 darcy
The height of the capillary rise of the water column: 0.698 m

The content of the controlled elements in the solution at different levels of the array was constantly monitored by mass spectrometry. The content of some ferrous and non-ferrous metals in the solution at the top level of the column is shown in Figures 3 and 4. The content of the elements in the solution during the experiment was highly chaotic. The contents of manganese, cobalt, copper, and iron did not show trends with time or at other levels, which indicated the absence of correlations. However, changes may occur over time. The experiments on ascending filtration mass transfer are ongoing. The values of the concentrations of the salts of the components in the solution and their fluctuations after entering the evaporation barrier were so insignificant that it was difficult to identify them , but the sediment accumulated on the evaporation barrier. We found some patterns in the change in the content of noble metals, including platinum, palladium, and gold (Figure 5). However, the content of noble metals remained stable throughout the experiment.

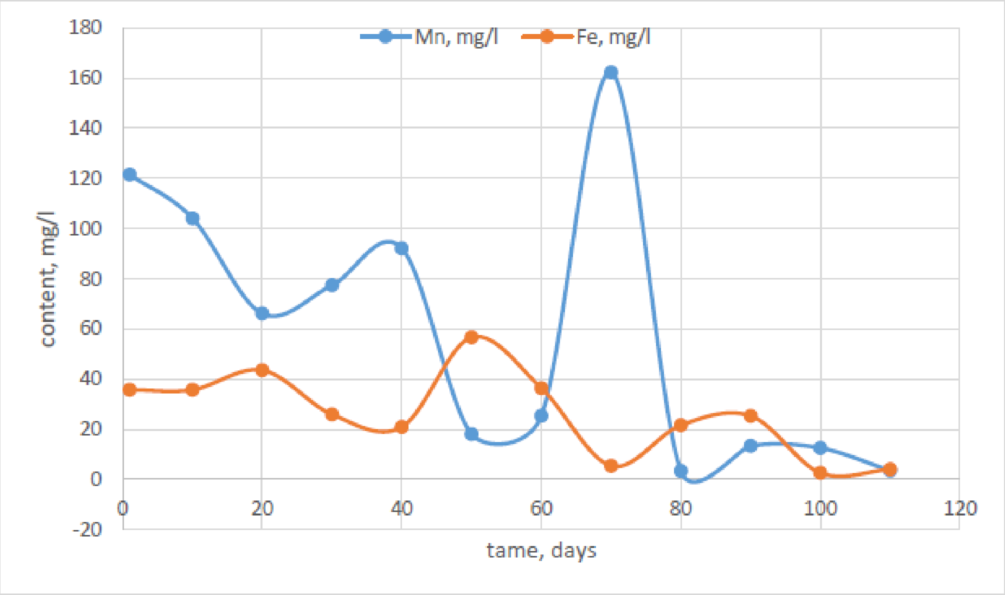

Figure 3 The content of Fe and Mn in the solution.

