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SUSTAINABLE PHOSPHATE ROCK MINING

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Abstract. The paper discusses ecologically and economically sustainable possibilities for phosphate rock mining at Toolse deposit in Estonia. The mining technologies studied include only those which guarantee safe treating of dictyonema argillite. In the case of open-cast mining, dictyonema argillite will be sealed. Mining production is estimated at 0.8 to 1.1 million tonnes of phosphate rock per year, yielding 52 to 72 thousand tonnes of phosphate concentrate per year with P_2O_5 content of 33 per cent. Mining might be profitable if the price of phosphate rock concentrate reaches 300 USD per tonne in the world market, which is three times higher than predicted today or for the near future. No efficient ecological methods are available for mining Estonia's phosphate rock today. Moreover, it is concluded that the phosphate rock of the Toolse deposit is not suitable for mining.

Key words: phosphate rock, dictyonema argillite, economic evaluation, ecology, open-cast mining, underground mining, sealing, backfilling, sustainable mining.

1. INTRODUCTION

Located in the north of Estonia, the Baltics' largest phosphate deposit (obolus phosphate rock) of Toolse and Kabala is well-explored. From 1968 to 1972, the Toolse deposit was studied under the research projects of the USSR Ministry of Fertilizer Industry. Preparations for open-cast and underground mining were completed by the late 1970s and early 1980s. The new Kabala and Toolse mining projects found strong public opposition. This opposition, informally called "phosphate rock war", was closely related to environmental issues. Because of very strong pressure, the development project of phosphate rock mining was stopped.

The main problem lies in dictyonema argillite because it tends to ignite spontaneously in the spoils. Occasional endogenic fires in the internal spoils of the Maardu phosphate rock open-pit support that opinion. Two basic methods of processing dictyonema argillite during mining are distinguished:

- utilizing dictyonema argillites by enrichment and desulphuration [1];
- hermetically sealing and burying of dictyonema argillite by current mining technology.

The Department of Mining of Tallinn Technical University has prepared four techniques: two for underground and two for surface mining. Both open-cast and underground productions are estimated at 1 million tonnes of phosphate rock per year.

The Toolse deposit is situated about 100 km from Tallinn, and the outcrop lies in the south of the town of Kunda. The depth of the phosphate rock layers increases from 50 to 150 m towards south and southeast. There is a working cement limestone quarry in the area of the deposit. The deposit lies close to two national protection areas: the Lahemaa National Park and the Pandivere Water Protection Area.

Near the Toolse deposit area, through small valleys, three slow rivers, the Kunda, the Toolse and the Selja, flow. As a result of dewatering the active mining area, mining at Toolse may have a significant effect on the local and regional ground water resources. Because of mining, water supply has been disrupted in several wells in the vicinity of the limestone quarry. The potential effects of mining on the Pandivere Water Protection Area, located to the south of the phosphate rock deposit, are unknown today.

Based on detailed geological explorations, the areas to be mined were selected using the following criteria:

- high productivity of P_2O_5 per square metre;
- small overburden thickness for open-cast mining;
- short transportation distance to the Kunda port;
- use of uninhabited and agriculturally worthless land.

The Toolse deposit contains a sequence of lower Cambrian sandstones, silt stones, and shales (Fig. 1). Its P_2O_5 layer thickness varies from 0.7 to 5.2 m, and the average thickness is 2.9 m. The average P_2O_5 content in the phosphate rock is 10.6 per cent. As mentioned earlier, a layer of dictyonema argillite or dictyonema shale overlays the phosphate rock layer. The dictyonema argillite contains a significant amount of organic matter and heavy metals. According to Pihlak [2] and others, on its exposure to the atmosphere, the dictyonema argillite ignites spontaneously and has been cited as the main environmental problem of mining the Toolse deposit. The dictyonema argillite in the Toolse deposit is from 1.25 to 2.05 m in thickness. Above the dictyonema argillite, in the lower Ordovician, is a clay layer from 1.60 to 2.65 m in thickness and a 0.70 to 1.30 m thick sequence of sandstones and limestones. The middle Ordovician contains fine crystalline limestone, dolomitized limestone and marls. This sequence is from 14 to 23 m in thickness, which increases southwards.

