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7.6 Study of underground mining explosions in the Khibiny Massif

History of mining activity in Khibiny

The "Apatit" joint stock company is the largest enterprise in the world for phosphorus ore extracting and enrichment. The sources of raw material for the company are the apatite - nepheline deposits of the Khibiny massif. The massif is a great alkaline intrusion connected with a regional tectonic fracture. It has oval shape, a size of about 1300 square km (36x45 km) and is situated about 900-1000 m higher than the surrounding plain of the Kola peninsula.

Apatite - nepheline ores in Khibiny comprise thick (100-200 m) stratum-like deposits (Kukisvumchorr (Kirovsk), Yukspor, Rasvumchorr) as well as a system of ore seams of 25-50 m thickness (deposits Koashva, Nyurkpakh). The correspondence between these deposits and the mines (1-6) shown on Fig. 7.6.1 is given in Table 7.6.1. A more detailed map of mines 1-2 is given in Fig. 7.6.2.

Surface mining in Khibiny began in 1930 with 250,000 tons of apatite extracted during the first year. In 1934 the extraction volume had increased to 1,136,000 tons. In 1933 the construction of Kirovsk underground mine was initiated. The first ripple-fired explosion of mine charges was made in 1936 during the Kukisvumchorr deposit development. By 1936 the ore extraction had reached 2,6 million tons per year.

During most of the Second World War the mines were not in operation. Mining was restarted in 1944. The pre-war level of ore extraction was re-achieved in 1950.

In 1951 the construction of the Yukspor mine was started and in 1955 it began operation. Since 1963 the Rasvumchorr and Central mines have also been in operation.

From 1965 to 1980 the annual ore extraction increased from 19.1 to 46.5 million tons. Since 1980 the Vostochny mine, which covers the Koashva and Nyurkpakh deposits has been operational.

By the early 1990s the mining company had achieved its highest annual volume of the ore extraction - about 60 million tons. In the underground mines the volume was: Kirovsk mine — 11.3, Rasvumchorr — 5.4, Yukspor — 5.1, and in the open mines: Central — 25, Vostochny — 7.0 million t. The rest of the volume was extracted by surface mining at the Northern and Saamsky open mines of Kirovsk and at the mountain part of the Rasvumchorr mine.

Nowadays Kirovsk and Yukspor mines are operated jointly and the work of the Nyurkpakh open mine is finished. Total volume of ore extraction in 1994 was 21 million tons: joint Kirovsk mine — 7,046,000 tons (994,000 tons from open mines), Central mine — 8,382,000 tons, Vostochny mine (Koashva deposit) — 4,081,000 tons, Rasvumchorr mine — 1,500,000 tons (400,000 tons from open mines).

Underground explosions

Analysis of ripple-fired explosions carried out at underground mines during 1981-1994 shows that since 1981 the average explosion size has increased from 68 to 140 tons of explosive material (EM). Since 1988, the average total charge size of ripple-fired explosions has been within the range 120 - 240 tons of EM, all of the largest ones (>180 tons) taking place at the southern part of the Kirovsk mine and at the horizon +320 m of the Yukspor mine.

At the same time as the total charge of ripple-fired explosions has increased, the typical maximum individual charge size has also gone up, from 11 to 27 tons and it sometimes amounts to as much as 35 tons. The time delay of the largest individual charge (commonly the 3rd one) is typically 46-69 ms after initiation.

Nowadays the average number of underground explosions per year is about 40, and most of the explosions take place during the 1st and 4th quarters of the year.

Open explosions

Ripple-fired explosions at the Central and Koashva mines are carried out weekly. During an explosion day (commonly Friday) 1-5 such explosions take place. Average release of explosive material for such a day amounts to 150-180 t. The maximal volume of fractured ore is about 500,000 cubic meters.

The technique in use is multi-row explosions with short delaying intervals (about 35 ms) using diagonal and diagonal-radial schemes. Average weight of EM per delaying phase is 2-3 tons and it sometimes amounts to 9 tons.

