NORSAR

NORSAR Scientific Report No. 1-2003

Semiannual Technical Summary

1 July - 31 December 2002

Frode Ringdal (ed.)

Kjeller, February 2003

6.2 Single array analysis and processing of events from the Kovdor mine, Kola, NW Russia

6.2.1 Introduction

In several regions of the world, the majority of observed seismic events are the result of mining activities. For example, on the Kola Peninsula in north-western Russia, there are several concentrations of mines where explosions are routinely carried out with varying frequency. The yield of explosives used varies from explosion to explosion as does the nature of the blasts; for example, whether they are underground or surface detonations, compact or ripple-fired.

Within the context of monitoring nuclear explosions, it is important to be able to identify such events and associate them with a specific source. In an automated monitoring process, the identification of events which can be attributed to activities at a given mine with a high level of confidence can free analytical resources to investigate events which cannot, with confidence, be ascribed to a known source.

In the monitoring context, situations will arise where an interesting event is only detected by a single array. It is therefore essential to quantify how accurately such events can be located.

The goal of this work is to use a single regional seismic array (ARCES) to characterize seismic signals resulting from explosions that are known to have occured at the Kovdor open cast mine in Russia (67.557^{o} N, 30.425^{o} E) and use these observations to determine whether other events recorded at ARCES are the result of operations at this mine. Wherever possible, events which are deemed to be likely candidates for Kovdor events are located to the best possible accuracy.

Figure 6.2.1 shows the location of the Kovdor mine relative to ARCES together with the Zapoljarny, Olenegorsk and Khibiny mining regions on the Kola Peninsula. The distance between ARA0, the central seismometer of the ARCESS array, and Kovdor is 298 kilometers with a receiver to source backazimuth of 135^{o}.

Ground Truth information for events at the mines indicated in Figure 6.2.1 has been provided by the Kola Regional Seismological Centre (KRSC) in Apatity on the Kola peninsula. Table 6.2.1 gives the reported yield information and approximate origin times for explosions at the Kovdor mine between October 6, 2001, and July 13, 2002.

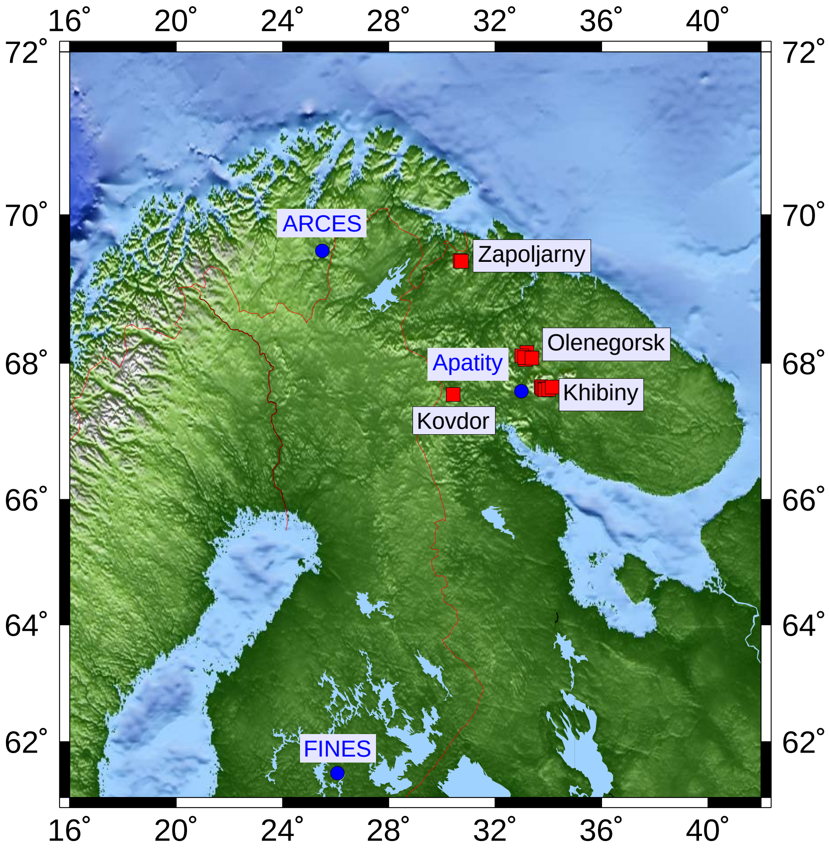

Fig. 6.2.1. Locations of the mining regions in NW Russia for which ground truth information is provided by KRSC. Also shown are the locations of the seismic arrays in the region (ARCES, Apatity and FINES).

A daily list of phase detections for the ARCES array is created by NORSAR's DP/EP processing system (Fyen, 1989, 2001). These detection lists (referred to as FKX lists) are used in two ways. Firstly, for the initial P-arrival (Pn phase) for each confirmed Kovdor event, the detection time from the ARCESS FKX lists is used as an initial estimate in determining accurate arrival times. In addition, the detection lists are also scanned for the presence of signals from further events which may originate at Kovdor.

