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7.7 Induced seismicity in the Khibiny Massif (Kola Peninsula)

The topic of this paper is to review recent processes of increasing seismic activity in the Khibiny Massif in the Kola Peninsula. It is a typical example of induced seismicity caused by rock deformation due to the extraction of more than $2 \cdot 10^9$ tons of rock mass since the mid-1960s. The dependence of seismic activity on the amount of extracted ore is demonstrated. Some, but not all, of the induced earthquakes coincide with large mining explosions, thus indicating a trigger mechanism. The largest earthquake, which occurred on 16 April 1989 ($M_L = 4.1$) could be traced along the surface for 1200 m and observed to a depth of at least 220 m. The maximum measured displacement was 20 cm.

Introduction

The Khibiny alkaline Massif (see Fig. 7.7.1) situated in the middle of the Kola Peninsula is tectonically unstable. Its seismic activity has been characterized by groups of a few earthquakes with typically 8-10 years between groups (Panasenko, 1969). The Massif consists of different blocks separated from each other by faults. The recent crustal movements are in the range from 2 to 4 mm/year (Yakovlev, 1982).

The exploitation of the Khibiny apatite ores started in 1929 and since then about $2.5 \cdot 10^9$ tons of rock have been mined from an area of about 10 km^2. This corresponds to a decrease of the gravitational component by typically 2.5-3.0 MPa, and for some parts of the Massif by as much as 9-12 MPa.

At the present time more than 10^8 tons of ore are extracted annually from three underground and three open-pit mines. The velocity of the uplift of the near-surface parts is of the order of 70 mm/year for some tunnels (Panasenko and Yakovlev, 1983).

Seismic activity of the Khibiny Massif

The extensive mining has disrupted the natural geodynamic process in the area, causing a redistribution of crustal stress, which in turn has led to increased seismic activity. Fig. 7.7.2 shows in this respect the cumulative seismic energy release and the amount of extracted ore for the mines in the Khibiny Massif. The seismic energy (E) released has been calculated from the formula (Meyer and Ahjos, 1985):

$$\log E = 12.30 + 1.27 M_L \qquad (1)$$

where E is expressed in ergs. The similarity of the two curves strongly indicates a causal connection. It should be noted here that the earthquake catalogue is considered homogeneous back to 1978.

The dependence of seismic activity on the extracted deposit volume has long been known from observations (Glowacka and Kijko, 1989). In the Khibiny Massif a more intensive excavation began in the mid-1960s, while the first significant tremors occurred in 1981. During that year four felt earthquakes (intensity I = 3-4 on the MSK scale) occurred in the vicinity of the mines. Some of these earthquakes were accompanied by sonic effects.

Around the same time, many rockbursts occurred near mines I and II (see Fig. 7.7.1), each of them displacing tons of rocks (1-10 m^3). In fact, during five hours on 17 May 1981 more than 20 rockbursts occurred. And for the first time the occurrence of an earthquake at the time of an explosion was observed. Now this situation is typical for events in the Khibiny Massif.

The largest earthquakes

An earthquake with intensity more than 5 in the nearby town of Kirovsk occurred on 29 August 1982 immediately after an explosion of 106 tons in mine II and at the time of a smaller quarry explosion (4.6 tons) between mines I and II.

The next significant earthquake, felt with intensity I = 5 at Kirovsk, was on 19 June 1984. Less than one second before this earthquake there was a small explosion (40 kg, mine II). A large block of rock (65x70x70 m^3) was broken and one part of it was displaced relative to another by about 5 cm. After this earthquake there were so many rockbursts that it was impossible to carry out work in this mine for two weeks.

The strongest such earthquake (M_L = 4.1), on 16 April 1989, occurred almost simultaneously with a large explosion (240 tons) in mine I. This earthquake was felt with I = 8 in the upper levels of the mine and I = 5-6 at Kirovsk. The maximum measured displacement was 20 cm, and it occurred along a fault striking at 125-135^o and dipping at 30-35^o NE. The displacement was traced along the surface for 1200 m and observed to a depth of at least 220 m. This event was recorded by all seismic stations within a distance of 1000 km. Fig. 7.7.3 shows ARCESS recordings of this earthquake (distance 420 km).

The earthquake was accompanied by a great number of aftershocks attaining several hundred for the two subsequent months. On 24 July 1989 another earthquake occurred here. Its size was much less (see Table 7.7.1); however, remarkable destruction again took place in this mine.