Blocks are exploded sequentially with time delays from 1 to 5 seconds. If the blocks are close to each other the simultaneous initiation of two blocks is possible (cascade exploding). Otherwise, if the blocks are far from each other, the time delay between the respective explosions may be up to 5-10 min.

The explosions at the open mines of Kirovsk usually are combined with underground explosions, but are carried out after them. Typical total weight of EM for the open mines is 10-15 tons, with 2-3 tons per delaying phase.

The open explosions at Rasvumchorr mine are not usually combined with underground ones. The total weight of EM is not more than 15 tons, with typically 2 tons per delaying phase, and a delay interval of 35 ms.

Data analysis of underground explosions

Table 7.6.2 lists underground explosions at Khibiny for the three years 1991-93. The table contains information on mine number, seismic magnitudes (local magnitude M_L and coda magnitude M_C), as well as the total yield (weight of explosive material).

We recall that there are 6 mines (with different kinds of explosions) in Khibiny. Mines 1, 2 and 3 have underground parts and quarries, whereas at mines 4, 5 and 6 there are open (quarry) explosions only. At mines 1 and 2 the underground and open (quarry) explosions take place on the same day (sometimes at very close times, with delays from seconds to hours). At mine 3 underground and open explosions are usually carried out on different days.

The underground explosions are single (ripple-fired) explosions with typical shot delays of 20-35 ms and typical total duration of a few hundred milliseconds.

The quarry explosions are made by separate charges situated at different places (distances up to 2 km) and the time shift between the individual explosions amounts to dozens of minutes.

Aggregate yield (total weight of explosive material) is:

15-400 t for underground explosions (mines 1,2,3, single (ripple-fired) charge);
0.5-50 t for quarry explosions at mines 1,2,3 (separate charges)
10-400 t for quarry explosions at mines 4,5,6 (separate charges)

The main source of information on types and yields of the explosions is the mine administration, whereas data on their times and magnitudes are taken from our seismic recordings.

When we started to study mining explosions in 1994, we found no direct correlation between aggregate yields of explosions and their magnitudes. For example, the data listed by Mykkeltveit (1992) show no distinct trend between magnitude and total yield. We have found that there are several reasons for this:

- numerous errors in messages from the mine staff
- different characteristics of open and underground explosions
- for open explosions it is impossible to determine which charge was exploded first
- impossiblity to separate simultaneous open and underground explosions
- absence of exact information about the times of explosions
- sometimes rockbursts take place immediately after an explosion, influencing the recording and, hence, the magnitude.

We have carefully checked our data and selected only underground explosions which are well distinguishable from rockbursts and open explosions (total 111 underground explosions at mines 1,2,3) and calculated the following parameters (see Tables 7.6.3 and 7.6.4):

$$\mathrm{Corr}(\log(Y), M_L) = 0.71, \qquad \mathrm{Corr}(\log(Y), M_C) = 0.73$$

$$\left\langle \frac{\log(Y)}{M_L} \right\rangle = 0.85 \pm 0.18 \qquad \left\langle \frac{\log(Y)}{M_C} \right\rangle = 0.77 \pm 0.10$$

This shows that the correlation is statistically reliable. Plots of log(Yield) versus magnitude are given in Figs. 7.6.3 and 7.6.4.

In addition we used a rank-order test to estimate the quantitative agreement between yields of underground explosions and their magnitudes (M_L). We checked the possibility to predict relative yields given the magnitudes, i.e., P(Y1>Y2) when $M_L1 > M_L2$. We used 105 explosions, and for all pairs of them calculated the number of cases when the sequence of yields coincides with the sequence of magnitudes (N good) and otherwise (N bad).

N total	=	5460 (105*104/2)
N good	=	3977 (about 73%)
N bad	=	1483

The number 73% is slightly higher than the linear correlation, and confirms that the yields and magnitudes are indeed correlated.

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References

Kremenetskaya, E.O. & V. M. Trjapitsin (1995): Induced seismicity in the Khibiny Massif (Kola Peninsula), PAGEOPH Vol 145, No 1 (in press).