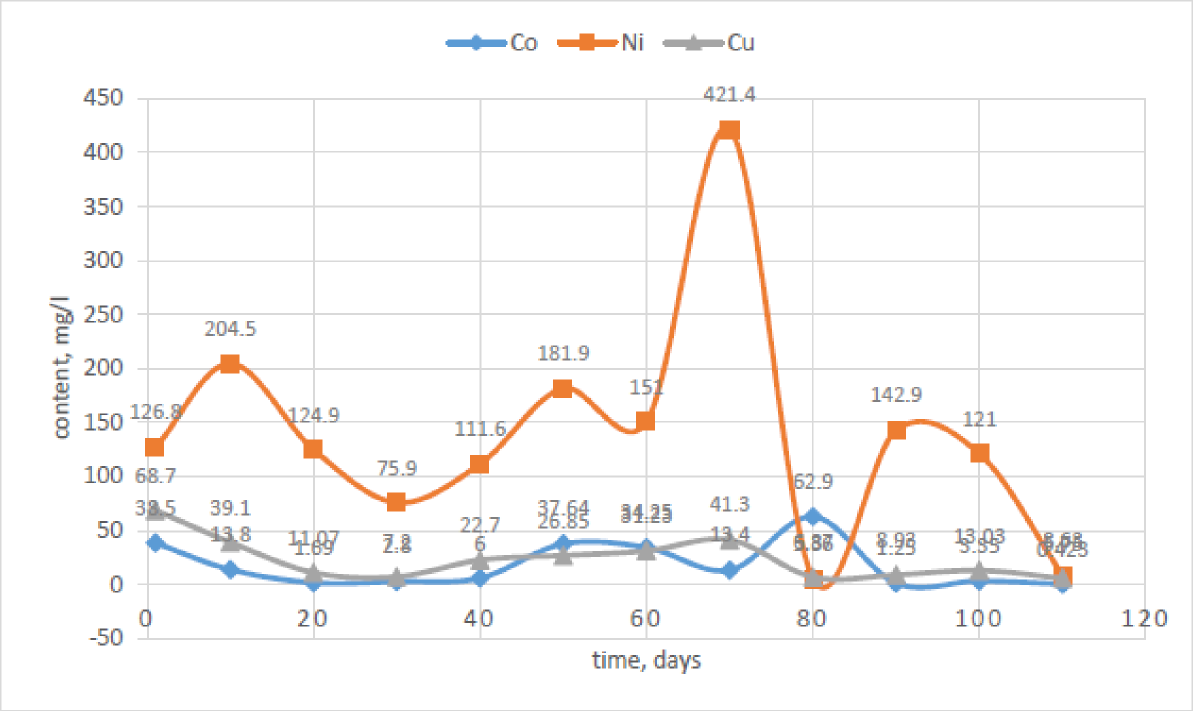

Figure 4 The content of non-ferrous metals Co, Cu, and Ni in the solution.

