Problems of Deep Open Pits Closure in the Kola Peninsula

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Abstract
Mine closure is the final specific stage of its lifetime. Deep mines hydrogeology is of special importance when closing the mines. Important expertise has been gained in Murmansk region in water-related issues. The redistribution of tectonic and gravity stresses in the rock mass should be taken into consideration too. Dynamic occurrence of stress-strain host rock mass has been often observed during open pit mining. All these factors should be taken into account when preparing the walls for semi permanent or permanent mine closure. Solid mining and geological information on deep open pits is required to be used for mine closure.

Key words: mine closure, open pit mine, ground water, dewatering, seismic hazard, Kola Peninsula

Introduction

Mine closure is inseparably related to construction and operation stages of the mine. The number of challenges to be solved, their significance, number of options and, above all, the uncertainty of conditions for decisions making as well as unknown consequences makes mine closure issues to be of equal importance with mine construction.

The hydrogeology of the deep open pits is of special importance when closing the mines. E. g., in spring the upland pit of the Centralny mine (JSC "Apatit") has serious problems with snow melting water resulting in the pit shutdown for several weeks. The Koashva open pit has extremely complicated situations during water inflow, which resulted in deformation of some benches. Some investigations have, also, been made against water income into the pit, which are to be used in mine closure.

Open pit walls as high as several hundred meters are most crucial engineered structures. Growing depth of the open pits should be taken into consideration. There is the redistribution of tectonic and gravity stresses in the rock mass of open pit walls. Stress redistribution occurs both in the vicinity of excavation and far from it. Besides, as a result of stress relief or additional loads (big waste rock dumps and tailings) deformation of geodynamic blocks is disturbed, thus, activating natural tectonics of the area. The latter results are in higher seismicity. Earthquakes in the central part of the Kola Peninsula are considered by many scientists to result from large scale open pit and underground mining operations.

Mine-induced water problem

Operation of large mining enterprises quite often leads to irreversible negative phenomena of regional character — to exhaustion of resources and deterioration of ground waters over large areas, adjacent to open pit and mine fields. During drainage of deposits huge amounts of water are pumped away — often without any restrictions on that — (hundreds and thousands cubic meters per hour), which results in the formation of depression funnels for dozens of kilometers around the mining workings (with reduction of pressure heads of water that sometimes measure hundreds of meters). Thus, the water balance of large territories becomes less efficient; the watersheds belonging to the impact area of drainage works essentially reduce their productivity or fail; the recharge conditions in open water reservoirs and water streams get disturbed; extensive zones of man-caused aeration get developed which disturbs the natural humidity conditions of soils and grounds.

At the same time the drainage of aquifers and discharge of pumped out water deeply modify the hydro-chemical balance which had developed in the area, leading, as a rule, to an appreciable deterioration of ground water quality. Contamination of ground water in areas of deposits development is quite typical and often inevitable consequence of diversion, discharge and accumulation in surface basins of mine and process water, and the direct result of drainage and water pumping from mining

workings.
All this turns the mining areas into the "hottest" spots of the planet in terms of ground water protection from exhaustion and pollution. The world practice of mining operations confirms the global character of the problem. According to the analysis many large errors of projects, which result in serious ecological shifts in natural conditions or economic losses, can be partially explained by weak coordination of engineering solutions with requirements of environment protection. Another important reason leading to such errors is the lack or poor quality of the initial hydro-geological information on which the designing work relies. At last, there should be mentioned as well the insufficient efficiency of water protection (both of active, as well as control and preventive character) and the control measures which form the basis for the ground water quality management in the mining areas. The latter fact is in many respects caused by the traditional "tough" approach to the designing, which constrain or even exclude the possibilities of adaptation of these actions to probable divergences with initial forecasts.
Proceeding from the above general assessment of the situation, we can understand the general sequence of works with respect to concrete entities in the following interconnected directions:

1) Identification and analysis of general laws and principal causes of regional and local changes in the hydrodynamic and hydro-chemical conditions of ground water, which define the possibilities of their progressive pollution under the influence of mining manufacture. We should stress it right away those scientific and methodical studies within the framework of the hydrodynamic direction were of limited nature as the latter is traditional enough for mining hydrogeology;
2) Typification of contamination of ground water conditions in mining areas;
3) Development of requirements to the level of hydro-geological studies of deposits, to the structure and kinds of hydro-geological studies, and to mining enterprises projects;
4) Substantiation of principles and methods of prediction of change of the ground water quality under the impact of mining operations;
5) Development of the technology of pilot (field and laboratory) hydro-geological works that during the deposits prospecting stage supply the data needed for the preliminary prediction of contamination of ground water processes in the mining areas;
6) Development of scientific-methodological bases of preparation, carrying out and interpreting of monitoring observation of the quality of ground water (in coordination with observations of hydrodynamic regime);
7) Development of practical recommendations concerning the above issues in conformity with concrete standard facilities;
8) Development of concrete water protective measures.