Mykkeltveit, S. (1992): Mining explosions in the Khibiny Massif (Kola Peninsula of Russia) recorded at the Apatity three-component station. Report PL-TR-92-2253, Phillips Laboratory, Hanscom AFB, MA, USA.

Deposit	Mine No.
Kirovsk, Kukisvumchorr	1
Yukspor	2
Rasvumchorr	3
Central	4
Koashva	5
Nyurpakh	6

Table 7.6.1. Reference numbers of the Khibiny mines.

Date	Time	Mine	ML	MC	Yield
1991 01 13	04 32 35.6	1	2.5335	2.4345	130
1991 01 26	18 30 34	3	2.5339	2.5475	150
1991 02 03	04 57 08.1	2	2.8701	2.7559	130
1991 02 10	03 11 04.8	2	2.2010	2.4378	56
1991 02 17	03 44 55.2	2	1.7697	2.3681	64
1991 02 23	12 08 41.5	3	2.1747	2.3980	60
1991 02 24	08 45 17.1	1	2.4953	2.7189	187
1991 02 24	11 11 15.9	2	2.2010	2.5188	142
1991 03 08	04 42 52.5	1	2.5335	2.4869	156
1991 03 24	04 23 17	2	2.3825	2.6927	89
1991 03 24	04 48 58.4	2	2.6877	2.5509	118
1991 03 31	06 29 37.1	2	2.4738	2.5419	211
1991 04 13	17 59 27.4	3	1.7540	2.3352	70
1991 04 21	06 40 05	1	2.3574	2.5486	118
1991 04 27	13 14 14.5	3	2.105	2.3737	130
1991 04 28	05 18 47.4	1	2.7206	2.7	150
1991 05 18	12 43 12.1	3	2.3561	2.5338	90
1991 05 19	08 47 13	1	2.5597	2.7581	225
1991 05 19	08 47 13	2	?	?	61
1991 06 16	05 39 49.9	2	2.4011	2.6142	112
1991 06 23	04 14 00.4	2	2.2802	2.4432	82
1991 06 30	06 33 00.9	2	2.5021	2.5855	117
1991 07 06	19 23 58.7	3	2.2811	2.2862	94
1991 07 07	05 33 35.4	1	2.3692	2.4561	133
1991 08 04	12 49 52.1	1	2.7143	2.6550	122
1991 08 10	18 00 02.1	3	1.9863	2.2154	50
1991 08 18	06 11 44.5	2	2.2882	2.5235	90
1991 08 31	16 08 20.4	3	2.0333	2.1226	100
1991 09 01	06 17 16.5	2	2.3012	2.4592	168

Date	Time	Mine	ML	MC	Yield
1991 09 15	04 07 42.8	1	2.2617	2.5303	57
1991 10 06	05 37 17.2	2	2.8631	2.7559	114
1991 10 20	04 36 59.3	2	2.1352	2.3681	112
1991 10 26	13 03 13.3	3	2.0389	2.3548	30
1991 10 27	01 32 32.1	2	1.8489	2.2504	15.4
1991 11 16	12 35 33.8	3	1.9406	2.1712	52
1991 11 17	04 59 19	1	2.4237	2.3703	150
1991 11 30	13 12 52.5	3	2.0857	2.2320	70
1991 12 08	08 29 30.6	1	2.2557	2.6242	167
1991 12 15	05 55 41.5	2	2.3260	2.4378	70
1991 12 22	07 25 35.1	2	2.5536	2.6142	238
1991 12 28	15 32 00.6	3	2.4572	2.7616	171
1991 12 31	08 48 48.5	1	2.4091	2.5349	198
1992 01 18	12 44 42.7	3	2	2.3	71
1992 02 02	05 05 00.4	1	2.7338	2.6913	107
1992 02 08	11 25 24.7	3	1.5726	2.1122	16
1992 02 09	04 09 40.8	2	3.0072	2.6021	116
1992 02 16	08 49 49.7	1	2.3226	2.7018	175
1992 02 22	12 00 19	3	2.1190	2.4489	60
1992 02 23	05 37 02.9	2	2.6035	2.6821	101
1992 04 19	02 33 22.1	2	2.4436	2.5141	48
1992 04 25	13 38 59.9	3	2.7035	2.6769	150
1992 04 26	03 31 56.7	1	2.4665	2.5018	84
1992 05 01	02 14 11.7	3	1.9194	2.4542	60
1992 05 01	03 02 56.8	1	2.8776	2.7018	150
1992 05 24	04 29 57.2	2	1.7239	?	112
1992 05 24	04 30 06.2	2	1.6929	?	106
1992 05 31	02 46 41.7	2	1.2168	2.2581	25
1992 05 31	03 41 10.1	1	2.4154	2.6770	217
1992 06 07	03 47 36.9	2	2.3717	2.6749	103

