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REMOTE MONITORING OF MINING SITUATION AND DISTURBED LAND ECOLOGY AT THE TEISK AND ABAGAS IRON ORE DEPOSITS

Scientific research recently undertaken either in Russia or in other countries increasingly uses remote Earth sensing techniques. At the next stage of our studies, we assess ecology of disturbed land represented by open pit mines, external dumps and tailings pond in the area of depleted iron ore deposits in the Republic of Khakassia. Monitoring of vegetation ecosystem in the specified area used free-access remote sensing data.

Based on the interpretation of satellite images over the monitoring period from 1998 to 2016, the change in the bold area at the depleted deposits is determined. The dynamics and structure of vegetable blanket in the open pit mines, at the dumps and tailings pond is revealed. An insignificant increase in the disturbed land area from 595 ha in 1999 to 633.3 ha in 2916 resulted in the proportional growth of the bold area of mining and dumping from 559.9 to 571.1 ha. By the end of the monitoring period in 2016, the vegetation ecosystem recovery coefficients without special reclamation of the distributed land were 0.031, 0.05 and 0.11 for the areas of the Teisk and Abagas open pit mines and the land occupied by external overburden dumps and tailings ponds, respectively.

The article illustrates application of satellite survey data in solving such critical problems as environmental impact of open pit iron ore mining. By our estimates, self-recovery of two separate industrial landscapes formed under mining of the Teisk and Abagas iron ore deposits on the eastern shoulder of the Kuznetsky Alatau has very low and environmentally unacceptable rates. Such conclusion is confirmed by the determined averaged coefficient of vegetation ecosystem recovery at the very low level of 0.088, which means healing and stable vegetation cover in the area making merely 8.8 % of the total disturbed land.

Key words: *Republic Khakassia, Teisk iron ore deposit, Abagas iron ore deposit, open pit mining, remote Earth sensing, long-term satellite monitoring, waste dumps, disturbed land ecology, vegetation ecosystem*

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Introduction

Currently in Russia, iron ore mining is carried out on the Kola Peninsula, in the Republic of Karelia, the Central Black Earth Region, Irkutsk Region and in the Urals. In the Krasnoyarsk Territory, iron ore has been extracted with the surface method at the Teisk deposit since the late 1950s and at the Abagas deposit since the early 1980s. Iron ore reserves suitable for opencast mining are totally depleted by now. The open pit mining area represents an industrial landscape of closed open pit mines and waste piles. The review of the mining ecology studies shows that the dedicated literature gives no information on ecosystem recovery in the discussed area. In connection with this, it seems theoretically and practically interesting to undertake long-term monitoring with the resultant evaluation of ecological balance recovery efficiency in the area of industrial landscape formed during mining of the mentioned deposits.

Relevance of the studies

The problems of mining ecology are being solved by ecologists on all continents lately. An emphasis is laid on assessment and reclamation of mining-disturbed lands, which is duly reflected in the special subject literature [1–12]. On the other hand, the scientific literature review discloses deficiency of the research into open pit mining ecology using data of different-time remote sensing. Intrinsically, this is a background for detecting long-term trends in the formation and evolution of ecosystems in any area of the Earth, including open pit hard mineral mining regions. Currently, the research into ecology of surface mining and disturbed lands using remote Earth sensing is undertaken by the Reshetov Siberian State Aerospace University and by the Nauka Special Engineering Bureau attached to the Institute of Computational Technologies, Siberian Branch of the Russian Academy of Sciences.

Research results

Opencast mining operations at the Teisk and Abagas iron ore deposits in the Republic of Khakassia resulted in the formation of an industrial landscape composed of two open pits and three waste piles nearby. The Teisk deposit was developed since 1958 by the Teisk Mine Management — one of the iron ore extracting and processing companies in the Krasnoyarsk Territory (since 1991 this territory belongs to the Republic of Khakassia). Surface mining at the Teisk and Abagas deposits since 1958 and 1983, respectively, supplied iron ore to the West Siberian Metallurgical Plant. Since 1983 the Teisk Mine Management included two opencast mines, which were located 125 km southwestward of Abakan and 110 km southeastward of Mezhdurechensk, a crushing and dressing plant and other auxiliary workshops.

