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## 7.5 Study of the calibration explosion on 29 September 1996 in the Khibiny Massif, Kola Peninsula

### *Introduction*

On 29 September, 1996, a 350 ton industrial explosion was carried out in the Kola Peninsula, Russia. The explosion was detonated in an underground mine in the Khibiny Massif, with coordinates 67.675N, 33.728E. The explosion was applied to provide data to calibrate the GSETT-3 network in this region.

The calibration experiment was carried out as a joint cooperative project between the Ministry of Defense of the Russian Federation and the Kola Regional Seismological Centre of the Russian Academy of Sciences. NORSAR participated in this experiment by providing seismic recordings as well as contributing to the data analysis.. The explosion was recorded by several stations in the GSETT-3 network, all of them at regional distances. The event was listed in the Reviewed Event Bulletin (REB) of the IDC with coordinates 67.57N, 32.54E and a magnitude ($M_L$) of 3.4.

In this paper we analyze available recordings of this explosion, with emphasis on recordings by stations at local distances. We further compare the signal characteristics to those of previously recorded underground explosions in the same mine. The IDC location estimates of this suite of explosions is compared to their true locations, and the differences are used to suggest a velocity model that is expected to largely eliminate systematic bias in the IDC location results for events in this region.

### *The Khibiny Massif*

The Khibiny Massif occupies a mountainous territory of 1327 square kilometers in the central part of the Kola Peninsula, northwestern Russia. The complex is part of the Kola Alkaline Province of the Baltic Shield. The eastern edge of Khibiny is only 5 km away from the Lovozero massif, therefore these massifs can be regarded as two parts of a single intrusive complex having similar ages. These alkaline intrusions consist of nearly the same rock types but differ in their internal structure.

The Khibiny massif intrudes in the contact zone between Archaean gneisses and Middle Proterozoic volcanic-sedimentary complexes. According to geophysical data and drilling, the outer edges of the massif are vertical down to a depth of 3 km. At deeper levels the western and southern edges plunge towards the center at an angle of 50-60 degrees. The eastern edge dips outwards at an angle of 80 degrees thus showing a possible joining with the Lovozero complex.

### *Khibiny Seismicity and Mining Activity*

The exploitation of the Khibiny apatite ores started in 1930 and since then about $2.5*10^9$ tons of the rock have been excavated from an area of about 10 sq. km. 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 in the Khibiny Massif has shown a significant increase since 1980. Two main factors seem to be jointly contributing to this increased activity. One is the change in tectonic stress regime caused by the removal of large masses of rock, the second is an apparent earthquake triggering effect observed in connection with some of the explosions.

During the time period since 1980 the annual ore excavation at the Khibiny mines has increased from 19.1 to 46.5 million tons. A correspondence between the amount of annual ore extraction and the energy release of recorded earthquakes was demonstrated by Kremenetskaya and Trjapitsin (1995). They explained this effect as a result of the disruption of the natural geodynamic process in the area, causing a redistribution of crustal stresses which in turn has led to increased seismicity.

Kremenetskaya et. al.(1995) made a detailed study of the proposed triggering effect, and showed that underground explosions in Khibiny in many cases act as a direct trigger of rockbursts. Such triggering effects were demonstrated to take place when the depth of the mining exceeds 100 meters. Currently about 30% of all underground explosions have been found to trigger significant rockbursts, i.e., rockbursts that are detectable at a distance of at least 50 km. The triggered rockbursts usually occur within a few tens of seconds after the explosion. These studies did not reveal any similar triggering effect for open-pit mining explosions in Khibiny.

There are 6 mines in the Khibiny Massif (see Table 7.5.1). 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, (within several seconds or minutes). At mine 3 underground and open explosions are usually carried out on different days.

**Table 7.5.1: Reference numbers and coordinates of the Khibiny mines**

| Name | Mine No | Latitude | Longitude |
|---|---|---|---|
| Kirovsk | 1 | 67.670 | 33.729 |
| Yukspor | 2 | 67.647 | 33.761 |
| Rasvumchorr | 3 | 67.631 | 33.835 |
| Central | 4 | 67.624 | 33.896 |
| Koashva | 5 | 67.632 | 34.011 |
| Nyurkpakh | 6 | 67.665 | 34.146 |

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 interval between the individual explosions amounts to several tens of minutes.

Aggregate yield (total weight of explosive material) is typically:

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 seismic recordings.

*The Station Network*

The regional seismic network in the Kola Peninsual currently comprises 7 seismic stations, as described by Kremenetskaya et. al. (1995). For the present study of the calibration explosion, only those stations with digitally recording equipment have been used. In addition, several stations in Fennoscandia recorded the calibration event, but we have only used data from the nearest station, the ARCESS array (distance about 400 km), in our analysis. All the station data are available both at NORSAR (Kjeller) and at KRSC (Apatity) via a dedicated satellite link connecting the two data centers. The stations are listed in Table 7.5.2, and a brief description is given in the following.

**Table 7.5.2: List of seismic stations used in this study**

| Name | Latitude | Longitude |
|---|---|---|
| APZ9 (Broadband) | 67.568N | 33.388E |
| PLQ | 66.410N | 32.750E |
| ARCESS (Array) | 69.534N | 25.511E |
| APA0 (HF element) | 67.603N | 32.994E |
| APA0 (Array) | 67.603N | 32.994E |

The Apatity array was installed in late September 1992, approximately 17 km to the west of KRSC in Apatity, at the location indicated in Fig. 7.5.1. The seismometers are placed on two concentric rings plus one in the center, and the aperture is approximately 1 km. Sampling rate for the array elements is 40Hz. The center element contains in addition a 3-component high-frequency system, with sampling rate of 80Hz. Seismic data registered at the array site are digitized on-site and transmitted via three radio channels to Apatity, where an array controller of type NORAC receives, time-tags and stores the data. Timing is provided by a GPS receiver.

The Apatity station APZ9 is a 3-component Guralp broadband system installed in 1991 in the town of Apatity. The location relative to the Khibiny Massif is shown in Fig. 7.5.1. The data are digitized at a sampling rate of 40Hz and multiplexed with the array data before being stored on disk and magnetic tape.

The station PLQ is normally operated as an analog recording station, but for the purpose of this experiment, a 3-component digital system was installed at this site. Timing was provided by GPS, and the data sampling rate was 50 Hz.

The ARCESS array in northern Norway comprises 25 SP seismometers distributed in four concentric rings together with a center element. The array diameter is 3 km. Data are digitized on-site (sampling rate 40 Hz), time-tagged using a GPS clock and transmitted by satellite to the NORSAR Data Center at Kjeller.

### *Data*

According to information available at this time, the parameters for the calibration explosion were as follows:

Date: 29 September, 1996

Origin time: 06.05.46.2 (GMT)

Total charge size: 350 tons

Location: 67.675N, 33.728E (inside Mine 1)

The explosion was ripple-fired, in 18 separate stages and a time delay of 23 ms between each stage. Each stage of the explosion comprised 200 separate explosive charges in individual boreholes, detonated simultaneously. The total duration of the explosion was 400 ms, which is similar to, although slightly shorter, than the duration of usual mining explosions of comparable size.

The explosive charges were distributed over an area covering 70 by 95 meters, as illustrated in Fig. 7.5.2. This figure also shows the location of the calibration explosion relative to selected other large explosions in the same mine.

