ANALYSIS OF INFRASOUND SIGNALS FROM EKIBASTUZ MINING BLASTS AT KURCHATOV, KAZAKSTAN

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ABSTRACT

Infrasound signals have been detected from large mining blasts in Kazakstan by the infrasound arrays at Kurchatov and Borovoye. For one month of data (March 1999) from the Kurchatov cross-array, we have recorded 163 events from the Ekibastuz mining region (Δ= 245 km, B-Az: 296°) in seismic channels, of which 63 (~43%) were detected in infrasound channels. For the same period of data, we have detected 122 events from the Kuzbass region (Δ= 740 km, B-Az: 58°) in seismic channels. Of these, 10 events have ground truth information. No corresponding infrasound detection is found. We also have detected four events in seismic channels at Kurchatov from a relatively less active mine in the Novotaubinka area (Δ= 197 km, B-Az: 123°). Infrasound signals from the Ekibastuz mining area at the Kurchatov array show two arrivals separated by about 60 s, though these arrivals can range between 40 and 90 s. The second arrival is observed in about 65% of the events (41 out of 63 infrasonically detected events). A simple ray tracing scheme through a suitable atmospheric model suggests that the first arrival that has a travel time of about 750 s propagates through the troposphere and is followed 60 s later by a stratospheric arrival. Best beams have been calculated for infrasound signals recorded at Kurchatov from the Ekibastuz and Novotaubinka regions. For Ekibastuz events, although the average best-beam azimuth from first arrivals varies within 3° to 7° from the seismically predicted azimuth, the phase velocity emerges slightly slower (about 280 m/s) than typical sound velocity of 330 m/s. The phase velocity for the second arrival, when present, is slightly higher, around 300 m/s.

For two months of data from Borovoye (December 1999 through January 2000), we have recorded 161 events from the Ekibastuz mining region (Δ= 381 km, B-Az: 113°) in seismic channels. The corresponding infrasound detection is very low (only 4). Infrasound detection is relatively high from nearby mines located NW of the array (Δ= 65 km, B-Az: 326°). From this period of data, we have recorded 36 events from the Kuzbass mining region (Δ= 1123 km, B-Az: 77°) in seismic channels. All of them have ground truth information. We were not able to detect positively any infrasound signals from the Kuzbass region at Borovoye. The infrasound signals that were recorded at Borovoye from the mines northwest and southeast of the array show one simple pulse with about 2- to 3-s duration. Best beams calculated from these infrasound signals show that predicted velocity is slightly slower than nominal sound speed, although predicted azimuth is similar to or slightly off from the seismically calculated azimuth. Best beam for signals from the Kuzbass region could not be resolved with confidence.

OBJECTIVE

The main objective of this project is to evaluate and characterize digital seismic and infrasound data from array sites in Kazakstan in order to improve event location and screening for nuclear explosion and Comprehensive Test-Ban-Treaty (CTBT) monitoring.

RESEARCH ACCOMPLISHED

Since spring of 1999, we have been acquiring infrasound signals from the Kurchatov and Borovoye arrays using available microphones. Several large mines in these areas routinely carry out large explosions that are detected seismically and with infrasound sensors. We have analyzed one month of data from the Kurchatov array and two months of data from the Borovoye array to better understand infrasound propagation in this region.

Station Deployment

We deployed infrasound arrays on the premises of Kurchatov and Borovoye Geophysical Observatories in Kazakstan (Figure 1). The Kurchatov Geophysical Observatory operates a 21-element short-period seismic borehole