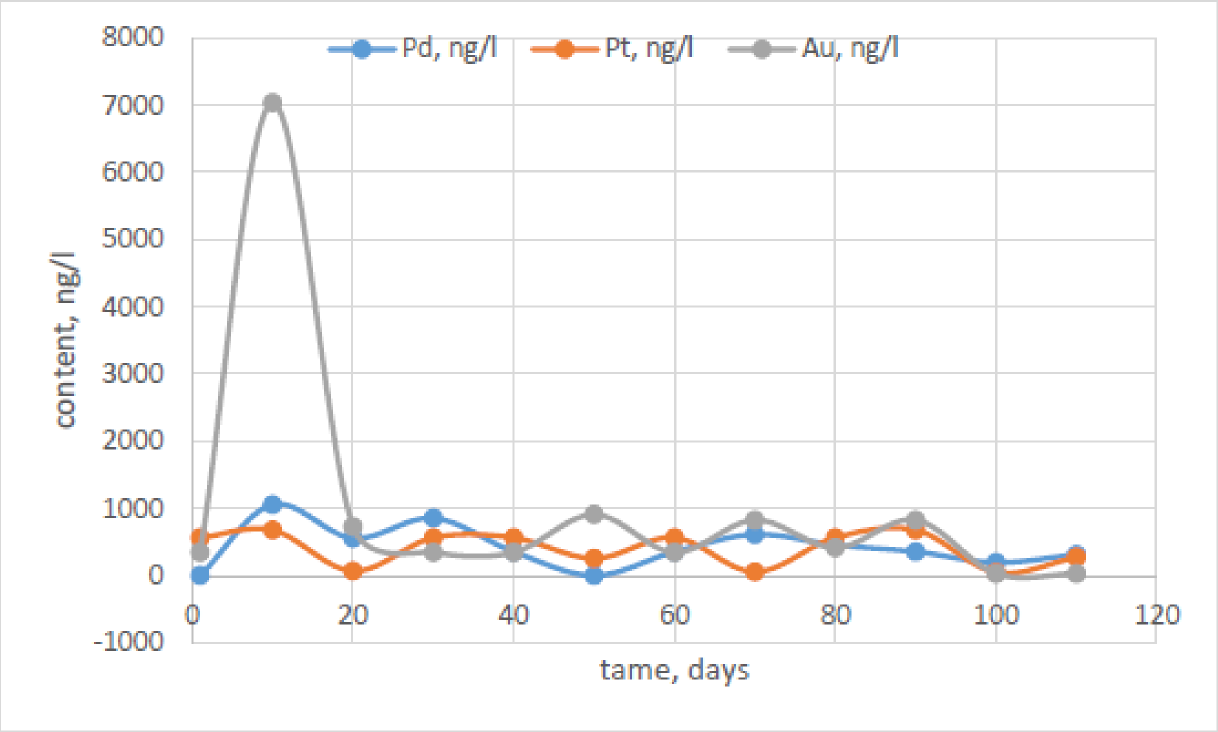

Figure 5 The content of noble metals Au, Pt, and Pd in the solution.

With the rise of solutions to the surface through the capillaries of the array, an important parameter of mass transfer is the regularity of the distribution of the concentrations of salts of the useful component in the layers of the array along the height. To evaluate the nature of the distribution of concentrations along the height, a series of experiments were conducted using an experimental setup for the upward capillary motion of the solutions. Purified quartz sand with a particle size distribution corresponding to the composition of the tailings was used as an array. Aqueous solutions of non-ferrous metal sulfates of various initial concentrations were used as production solutions. In the experiment, parameters such as the flow rate of the solution during supply, the duration of the process, air temperature, array temperature, air humidity, and atmospheric pressure were controlled. The duration of the experiment was 800 h and 1,600 h, after which the installation was dismantled, and samples were collected for geochemical analysis. The samples were taken from four levels. The uppermost part was a structurally distinguished crust that was present to a depth of 2–3 cm on the surface of the massif. Under the crust below the surface (top position) were the middle zone and the lower zone. The samples were analyzed, and the results for copper sulfate are shown in Table 1.

Table 1 Height distribution of the experimental column.

Sampling zone	Sample mass, g	Area specific weight, %
Crust	2199	71.2
Top	855	27.6
Middle	34	1.2
Bottom	-	-
Total	3088.0	100.00

The highest content of copper sulfate (31.56%) corresponded to the barrier surface-salt crust. Under the crust, the content of copper sulfate decreased sharply from 31.56% to 16.74%. The content of copper sulfate increased from the surface of the evaporation barrier to the bottom of the column (almost to the mirror) and the lower part of the aeration zone of the massif. The patterns of change in the evaporation rate were statistically evaluated based on all the studied parameters. Based on the results of the multiple regression analysis, the most significant factors were selected. The evaporation rate was affected by the duration of the process, air humidity, and massif temperature. The duration of the process and the humidity of the air were significant factors. Over time, copper sulfate precipitated in the sandy mass and clogged the capillaries through which the solution passed. Thus, the cross-sectional area of the capillaries decreased. An increase in humidity decreased the rate of evaporation of the liquid; the air humidity ranged between 20% and 49%. The change in the evaporation rate was affected by the mutual correlation of the massif temperature, air humidity ($R = -0.62$), and the duration of the process ($R = -0.44$). The dependence of the evaporation rate was obtained by performing a multiple regression analysis (multiple regression coefficient $R = 0.74$). After a full load of copper sulfate, drinking water was supplied for three weeks. Most of the sulfate content (97.7%) was deposited in the surface crust (~72%) and the aeration zone of the massif (~28%).

In the following selective separation experiment, a similar laboratory ascending column was used. A complex solution of three nonferrous metal sulfates was used, containing $ZnSO_4$, $NiSO_4$, and $Co(NO_3)_2$ in equal volume fractions.

The initial data are presented in Table 2.

Table 2 The initial data on the complex solution.