### *Waveform recordings*

Short period seismic recordings for the stations in the Kola Peninsula are shown in Figs. 7.5.3 through 7.5.6. These stations are all at local distances (less than 200 km) and the seismic phases P, S and Rg can be clearly identified. As is well known, the presence of the Rg phase is indicative of the shallow depth of the explosion, and Rg is in fact the largest amplitude phase on the seismogram. Fig. 7.5.7 shows a summary plot of the SPZ sensor trace for each of the stations used in this study.

We have calculated the signal-to-noise ratio (SNR) of the P-wave at each of the stations. Not unexpectedly, the SNR, which represents the maximum linear ratio STA/LTA, is highest (more than 1000) for the array beam at the Apatity array. However, even for the 3-component station PLQ (and also for the ARCESS array) the SNR exceeds 100.

In comparison, SNR for other GSETT-3 stations recording this event is at best around 10, even though these stations are also within a relatively short distance (about 10 degrees or less) from the epicenter. This emphasizes the usefulness of the local recordings, not only in terms of detectability, but perhaps more importantly: the onset time readings at these stations can be made with a far higher precision than for low-SNR stations at greater distances. This is part of the problem of location precision that will be further addressed below.

### *Automatic detection processing*

All of the arrays in the regional network, with the exception of PLQ, have telemetry to the NORSAR data center at Kjeller. This enables continuous automatic detection processing to be made, supplemented by interactive analysis of the detected signals. Such analysis is carried out both at NORSAR and at KRSC. The resulting regional bulletins complement the bulletins produced at the GSETT-3 IDC, and provide a useful reference for evaluation and calibration purposes. NORSAR has produced such regional bulletins since 1989.

The regional processing algorithms in use at the NORSAR Data Center comprise the following steps:

- Automatic single array processing, using a suite of bandpass filters in parallel, and a beam deployment that covers both P and S type phases for the region of interest.
- An STA/LTA detector applied independently to each beam, with broadband f-k analysis for each detected phase in order to estimate azimuth and phase velocity.
- Single-array phase association for initial location of seismic events, and also for the purpose of chaining together phases belonging to the same event, so as to prepare for the subsequent multiarray processing.
- Multi-array event detection, using the Generalized Beamforming approach (Ringdal and Kværna, 1989) to associate phases from all stations in the regional network, and thereby provide automatic network locations for events in all of northern Europe.

The processing steps described above result in an automated bulletin that is made available on-line via the Internet. Experience over the past several years has demonstrated that the procedure described above is extremely efficient, and is furthermore "complete" in the sense that it provides an exhaustive search of all possible phase combinations that could correspond to real events. The processing steps described above have now been adopted, with appropriate modifications,at the IDC for global processing, and are also gaining use for other networks.

The automatic bulletin produced by the NORSAR Generalized Beamforming for the Kola calibration event is shown in Table 7.5.4. As can be seen, a total of 25 phases from the regional array network have been associated to this event, with 13 phases used in the automatic location process. The resulting location (67.75N, 33.65E) is quite close to the true location of the event, and forms a useful starting point for further interactive processing.

### *Location and signal characteristics*

Because of the excellent coverage of stations at local distances, we have been able to estimate a very accurate location of the calibration event by interactive analysis of the available seismic data (see Fig. 7.5.1). However, in the context of the GSETT-3 experimental monitoring system, the location problem becomes far more difficult because of the sparseness of the GSETT-3 network. Partly, the difficulties are related to the problems in reading accurate phase onsets at low SNR. Another problem is the possible inaccuracy of the seismic travel time curves employed for this region. Such inaccuracy will cause a systematic mislocation, whereas the uncertainty in onset time readings could cause a mixture of random error and systematic error (the latter occurring, e.g., if P-wave arrivals are read consistently late).

We have collected data for all large underground explosions in Mine 1 so far during GSETT-3, and compared the IDC solutions to the actual epicenters. The events (15 in all) are listed in Table 7.5.3. Fig. 7.5.8 is a plot showing the IDC locations for these events. The explosions are mislocated by typically 20-30 km. A systematic shift in epicenters is clearly seen, with a general shift westwards compared to the true location.

**Table 7.5.3: Explosions in Khibiny Mine 1 processed by the IDC**

| DATE | IDC Origin time | Latitude (IDC) | Longitude (IDC) | Yield tons | $M_L$ IDC | $M_L$ KRSC |
|---|---|---|---|---|---|---|
| 1995/01/22 | 04:27:07.2 | 67.5400 | 33.2600 | 136 | 2.1 | 2.1 |
| 1995/02/12 | 03:34:54.1 | 67.6800 | 33.0200 | 131 | 2.2 | 2.6 |
| 1995/03/19 | 03:15:05.3 | 67.6000 | 33.4100 | 67 | 2.2 | 2.4 |
| 1995/04/02 | 03:26:43.4 | 67.6100 | 32.6900 | 59 | 2.5 | 2.8 |
| 1995/05/21 | 03:23:35.3 | 67.5900 | 32.5800 | 123 | 3.7 | 2.2 |
| 1995/07/30 | 09:23:40.9 | 67.5600 | 32.8200 | 100 | 3.6 | 2.1 |
| 1995/10/01 | 04:27:58.4 | 67.5600 | 32.7500 | 152 | 3.9 | 2.1 |
| 1995/10/29 | 04:53:45.0 | 67.6100 | 32.7700 | 156 | 3.2 | 2.7 |
| 1995/12/11 | 04:42:17.4 | 67.5200 | 33.1600 | 245 | 3.3 | 2.4 |
| 1995/12/31 | 03:45:18.4 | 67.5600 | 33.0200 | 100 | 3.3 | 2.3 |
| 1996/01/28 | 03:47:17.9 | 67.7100 | 33.3500 | 148 | 3.1 | 2.0 |
| 1996/03/31 | 03:40:24.9 | 67.5200 | 32.8400 | 92 | 3.1 | 2.0 |
| 1996/06/23 | 02:34:15.3 | 67.5200 | 32.6300 | 82 | 3.0 | 2.4 |
| 1996/07/28 | 03:14:31.0 | 67.6700 | 33.2800 | 95 | 2.9 | 2.4 |
| 1996/09/29 | 06:05:50.0 | 67.5700 | 32.5400 | 350 | 3.4 | 2.9 |

We have carried out a simple experiment to model the combination of random and systematic errors causing the observed scatter in IDC locations. In this model, we used only the parameters that are the most significant for the IDC solutions, namely, the arrival times of P and S phases from ARCESS, NORESS and FINESS. We did not consider azimuths, since these have relatively modest effect on the network location estimates.

For each of the phases mentioned above, we assigned a random uncertainty of 1.0 seconds (P) or 2.0 seconds (S). While these values may seem high, especially for the P-phase, it must be remembered that low SNR contributes to the reading uncertainty, especially for the more distant stations. Furthermore, we assumed a systematic error in the IDC velocity model of 0.15 km/sec (P-waves) and 0.09 km/sec (S-waves) for this area.

The resulting 90 per cent "uncertainty" ellipse is shown in Fig. 7.5.8, and seems to correspond well to the actually observed data. Thus, a first order correction to the model would be quite simple to make, and as a result the epicenters would be shifted towards the true location, although the scatter would not be reduced. In practice, station-specific travel time corrections would probably be the simplest way to implement this improvement. This is also consistent with the general philosophy now applied at the IDC, which is based upon global and regional geographical grid systems of varying density to assign regional calibration corrections.

We note that the travel-time corrections introduced on the basis of this calibration explosion could be expected to be appropriate for the general Khibiny region, not just Mine 1. An interesting question is to which extent these corrections would apply to the entire Kola Peninsula, or more generally, the Baltic Shield as a whole. This will require extensive study, and is outside the scope of this paper.