The Teisk deposit holding the West Siberia's largest proven reserves of magnetite ore lies at the border of Gornaya Shoria and Khakassia, on the southeastern periphery of the Kuznetsk Alatau, on the west shoulder of the Abagas Mountain (1395 m). The deposit is enclosed by ancient Yenisei-formation dolomitic limestone with silicate rock interbeds. The mineralized zone is 1200 m long on the surface. Ore is traced down dip to a depth of 775 m and below. The footwall of the

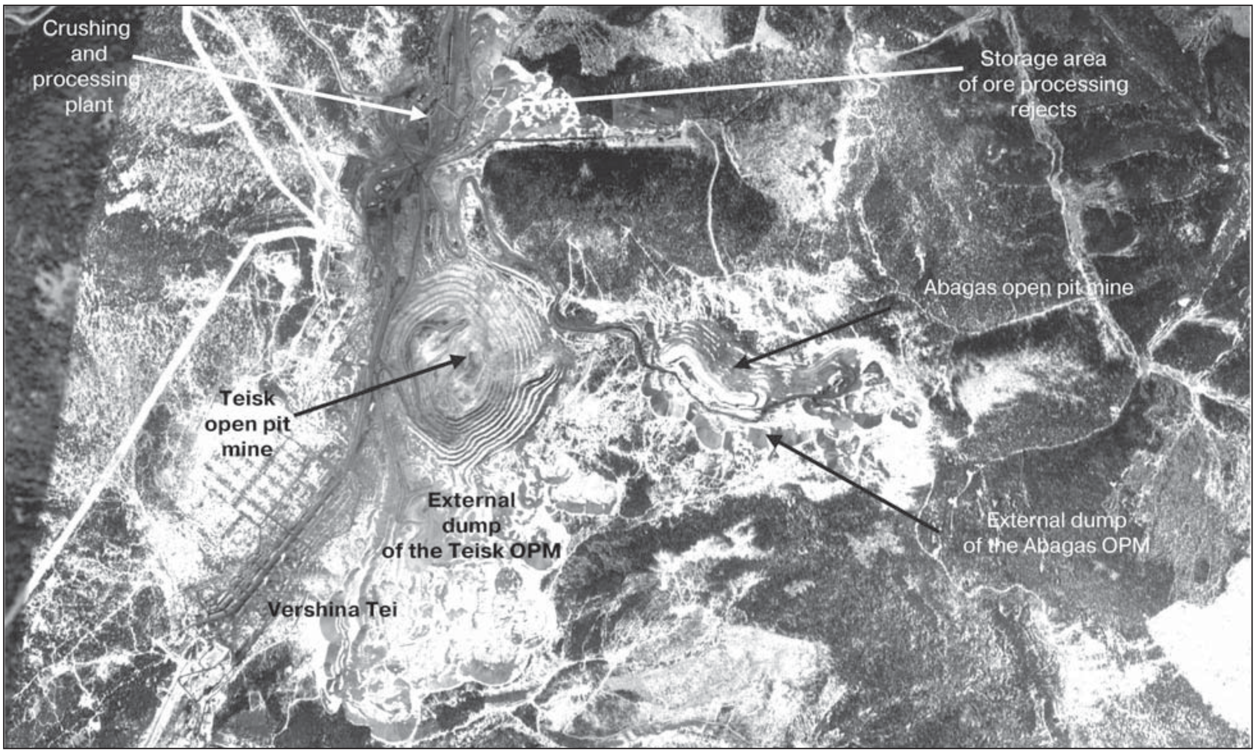

Fig. 1. Satellite image of physical layout of open pit mines and waste dumps of the Teisk Mine Management

ore zone has a tectonic nature contact with limestone. The average iron content is 30.8%. The main metal is magnetite, the secondary minerals are mushketovite, hematite and pyrite. In plan view, the Teisk ore zone is shaped as a scimitar lens more than 1000 m along the strike with maximum horizontal thickness of 380 m. Here, 5 high-dip ore bodies hold nearly 80% of total reserves. The Abagas deposit contains two ore zones: South (more than 2600 m long) and North (total length of 2300 m). In-place iron ore reserves mineable with the opencast method and ranked as categories B + C_1 + C_2 in 1985 totaled more than 137 Mt at the Teisk deposit and above 73 Mt at the Abagas deposit [13].