Drainage regional system
In the territory of Murmansk region there are 19 unwatering and drainage systems around mineral deposits sites, where mining operations take place, 18 of them are operating with total withdrawal of drainage water amounting to 328 043 m^3/day (Melikhova 1998). The largest unwatering systems are established at Vostochny mine of the Koashva open pit mine, which is undercutting the intermountain valley of Vuonnemyok River, with the total discharged amount of 111 551 m^3/day, at "Zhelezny" mine in Kovdor City, crossing the valley of the Kovdora River, with the total discharge of 54 622 m^3/day, as well as the Karnasurt mine undercutting the Ilmajok River valley, with the amount of discharge 23 351 m^3/day. The rest of solid mineral deposits are being developed in simplified hydro-geological conditions. Drainage water is not used for domestic-drinking supply as it underwent mining-induced pollution, only a small part of it, in the amount of 4 814 m^3/days is supplied as mineral processing water.
Intense economic activity in a number of industrial areas of the region resulted in essential pollution of surface waters. In the zone of impact from industrial enterprises the total salinity of potable water from surface water intakes increased up to 0.07-0.1 g/dm^3 (Imandra Lake – Apatity city, the Yona River – Kovdor city, lake Luchlompolo – Nikel settlement), from ground water intakes up to 0.205-0.437 g/dm^3 (the railway station of Ruchji Karelskiye, Poyakonda railway station, Belokamenka settlement, Laplandia railway station). Besides, there has been registered the change of ratio between the main

cations and anions, and a shift towards a composition type, mixed in its anion structure, at the expense of cations Cl^{-} SO_4^{2-}, anions Ca^{2+}, Mg^{2+} content increase. The hydro-chemical state of potable water in natural conditions is typical for the entire region, and it meets GOST (State Standard) requirements for the majority of components.

Chemical composition of ground water in the zone of free water exchange of the territory, i.e. in the discontinuous layer of overburden and in the top fractured zone of crystalline rocks, is formed under the influence of a package of factors: various geological, geomorphological, climatic and man-caused ones.

Dominating are hydrogen carbonate and sulfate- hydrogen carbonate waters with mixed cation structure where calcium-sodium and magnesium-calcium components prevail. In terms of salinity ground waters, basically, are ultrafresh and fresh, the total salinity value does not exceed 1/dm^3 By the value of hydrogen index (pH) ground water can be referred to neutral and subacidic. By the total hardness value very soft waters and seldom soft ones prevail, and even more seldom the moderately hard type can be found.

Along with these waters within the western part of the described territory some foci with the raised content of normalized components have been found there. It is due to the natural quality of ground waters, as well as foci of man-caused pollution of ground waters due to industrial sources – basically, the mining and metallurgical enterprises of the region.

The basic source of pollution of ground water in Pechenga area are the copper-nickel smelter of "Pechenganikel" (Nikel settlement) and the copper-nickel concentrating mill (Zapolyarny) with tailing dumps settling ponds. Pollution of ground water takes place through surface waters of the Kolosjoki River in which "Pechenganikel" smelter discharges its waste water. The areas of mining-induced pollution of ground waters around the Nikel settlement of and Zapolyarny city of make around 45 км^2 each. The concentration of nickel reaches 4 maximum allowed concentration (MAC) values, aluminium – 7.7 MAC, fluorine – 1.2 MAC, manganese – 11 MAC and iron – 9.6 MAC. In the ground water of local pollution areas, with the surface area varying from 4 to 32 км^2, revealed to the north from towns of Nikel – Zapolyarny and southeast of Zapolyarny, there was observed the content of aluminium up to 8.6 MAC and fluorine up to 1.2 MAC (the result of mining-induced pollution), as well as manganese – up to 1.4 MAC and iron – up to 1 MAC (the result of natural pollution).

Contamination of ground water in Lovozero district is concentrated in the impact zones of industrial sites of mines “Karnasurt”, “Umbozero” and Revda settlement. The mining-induced pollution of ground waters with manganese (up to 2.5 of MAC), iron (up to 2.9 MAC), and aluminum (to 1.3 MAC) is registered near “Umbozero” industrial site. Concentration of manganese (up to 2 MAC), aluminium (up to 12.9 MAC) and iron (up to 15 MAC) is registered near “Karnasurt” industrial site. Increased content of fluorine in springs of Revda settlement (up to 1.3 MAC) most likely, has a natural character as fluorine is a part of rocks, composing the Lovozero rock mass. Though the probability of man-caused pollution of ground water is not excluded.