A comparison of the waveforms of 5 large underground explosions at Mine 1 is shown in Fig. 7.5.9. The recordings have been made by the vertical component of the High-frequency element in the Apatity array. The calibration explosion (bottom of the figure) is not possible to separate from most of the other explosions, based upon the waveform characteristics. The only explosion that appears different is explosion no. 2 from top (5 Dec. 93), which has a relatively much larger Rg phase than the others, and correspondingly lower proportion of high frequency energy.

We have investigated the explosion of 5 Dec. 93 in some detail, and have found that it was followed by a significant number of rockbursts. It is therefore possible that there was some tectonic release occurring simultaneously with the explosion, and that this could explain the anomalous recording. None of the other explosions in this figure had a similar aftershock sequence, although the calibration event was in fact followed by a few rockbursts. In conclusion, the seismic "signature" of the calibration event is not unusual compared to other explosions in the same mine.

We also make a note on the magnitudes provided in Table 7.5.3. The IDC magnitudes were generally lower than our ML values during the first half of 1995, but have been significantly larger since then. This is because the IDC changed its local magnitude estimation procedure at that time. The KRSC magnitude estimates are consistent throughout the period, and have in fact been shown to have a good correlation with yield, when considering underground mining explosions in Khibiny in general (Kremenetskaya, Asming and Ringdal, 1995).

*Conclusions*

The calibration explosion of 29 September 1996 has provided valuable data for the purpose of improving the routine location process at the IDC for the Khibiny area. The excellent recordings achieved by the stations in the Kola Peninsula could prove useful also for more detailed geophysical investigations, including mapping the crustal velocity structure.

This explosion has been one of the first conducted for calibration purposes in GSETT-3. There is clearly a need for additional such explosions in various areas, including other explosions in Fennoscandia to validate the travel-time corrections for other areas. In addition, the efforts to obtain detailed "ground truth" data for selected mining explosions should continue.

It has been argued that calibration events are most useful if they are large enough to be detected teleseismically. While this is generally true, it seems unrealistic to obtain such events in all regions of the world where calibration is needed. Calibration explosions that are recorded only at regional distances are therefore also important, and will contribute to improve the processing of many small events that might otherwise be significantly mislocated in the IDC bulletin.

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### *References*

Kremenetskaya, E.O., V.E. Asming and F. Ringdal (1995): Study of underground mining explosions in the Khibiny Massif. In: NORSAR Semiannual Tech. Summ. 1 Oct 94-30 Mar 95, NORSAR Sci. Rep. No. 2-94/95, Kjeller, Norway.

Kremenetskaya, E.O., F. Ringdal, I.A. Kuzmin and V.E. Asming (1995): Seismological aspects of mining activity in Khibiny, Kola Science Centre, Apatity

Kremenetskaya, E.O. & V. M. Trjapitsin (1995): Induced seismicity in the Khibiny Massif (Kola Peninsula), PAGEOPH Vol 145, No 1, pp 29-37.

Panasenko, G.D. and Yakovlev, V.M. (1983). About the nature of anomalous deformation of a transport tunnel in the mountain Yukspor. In: Geophysical Investigations in the European North of the USSR, KB AS USSR, Apatity, pp. 38-44 (in Russian).

Ringdal, F. and T. Kværna (1989), A multi-channel processing approach to real time network detection, phase association and threshold monitoring, Bull. Seism. Soc. Am. 79, 1927-1940.

## Table 7.5.4: Kola explosion 29.09.96 — NORSAR's automatic Generalized Beamforming solution

| Origin time | Lat | Lon | Azres | Timres | Wres | Nphase | Ntot | Nsta | Netmag |
|---|---|---|---|---|---|---|---|---|---|
| 1996-273:06.05.46.0 | 67.75 | 33.65 | 9.63 | 1.86 | 4.27 | 13 | 25 | 5 | 2.41 |

| Sta | Dist | Az | Ph | Time | Tres | Azim | Ares | Vel | Snr | Amp | Freq | Fkq | Pol | Arid | Mag |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| APA | 32.4 | 58.6 | Pg | 06.05.50.8 | -0.5 | 76.8 | 18.2 | 6.1 | 1249.4 | 6678.8 | 1.26 | 1 | | 221346 | - |
| APA | 32.4 | 58.6 | Lg | 06.05.59.1 | 4.1 | 82.7 | 24.1 | 5.2 | 9.5 | 13516.3 | 4.71 | 3 | -3 | 221350 | 1.27 |
| ARC | 386.1 | 117.1 | Pn | 06.06.41.9 | 0.9 | 121.4 | 4.3 | 7.7 | 163.5 | 5055.7 | 5.74 | 2 | 1 | 221366 | - |
| ARC | 386.1 | 117.1 | p | 06.06.50.1 | | 109.6 | -7.5 | 7.4 | 8.7 | 4648.5 | 2.34 | 1 | 1 | 221367 | - |
| ARC | 386.1 | 117.1 | p | 06.06.59.3 | | 126.1 | 9.0 | 7.7 | 2.6 | 1177.0 | 5.87 | 3 | | 221371 | - |
| ARC | 386.1 | 117.1 | Sn | 06.07.22.7 | -2.1 | 126.3 | 9.2 | 4.4 | 4.7 | 5079.8 | 4.83 | 2 | -2 | 221373 | 1.96 |
| ARC | 386.1 | 117.1 | s | 06.07.29.6 | | 124.8 | 7.7 | 3.9 | 2.5 | 3785.3 | 1.63 | 2 | | 221378 | - |
| ARC | 386.1 | 117.1 | Lg | 06.07.32.6 | -1.4 | 112.4 | -4.7 | 3.7 | 6.9 | 5569.9 | 1.25 | 2 | -2 | 221381 | 2.02 |
| ARC | 386.1 | 117.1 | s | 06.07.39.9 | | 115.0 | -2.1 | 3.7 | 3.1 | 8202.0 | 1.94 | 1 | -3 | 221384 | 2.42 |
| ARC | 386.1 | 117.1 | s | 06.07.45.3 | | 116.7 | -0.4 | 3.7 | 2.5 | 8657.8 | 2.66 | 3 | | 221385 | - |
| ARC | 386.1 | 117.1 | Rg | 06.07.57.6 | 0.7 | 106.7 | -10.4 | 3.2 | 3.2 | 11081.5 | 0.86 | 1 | | 221387 | - |
| FIN | 790.8 | 23.9 | Pn | 06.07.29.9 | -0.5 | 23.6 | -0.3 | 8.2 | 7.4 | 111.1 | 5.27 | 3 | | 221358 | - |
| FIN | 790.8 | 23.9 | p | 06.07.35.9 | | 16.9 | -7.0 | 8.2 | 4.5 | 62.1 | 4.90 | 2 | | 221363 | - |
| FIN | 790.8 | 23.9 | p | 06.07.38.9 | | 24.7 | 0.8 | 8.5 | 6.3 | 116.1 | 4.81 | 2 | | 221369 | - |