The work described in this report is performed in two stages.

1. Firstly, using the origin information reported by KRSC, we study a set of events which are known to result from explosions at the Kovdor mine. The characteristics of the signals are described in section 6.2.2.

2. The FKX automatic detection lists for the ARCES array are used to obtain a list of events which could originate from Kovdor, irrespective of whether or not they were reported by KRSC. Based upon the properties observed for the known events in Step 1, a series of tests (described in section 6.2.3) is carried out on ARCES data in order to estimate the likelihood that such an event is a genuine Kovdor event.

Date	Origin time	Yield (tons)
Sat, Oct 6, 2001	2001-279:10.28.15	307
Sat, Oct 13, 2001	2001-286:10.28.51	284
Sat, Oct 20, 2001	2001-293:10.35.50	255
Sat, Oct 27, 2001	2001-300:10.24.45	293
Sat, Nov 3, 2001	2001-307:11.27.15	281
Sat, Nov 10, 2001	2001-314:11.20.39	213
Sat, Nov 17, 2001	2001-321:11.44.34	304
Sat, Nov 24, 2001	2001-328:11.20.42	148
Wed, Nov 28, 2001	2001-332:12.04.48	112
Sat, Dec 1, 2001	2001-335:11.20.18	155
Sat, Dec 8, 2001	2001-342:11.39.15	308
Sat, Dec 15, 2001	2001-349:11.17.23	220
Sat, Dec 22, 2001	2001-356:11.21.12	244
Sat, Dec 29, 2001	2001-363:10.55.19	293
Sat, Jan 5, 2002	2002-005:11.15.48	185
Sat, Jan 12, 2002	2002-012:11.12.55	181
Sat, Jan 19, 2002	2002-019:11.33.25	368
Sat, Jan 26, 2002	2002-026:11.20.54	291
Sat, Feb 2, 2002[a]	2002-033:11.17.12	212
Sat, Feb 9, 2002	2002-040:11.31.27	198

a. Note that there is no ARCES data available for this event.

Date	Origin time	Yield (tons)
Sat, Feb 16, 2002	2002-047:11.47.17	406
Fri, Feb 22, 2002	2002-053:11.24.45	292
Sat, Mar 2, 2002	2002-061:11.16.08	216
Thu, Mar 7, 2002	2002-066:11.27.43	179
Sat, Mar 23, 2002	2002-082:11.29.21	226
Sat, Mar 30, 2002	2002-089:11.10.43	196
Sat, Apr 6, 2002	2002-096:10.13.27	244
Sat, Apr 13, 2002	2002-103:10.23.52	195
Sat, Apr 20, 2002	2002-110:10.22.50	315
Sun, Apr 28, 2002	2002-118:10.12.49	365
Sat, May 4, 2002	2002-124:10.13.19	108
Wed, May 8, 2002	2002-128:10.19.54	98
Sat, May 18, 2002	2002-138:10.29.47	221
Sat, May 25, 2002	2002-145:10.16.45	185
Sat, Jun 1, 2002	2002-152:10.16.45	203
Sat, Jun 8, 2002	2002-159:10.22.29	405
Sat, Jun 15, 2002	2002-166:10.16.17	240
Sat, Jun 22, 2002	2002-173:10.21.37	312
Sat, Jun 29, 2002	2002-180:10.20.18	247
Sat, Jul 6, 2002	2002-187:10.31.01	256
Sat, Jul 13, 2002	2002-194:10.32.30	256

Table 6.2.1. List of events reported by KRSC from the Kovdor mine between October 6, 2001 and July 13, 2002.

6.2.2 A study of events confirmed to have originated at the Kovdor mine

Based upon the origin times listed in Table 6.2.1, the ARCES detection lists were searched for the first (Pn phase) arrivals resulting from each of these events. The *barey* velocity model is derived from the Barents model of Kremenetskaya *et al.* (2001) and provides a good representation of paths from the Kara Sea to Fennoscandia (see Schweitzer and Kennett, 2002). According to *barey*, an event at a distance of 298 km is followed by Pn, Sn, and Lg phase arrivals at 44.1, 77.2, and 83.3 seconds respectively.