Quaternary sediments, composed of glacial tills, sands, clays, and peat deposits, cover this sequence and range in thickness from 2 to 3 m. Quaternary sediments can reach a thickness from 35 to 40 m in river valleys, buried by glacial deposits.

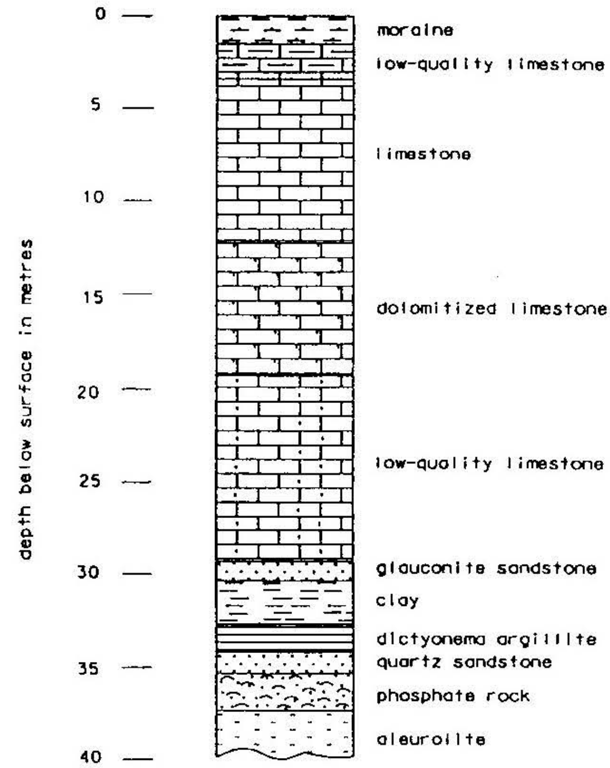

Fig. 1. Geological cross-section of the layers in the Toolse phosphorite deposit.

2. OPEN-CAST MINING

The open-cast area, located in the south-eastern part of the Toolse deposit, covers 6.03 square kilometres. In the same area, a cement limestone quarry is operating. During limestone quarrying, part of the phosphate rock overburden is removed.

The location of the present openings was chosen taking into account the highest concentration of P_2O_5 and the possibility of building a flotation plant near the mining field. Openings will be located on the western edge of the mining field, parallel to the Rakvere–Kunda railroad, where the productivity of P_2O_5 is from 0.5 to 0.6 tonnes per square metre. Eastwards, the productivity is 0.3 tonnes per square metre, an average productivity of 0.38 tonnes per square metre and reserves amount to 1.53 million tonnes. The overburden increases from north to south with an average thickness of 16 m.

The main trench and several trenches for transport will open the mining field on the western edge. During the detailed planning, the exact location and dimensions of the trenches will be determined. The spoil area is planned parallel to the main trench. The open-cast face will advance from west to east, and all benches will advance from south to north. The main trench may extend over the whole field, or it may be divided into shorter production sections.

A 16 m thick layer of overburden will be removed using four bench strippings and a direct dumping (Figs. 2 and 3).