SPI 06.08.30.8

| Sta | Dist | Az | Ph | Time | Tres | Azim | Ares | Vel | Snr | Amp | Freq | Fkq | Pol | Arid | Mag |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FIN | 790.8 | 23.9 | Sn | 06.08.58.0 | 6.2 | 25.7 | 1.8 | 5.0 | 2.5 | 371.4 | 2.53 | 1 | | 221379 | 2.16 |
| FIN | 790.8 | 23.9 | s | 06.09.09.7 | | 13.1 | -10.8 | 4.6 | 2.9 | 561.2 | 2.82 | 1 | | 221388 | - |
| FIN | 790.8 | 23.9 | s | 06.09.20.4 | | 19.2 | -4.7 | 3.7 | 8.4 | 1455.6 | 1.33 | 1 | | 221392 | - |
| FIN | 790.8 | 23.9 | Lg | 06.09.30.7 | 3.5 | 22.4 | -1.5 | 4.2 | 2.7 | 1099.2 | 2.54 | 1 | | 221398 | 2.63 |
| HFS | 1285.9 | 40.4 | Lg | 06.11.44.4 | -1.3 | 55.0 | 14.6 | 4.6 | 4.1 | 277.1 | 2.05 | 1 | | 221374 | 2.99 |
| NRS | 1316.8 | 44.3 | Pn | 06.08.33.2 | -1.1 | 59.8 | 15.5 | 8.4 | 7.3 | 271.1 | 2.81 | 2 | | 221357 | - |
| NRS | 1316.8 | 44.3 | Sn | 06.10.42.6 | -1.0 | 60.3 | 16.0 | 4.2 | 2.9 | 441.8 | 2.20 | 2 | -1 | 221390 | 2.37 |
| NRS | 1316.8 | 44.3 | s | 06.10.48.6 | | 45.5 | 1.2 | 4.9 | 3.6 | 622.0 | 1.84 | 2 | | 221397 | - |
| NRS | 1316.8 | 44.3 | Lg | 06.11.55.4 | 1.1 | 39.8 | -4.5 | 3.8 | 2.8 | 1890.9 | 1.27 | 1 | | 221405 | 2.64 |
| NRS | 1316.8 | 44.3 | s | 06.12.01.4 | | 52.2 | 7.9 | 4.7 | 2.7 | 597.9 | 2.33 | 2 | | 221407 | 2.77 |
| NRS | 1316.8 | 44.3 | s | 06.12.02.6 | | 50.1 | 5.8 | 4.3 | 3.6 | 967.6 | 1.72 | 2 | | 221412 | - |

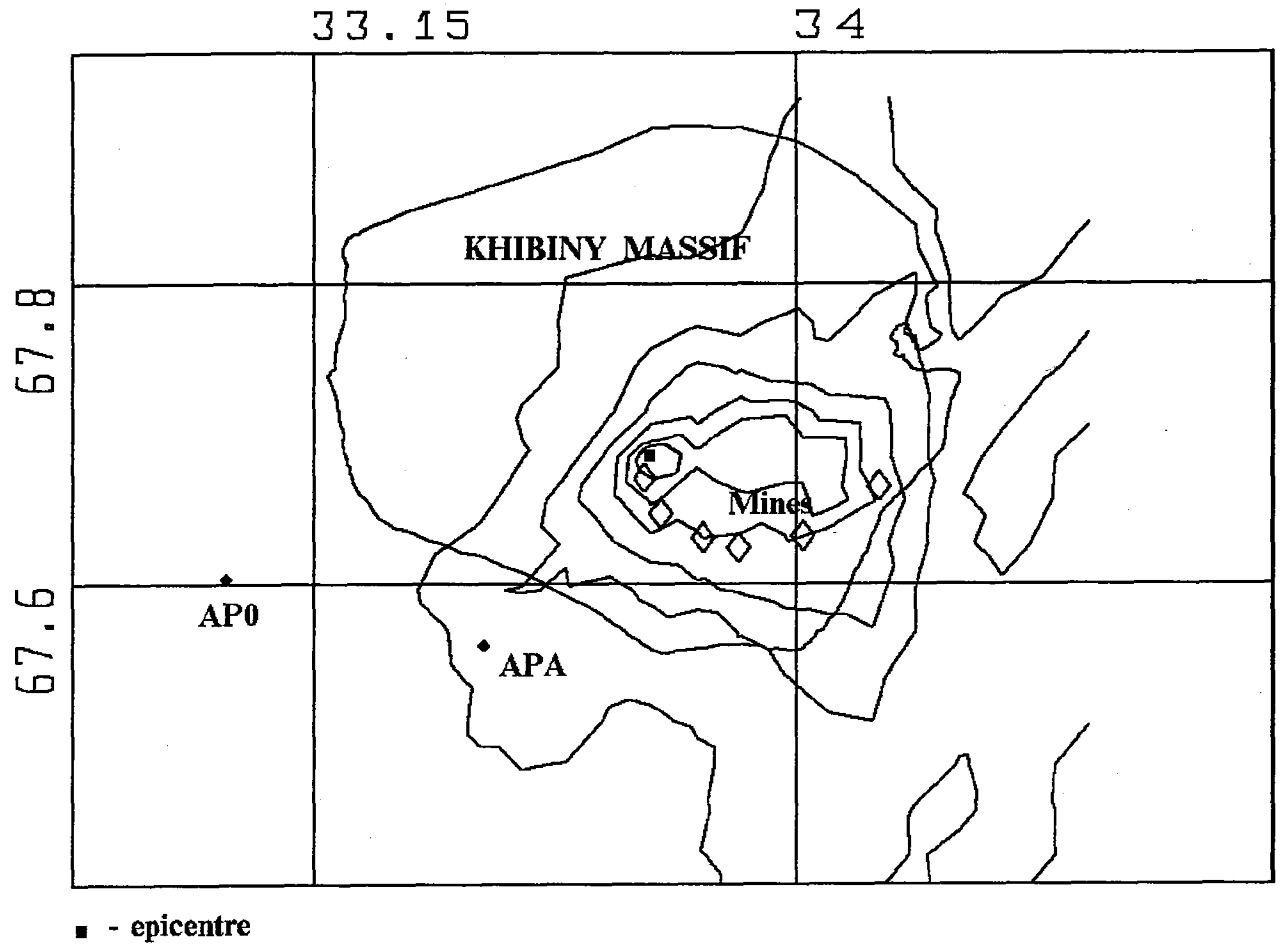



*Fig. 7.5.1. The Khibiny Massif, with locations of 6 mines. The seismic stations AP0 (array) and APA are shown, together with the epicenter of the calibration explosion estimated from seismic recordings.*