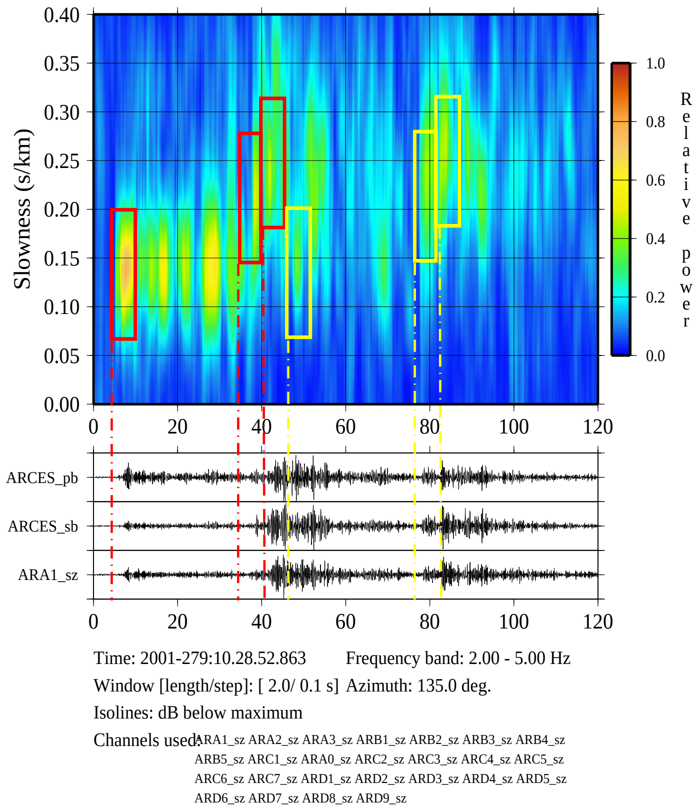

Fig. 6.2.2. Vespagram of the 2001-279 event for the frequency band 2.0-5.0 Hz and constant azimuth 135^{o}. ARCES_pb and ARCES_sb are beams with azimuth 135^{o} and apparent velocity 8.0 kms^{-1} and 4.0 kms^{-1} respectively.

The ARCES recording of one such confirmed event is illustrated in Figure 6.2.2. Red boxes have been drawn around the Pn (slowness 0.14 skm^{-1}), Sn (slowness 0.21 skm^{-1}), and Lg (slowness 0.24 kms^{-1}) phases. Phases corresponding to a secondary event occurring approximately 40 seconds after the first are highlighted by yellow boxes. Such secondary events are very characteristic of blasts at the Kovdor mine.

On identification of the automatic ARCES detection corresponding to the first Pn-arrival from a confirmed event, the following process was initiated:-

1. A beam was formed from the sz (short period, vertical) component traces from the ARCES array with a velocity 7.25 kms^{-1} and azimuth 135.0^{o}, and then filtered in an "optimal frequency band", calculated to maximize a combination of band-width and signal to noise ratio (SNR). This filtered trace was used to calculated an accurate time for

the Pn arrival, t_P, using the AR-AIC onset picker (Akaike, 1974, GSE/JAPAN/40, 1992, Kværna, 1995).

2. Azimuth and slowness for the Pn-phase were calculated using fk-analysis in three fixed frequency bands; 2-5 Hz, 3-8 Hz, and 8-16 Hz. All the ARCES sz instruments were used for the first two frequency bands and all but the D-ring for the third, given the decrease in coherency which occurs at these higher frequencies. The time window used was (t_P-0.5,t_P+2.5) seconds.
3. Fk-analysis was performed in two fixed time windows: (t_P+32.5, t_P+35.5) for the Sn phase and (t_P+36.5,t_P+39.5) for the Lg phase. For both of these phases, all sz traces were filtered in the single frequency band 2-5 Hz.
4. AR-AIC onset times for the Sn- and Lg- phases were determined from beams filtered in the 2-5 Hz frequency band. In addition to the sz beam, the transverse beam from the rotated ARA0, ARC2, ARC4, and ARC7 horizontal components was used, the onset time taken being that from the beam giving the greatest SNR value. Irrespective of the results of the fk-analysis, the Sn and Lg beams had apparent velocity 4.5 and 4.0 kms^{-1} respectively and azimuth 135°. The initial guesses of 33.0 and 37.0 seconds after t_P for Sn and Lg respectively were decided upon following the manual inspection of many seismograms and vespagrams.

The time windows for the Pn, Sn, and Lg phase fk-analysis are shown together with the filtered beams and AR-AIC onset picks in Figure 6.2.3.