Date	Time	Mine	ML	MC	Yield
1992 06 19	11 23 35.1	3	2.2204	2.5521	80
1992 07 05	04 01 39.1	2	2.3717	2.7559	118
1992 07 12	03 24 46.4	1	2.1542	2.7087	103
1992 07 26	03 56 06.3	2	2.2106	2.5093	38
1992 08 22	10 33 54.9	3	2.2204	?	45.5
1992 08 23	03 10 43.5	2	2.5179	2.7777	60
1992 08 30	03 11 56.4	1	2.8167	2.8183	91
1992 09 27	05 22 35.8	2	2.6294	2.8162	198
1992 10 18	03 24 08.9	2	2.1847	2.4268	25
1992 11 07	06 31 43.4	1	2.5657	2.7949	177
1992 11 21	12 29 56.6	3	2.0944	2.4596	96
1992 11 22	04 46 44.8	2	2.7082	2.7685	99
1992 11 29	04 08 46.1	2	2.0250	2.6142	119
1992 12 05	10 42 30.8	3	2.2311	2.3799	70
1992 12 20	07 10 46	1	2.4358	2.5162	163
1992 12 31	04 35 17.9	2	2.4857	2.4948	89
1993 01 16	11 00 00	3	?	?	15
1993 01 24	08 04 42.9	2	1.7428	?	26
1993 01 30	13 07 08.9	3	2.5976	2.6622	272
1993 01 31	04 14 05.9	1	2.3940	2.4177	148
1993 02 13	12 05 34.8	3	2.5628	2.8	148
1993 02 14	07 39 39.7	1	2.6237	2.5210	182
1993 02 28	04 23 56.4	2	1.6260	2.1748	27
1993 03 06	11 00 31	3	2.2716	?	134
1993 03 07	04 14 31.3	2	2.1641	2.4212	57
1993 03 28	04 48 02.6	2	2.3761	2.6927	219
1993 04 03	08 29 16.6	3	1.2204	?	45
1993 04 04	03 22 22	2	2.3260	2.6061	88
1993 04 10	08 28 56.8	3	1.3220	2.1122	15
1993 04 11	03 45 44.6	2	2.2351	2.3228	30

Date	Time	Mine	ML	MC	Yield
1993 04 18	03 17 54.6	1	2.2434	2.6913	127
1993 04 30	23 21 37.2	1	2.1	2.4	17
1993 05 09	03 14 45.1	2	2.3472	2.6892	98
1993 05 23	02 36 09.5	1	2.7408	2.5018	196
1993 06 20	02 28 18.1	1	2.3278	2.4666	73
1993 06 27	02 42 07.2	2	2.5731	2.5553	71
1993 07 03	10 01 15.4	3	1.9194	2.2935	60.5
1993 07 18	02 57 12.1	2	2.616	2.5374	117
1993 07 25	06 43 52.8	2	1.8341	2.1169	16
1993 08 01	08 57 19.2	1	1.0694	1.8827	22
1993 08 05	04 42 11.6	2	1.8836	?	22
1993 08 21	13 25 16.1	3	1.7847	2.1226	40
1993 08 22	02 21 46.2	1	2.7418	2.4177	75
1993 09 05	04 29 45.2	2	2.5826	2.7653	249
1993 09 19	05 20 34.7	2	2.8742	2.7031	140
1993 09 19	07 00 37.7	2	1.1499	1.9138	24
1993 10 03	03 52 30.8	2	2.6035	2.6338	167
1993 10 10	03 34 16.3	2	2.4011	2.3983	44
1993 10 24	05 34 25.4	1	2.7610	2.4062	43
1993 11 20	18 46 54.3	3	1.4423	2.1327	13
1993 12 05	06 50 18.1	1	2.5744	2.7612	254
1993 12 31	08 01 48.3	2	2.6148	2.8497	360