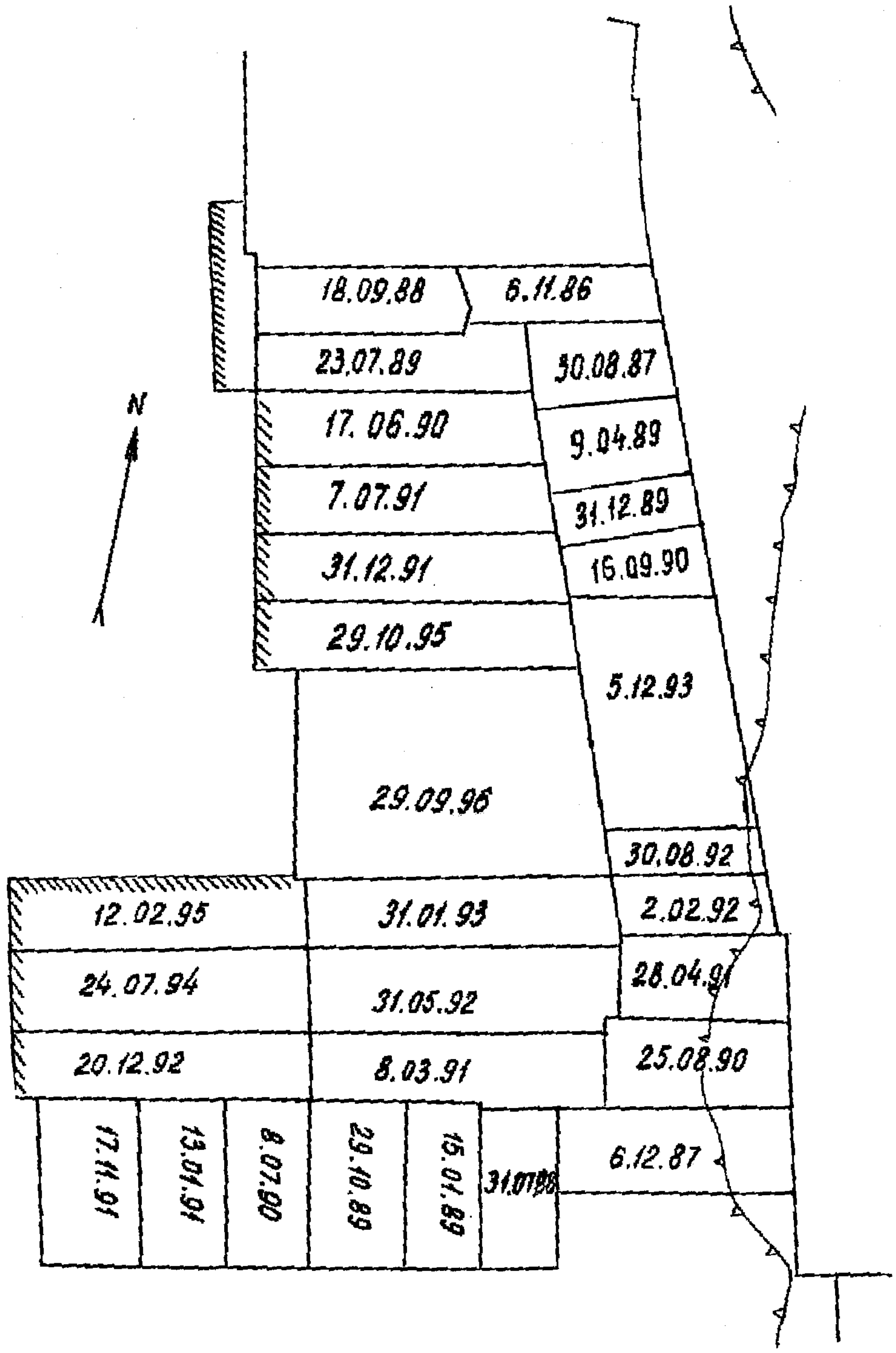



*Fig. 7.5.2. Relative locations of selected large mining explosions in Khibiny Mine 1. The calibration explosion of 29.09.96 took place near the center of the mine.*

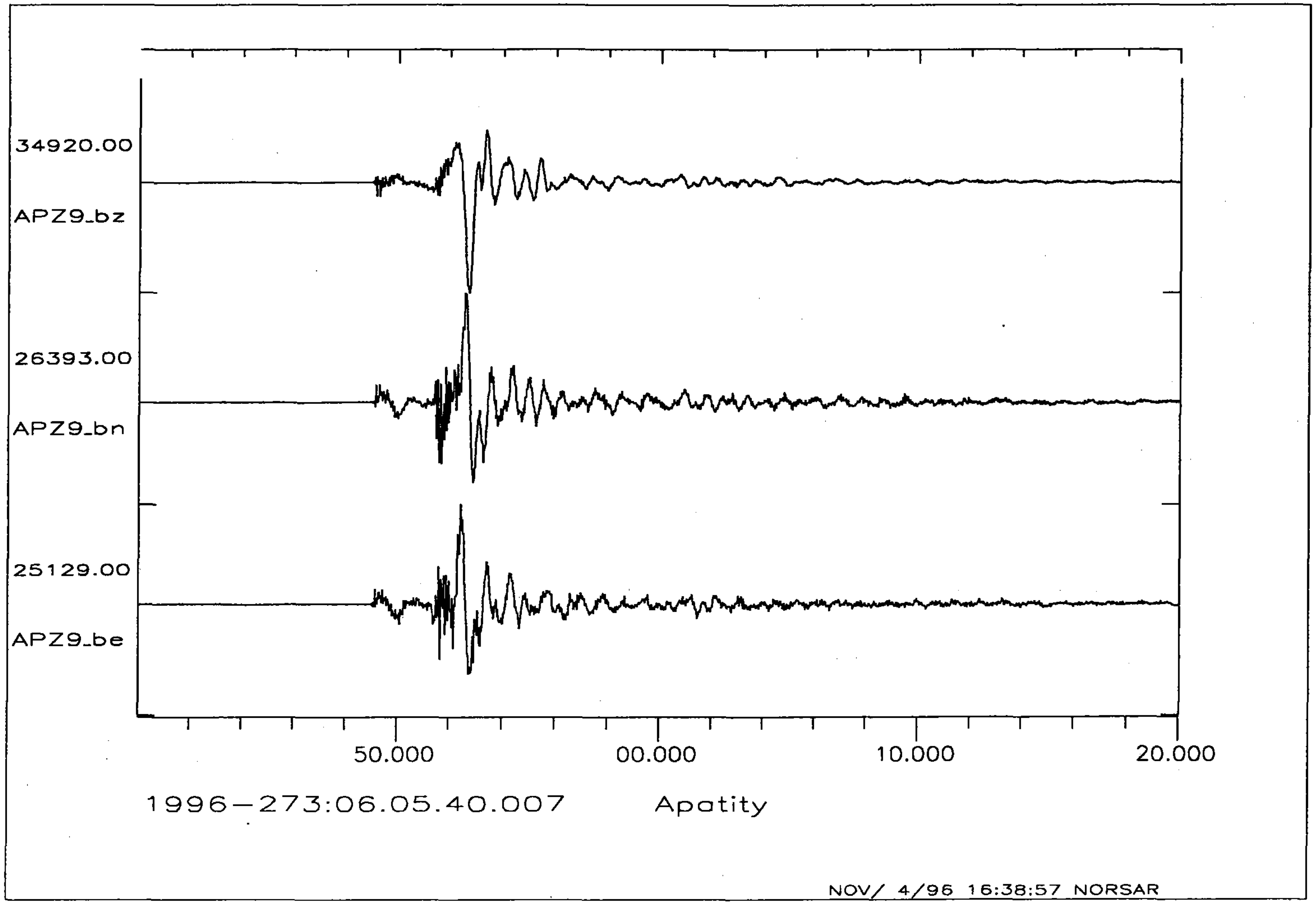



*Fig. 7.5.3. Kola explosion 29.09.96 — Station APZ9; 3-component broadband recordings.*