Index	$ZnSO_4$	$NiSO_4$	$Co(NO_3)_2$
Maximum solubility, g/L	220.00	383.00	1024.00
Content at solubility 80% of the maximum, g/L	176.00	306.40	819.20
Concentration from maximum solubility, %	58.67	102.13	273.07
Concentration from maximum solubility, %	26.70	26.70	26.70
Mass of 1 mole of substance, g	161.40	154.70	182.90
In 1 mole of $ZnSO_4$, the content of Zn, %	40.52	—	—
Ni content in 1 mole of $NiSO_4$, %	—	37.94	—
In 1 mole of $Co(NO_3)_2$, the content of Co, %	—	—	32.20
Received in the column, g	85.65	149.11	398.68

The results of the experiment are presented in Table 3.

Table 3 The results of the filtration sample analysis.

Array range	Sample mass, g	Substance mass by layers, g			Substance content, %			
		$ZnSO_4$	$NiSO_4$	$Co(NO_3)_2$	$ZnSO_4$	$NiSO_4$	$Co(NO_3)_2$	Σ
Crust	791.1	425.2	99.3	267.8	71.0	82.5	75.2	73.9
Top	241.2	150.4	16.1	75.2	25.0	13.3	21.3	22.5
Middle	40.0	24.1	5.5	11.3	4.0	4.2	3.5	3.6
Bottom	-	-	-	0.1	-	-	-	-
Total	1072.3	599.7	120.9	354.4	100.00	100.00	100.00	100.00

The crust on the surface had the highest concentrations of substances for all components. The content of the substances directly under the crust on the surface of the massif material was significantly lower (2 to 5 times). A residual concentration was found in the middle zone of the massif. The sulfate content in this zone was associated with the sorption properties of the mineral substance. If water was further supplied to the lower part of the array, the compounds of useful components might have been completely removed. The experiment to remove sulfates from the middle zone is ongoing. Statistical analysis of the distribution of the compounds of different non-ferrous metals in the complex was conducted. Paired relationships were observed. The coefficient of multiple regression was determined, and for this complex, the coefficient (R) was 0.89. The formation of sediment on the surface of the massif showed specific regularities. Copper sulfate in the surface crust crystallized with the formation of capillaries which facilitated the rise of solutions without decreasing the kinetics of the capillary motion of solutions compared to the capillary rise in the massif. This type of movement is limited by the height of the crust. The formation of a surface crust of salts should be further studied.

4. Some Technological Solutions for the Application of the Principle of Upward Capillary Leaching

Small areas with near-surface localization of ore minerals and off-balance areas of deposits can be profitably formulated by the proposed technological methods of ascending capillary leaching. In such cases, the principle of the above-mentioned method might be applied. Briefly, in this method, an area with ore mineralization (Figure 6) can be subjected to explosive loosening to increase the permeability of water. The adjacent territory of the array might be drained through drainage wells. The leaching solution can be fed to the bottom through these drainage wells. During the operation, a pressure gradient needs to be maintained in the supply wells to ensure that the entire array is saturated with a solution that inhibits the penetration of groundwater. Then, the leaching solution can rise from the bottom to the surface through the capillaries of the array and accumulate in the sump. By maintaining the level of fluid in the supply system, the supply of the solution to the bottom of the array can be commensurate with the rate of capillary exit to the surface. As the production solution accumulates on the surface, useful components can be extracted.