Conclusions

This paper has discussed to principal topics: a) the question of induced seismicity caused by rock excavation and b) the question of mining explosions as a trigger for earthquakes and rockbursts.

At present it is too early to make a definite conclusion about the triggering mechanism between explosions and earthquakes. In some cases pairs of such events are separated by some milliseconds (for example, 16 April 1989, Fig. 7.7.3); in other cases they are separated by some seconds or more, sometimes they are not connected in time (for example, 2 June 1992, Fig. 7.7.4).

However, the increase of seismic activity in the Khibiny Massif caused by the rock deformation due to the extraction of large volumes of rock mass is clearly demonstrated.

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No.	Date	Origin time	Distance (km)	Coordinates		ML	Seismic energy (ergs)
1	1948	0923 0000	17.0	67.70 N	33.60 E	3.1	1.58E16
2	1955	0808 172059	17.0	67.70 N	33.60 E	3.2	2.24E16
3	1955	0831 2115	17.0	67.70 N	33.60 E	2.5	2.80E15
4	1960	0209 210731	10.0	67.60 N	33.60 E	2.0	7.08E14
5	1974	0930 091142	17.0	67.70 N	33.70 E	3.5	6.31E16
6	1979	1212 113452	13.0			2.1	9.27E14
7	1981	0416 205634	20.0			2.1	9.27E14
8	1981	0517 075528	17.0			2.3	1.30E15
9	1981	0818 000747	19.2			2.5	2.98E15
10	1982	0422 110258	22.5			2.1	9.27E14
11	1982	0829 053335	17.0	67.70 N	33.70 E	3.3	3.10E16
12	1984	0619 054731	17.0	67.33 N	33.70 E	3.9	1.79E17
13	1984	1030 105158	35.0			2.2	1.24E15
14	1984	1030 142148	17.5	67.68 N	33.72 E	2.3	1.66E15
15	1987	0725 161339	22.5	67.66 N	33.90 E	2.9	9.60E15
16	1988	0113 025153	25.0	67.73 N	33.83 E	2.6	4.00E15
17	1988	0118 020948	24.0	67.65 N	33.96 E	2.6	4.00E15
18	1988	0120 121510	6.0	67.60 N	33.50 E	2.6	4.00E15
19	1988	0211 124113	27.0			2.2	1.20E15
20	1988	0304 231701	18.0	67.70 N	33.70 E	2.1	9.30E14
21	1988	0416 115725	18.0	67.66 N	33.75 E	2.1	9.30E14
22	1988	0622 013408	10.5	67.65 N	33.47 E	2.4	2.20E15
23	1988	1006 094741	32.0	67.61 N	34.19 E	3.3	3.10E16
24	1988	1123 211108	23.0	67.60 N	33.80 E	2.5	3.00E15
25	1989	0203 102741	33.7	67.80 N	33.90 E	2.2	1.20E15
26	1989	0416 063442	18.0	67.61 N	33.81 E	4.1	3.20E17
27	1989	0707 114924	26.5	67.71 N	33.93 E	3.4	4.10E16
28	1989	0724 223234	15.0	67.60 N	33.78 E	2.5	3.00E15
29	1989	0804 012618	21.0	67.60 N	33.90 E	2.1	9.30E14
30	1990	0210 163907	37.1	67.89 N	33.48 E	2.2	1.20E15
31	1990	0403 075417	26.5	67.60 N	33.90 E	2.1	9.30E14
32	1990	0612 113532	36.7	67.63 N	34.29 E	2.1	9.30E14
33	1990	0621 130954	20.5	67.67 N	33.83 E	2.3	1.70E15
34	1990	0621 231904	15.5	67.67 N	33.66 E	2.2	1.20E15
35	1990	0622 015115	16.5	67.61 N	33.81 E	2.4	2.20E15
36	1990	0624 065848	19.4	67.61 N	33.88 E	2.4	2.20E15
37	1990	0625 062215	16.2	67.56 N	33.82 E	2.3	1.70E15
38	1990	0625 113116	16.1	67.61 N	33.80 E	2.2	1.20E15
39	1990	0625 215128	15.3	67.67 N	33.66 E	2.3	1.70E15
40	1990	0626 052403	19.1	67.72 N	33.30 E	2.4	2.20E15
41	1990	0627 004129	24.4	67.77 N	33.29 E	2.3	1.70E15
42	1990	0627 025428	19.6	67.67 N	33.79 E	2.2	1.20E15
43	1990	0627 051520	23.6	67.59 N	33.99 E	2.4	2.20E15
44	1990	0627 064141	29.0	67.66 N	34.07 E	2.8	7.20E15
45	1990	0628 015919	22.8	67.74 N	33.22 E	2.6	4.00E15
46	1990	0629 041211	19.4	67.69 N	33.75 E	2.8	7.20E15
47	1990	0630 045139	20.4	67.62 N	33.90 E	2.4	2.20E15
48	1990	0630 064224	28.0	67.64 N	34.10 E	2.6	4.00E15
49	1991	0305 000836	23.7	67.55 N	34.00 E	2.1	9.30E14
50	1991	0505 054802	28.5	67.65 N	34.07 E	2.1	9.30E14
51	1991	0815 083545	24.1	67.63 N	33.98 E	2.1	9.30E14
52	1991	1229 151425	27.0	67.70 N	33.96 E	2.1	9.30E14
53	1991	1229 152044	25.0	67.57 N	34.03 E	2.1	9.30E14