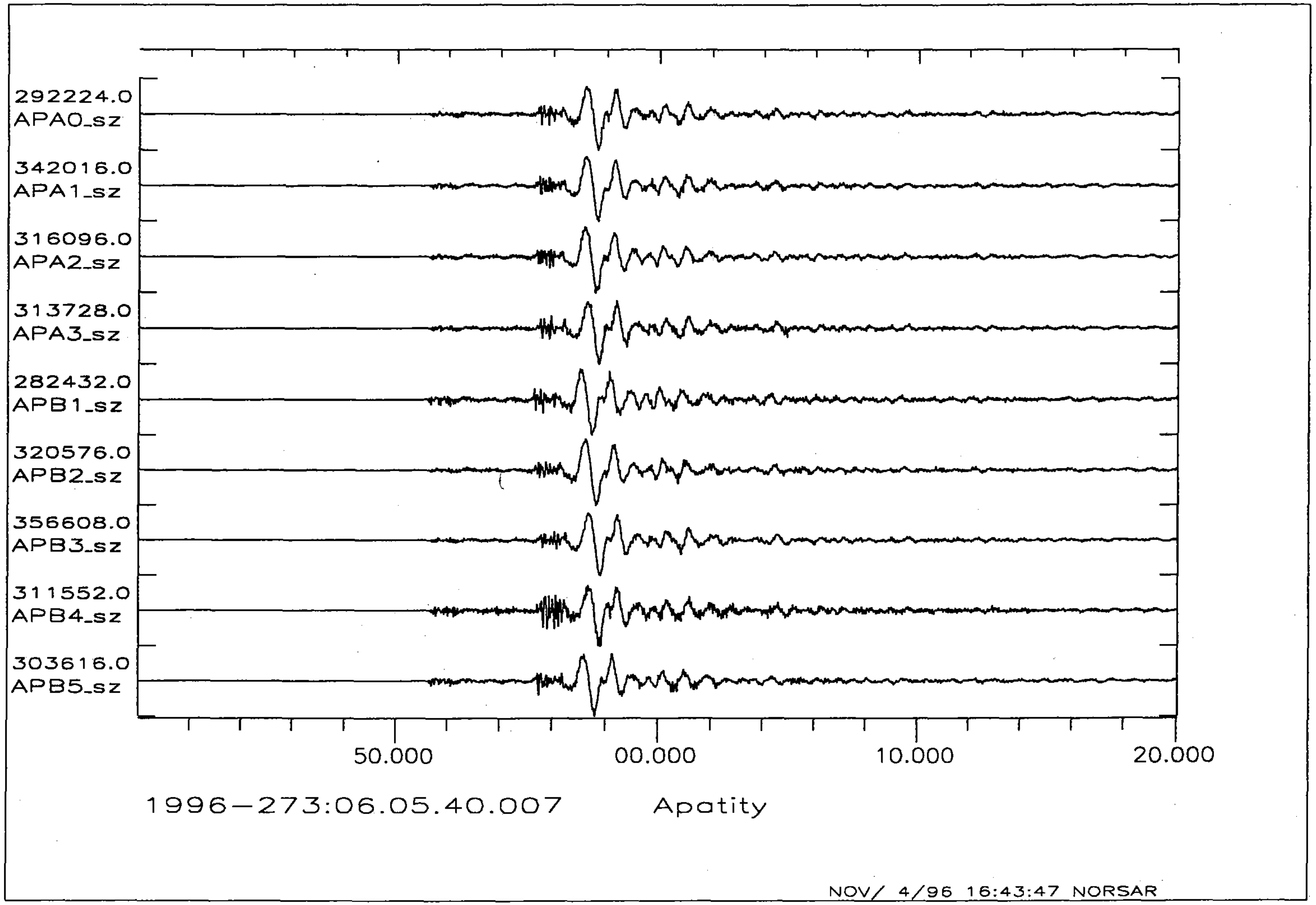



*Fig. 7.5.4. Kola explosion 29.09.96 — Apatity array (APA0).*

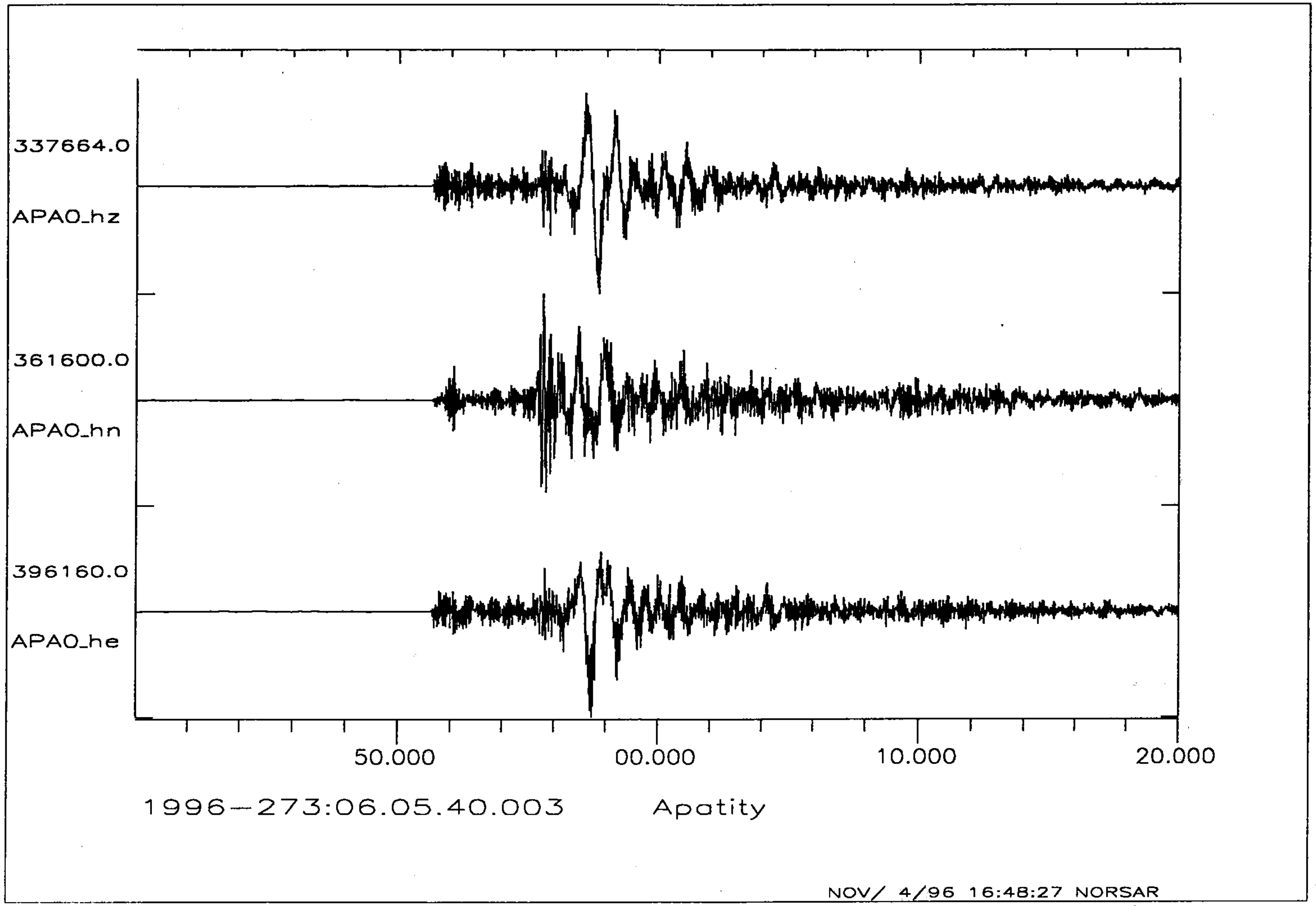



*Fig. 7.5.5. Kola explosion 29.09.96 — Station APA0; high frequency element, 3-component recordings.*