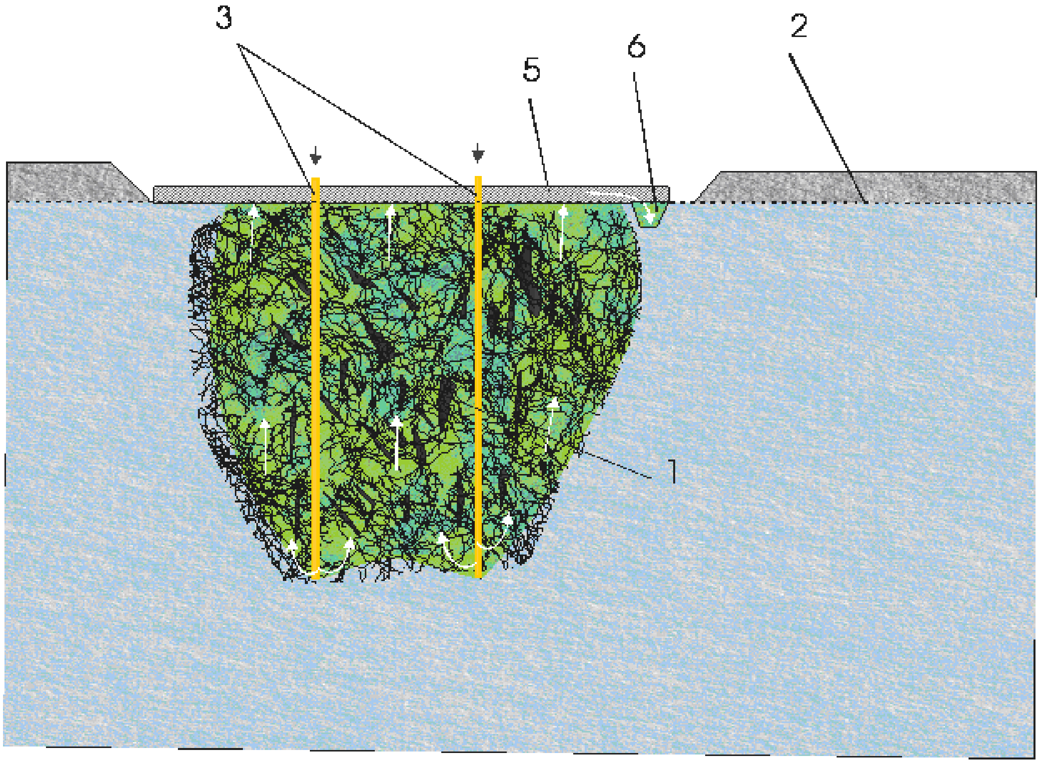

Figure 6 The schematic representation of the geotechnological development of a local area of the field; 1: the mineralization zone, 2: groundwater level, 3: solution supply well, 5: the hygroscopic surface layer, and 6: production solution intake sump.

For a man-made facility, for example, in the hydraulic structure of flotation tailings (Figure 7), the preparation scheme can be represented as follows. The leaching solution might be supplied to the base of the waste massif from the surface through a well or sump, with the feed level corresponding to the day surface of the array. The leaching reagent can enter the lower part of the array and rise to the surface through capillaries. A geochemical barrier might be placed on the surface for the sedimentation of useful components, or the productive solution might be collected in the created pits and pumped out for extraction.

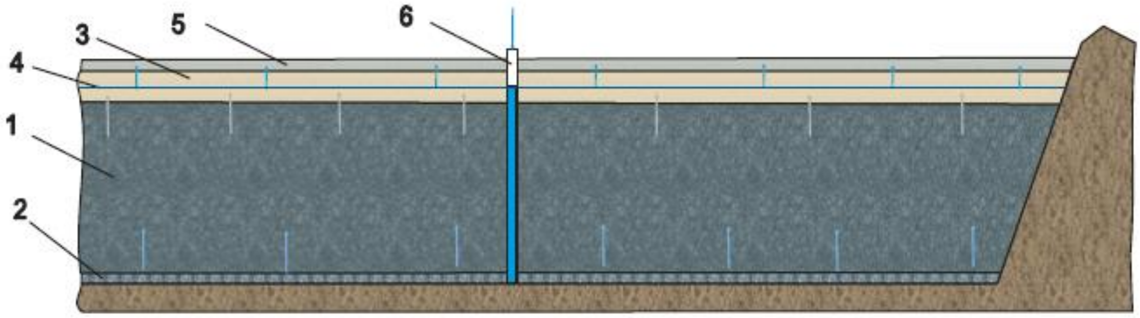

Figure 7 A schematic representation of the extraction of useful components from enrichment wastes in hydraulic structures. 1: array of enrichment wastes; 2: drainage base; 3: geochemical barrier; 4: filling level; 5: hygroscopic layer; 6: supply of solutions and maintenance of the level.