Table 7.6.2. List of underground explosions in Khibiny during 1991-1993.

	log(Yield)	M_L	M_C
log(Yield)	-----	0.7059	0.7323
M_L	0.7059	------	0.7954
M_C	0.7323	0.7954	------

Table 7.6.3. Correlation matrix for M_L and M_C versus log(Yield)

	log(Y)/M_L	log(Y)/M_C
Number of known values*	109	102
Min	0.5859	0.51270
Max	1.3546	0.94220
Average	0.8606	0.77400
Standard deviation	0.1334	0.09557

*The numbers are less than 111 because for some explosions M_L or M_C are unknown.

Table 7.6.4. Statistical parameters for log(Y)/M_L and log(Y)/M_C.

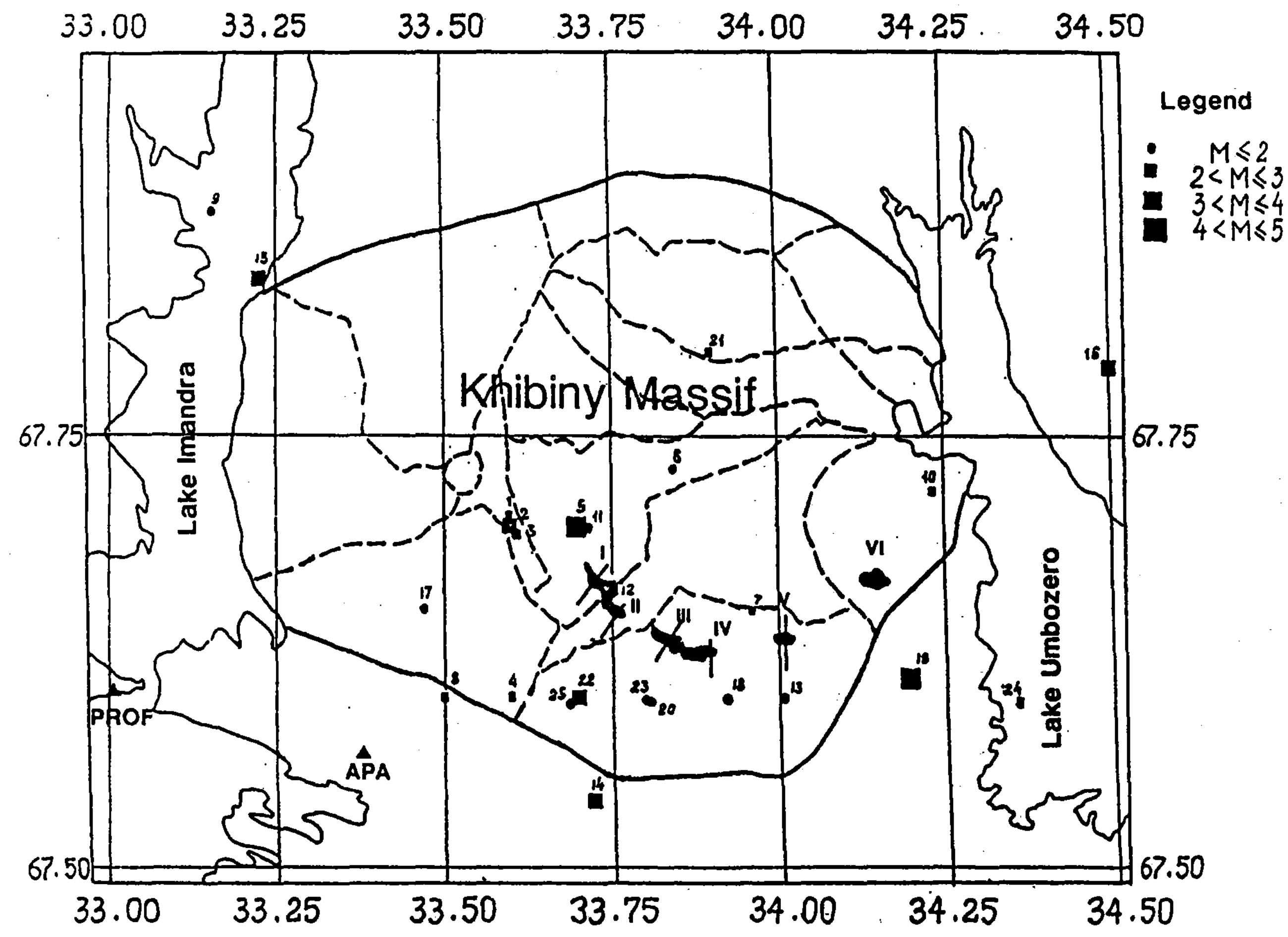

Fig. 7.6.1. The position of mines (I-VI) in the Khibiny Massif together with fault structures and earthquakes. Mines I, II and III are underground, whereas IV, V and VI are open-pit mines. The location of the Apatity seismic station (APA) is also shown. (After Kremenetskaya and Trjapitsin, 1995.)