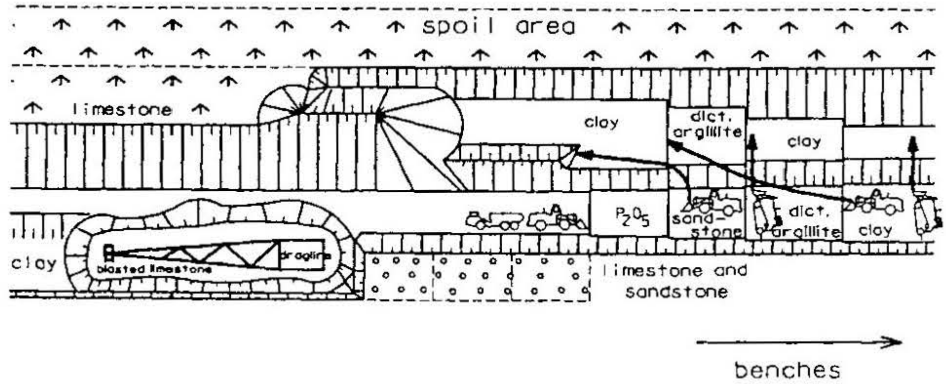

Fig. 2. Limestone stripping by an excavator.

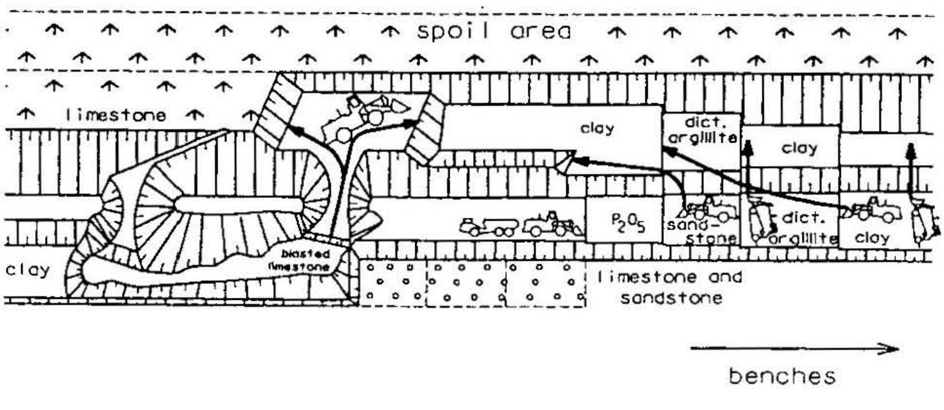

Fig. 3. Limestone stripping by dumping.

After limestone quarrying, the upper bench, containing low quality limestone (not suitable for cement production) and glauconite sandstone, will be blasted and transported to the top of the spoil area. There are two ways of transporting the overburden limestone and glauconite sandstone to the spoil heap:

- by wheel loaders with 16-cubic metre buckets;
- a dragline with a 15-cubic metre bucket.

During mining with wheeled loaders, the top of the spoil area will be divided into two or three benches. With the dragline, a bulldozer will level the top of the spoil. The clay layer will be divided into two parts. Two thirds of it will be transported by a 40-tonne bulldozer directly to the spoil area to form the lower water resistant bed for burying the dictyonema argillite. The remaining one third will be ripped and transported by a 5-cubic metre wheeled loader to the top of the dictyonema argillite layer. This bed will form a water-resistant cover to prevent spontaneous ignition of the dictyonema argillite. The third bench, the dictyonema argillite, will be ripped and removed by the same bulldozer to the top of the clay bed. The next bench, quartz sandstone, will be removed with the 5-cubic metre wheeled loader to the top of the lower clay layer. The wheeled loaders will load phosphate rock into 23-tonne articulated trucks. The trucks will transport it over temporary roads to the flotation plant. Drilling and blasting of the limestone layer will be carried out by subcontractors.

As the layers have a small dip to the south, a water ditch will be excavated on the south edge of the open-cast area. During mining, two or three loosened zones will be ripped at the bottom of the working area between the benches and the spoil. These zones will be interconnected over small distances to prevent blockage. Water will be first pumped into the settling ponds and then into the Toolse river. The spoil areas and the loosened zones at the top of the limestone bench will also be drained.

3. UNDERGROUND MINING

The geological conditions of the underground can be summarized as follows:

- thickness of the phosphate rock layer from 2.5 to 4.0 m;
- depth from 18 to 32 m;
- productivity of 5.9 tonnes per square metre.