By investigating the process of ascending mass transfer with the formation of surface zones of concentration and redistribution of compounds in situ, we validated the technological foundations for the efficient and environmentally safe extraction of useful components from the bowels before surface reclamation. We also experimentally established the distribution of metals over mineral phases for various thicknesses of the filter layer of the rock mass and different barrier properties in the concentration zones. The degree of transition of the components into the solution was correlated with the thickness of the filter layer. The presence of water-soluble forms of metals in the experiment allowed us to consider the possibility of eco-friendly extraction processes based on the considered technological schemes to develop new approaches for extracting useful components from the subsoil in situ, bypassing the enrichment redistribution in special production lines. The proposed approach might increase the resource mineral base by involving small deposits (ore occurrences) and waste from processing and metallurgical industries, thus facilitating cost-effective development. Overall, the proposed approach is cost-effective and eco-friendly since it is based on natural geological processes.

5. Conclusion

We have developed a new principle of artificial formation of concentration zones. The new principle is based on the geological process of ascending filtration rise of useful components in solution to the day surface of the massif. This approach makes it possible to move to the paradigm of growing deposits. The redeposition of the compounds of useful components was experimentally confirmed by using water-soluble sulfates of non-ferrous metals on the surface and in the near-surface aeration zone of the massif. We proposed new technological solutions for extracting useful components. We also confirmed the main factors that influence the processes of filtration and mass transfer. A new approach was proposed for extracting useful components from enrichment waste before surface reclamation. For the motion related to the rise of solutions in the capillary, the kinetics was experimentally determined in association with the rate of evaporation of the solutions in the aeration zone of the massif, and their quantitative relationship was evaluated. On the surface of the evaporation barrier at the upper level, the content of water-soluble salts of non-ferrous metals exceeded 2 to 5 times, on average, up to the crust. We experimentally found that sedimentation occurred throughout the aeration zone with a linear decrease in the content of useful components from the groundwater level to the massif surface. This distribution was typical for both complex and homogeneous solutions. The correlation characteristics of complex solutions and the possibility of their choice for more rational implementation were established. We also established experimentally that an increase in the temperature of the air and mass from 20°C to 30–35°C can increase the evaporation rate by 2.5–3.5 times. In the aeration zone, we did not find the selective precipitation of salts from complex solutions during capillary motion. Some technological solutions for the use of upward capillary leaching were proposed for further consideration. Understanding the process of upward mass transfer with the formation of surface zones of concentration and redistribution of compounds in situ might validate the technological foundations for the efficient and eco-friendly extraction of useful components from the bowels before surface reclamation. The distribution of metals over mineral phases was experimentally determined for various thicknesses of the filtering layer of the rock mass and various barrier properties in the concentration zones. The degree of transition of the components into the solution was correlated with the thickness of the filter layer. The presence of water-soluble forms of metals during the experiment allowed us to consider the possibility of an eco-friendly extraction process based on the considered technological schemes to develop new approaches for extracting useful components from the bowels in situ, bypassing the redistribution of enrichment on special technological lines. The proposed approach might increase the mineral resource base by involving small deposits (ore occurrences) and waste from processing and metallurgical industries, thus facilitating cost-effective development. Overall, the proposed approach is cost-effective and eco-friendly, since it is based on natural geological processes.

Author Contributions

Author A. Mikhailov developed the idea, approach, literary search. Author I. Vashlaev developed the method, laboratory experiment, analysis, calculations

Competing Interests

The authors have declared that no competing interests exist.

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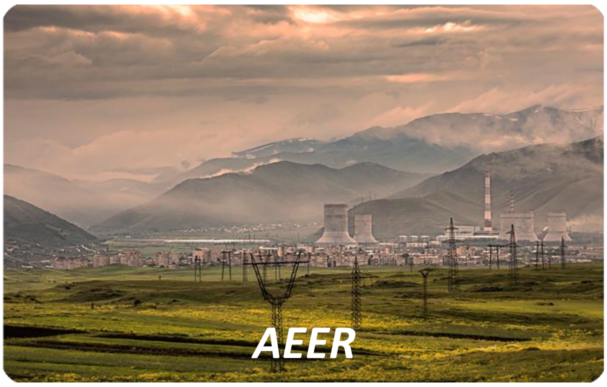
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