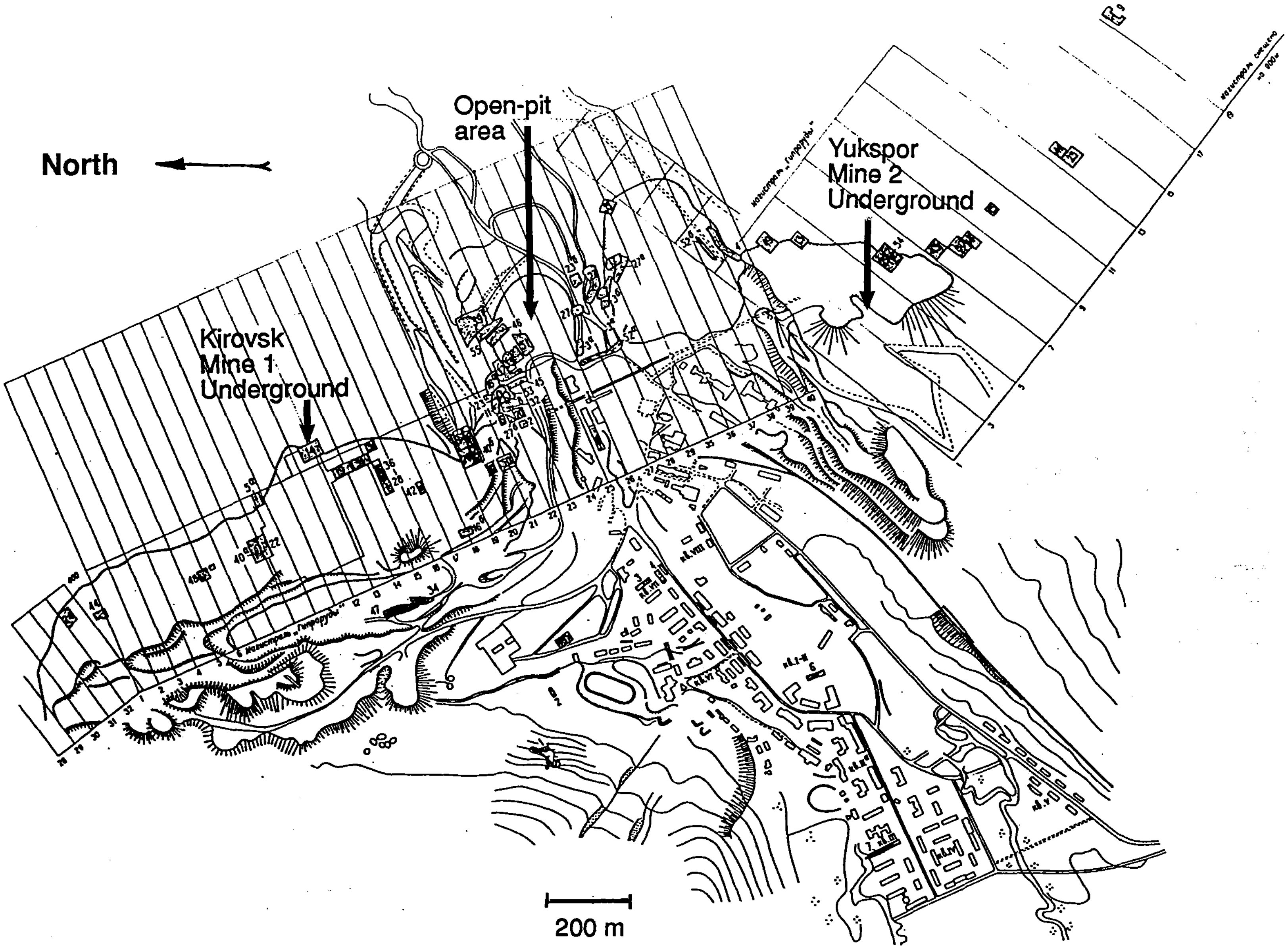

Fig. 7.6.2. Schematic plan of Mines 1 and 2. Part of the town Kirovsk is seen on the map.

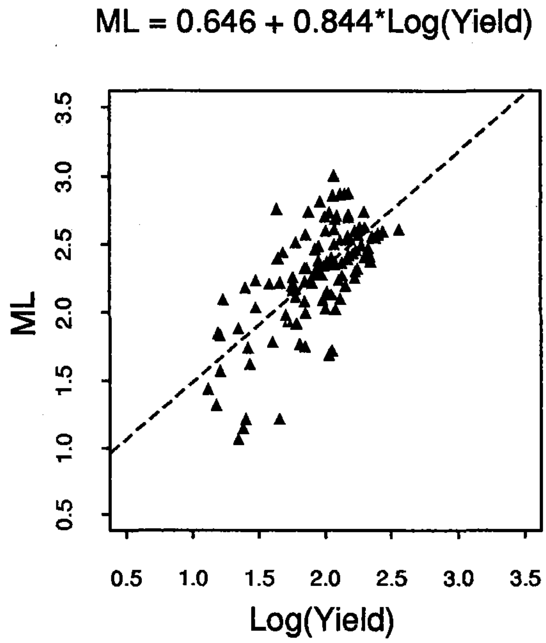

Fig. 7.6.3 Plot of M_L versus