The area of the proposed underground mining field is 9.96 square kilometres. The cement limestone reserve lies within this area, covering 2.33 square kilometres. The road from Rakvere to Kunda passes through the middle of the field. The average productivity of P_2O_5 in the field is 0.65 tonnes per square metre and reserves are 6.5 million tonnes. The bottom of the phosphate rock layer consists of aleurolite and the immediate roof layer above phosphate rock consists of quartz sandstone, dictyonema argillite and clay. Typically, in an Estonian oil shale deposit, the main roof consists of several layers of limestone.

Again, the main factor which determines locating of the openings is the productivity of P_2O_5. The highest productivity area (0.8 tonnes per square metre) covers about 0.75 square kilometres and is situated in the centre of the mining field. At the northern border, the productivity is 0.5 tonnes per square metre and at the southern border, 0.4 tonnes per square metre. Eastwards, in the Toolse river valley, P_2O_5 is absent.

The first drifts will be cut from the middle of the eastern border to the centre of the mining field. The mine will be opened with the main drift sloping at 8° for haulage trucks. Further drifting will start from the centre of the field, where the main and auxiliary haulage galleries will be located. The drifts are located in the phosphate rock layer. In the main drifts, concrete support will be used as the side walls consist of weak rocks.

Some technological problems of underground phosphate rock mining by the cut-and-fill techniques have been analysed by Päsok [3].

This study compared two underground mining methods: longwall mining and room-and-pillar mining.

Longwall mining. The deposit lies in the northeast- and northwest-directed tectonic fissures. In longwall mining, the working face will move from east to west, because then the main roof can be supported safely (Fig. 4). Longwall mining facilitates both breaking the roof and backfilling.

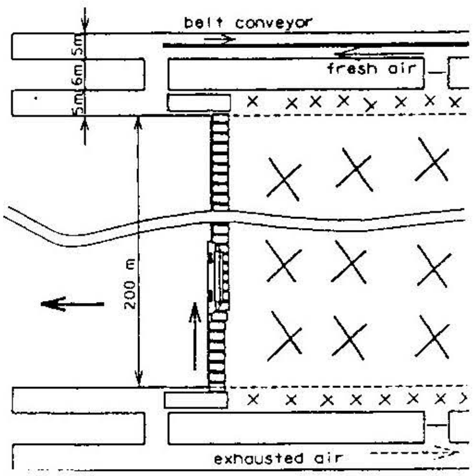

Fig. 4. Longwall mining by a shearer loader.

Tests were carried out by a shearer loader in the Maardu phosphate rock mine in the 1960s. The type of the shearer loader used was 2K-52M (Russian, 105 kW, cutting tools available were not suitable for abrasive rock).

For calculations we have selected the double drum EDW-300 shearer loader (Eickoff, Germany). Its cutting range is 0.625 m, and it can operate at 300 or 600 kW, at the working speed of 3.5 m per minute. The shearer loader must be equipped with cutting tools such as disc cutters, which can operate in abrasive sandstone such as phosphate rock. The expected consumption of turning tools and disc cutters is 100 and 10 units per shift, respectively. Other equipment in the panel section will be: a scrape conveyor, designed specially for abrasive rocks; supports; and a belt conveyor. The shearer loader will cut in one direction only to reduce the health hazard from the silicon dioxide dust.

The rocks in the immediate roof are so soft that if the whole roof collapses, the main roof will compress them, sealing the dictyonema argillite and preventing its spontaneous ignition. The collapse of the roof would cause the ground at the surface to be depressed by 1.63 to 2.6 m.