In Monchegorsk district, within the city dump of sanitary waste of "Severonikel" smelter, over the area of nearly 18 км^2, the man-caused contamination of ground water with nickel (to 2.3 MAC), with aluminium (to 10.8 MAC), fluorine (1 MAC) and lead (1.8 MAC) was found.

The basic source of pollution in the Kirovsk-Apatity district are the mining-processing enterprises of "Apatit" JSC (ANOF-II, ANOF-III concentrating mills, tailings), as well as farmlands. Pollution of ground water is both of natural and man-caused character. The man-caused pollution with nitrates making up to 1.44 MAC and fluorine up to 1.06 MAC is observed in a spring located within the territory of industrial site of ANOF-II concentrator. Pollution is of a seasonal nature and it increases during the flood periods of the year and is of local distribution (2 km^2).

Ground water of overburden in the areas of ANOF-II, ANOF-III tailings at some points is characterized by the increased content of iron and manganese, exceeding 8-12 times the MAC for manganese, for iron – 3 times. Pollution of ground water with manganese and iron probably has partially natural character.

For the last years there is clearly traced nitrate pollution of ground waters and the lakeside lowland of Bolshoy Vudyavr Lake due to discharge of mine water from mines of "Apatit" JSC. From 1984 to 1996 in the ground water of ostashkovian water glacial horizon the content of nitrates increased approximately 10 times, reaching the maximum values of 30 mg/dm^3 (the Yuksporr valley). The nitrate pollution covers practically all Yuksporr and Saami valleys and has constant character. The pollution degree depends on the season of the year and is maximum in the low-water season. In the intermountain basin of Bolshoy Vudyavr Lake there is mined the Vudyavrskoye deposit with unsatisfactory quality of ground water of the operated horizon for aluminum content (up to 1.9 mg/dm^3) and for hydrogen index (pH up to 10.3), which is due, on the one hand, to the natural quality of ground water, on the other hand, to the adverse ecological conditions within the "Tsentral" ground water intake – the content of nitrates is up to 20 mg/dm^3, as a result of operation of mining enterprises of "Apatit" JSC.

The drainage is typically contaminated with some components of the man-caused pollution, which depends on the method of mining and peculiarities of the deposit. So, for apatite-nepheline deposits, nitrates (up to 886 mg/dm^3) act as pollutants of drainage waters, for nickel deposits – nickel and sulphate.

The protection of ground water is determined by the thickness and lithological structure of rocks composing the aeration zone. Aquifers are subdivided in reliably protected, conditionally protected and unprotected (Melikhova 2000).

The aquifers reliably protected from pollution include the areas where the basic ones are head aquifers, overlapped by persistent low-permeable clay deposits – water-glacial deposits of intermountain river valleys with a multilayer structure of rock mass, less frequently sea and fluvioglacial deposits in areas of accumulative relief development.

Conditionally protected aquifers are typical for territories with gravity-feed aquifers, with the thickness of aeration zone of over 8-10 m, provided the structure of zones like this has interlayer of low-permeable rocks, with the thickness reaching at least 3 m — basically, under the discontinued and non-uniform moraine cover.

Territories with unprotected aquifers include the gravity-feed ones with small thickness of the aeration zone and with no or little thick (less than 3 m) low-permeable deposits; aquifers getting recharge from rivers due to direct connection of the operated aquifer with surface waters; the pressure head aquifers, provided there are “hydro-geological gaps” in overlapping deposits, if the level of pressure head water is below the level of ground water – outcroppings of crystalline rocks in the day surface and the areas of modern sandy soils, located in relief depressions.

Some mining enterprises practice dewatering and drainage: "Apatit" JSC (Vostochny mine, Koashva open pit mine, Yukspor mine, Rasvumchorr mine, Kirovsky mine), "Olkon" JSC (Kirovogorsk iron ore open pit mine, Olenegorsk iron ore open pit mine), "Sevredmet" JSC (Karnasurt mine, Umbozero mine), “Kovdorsky GOK” JSC (Zhelezny mine), "Kovdorslyuda" JSC ("Yona" mine, "Kovdor" mine, "Rikolatva" mine), GMK “Pechenganikel” JSC (Tsentralny and Zapadny open pit mines, "Severny" mine, "Kaula-Kotselvaara" mine, "Vostok" mine). Within the mine lease of the above mining enterprises, due to dewatering and drainage of ground water, there develop processes of ground water exhaustion, the hydro-chemical balance is upset, the quality of ground waters deteriorates, hydrodynamic conditions change. The change of water balance in these territories is manifested in the formation of funnels of depression, in the change of stream movement direction, in transformation of relief areas into recharge areas, reduction of the surface drain (Zhelezny mine), drainage of soils due to decrease in level of ground waters and processes of vegetation suppression, connected with it, establishing settling ponds for drainage waters in natural depressions of the relief, which results in the territory swamping (unwatering system of Vostochny mine, drainage system of the Koashva open pit mine). Depending on the amount of drainage water withdrawal and on the peculiarity of hydro-geological conditions of certain mineral deposits, the degree of environment impact is manifested differently.