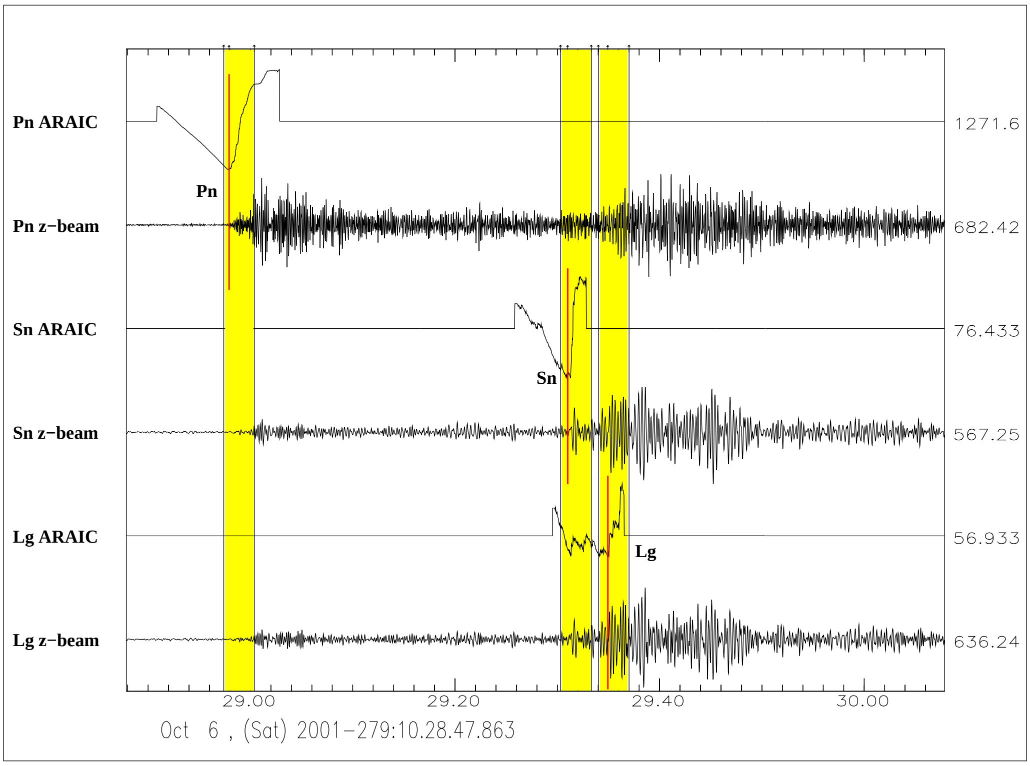

Fig. 6.2.3. Fixed time windows relative to the Pn onset for fk-analysis of phases as indicated displayed with Pn, Sn, and Lg onset picks for the KRSC verified Kovdor event of 2001-279.

The results of this procedure are summarized in Table 6.2.2. For several events, the result of the fk-analysis was demonstrably unrepresentative of the seismic phase being measured. For example, many fk results from the (t_P+32.5, t_P+35.5) second time window gave far higher apparent velocity values than could be accounted for by an Sn-phase from a Kovdor event. In all of these cases, the cause was identified as a Pn-phase from a secondary event superimposed on the Sn-signal. The Lg fk-analysis results displayed a large spread in azimuth but were more robust, probably due to the larger amplitude of the Lg-signal.

Phase	Filter band (Hz)	Apparent velocity (kms^{-1})			Azimuth (^{o})			Number of events used
		Min	Mean	Max	Min	Mean	Max	
Pn	2-5	6.68	**7.15**	7.81	132.1	**134.9**	136.7	39
	3-8	7.03	**7.35**	7.83	132.2	**136.0**	139.4	40
	8-16	6.92	**8.03**	8.94	132.2	**138.5**	144.1	33
Sn	2-5	3.92	**4.63**	5.49	132.2	**138.0**	143.6	33
Lg	2-5	3.43	**3.93**	4.41	128.6	**137.6**	144.8	39

Table 6.2.2. Summary of the fk-analysis for the 40 confirmed Kovdor events listed in Table 6.2.1 for which there exists ARCES data.

6.2.3 Classification of detections which correspond to likely Kovdor events

We wish to use the ARCES regional array to be able to identify and locate any seismic event likely to originate from Kovdor. This is achieved by the automatic process displayed in Figure 6.2.4. The following notes provide details for the tests conducted:

- TEST ONE: We decide whether a detection in the ARCES FKX list could correspond to an initial Pn-arrival from a Kovdor event. The decision is based upon whether or not both the apparent velocity (*vel*) and azimuth (*azi*) fall within appropriate ranges. The ranges of interest were determined by considering the *vel* and *azi* values obtained for 40 confirmed Kovdor events listed in Table 6.2.1 which were detected by ARCES. These events registered *vel* in the range 6.5 kms^{-1} to 16.2 kms^{-1} and *azi* in the range 118^o to 143^o. In order to catch all potential Kovdor events, the ranges had to be considerably larger and the acceptable *vel* and *azi* ranges were set to [6.1-18.0] kms^{-1} and [100^o - 160^o] respectively.
- TEST TWO: The Pn-onset time and fk-analysis for the Pn time window were carried out exactly as described for Steps 1 and 2 in Section 6.2.2. It is therefore appropriate to base our acceptance criteria on the minima and maxima obtained for the confirmed events (Table 6.2.2). An event passed the test if *vel* and *azi* were within range for either the 3-8 Hz band, or both of the bands 2-5 Hz and 8-16 Hz.
- TEST THREE: The fk-analysis for the Sn and Lg phases was identical to that carried out in Step 3 of Section 6.2.2 and so, based upon the minima and maxima in Table 6.2.2, an Sn fk-result was accepted if *vel* and *azi* fell in the ranges [3.8,5.5] and [131,145] respectively, and an Lg fk-result was accepted if *vel* and *azi* fell in the ranges [3.3,4.5] and [127,146] respectively. This test was passed if either Sn or Lg phases were acceptable.