log(Yield) (in tons) for underground explosions listed in Table 7.6.2.

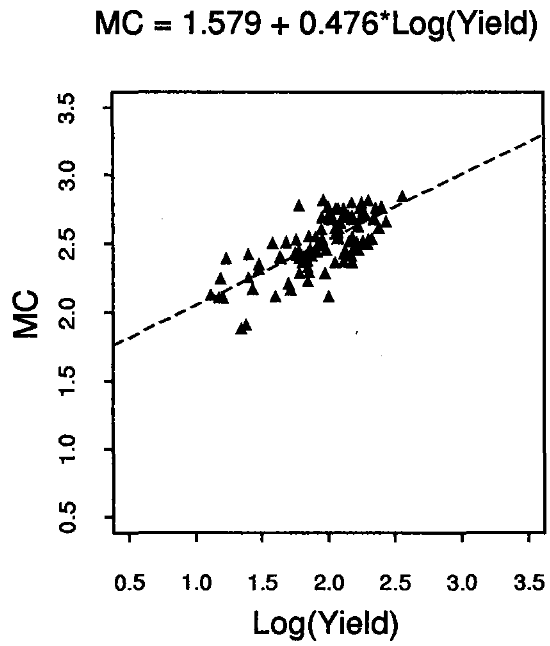

Fig. 7.6.4 Plot of M_C versus log(Yield) (in tons) for underground explosions listed in Table 7.6.2.