Room-and-pillar mining. Panel drifting will be used in the room-and-pillar mining method (Fig. 5). The line pillars supporting the roof will be located in a "V" shape. The working faces will advance from southwest to northeast. In the working area, karst rocks will be located between neighbour tail gates. The face will be broken by drilling and blasting, using the following equipment:

- two units consisting of 35 cubic metre trucks;
- two units of 4.6 cubic metre LHDs;
- three drill jumbos;
- one roof bolter.

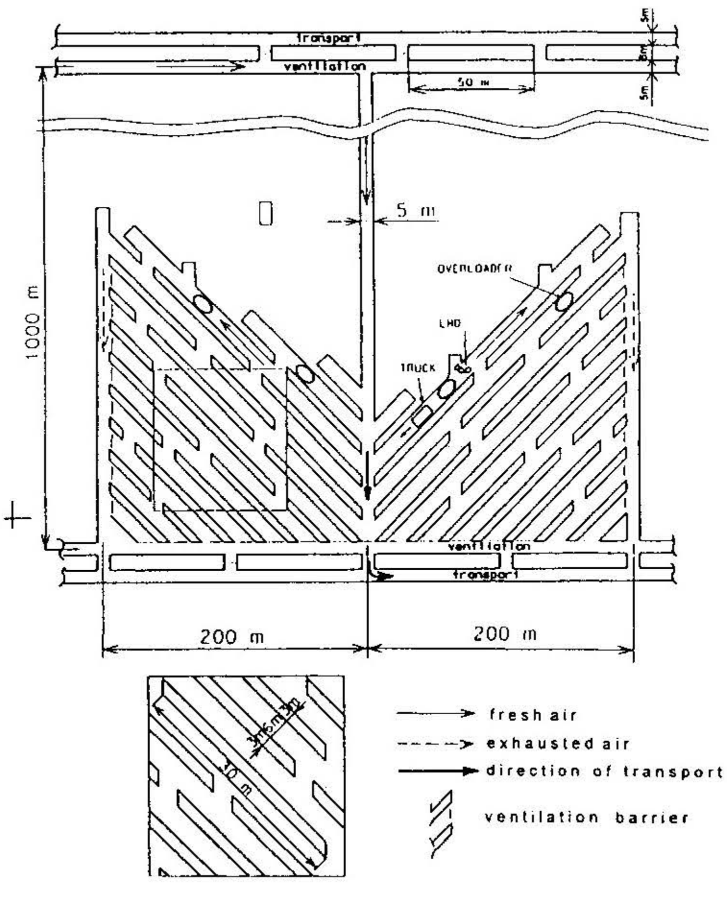

Fig. 5. Room-and-pillar mining.

Drilling and blasting will take place over two five-hour shifts per day. The charges required will be calculated at 0.6 kg per cubic metre. Concrete supports will be used in the drifts and anchor bolts in rooms. The two-metre long concrete anchors will be located at one-metre distances. Without backfilling, there is always a danger of an immediate roof collapsing and the dictyonema argillite igniting. We have no knowledge of the stability of the immediate roof. Ventilation is provided by local blowing.

Backfilling. Hydro-filling will be used in both cases. After compacting the remainder phosphate mineral will be mined. Waste sand and oil shale ash will be used for filling. The waste sand and ash will be transported by road and railway.

The following losses of ore are expected: 25 per cent by longwall mining and 22 per cent by room-and-pillar mining with backfilling.

4. ECONOMIC EVALUATION

The open-cast and the underground mining technologies use the same flotation plant, located in the Toolse River Valley. It was assumed that the conventional flotation technology is suitable for concentrating Estonian phosphate rock. Calcination was not planned. The yield of commercial concentrate is estimated as:

$$S = \eta \times a/k,$$

where according to Reinsalu [4] the degree of flotation η is estimated as

$$\eta = 1 + 0.14 \ln((\chi - k)/(\chi - a)),$$

where a, average P_2O_5 content in the ore, accounted for 10 per cent; k, P_2O_5 content required in the commercial product, accounted for 33 per cent; and χ, the theoretical P_2O_5 proportion for the Toolse phosphate rock, accounted for 35 per cent. Substitution of the above values in the equation for η gives the result of $\eta = 0.65$.