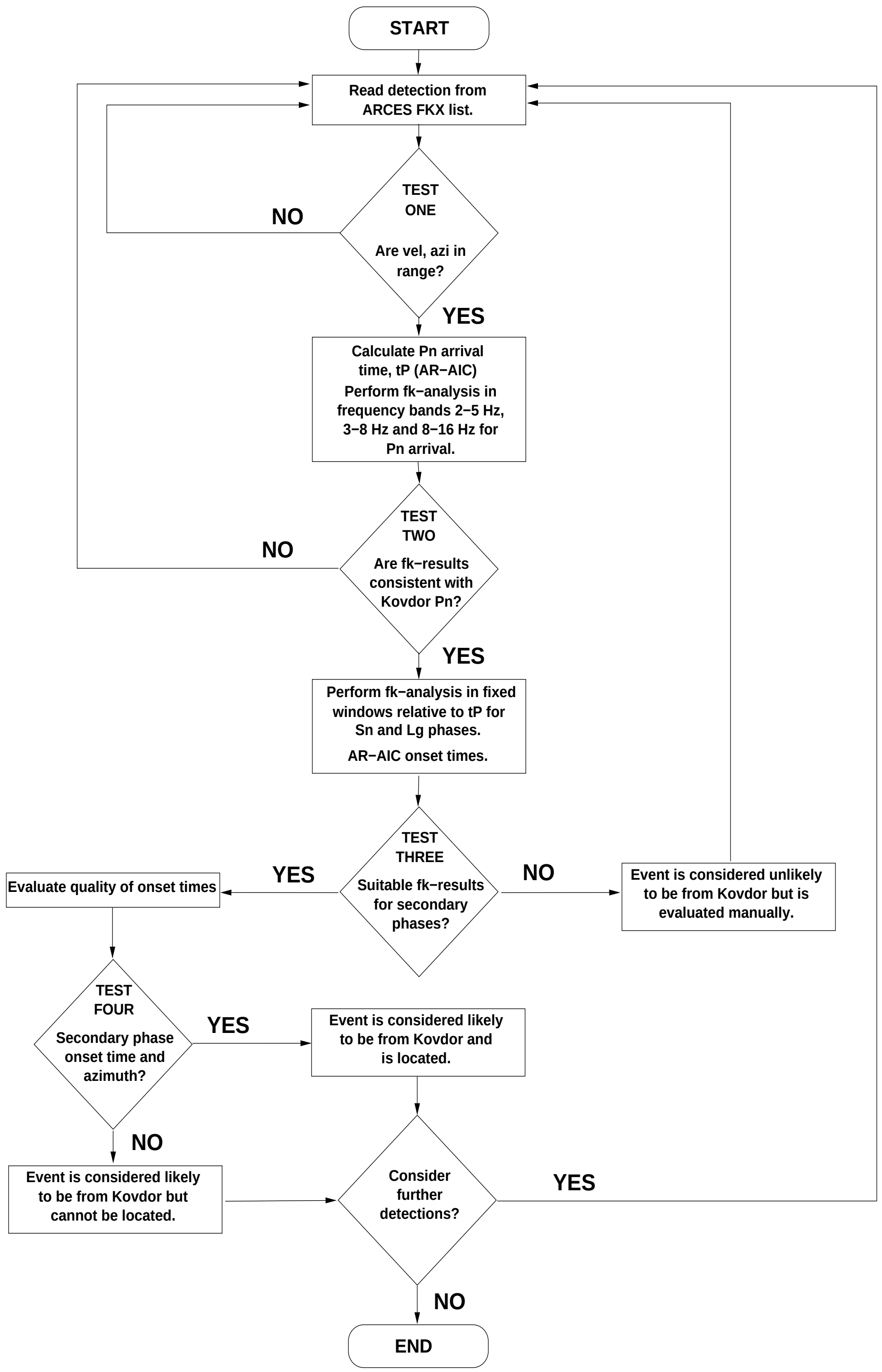

Fig. 6.2.4. Flowchart of steps in the automatic identification of events from the Kovdor mine.