Problems arising due to mining operations

Kovdor iron ore deposit is located in the southeast part of the Kola Peninsula and initially was confined to Zhelezorudnaya Mountain. The local relief is mountainous, rugged, with smoothed outlines of heights. Absolute marks of the surface vary from 210 m in the east in the valley of Lake Kovdoro to 450 m in the north of the district.

Hydro-geological conditions of the deposit are reputed to be very complex and are characterized by the presence of two aquifers: one in loose integument sediments and one in the zone of decomposition and strong fracturing rocks. These aquifers form a unified water bearing complex with common hydrodynamic regime. River sediments have the maximum abundance of water which filtration factor reaches 115 m/day. There is identified a highly fractured zone in hard rocks with water seepage factors of 5-10 m/day (Bogomazov 2002). The ground water has direct hydraulic connection with surface waters of the river and lake. The thickness of aquifer complex in the basic territory makes an order of 50 m, while in zones of numerous tectonic faults it reaches 100-150 m (Figures 1, 2).

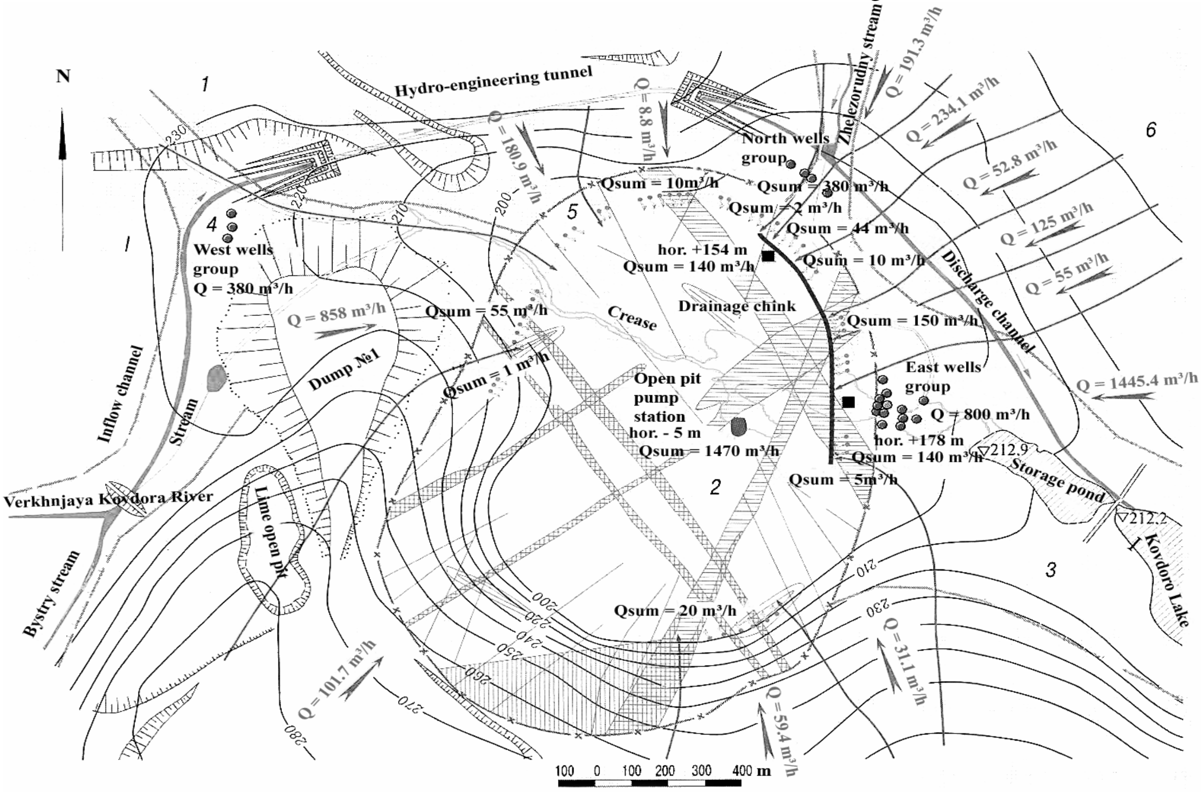


Figure 1 *Hydrodynamic structure of inflow groundwater forming in the open pit on 2000:*
1 — alluvial sediments zone; 2 — broken disturbances zone; 3 — hydroisohyps; 4 — dewatering well; 5 — pit wall groundwater outlet; 6 — water current lines.