Open pit mining condition at the Teisk deposit was estimated using a satellite image of 2002. The layout of industrial objects of the Teisk Mine Management is shown in **Fig. 1**.

Both deposits were developed using the truck-and-shovel system with gradual transition to deeper levels and with external dumping. Loading operations were carried out by cyclic shoveling machines EKG-5 and EKG-8i, haulage was executed with BELAZ dump trucks with capacity to 40 t. Dumping was implemented using bulldozers DET-250 [14]. In 1988 ROM ore production made round 4.4 Mt at the iron content of 28.4%. Ore dilution was 99.5%. Magnetite ore was subjected to pre-treatment by crushing and dry magnetic separation at the crushing and dressing plant. In 1988 production of primary concentrate totaled 2.9 Mt at the iron content of 37.1%. The concentrate was shipped to the Abagur Processing and Agglomeration Plant in the Kemerovo Region by railway.

In the satellite image, 5 objects were chosen for the remote monitoring of ecological indexes of the mining-disturbed land: Teisk open pit mine (OPM) and waste pile placed southward of it; Abagas OPM and southward external dumps; iron ore processing waste located eastward of grinding-and-sorting factory [14].

In 2002 the Teisk open pit mine had area size of 1370 m from west to east and 1420 from north to south. The pit was shaped as a circle with a radius of 700 m. The overburden haulage distance on the ground surface to the external dump southward of the open pit mine was 2.11 km, or 5.99 km with the inner pit roads taken into account. The ROM ore was hauled to the crushing-and-dressing plant at a distance of 6.2 km. The depth of the open pit including the hill part was 365–370 m by 2002. Mining equipment included two drilling rigs SBSG-250, one shovel EKG-8i and four shovels EKG-5. The annual rock mass capacity of the open pit mine totaled 2.8–3 Mm^3.

The upland-type Abagas open pit mine reached the depth of 210 m by 2002. The highest elevation of mining was 1360 m above sea level.

The waste haulage distance was 0.8 km from the processing plant to the processing rejects storage.

Ecological state of the mining landscape was estimated using remote sensing data obtained at different times. The estimation included such factors as climate, soil and natural vegetation cover.

The climate of the region of the Teisk and Abagas OPMs is extremely continental. Winter is long and hard, and summer is short and indulgent. The average annual temperature is at the level of 0 °C. The coldest and low-snow winter month is January with the temperature to –40 °C; the warmest and driest month is July with +24.2 °C. The daily range of temperatures is wide. The autumn and spring frost is very often. The average annual amount of precipitation reaches 600 mm. The dense snow cover has a thickness not more than 1 m. On the east shoulder of the Kuznetsky Alatau, where tundra and steppe interchanged time and again in the Ice Age, pre-Quaternary weathering crusts are lost. As a consequence, the coarse humus low-productive forest earth is spread in this area. Between the elevations of 800 and 1300 m, aspen–firry grass forest alternates with the firry and cedar taiga with almost continuous cover of moss and lichen, or with larch taiga on the less wet arms of the east shoulder of the Kuznetsky Alatau [15].

In the heavy wet areas at the elevations between 800 and 1300 m, the fir and spruce forest takes turns with the fir and cedar taiga. The underbush and grass layer are weak. Unlike in the fir and spruce forest, the fir and cedar taiga has a thick continuous moss and lichen cover, and such taiga plants as blackberry, clusterberry, wild rosemary, wintergreen and northern Linnea. On the less wet arms of the east shoulder of the Kuznetsky Alatau, at an elevation of 850–1200 m, the larch or pine-larch forest with the thick gross cover grows on soddy-podzolic soil. Thus, the mining area experiences influence of natural climate factors which can considerably decelerate restoration of disturbed vegetation.

Ecological state of the mining landscape at the Teisk and Abagas deposits was estimated using remote sensing data obtained at different times. The time-and-space analysis of revegetation dynamics used images of Landsat 5 and 8 satellites over a period from 1998 to 2015. The vegetation types were determined using spectral data in the near infrared, red and green ranges.

For general understanding of long-term trends in the formation and growth of vegetation ecosystem in the worked-out open pits and at waste dumps, four classes of the mining landscape with the mature vegetation cover clearly seen in the satellite images were distinguished: well-developed forest—stand; young forest — brushwood which will become well-developed in 10–12 years; sites with the signs of the vegetation cover recovery; sites with grass cover. The shape of the water body in plan view repeats the open pit mine geometry with spoil benches at the bottom. By the authors' estimate, the man-made water body is 30 m deep.