For one-product flotation plants, calculations of the capital and operating costs of the concentration were performed according to Camm [5]. The capital costs for the construction of the flotation plant are estimated at 190 million EEK and the operating costs per tonne of ore at 54 EEK/t (in 1998) to 71 EEK/t (in 2004). Mining equipment was chosen according to overburden and phosphate rock capacities. The costs of landed property were taken as established in the Lääne-Viru County. Road construction and electric power line costs were based on Camm [5]. Capital costs of recovering water supply and local well system were taken at 1.5 million EEK. Other costs, 4.5 to 5.7 million EEK per year, taken at 5 per cent from operating cost, included reclamation costs. Taxes and insurance were included in the cost estimation. Salaries were estimated at a level higher than the current Estonian average, reaching Finnish rates in 8 to 10 years. Equipment costs are quoted in US dollars, converted into Estonian kroons (EEK) at an exchange rate of 14 EEK per USD. Building and machinery costs will be covered by loans at an assumed interest rate of 8 per cent per year. Inflation was assumed to be 5 per cent per year.

Main results of the economic evaluation

Indicators	Mining technologies			
	Surface		Underground	
	wheel loader	dragline	room-and-pillar	longwall
Capacity, million tonnes phosphate rock per year	1.1	0.8	1.0	1.0
Output, thousand tonnes concentrate per year	71.5	52.0	65.0	65.0
Capital costs, million EEK	414	347	392	484
Equipment	155	86	65	194
Buildings, incl. flotation plant	259	262	327	291
Number of employees (miners)	62	76	74	77
Accounting concentrate price, USD per tonne P_2O_5	300	300	300	300
Net present value cash flow at interest rate of 15 per cent	206	75	220	153

5. CONCLUSIONS

Among environmentally safe mining methods, the wheeled loaders are best for surface mining the Toolse phosphate rock deposit. In addition, the equipment can be rented out or sold easily, if necessary, which is not the case with the dragline equipment.

The most efficient method for underground mining is room-and-pillar technology with backfilling. Moreover, this method facilitates prevention of spontaneous ignition of dictyonema argillite, which may otherwise occur if the roof collapses.

The Table shows that no efficient methods are available for mining Estonia´s phosphate rock today, since the marginal price of the phosphate rock is 100 USD per tonne. Moreover, it can be concluded that the phosphate rock of the Toolse deposit is not suitable for mining, the main reasons being:

- the low grade of the ore;
- the thickness of the beds;
- the difficulties of sealing dictyonema argillite in the spoils.

Mining might be profitable if the price of phosphate rock concentrate in the world market reaches 300 USD per tonne.

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FOSFORIIDI SÄÄSTLIK KAEVANDAMINE

Alo ADAMSON, Enno REINSALU, Lauri JUUSE ja Ingo VALGMA

On käsitletud Eestis asuva Toolse fosforiidimaardla majanduslikult ja ökoloogiliselt õigustatud kaevandamise võimalusi. Vaatluse alla on võetud vaid need kaevandamistehnoloogiad, mis tagavad kaasneva diktüoneemaargilliidi ohutu käitlemise. Pealmaakaevandamise puhul on uuritud diktüoneemaargilliidi matmist. On näidatud, et 0,8–1,1 milj. tonnist kaevandatavast maagist saaks 52 000–72 000 tonni fosforiidikontsentraati kasuliku ainese (P_2O_5) sisaldusega 33%. Kaevandamine õigustaks ennast, kui kontsentraadi müügihind oleks 300 USD/tonn.

Uuringu tulemusena selgus, et Eesti fosforiidi majanduslikult tasuv ja keskkonnahoiu seisukohalt talutav kaevandamine pole võimalik ja asjakohane oleks fosforiidi kustutamine Eesti maavarade nimistust.