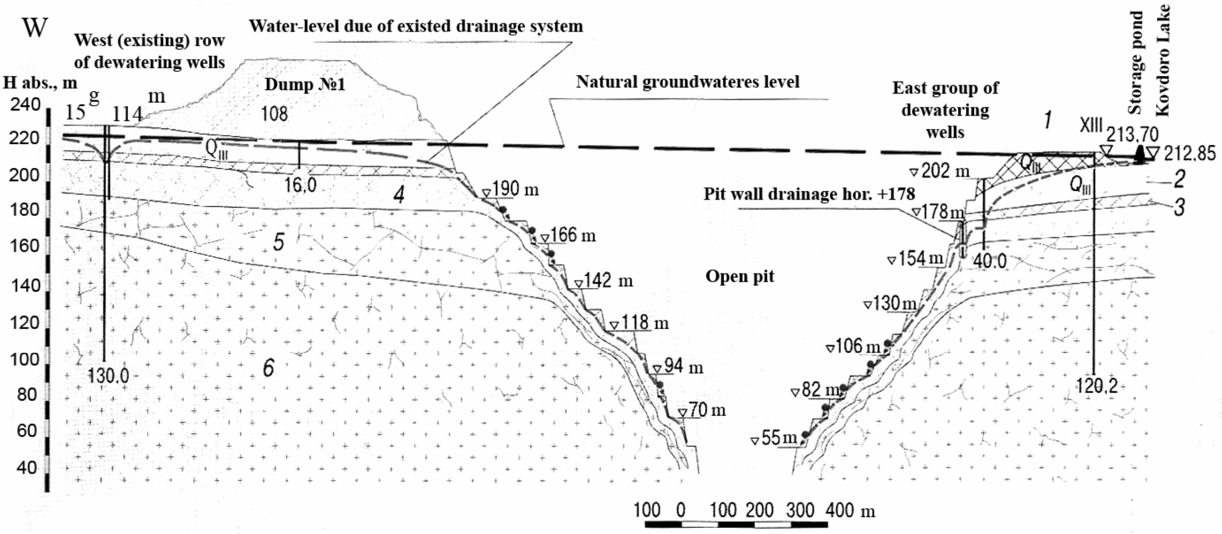


Figure 2 *Hydro-geological section along line 1 — 1 (see Figure 1):*
1 — embankment; 2 — alluvial sediments; 3 — disintegration zone; 4 — interconnected strong fissuring zone; 5 — interconnected weak fissuring zone; 6 — uninterconnected weak fissuring zone.

Water inflow of ground water on open pit benches are confined basically to zones of tectonic dislocations. The total flow rate of sources reaches 300 m^3/hr. According to mathematical modeling the basic sources of formation, ways and intensity of the ground water stream towards the open pit have been determined. By the identified characteristic bands of current it is found, that the general water inflow arriving in the open pit and in the drainage system, makes 3350 m^3/hr.

The largest (up to 2120 m^3/hr) inflow is formed in the east and northeast flanks from the direction of mine water settling pond (1450 m^3/hr) and by tectonic faults from an old bed of Zhelezorudny stream (660 m^3/hr), which makes 63% of the total inflow. In the western flank from the direction of Verkhnjaya Kovdora River and the discharge channel by sediments of the old bed there is formed an inflow of an order of 1040 m^3/hr, or 31% of the total inflow. The other 6% of the total inflow account for southern (200 m^3/hr) and northern (10 m^3/hr) flanks.

The physical factors determining the negative impact of ground waters on the stability of cutoff part of the mass include: mechanical impact, hydrodynamic pressure and hydrostatic weighing.

Mechanical impact of the ground water getting out on slopes, composed of hard rocks and half-rocks, is manifested in the formation of taluses, loss of stability of some block masses and inrushes. A special role in the circumstances of operation of «Kovdorsky GOK» JSC is played by the processes connected with the repeated alternate freezing and thawing of water in the fractured zones of the near slope mass. Their impact is manifested in the expansion of fractures and decrease of rock strength directly in the contact zone of slopes, which results at the initial stage in formation of taluses and inrushes of separate rock lumps.

At the open pit bench slope position being close to vertical, the negative impact of ice mounds, formed on slopes increases. Their formation is observed at sites of the most intensive water egress onto the slopes. By rough calculations, the weight of ice mounds, per 1 m of slope, can reach 100 kN, and at double benches — 200 kN.