Table 7.7.1. Known earthquakes (M_L>2.0) in the Khibiny Massif 1948-1991. The distance to the APA station in Apatity is indicated.

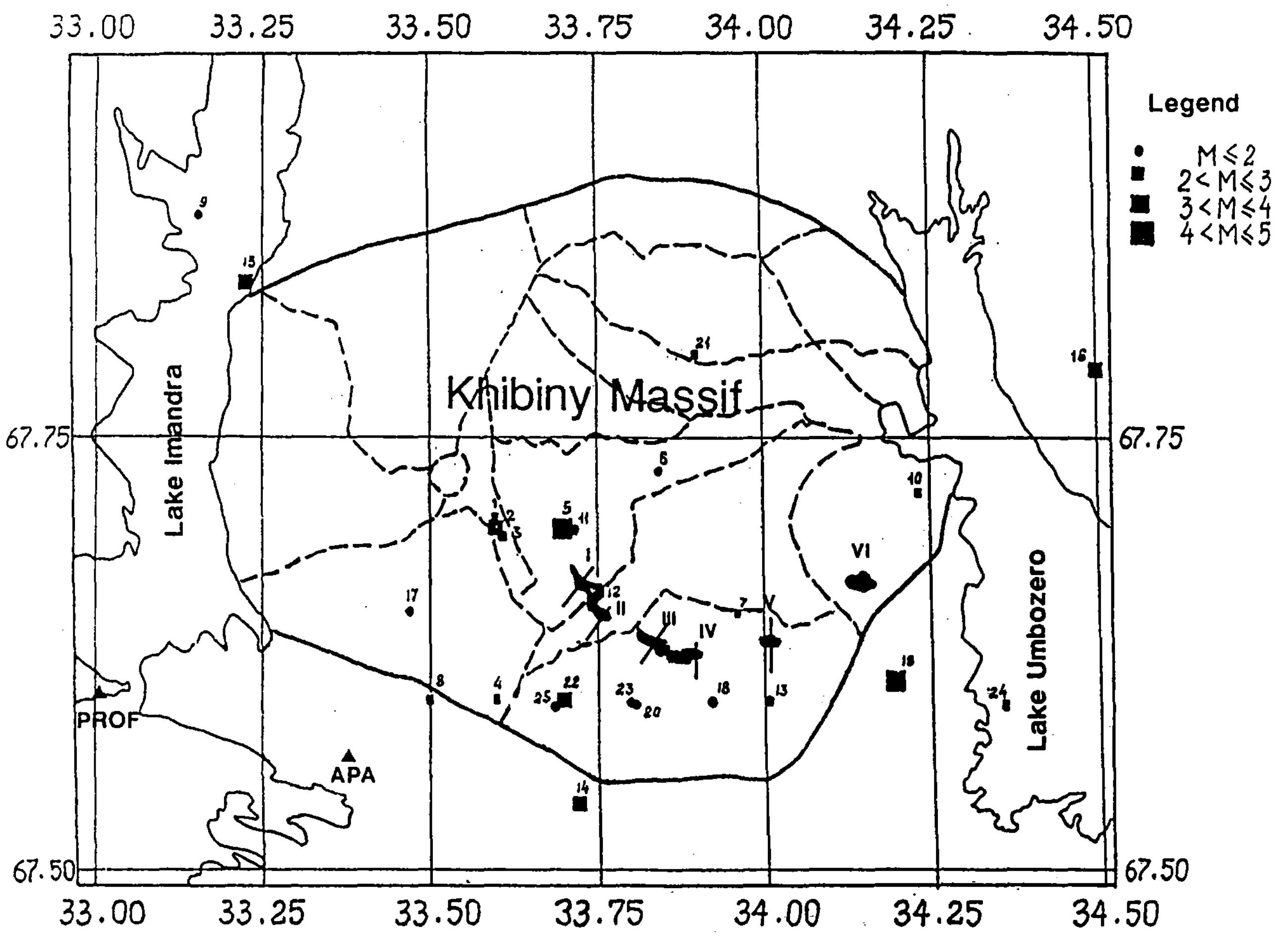

Fig. 7.7.1. The position of mines (I-VI) in the Khibiny Massif together with fault structures and earthquakes. Mines I, II and III are underground, whereas IV, V and VI are open-pit mines. The location of the Apatity seismic station (APA) is also shown.