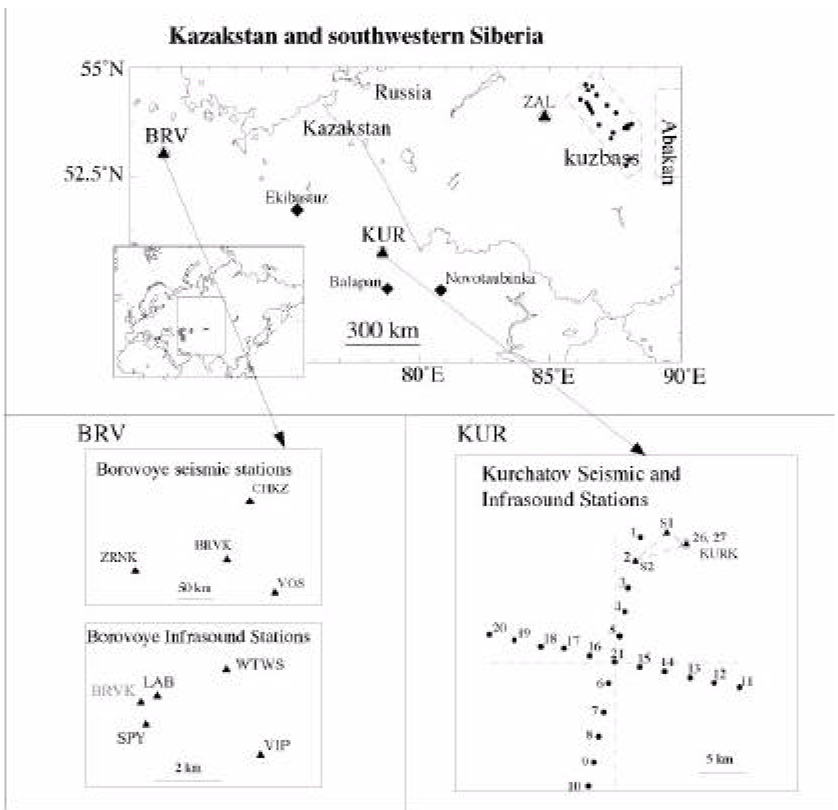

Figure 1. (top) map of Kazakstan and southwestern Siberia showing location of broadband seismic stations (solid triangle), active mining areas (diamond), Kuzbass and Abakan mining regions, and the Kurchatov (KUR) and Borovoye (BRV) Geophysical Observatories, where seismic and infrasound monitoring systems are deployed. (bottom) shows seismic and infrasound system configuration at both observatories (labelled). At KUR, 1 through 21 are short-period seismographic stations (spacing 2.25 km), KURK is a three-component broadband station, and S1, S2, 26, and 27 are infrasound stations.

array (cross-array) and a three-component broadband seismic station. A 4-component large aperture infrasound array (S1, S2, 26, and 27 in Figure 1) was constructed in the spring of 1999 at the Kurchatov Geophysical Observatory.

Each sensor is connected to six 70-m-long underground pipes extending radially from a central chamber that act to reduce wind noise. Sensor spacing varies between 2 and 4 km. Two types of capacitor microphones have been utilized with the pipe arrays configuration; Globe microphones at sites S1 and S2, and Soviet-built K301's at sites 26 and 27. The Globe microphone has a flat amplitude response between 0.1 and 300 Hz (ReVelle *et al*., 1997).

At the Borovoye Geophysical Observatory, we deployed a 4-element infrasound array (Figure 1). The spacing between infrasound stations is 2-3 km, and they are located within 2 km of central seismic station BRVK. The broadband seismic stations are recording signals in a continuous mode at 40 samples per second (sps), and have a flat response to velocity between 0.08 and 16 Hz. Globe microphones have been utilized to record infrasound signals. The microphones use a pipe array configuration to reduce local wind noise, similar to the Kurchatov infrasound system. The signals are recorded at 20 sps in a continuous mode. Infrasound signals in the frequency band of 0.8 - 3 Hz have been used for detection and array processing.

Seismic and Infrasound Observations at Kurchatov

Several large mines in Ekibastuz and surrounding areas generate explosions that are routinely detected seismically, and in many cases, are also detected with infrasound sensors. The Ekibastuz mine, 250 km northwest of the Kurchatov cross-array, regularly produces between four and six seismic detection per days. The location of these events are set to a central location of the Ekibastuz mine (51.61°N and 75.36°E) as determined by satellite photographs (Thurber et al., 1989), and their origin time is calculated from the IASPEI91 model.