The hydrodynamic pressure resulting from rock resistance to the movement of ground water stream is directed along current lines and is a volume force, which specific value (per volume unit) at the free egress of the stream on a slope is defined by the value of the stream pressure head gradient. During the movement of ground water in cutoff part of the mass the angle of their stream, and, hence, hydrodynamic pressure, increase 2.1-7.4 times, and in the outline zone of abrupt slopes — 23 times. With slope inclination angles of open pit walls of 55° the maximum gradients of pressures in separate areas of open pit can reach the value of 1.43, and hydrodynamic pressure accordingly 14.3 kN/m^3.

Rocks which are underlying below the level of ground waters undergo the hydrostatic weighing. The influence of weighing forces causes a sharp reduction of the internal friction angle of water containing rocks and, finally, a decrease of the value of friction forces along the potential surface of sliding (separation). In the southern wall of the open pit, in the cutoff part of the mass intercalation of waterproof tectonic zones with gouge and the watered zones containing pressure head waters. Due to forces of hydrostatic weighing the specific weight of ijolites and fenites, composing this wall, decreases to 37-38% by calculations.

The water inflow especially affects the stability of the cutoff part of the mass during the periods of abundant rains and snowmelt, as well as during bulk blasting in the open pit.

The above factors in combination with the results of hydro-geological study and mathematical modeling were used as substantiation of the necessity of strengthening and development of the open pit drainage system (Figure 3).

The impact of various pollution sources on the ground water quality in this area is quite definitely diagnosed by the results of hydro-chemical sampling of drainage and open pit waters. In particular, these materials allowed to reveal the tailing dump discharges approaching the southern flank of the deposit: the water discharged in the open pit here is characterized with rather high pH values (> 9), presence of carbonates (CO_3) in water, moderate concentration of solutions (up to 100-120 mg/l), as well as content in water of such specific components, as surface active substances, phenols, tall oil. As a whole the monitoring of ground water pollution with industrial discharges from the tailing dump present one more example of limited possibilities of self-cleaning of ground waters migrating in the masses of hard fractured rocks.

In the western and northern flanks of the Kovdor deposit a special hydro-chemical type of ground alkaline (pH = 8.2-8.45) waters of essentially sulphate calcium composition is formed, while, at the same time it is possible to speak about a clearly manifested sulphate pollution; the concentration of

SO_4^{2-} ions here almost two orders exceeded the background values, reaching two-three MACs (according to standards for fishery water management). It is important, that monitoring observations allowed to reveal the general tendency towards accumulation of SO_4^{2-} ions in drainage and open pit water, which has been taking place especially actively since 1983, as well as some growth of pH index in time.