- TEST FOUR: For an onset time for a secondary phase to be valid it had to satisfy a signal to noise ratio condition, be within an anticipated range, and be associated with an fk-result deemed to be acceptable from the previous test. For both Sn and Lg onset determinations, t_{Sn} and t_{Lg}, O_SNR was defined to be the 1 second mean of the envelope immediately following the onset divided by the 3 second mean immediately before the onset. For Sn picks, O_SNR had to be greater than 1.95, and, for Lg picks, O_SNR had to be greater than 2.0. t_{Sn} had to be within 1.2 seconds of t_P+33.0 and t_{Lg} had to be within 1.5 seconds of t_P+37.0. Any event for which an acceptable onset pick for a secondary phase was made was subsequently located using the HYPOSAT program (Schweitzer, 2001).

A very large number of ARCES detections passed the first test; 6176 between 2002-001 and 2002-208. This is inevitable given the large ranges of velocity and azimuth required to catch all potential events. The slowness and azimuth values from these detections are displayed in the left hand plot of Figure 6.2.5 with KRSC confirmed events highlighted as red triangles. The results from the new fk-analysis are displayed in the right hand plot and the scatter for the confirmed events is demonstrably reduced. All of the detections displayed here were calculated with the old ARCES detection recipes; the new recipes, introduced on 21 November 2002, appear to give more robust and reliable estimates of slowness and azimuth.

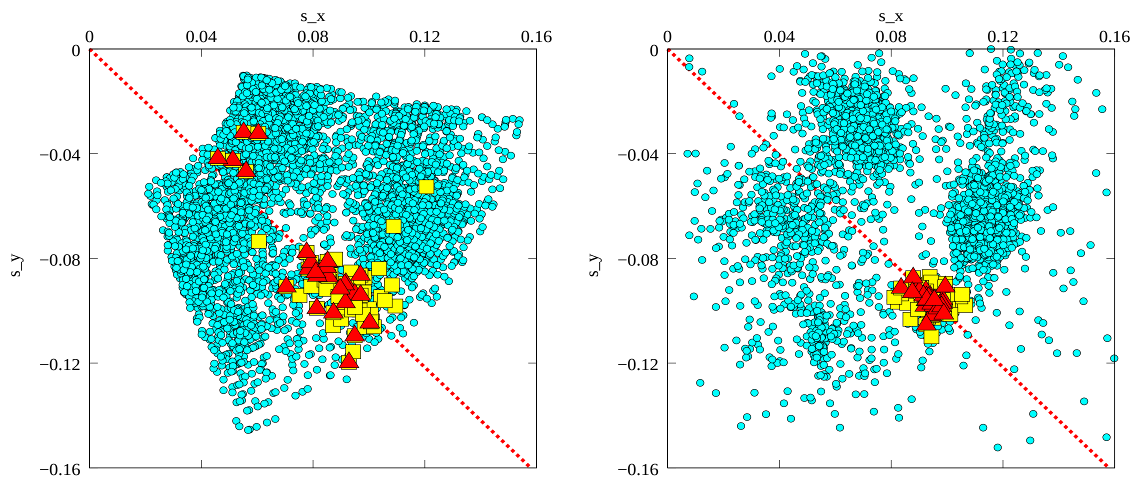

Fig. 6.2.5. The x and y components of horizontal slowness from the automatic ARCES detection list (left hand plot) and as given after autoregressive reestimation of onset time and new f-k analysis in the 3-8 Hz frequency band (right hand plot). P-phases corresponding to KRSC confirmed events are indicated by red triangles, whereas yellow squares correspond to P-phases of secondary Kovdor events and other events subsequently located close to the Kovdor mine

For the second test, in practice, only the result from the 3-8 Hz frequency band was usually required; for cases where both the 2-5 Hz and 8-16 Hz fk-analysis produced *vel* and *azi* in the accepted ranges, the velocity and azimuth calculated in the 3-8 Hz band were also within the appropriate limits. A total of 72 detections passed both of the first two tests and thus had been associated with an arrival which had a velocity and azimuth consistent with a Pn-arrival from a Kovdor event.

Of these 72 detections, 24 were discarded after the third test as they showed no indication of either an Sn or Lg phase consistent with a Kovdor event. Figure 6.2.6 shows fk-plots for the Sn phase for three detections. The first of these, 2002-026, is a confirmed Kovdor event which gives a high-quality fk-plot and a velocity and azimuth within the expected ranges. The second plot in Figure 6.2.6 also displays the results from a confirmed event (2002-012) which recorded an acceptable azimuth, but an apparent velocity which was too high to correspond to an Sn phase. Inspection of the waveforms indicates that this time window is in the coda of the P-arrival from a secondary event which, due to a good fk-result and onset pick for the Lg phase, was able to be located close to Kovdor. The third plot shows analysis of a hypothetical Sn window corresponding to a Pn detection consistent with a Kovdor event. There is no evidence for a signal from the correct azimuth and thus no evidence for a Kovdor-consistent Sn phase. Using data from the ARCES and FINES arrays, the NORSAR GBF (Generalized Beamforming) system (Kværna et al., 1999) located the event at 62.21^{o}N, 40.54^{o}E, or 1062 km from ARCES with an azimuth of 133^{o}; the corresponding secondary phases will arrive later than under the Kovdor event hypothesis.