The different-type mining landscape, the earth structure and the coverage characteristics were determined using ArcGIS software. First, four objects marked with the numbers in **Fig. 2** were chosen for the research: two external dumps 1 and 2, Teisk OPM 2 and the Abagas OPM with the external dump 3. The latter was analyzed as an integrated object. Figure 2 also shows the area decoding results with the delineated areas in accordance with the mining landscape classes.

The open pit mines under analysis belong to the upland type and have all integral features of such mining operations. The external dumps are placed in the areas of natural landscape covered with the continuous taiga forest. Here, we clearly see transformation of the landscape with the natural forest ecosystem into mining waste dumps almost free from any vegetation cover. Moreover, no technical and biological reclamation was performed in the open pit mines or at the dumps. By the authors' opinion, such situation was caused, first, due to the absence of governmental standards for mining-disturbed land reclamation (in the 1950s) and, second, due the disregard of remediation activities included in the later project designs.

Mining-disturbed land always has sites of spoil benches, or external dumps in the form of truncate cones. Such cones are made of two–three layers. One layer may reach 115 m in height (when made on hillside). The dumps, benches, areas between the benches and the bottom of the Teisk open pit mine are absolutely free from vegetation.

The transformation of the above-classified man-made landscape and vegetation ecosystem is described in **Fig. 3**.

It is found that the total area of all objects of the industrial landscape grew insignificantly in the period under analysis — from 595 to 622.6 ha. The change in the area of the grass vegetation sites exhibited alternation of the upward/downward trends, in 1998 this index was 21.9 ha and increased slightly to 26.9 ha by 2008. Then, the area of vegetation cover sites began to reduce and decreased to 24 ha by 2016.

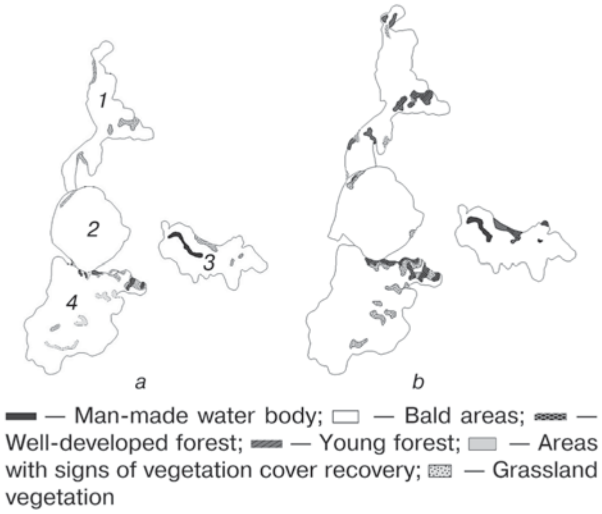

Fig. 2. Fragments of study land images with the decoded objects of industrial landscape at the abandoned Teisk and Abagas iron ore deposits:
***a* — July 1998; *b* — July 2016**

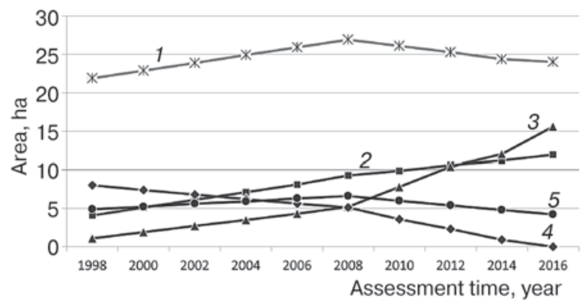

Fig. 3. Satellite monitoring data on vegetation cover and man-made water body in the area of industrial landscape resulting from the iron ore mining at the Teisk and Abagas deposits:
***1* — Herb stratum, ha; *2* — Young mixed forest, ha; *3* — Well-developed mixed forest, ha; *4* — Areas with the signs of vegetation recovery, ha; *5* — Man-made water body, ha**

The change in the areas of the young and well-developed forest shows an upward trend. In 1998 the young forest area was 4.1 ha, then it grew 3 times and made 12.6 ha by 2016. The well-developed forest area increased by 15 times within the study period and was 16.6 has in 2016.