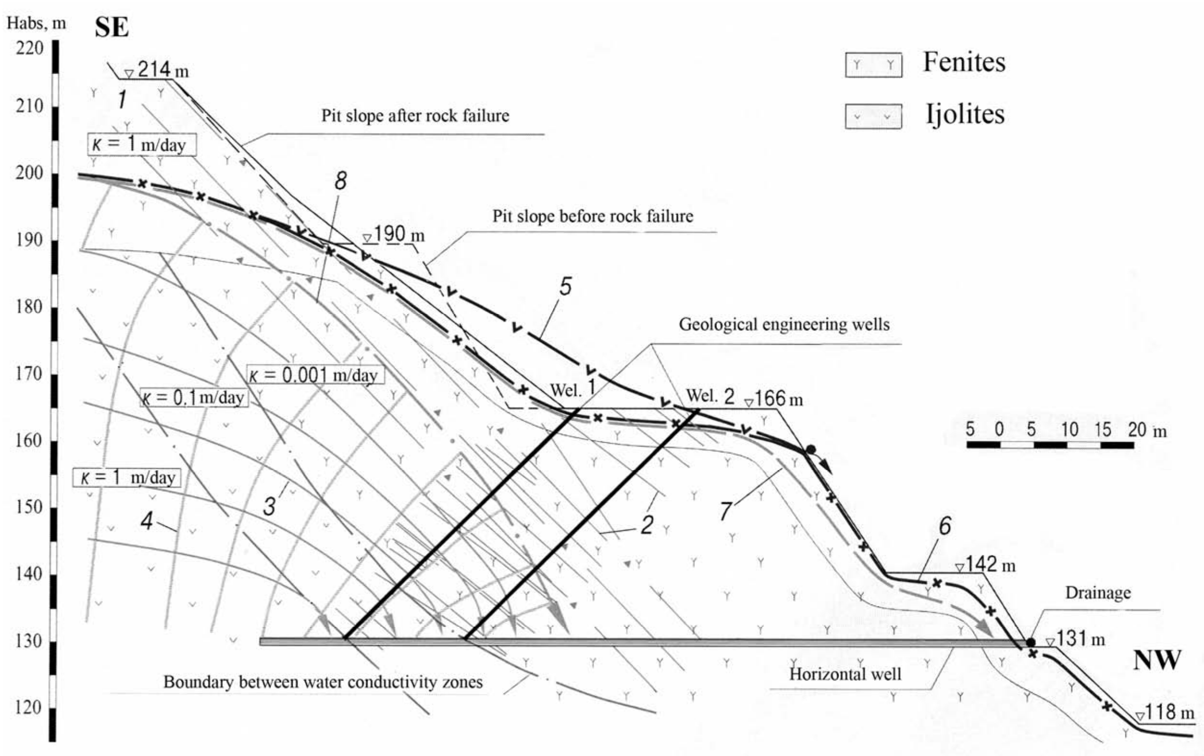


***Figure 3** Scheme of seepage with horizontal well working:*
1 — decomposition zone; 2 — tectonic disturbance;
flow net: 3 — current line, 4 — equal pressures lines;
existing groundwater levels: 5 — with free surface, 6 — piezometric of pressured zone;
reduced groundwater levels: 7 — with free surface, 8 — piezometric of pressured zone.

It is necessary to notice, that the considered ground waters are also characterized with sharply increased contents of nitrogen compounds.

The tendency towards the increase in concentration of SO_4 ions during the flood (summer-autumn) period when the interaction of atmospheric moisture with dump rocks becomes more active is distinctly manifested; on the other hand, melt water, polluted with sulphur compounds from atmospheric emissions gets into the aquifer in this period. The minima of SO_4 concentration correspond to the winter low-flow period when the role of the above factors is insignificant.

Mining-induced seismicity

Large-scale mining operations actively influence the condition of the geological setting. During the excavation and moving of considerable volumes of rock there occurs a redistribution of operating pressures within the mass. Therefore, the geological setting passes into unstable condition from the stable one. Since the rock mass is a hierarchic-block environment, the direct consequence of pressure redistribution in any separate block (or in several blocks interconnected between themselves via zones of reciprocal influence) there will be reaction of the mass to these changes. More often it is manifested as release of seismic energy due to a sharp change of pressure at various movements occurring within the mass (Fedotova 2004).

The seismic response of the mass within which the mine field of the operating mine is located, is influenced by both the geological and tectonic structure of the mass, the mining technique of the deposit under question, the amount of the blasted explosives or the rates of mining operation implementation. The hydrological conditions of the area under question exert certain influence as well. Presence of non-uniformly scaled fracturing causes the saturation of rocks with liquid. Depending on the porosity and humidity permeability of rocks, composing the mined deposit, the seismic response of the mass can be different.

Low saturation and permeability are characteristic for hard rock masses. However, this fact poses a certain threat of occurrence of a strong seismic event in presence of faults filled with permeable material. Being quickly absorbed, the moisture gets to a considerable depth, going down through the fault filler between its edges. The saturated filler becomes an excellent lubricant, for unobstructed displacement of massive blocks relative to each other since the value of rocks adhesion at the block-fault boundary becomes actually close (and in some cases is even equal) to zero. Such displacement leads to release of considerable seismic energy which is caused by the scale factor as in hard rocks; the block sizes considerably exceed the size of block of the fractured mass.

So, for example, near a large-scale development of deposits in the Khibiny massif, the total increase of seismicity is due, as a rule, to increase of rock saturation as a result of intense snow melt, long and intense rains, a sharp change of temperature conditions, stressed state of the mass and the carried out blasting operations, both in open pit and underground mines. Presence of relief surfaces in a rock mass in the form of rocks oxidation zones, fracturing zones and other non-uniformities of geological setting substantially reduces strength properties of rocks as a whole, which provides conditions for occurrence of mining-induced earthquakes (Fedotova 2005).

At the moment of the earthquakes registered within the zone of joining of Rasvumchorr underground mine and the Tsentralny open pit mine in the 2004-2007, there were occurring some movements along dislocations with a break of continuity present in the mass, represented with oxidized rocks (Melnikov 2007). As a result of each of the strongest earthquakes, a block resting on a dislocation with a break of continuity under the influence of changes in the stress state of the mass was displaced relative to the underlying block which usually resulted in various failures of underground workings and surface buildings and structure (Figure 4).

If we consider the issue of the Tsentralny open pit decommissioning one of the basic peculiarities of this mine closure project development will be the issue of minimizing the impact from processes, occurring in the open pit, on the workings of Rasvumchorr underground mine located under it.

The monitoring results of correlation between hydrology regime and rock mass seismicity in May 2005 are shown on the Figures 5, 6, 7.