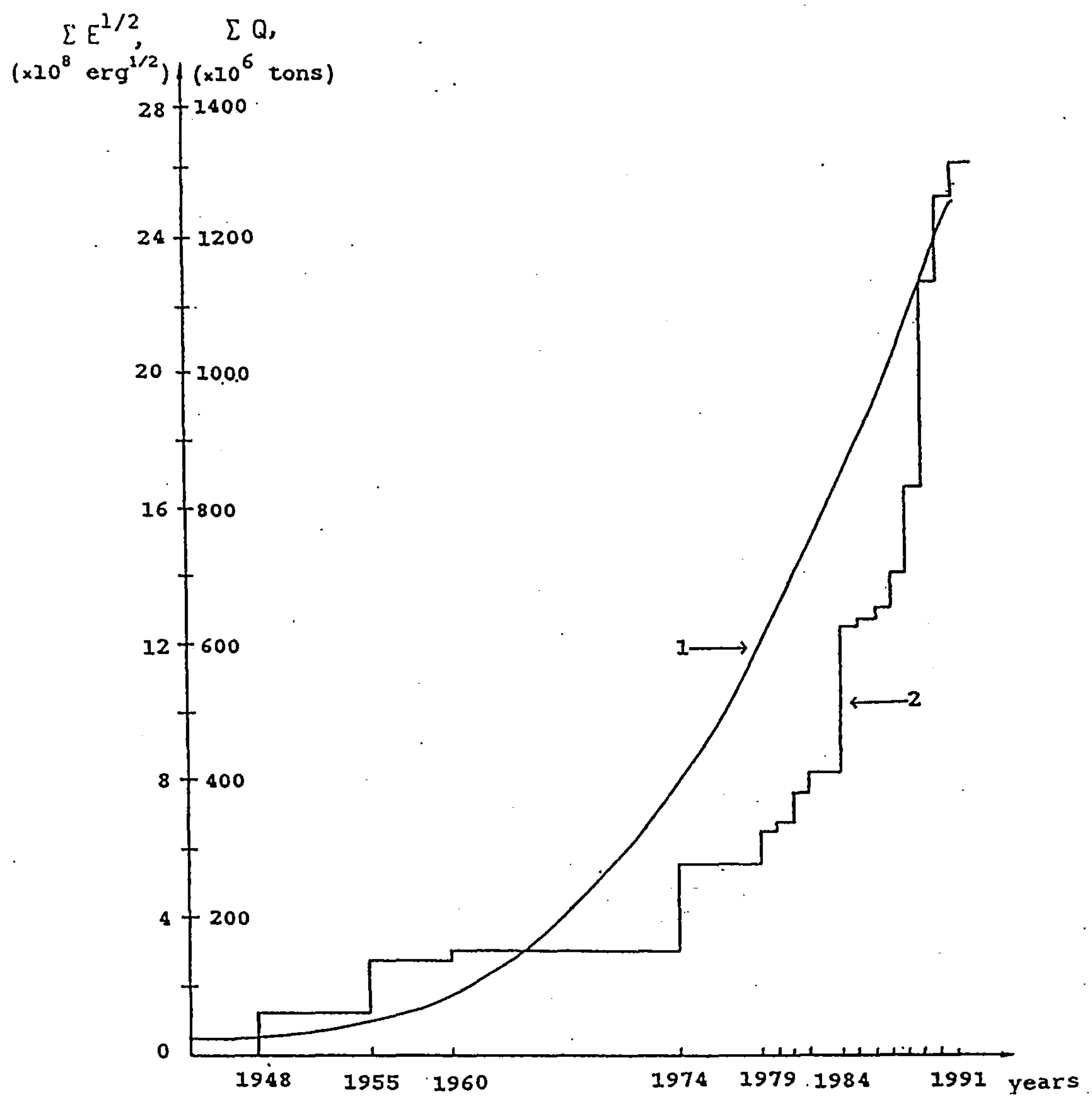

Fig. 7.7.2. Cumulative distributions versus time of extracted masses of the apatite mineral (1) and Benioff's graph of released energy (2) for the Khibiny Massif. Note the similarity between the two graphs.