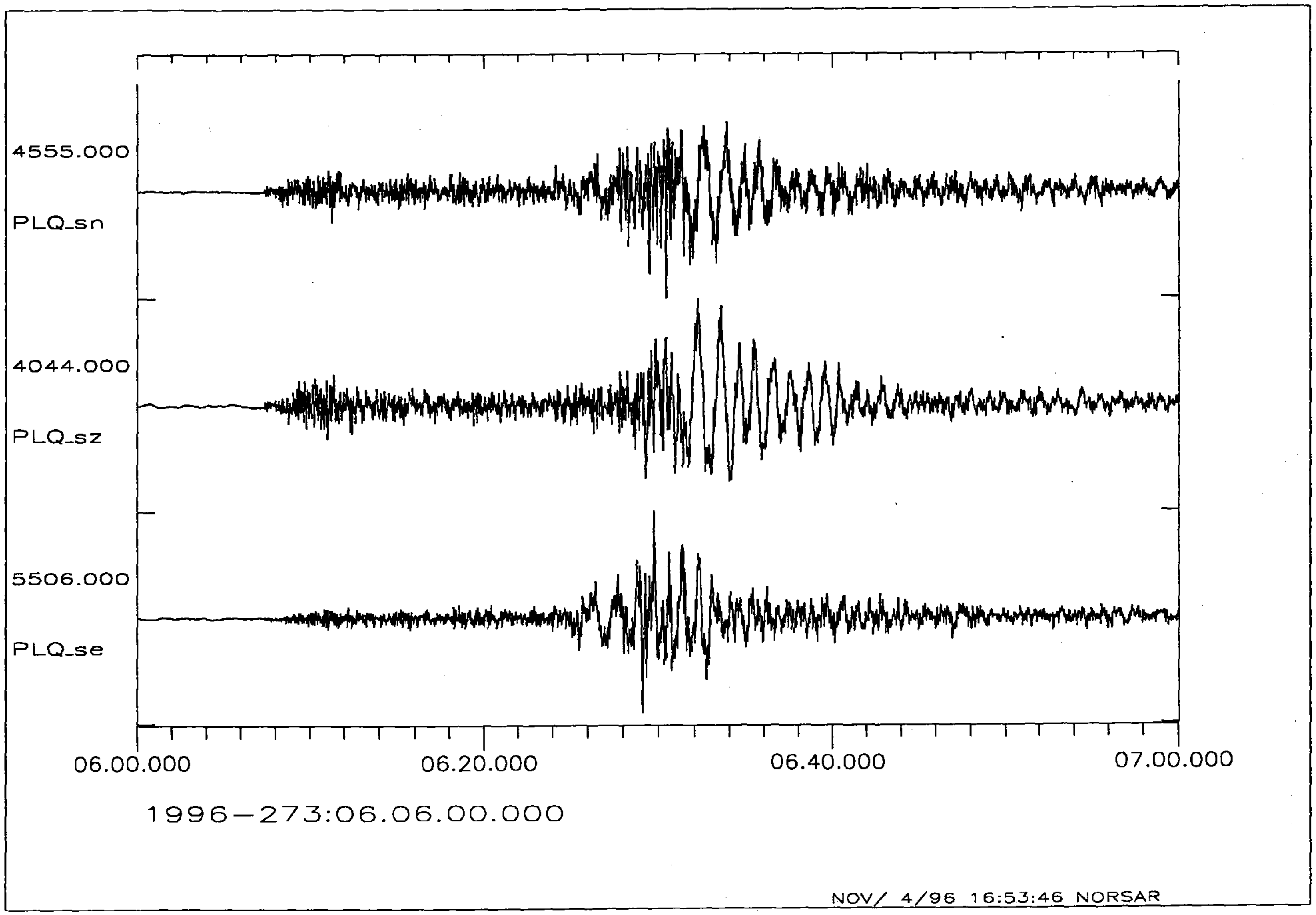



*Fig. 7.5.6. Kola explosion 29.09.96 — Station PLQ; 3-component recordings.*

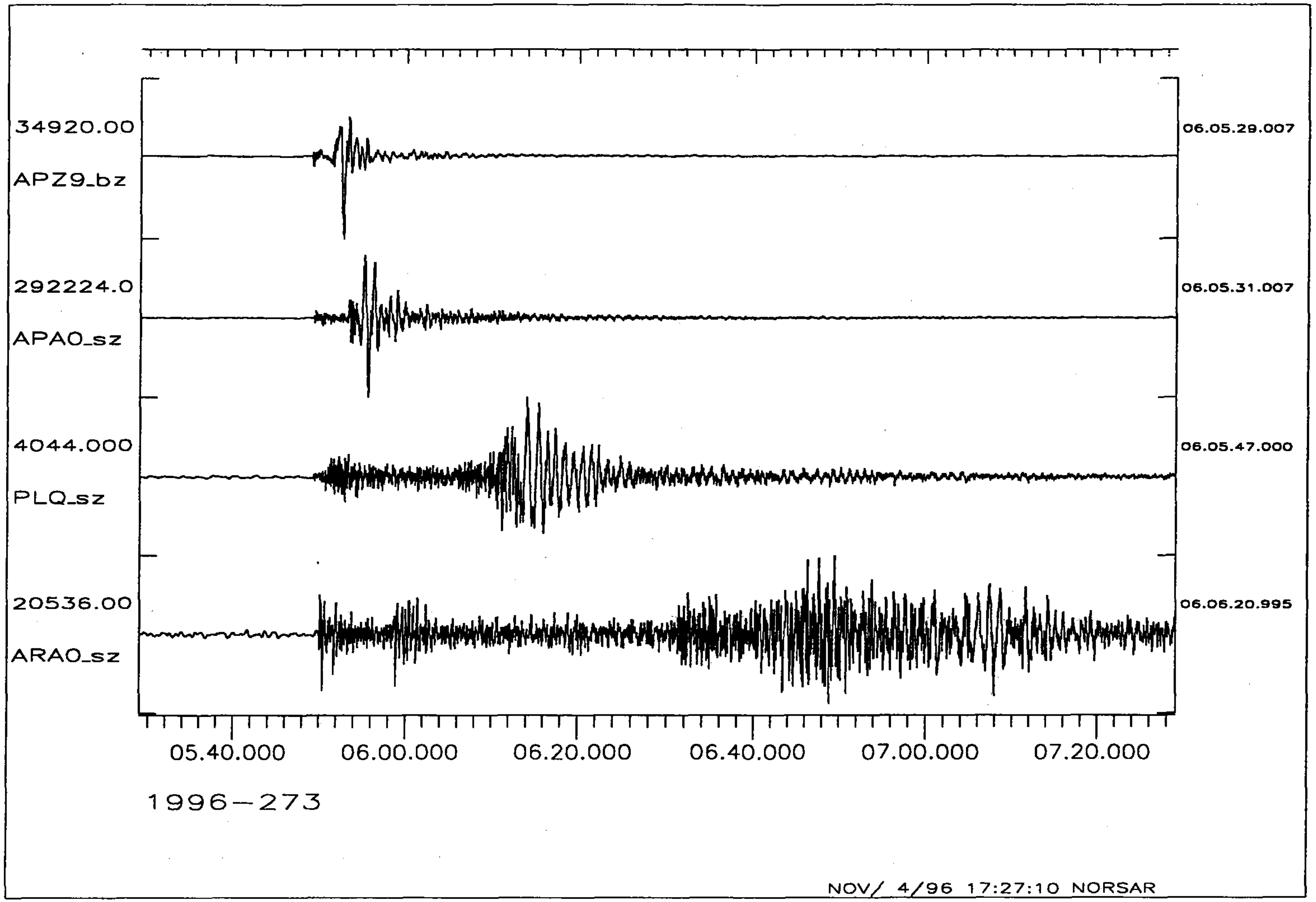
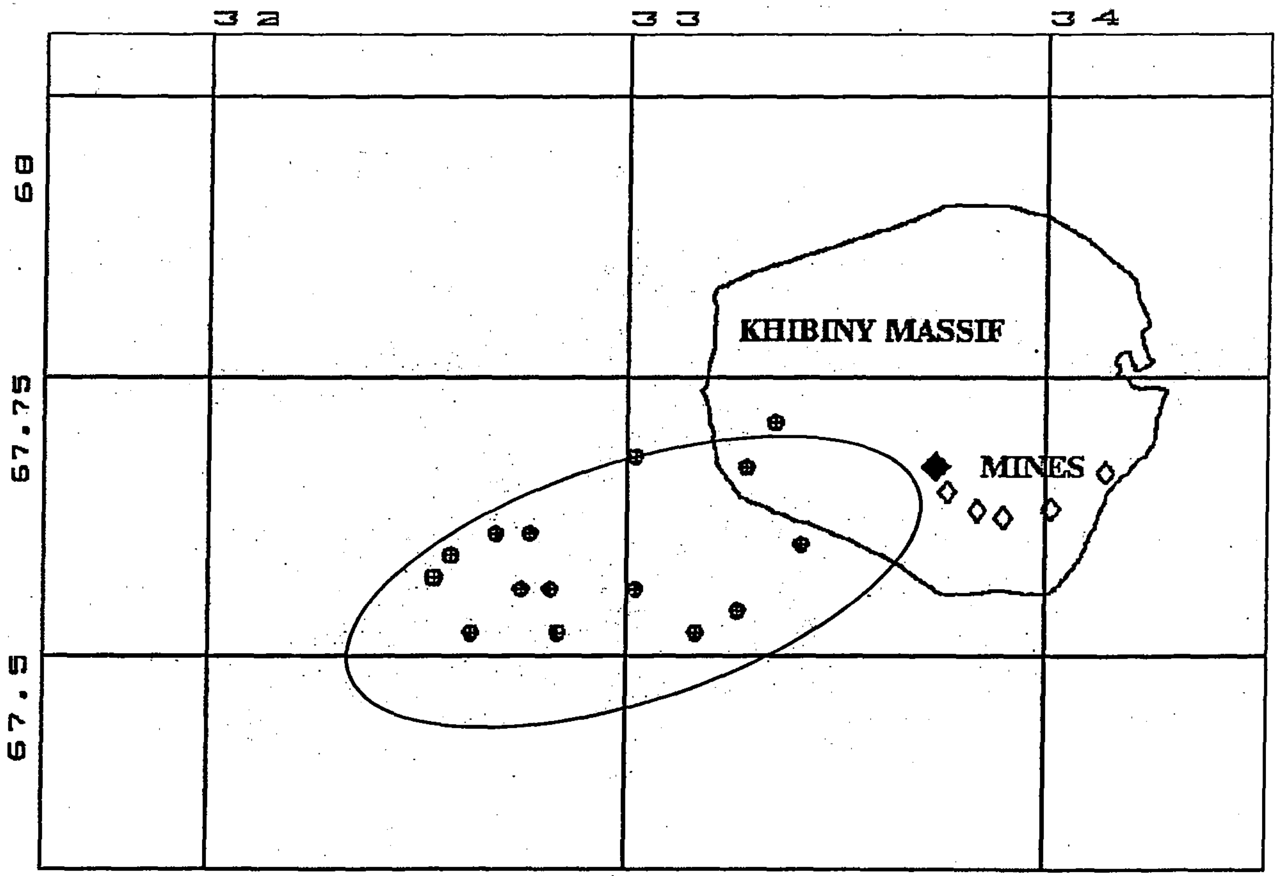