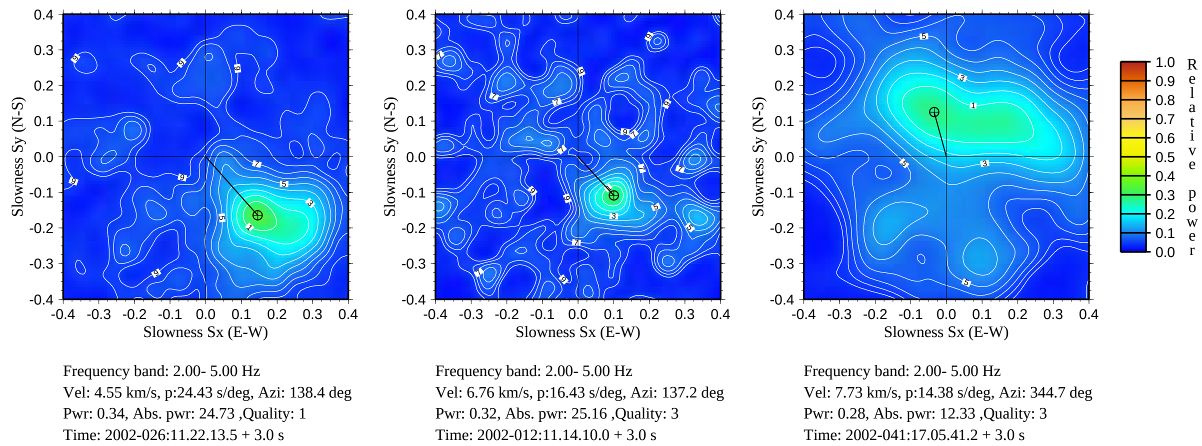

Fig. 6.2.6. Results of fk-analysis for the Sn time window for three events which passed the first two tests as indicated in Figure 6.2.4.

The first three tests resulted in 48 event hypotheses. Of these, only a single one was untrue. This is to say that the detection was the result of an event which did not occur at Kovdor; the NORSAR GBF system located it approximately 80 km south-east of Kovdor, using ARCES and Apatity data.

Of the KRSC confirmed Kovdor events, 29 occurred within the period of study (2002-001 to 2002-208) and 28 were recorded by ARCES. All of these resulted in ARCES detections which passed the first three tests, and 25 of them could be located using HYPOSAT. For the three events which could not be located, this was due to the contamination of the secondary phases with P-phases from secondary events. 19 of the true event hypotheses were the result of events not explicitly reported by KRSC, although 16 of these were secondary events occurring within 3 minutes of a confirmed event. A total of 38 events could be located.

6.2.4 Event location

Locations were determined using HYPOSAT and the ‘barey’ velocity model. In addition to a variability in the azimuth and differential travel times obtained, there were systematic deviations of azimuth from the geographical azimuth, and secondary phase arrival times from those predicted by the velocity model. Biases relative to the barey model were calculated from the 14 confirmed events which occurred in 2001 (see Table 6.2.1) and are displayed in Table 6.2.3. The events from 2001 were used in order to separate the population for which the biases are calculated from the testing population.

Phase	Á priori errors (uncorrected)		Travel-time biases relative to 'barey' model (s)	Azimuth bias (°)	Á priori errors (with data corrected for bias)	
	Time	Azi			Time	Azi
Pn	0.25	1.7	-	0.193	0.25	1.6
Sn	1.0	4.2	0.083	3.146	1.0	3.2
Lg	1.2	3.4	-2.549	1.425	1.0	3.2

Table 6.2.3. HYPOSAT Parameters

As we did not have absolute origin time information available, we had to use the time differences between the different phases to estimate the travel-time biases relative to the 'barey' model. Pn was set to have no bias. Based on the observed variation in relative travel-time and azimuth estimates of the 2001 events, the á priori estimates of errors of the HYPOSAT input data were set conservatively as listed in Table 6.2.3.