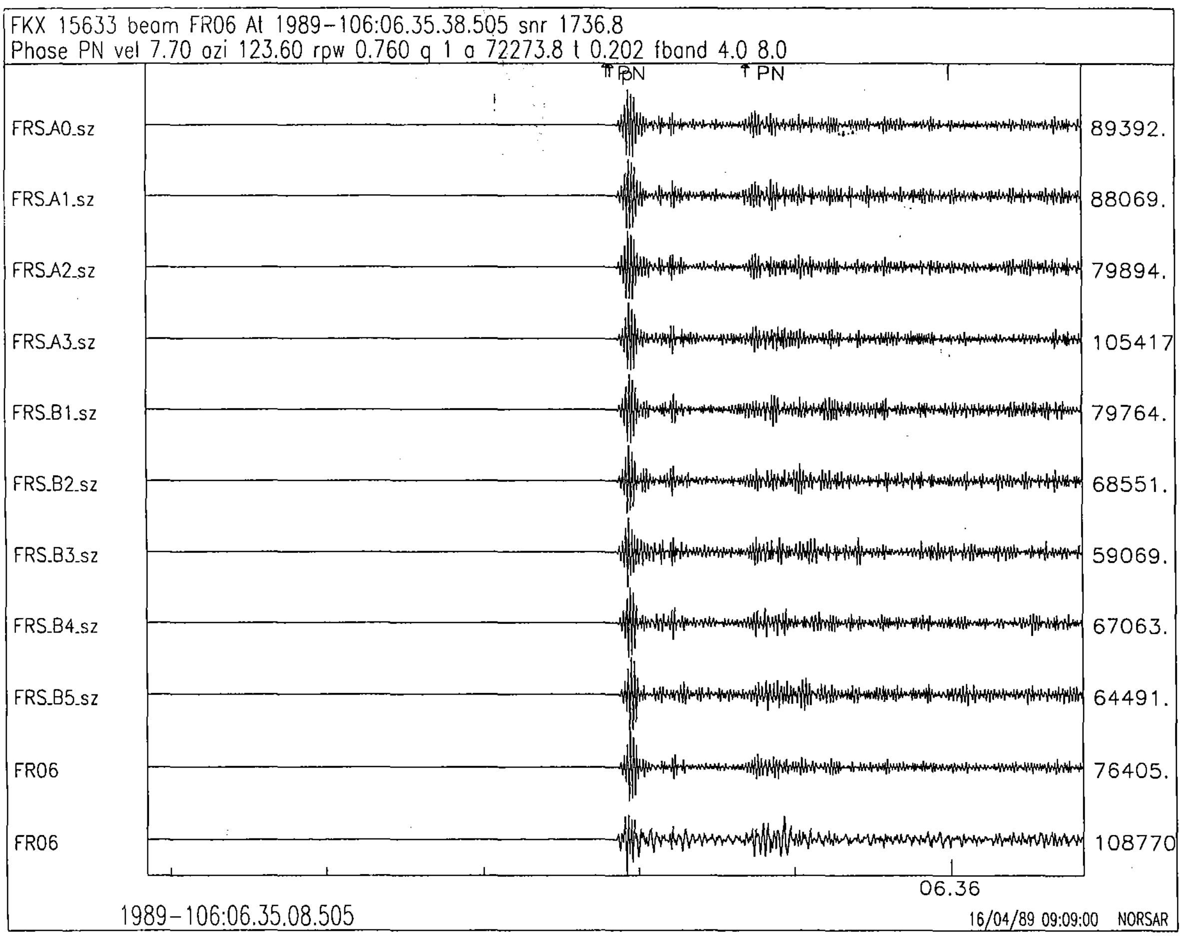

Fig. 7.7.3. ARCESS recordings of the 16 April 1989 earthquake (M_L = 4.1) in the Khibiny Massif. The earthquake occurred almost simultaneously with a 240 ton explosion, and it is not possible to visually separate the P phases for the two events.