***Figure 4** West-North pit wall of Tsentralny mine failure*

Figure 5 *Precipitations dynamic, mm*

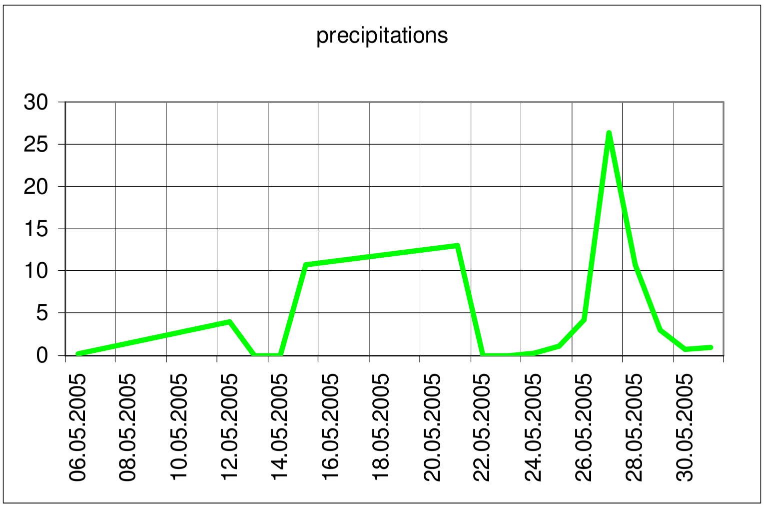


Figure 6 *Temperature dynamic, °C*

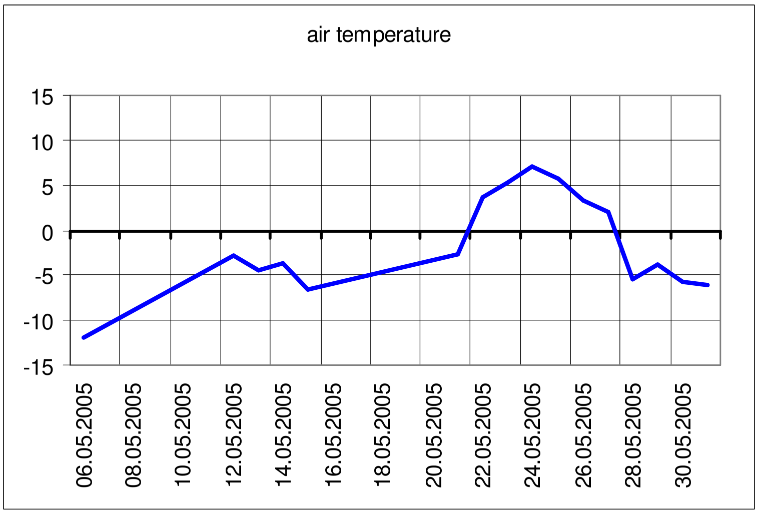
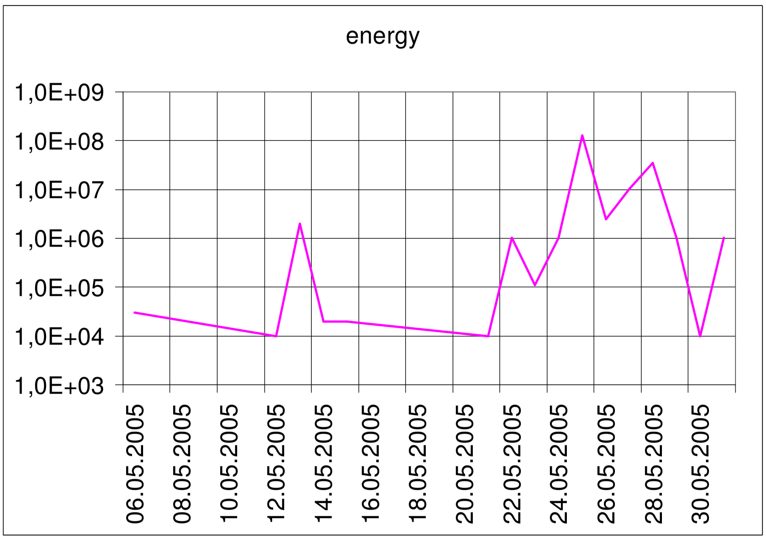


Figure 7 *Seismicity dynamic, J*



Conclusions

Closure of mine means solving both technical issues and social, economic and environmental problems, as well as ensuring long term technological safety and environmental integrity. Mine closure is accompanied with both positive and negative changes of the environment. Negative factors include changes of underground hydrosphere, hydrodynamics and hydro-chemistry resulting in aquifers contamination; ground deformation and submergence in mining-induced areas; continuous gas emissions on the territory of liquidated mines in new hydrodynamic conditions, etc. Positive changes include less impact on atmosphere, soil, surface and ground waters, on flora and fauna; land rehabilitation.

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