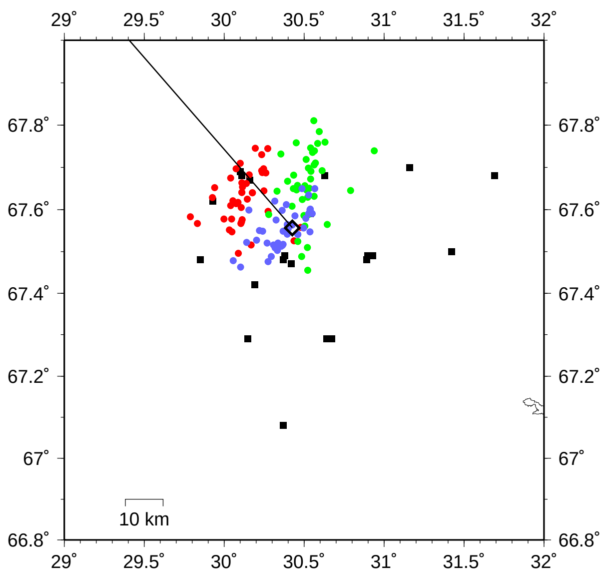

Fig. 6.2.7. Different types of event locations for Kovdor events.
Black diamond: Kovdor mine
Black line: Azimuthal line from the Kovdor mine to ARCES.
Red: One-array locations without travel-time and azimuth corrections.
Blue: One-array locations with travel-time and azimuth corrections.
Green: Manually (analyst) reviewed network locations.
Black: Automatic network locations (GBF method).

The event locations are displayed in Figure 6.2.7 and the statistics of these locations are given in Table 6.2.4.

Location type	Number of events	Location difference (km)			
		90%	95%	Median	Maximum
Automatic network locations (GBF method)	36	32.1	42.9	20.3	102.7
ARCES one-array locations without bias corrections	38	22.7	23.3	16.6	27.3
ARCES one-array locations with bias corrections	38	12.0	12.8	5.8	18.0
Analyst reviewed network locations[a]	40	21.7	24.3	11.0	28.9

a. Note that the manual locations did not apply any bias corrections.

Table 6.2.4. Statistics of event locations relative to the Kovdor mine.

6.2.5 Conclusions

We have developed a stepwise, fully automatic algorithm for identifying, processing, and locating events from the Kovdor mine, using only data from the ARCES array. Using results from the analysis of confirmed Kovdor events, we have developed a set of criteria to help determine whether or not detections from ARCES result from events at Kovdor. A detection is considered very likely to result from a Kovdor event if it passes the following three tests:-

1. The automatic ARCES detection list gives velocity and azimuth values within appropriate ranges, determined from confirmed Kovdor events.
2. Velocity and azimuth values obtained from a fixed frequency band fk-analysis are consistent with a Pn-arrival from a Kovdor event.
3. There is evidence of a secondary phase (appropriate velocity and azimuth from fixed frequency band fk-analysis within a time window at a fixed delay after the first P-arrival).

The automatic process was run on ARCES data from January 1, 2002, to July 27, 2002.

- A total of 6176 detections passed test 1.
- 72 detections were still considered likely candidates after test 2.
- 48 detections were still considered likely following test 3, of which only one was found to correspond to an event located at a different site.
- All of the events confirmed by KRSC to have originated at Kovdor were successfully identified by these three tests.

Of the events which are successfully identified as likely Kovdor candidates, those satisfying a fourth condition - that at least one secondary phase has been assigned a satisfactory arrival time - may be located within the automatic process. A total of 38 events were located in this way with an error comparable to that of the manually reviewed network locations.

References

Akaike, H. (1974): Markovian representation of stochastic processes and its application to the analysis of autoregressive moving average processes. Ann. Inst. Stat. Math. **26**, 363-387.

Fyen, J. (1989): Event processor program package. In NORSAR Semiannual Technical Summary. 1 Oct 1988 - 31 Mar 1989. Scientific Report **2-88/89**. Kjeller, Norway.

Fyen, J. (2001): NORSAR seismic data processing - user guide and command reference. NORSAR (contribution 731) Kjeller, Norway.

GSE/JAPAN/40 (1992): A Fully Automated Method for Determining the Arrival Times of Seismic Waves and its Application to an on-line Processing System

Kremenetskaya, E., Asming, V. and Ringdal, F. (2001): Seismic Location calibration of the European Arctic. Pure appl. geophys. **158**, 117-128.

Kværna, T. (1995): Automatic onset time estimation based on autoregressive processing. Semiannual Technical Summary, 1 April - 30 September 1995, NORSAR Sci. Rep. No. 1 95/96, Kjeller, Norway.

Kværna, T., Schweitzer, J., Taylor, L. and Ringdal, F. (1999): Monitoring of the European Arctic using Regional Generalized Beamforming. In: NORSAR Semiannual Tech. Summ. 1 October 1998 - 31 March 1999, NORSAR Sci. Rep. 2-98/99, Kjeller, Norway, 78-94.

Schweitzer, J. (2001): HYPOSAT - An Enhanced Routine to Locate Seismic Events. Pure appl. geophys. **158**, 277-289.

Schweitzer, J. and Kennett, B. L. N. (2002): Comparison of location procedures - The Kara Sea event of 16 August 1997. In: NORSAR Semiannual Tech. Summ. 1 July - 31 December 2001, NORSAR Sci. Rep. **1-2002**, Kjeller, Norway, 97-103.

S. J. Gibbons
T. Kværna
F. Ringdal