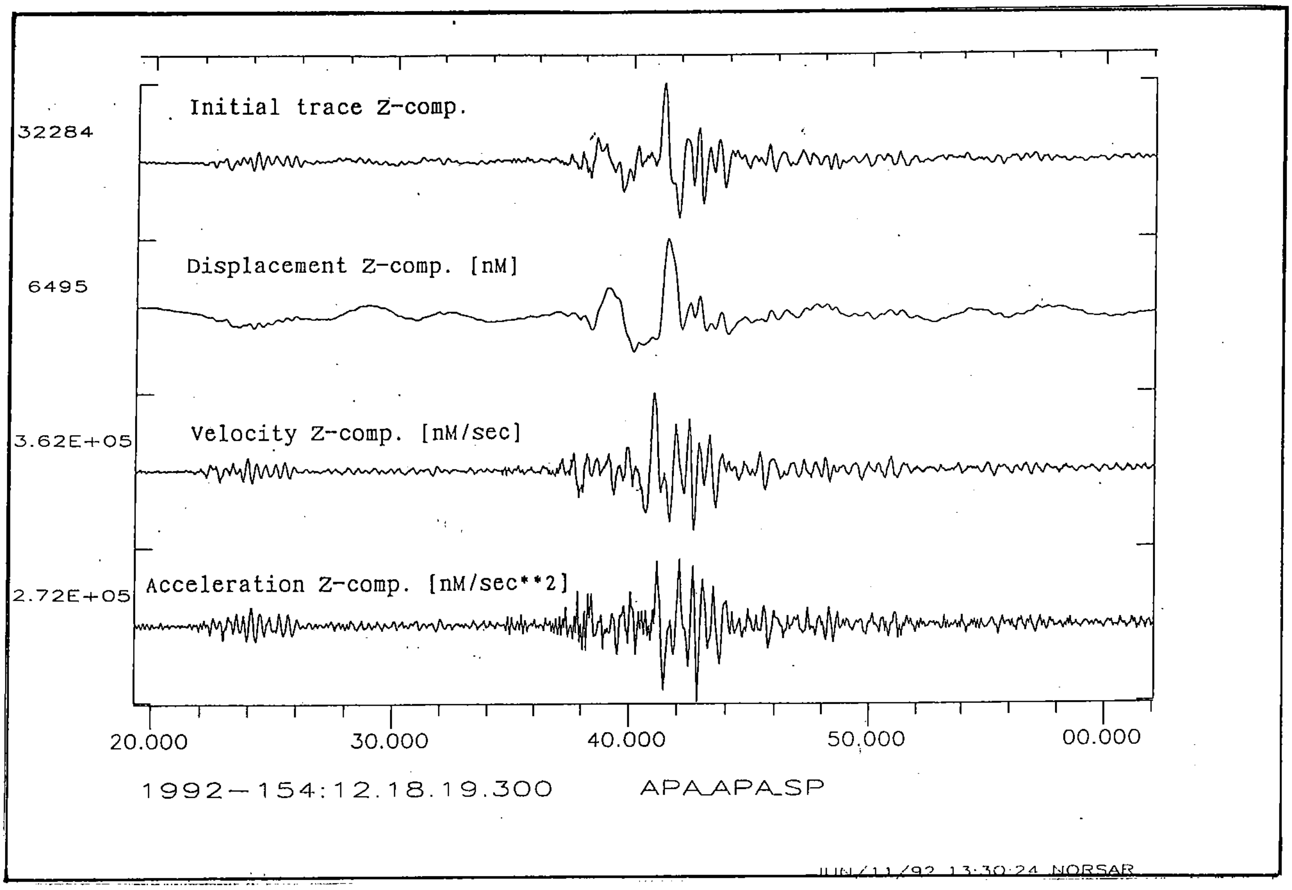

Fig. 7.7.4. A double earthquake in the Khibiny Massif on 2 June 1992 (M_L(ARCESS) = 2.0 and 2.5, respectively). The figure shows APA SPZ recordings, initial trace as well as displacement, velocity and acceleration. These earthquakes were not associated with any mining explosion.