*Fig. 7.5.7. Kola explosion 29.09.96 — Comparison of station recordings. The figure shows 2 minutes of data for each trace, and the traces are lined up according to their P-arrival times.*




◆ - place of the explosions; ⊕ - IDC locations; ◇ - modelled locations;

*Fig. 7.5.8. GSETT-3 IDC location estimates for large explosions in Mine 1. The ellipse indicates the model simulation described in the text.*

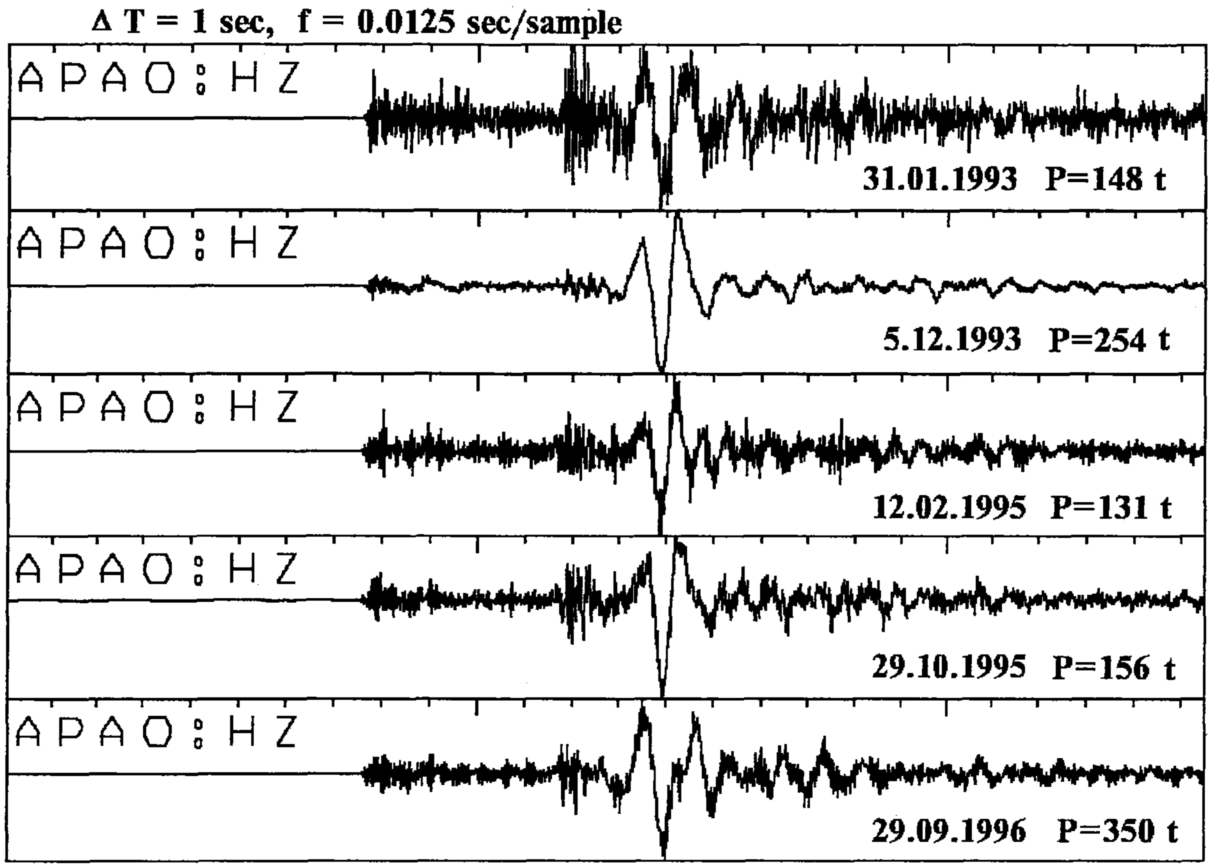



*Fig. 7.5.9. Waveform comparisons of 5 large explosions in Mine 1. Note the similarities of the waveforms, except for no. 2 from top (see text for details).*