The area with the signs of the vegetation cover recovery was 8 h at the beginning of monitoring; by 2016 this index was at the zero level, which meant that the areas totally passed to the category of sites with the grass cover.

The sites with the vegetation cover locate on the southward pitwall. The total area with the vegetation cover was 8.33% of the industrial landscape in 2016. Geographically such areas occur on the slopes of dumps made in the early period of the Teisk deposit mining in the 1960s–1970s. The average annual increase in the area of all vegetation cover types was 1.08 ha.

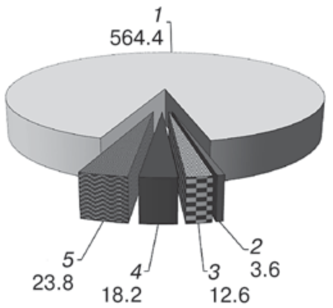

Fig. 4. Structure of the recovered ecosystem of the objects of industrial landscape formed under mining at the Teisk and Abagas iron ore deposits by 2017, ha

At the bottom of the Abagas OPM, the area of the spontaneous man-made water body was 4.5 ha in 1998. Over the period from 1998 to 2008, its area gradually grew to 6.6 ha. By 2016 the water body area decreased to 4.2 ha. Such situation can be explained by the influence of natural factors such as snowfalls and rainfalls in winter and summer, respectively.

The sites with the vegetation cover occur at the top of the southward pitwall of the Abagas OPM, which was put out of operation in the late 1980s – early 1990s. These sites have maximum solar thermal energy. The total area with the mature vegetation cover in 2018 was 5.8% of the area of the open pit mine and external dumps.

Having analyzed the structure of ecosystem recovered by 2018 in the area of industrial landscape resulted from mining at the Teisk and Abagas iron ore deposits with the total area of 622.2 ha, the authors have arrived at some major conclusions. The self-recovery (reclamation) coefficient of vegetation ecosystem in the eastern Kuznetsky Alatau regions, Republic of Khakassia, under extremely continental climate is very low — 0.088 (**Fig. 4**).

The vegetation ecosystem recovery coefficient is calculated without regard to the man-made water body area and with regard to the change trends in the areas with all kinds of vegetation by the remote sensing data.

The grass layer continuum is mature in separate sites with the total area of 3.83% of the industrial landscape. The young forest layer is grown in separate sites of the waste dumps and processing rejects storage and makes 2.2% of the total area under study. The well-developed forest occupies the total area of 18.2 has (2.92%) in 2018. The man-made water body in the Abagas pit has an area of 0.58% of the total industrial landscape territory. The low value of the vegetation recovery coefficient means that the disturbed lands were not subjected to any reclamation activities. The other factor governing slow healing of the industrial landscape in the course of natural spreading of aboriginal species of all vegetation levels is the geographic position of the analyzed territory in the upland at the elevation from 900 to 1400 m.

Conclusion

Considering vegetation recovery rate in the territory under analysis, the period of expansion of forest over the industrial landscape can take more than 500 years. In order to improve ecosystem recovery, special rehabilitation measures are required to be undertaken on the disturbed land. In this case, restoration of ecological balance can take tens times less time. In view of the extremely unfavorable ecological situation, it is necessary to find ways to enhance efficiency of nature management and control in the analyzed area of industrial landscape. Improvement of ecological situation and recovery of ecological balance is possible after:

— advanced extraction of mineral reserves down to the bottom limit of open pit mine, which allows a mined-out area for overburden dumping and a reduction in natural landscape area planned for external dumping;

— covering the dumps with a surface layer not less than 1 m thick made of humus-bearing soil after first layer stripping, capable to support development of all vegetation layers and mixed with loose Quaternary rocks (clay, loam, sand, sandy loam, etc.);

— in case of deficient Quaternary rocks to make the surface layer on the dumps, the latter should be ripped by bulldozers to a depth not less than 1 m in order to soften the top layer compacted by shovels; this will promote detention of vascular plant seeds spread in the wind over the loosened slopes and offer conditions for the plant growth;

— creation of botanic points as forest reclamation areas 0.5–1 ha in size by means of staggered-order planting of hardwoods on the slopes of dumps.

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