For one month of data (March 1999) from the Kurchatov cross-array, we have detected 163 events in seismic channels from the Ekibastuz mine, of which 63 (~39%) were detected in infrasound channels. The infrasound signals of these events are visually examined for accurate picks and are bandpass filtered at 0.8-3 Hz for enhancing signal-to-noise ratio. For noisy data, signals are often Hilbert transformed to make them stand out from surrounding noise. The infrasound detection rate from this large aperture array is about four times larger than that detected from the small aperture array operated at Kurchatov between 1995-1997 (Hagerty *et al*., 2002).

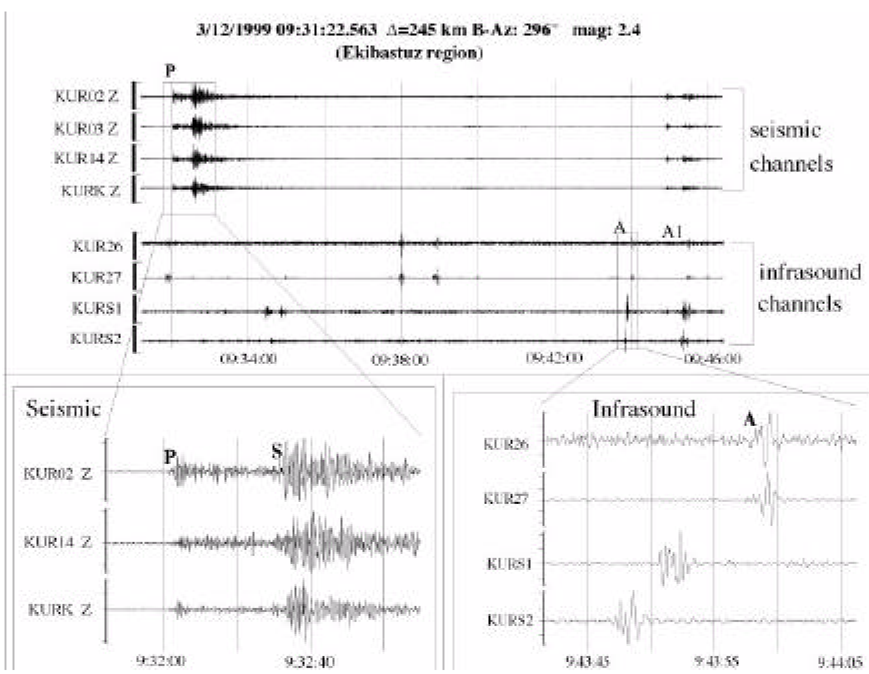

Figure 2. (top) showing a 15-min. time window of selected seismic and infrasound arrivals at the Kurchatov array. The event is located about 250 km NW of the network at the Ekibastuz mining area. Note two infrasound arrivals for this event (A and A1); the first arrival has a travel time of 756 s, and the second a travel time of 843 s. Simple ray tracing indicates this second arrival as wavetrains reflected back from the Stratospheric layer. (bottom) The figure displays close-up views of seismic and infrasound channels (labelled).

The infrasound wavetrain generated by Ekibastuz explosions exhibits two arrivals separated by about 60 s, though the separation time of arrivals can range between 40 and 90 s (Figure 2). The first arrivals show multiple pulses of 2- to 3-s duration, while the second arrivals show two pulses separated by 10 s. The travel time of the first arrival is about 750 s, corresponding to an apparent group velocity of 330 m/s. The second arrival is observed in about 65% of the events (41 out of 63 infrasonically detected events). The time difference between first and second arrivals exhibits great variation for Ekibastuz events, indicating that infrasound signals traverse through varying atmospheric conditions such as transient propagation ducts (Georges and Beasley, 1977).

For the same month of data, we also have detected four events in seismic channels from a relatively less active mine in the Novotaubinka region, of which, one was detected in infrasound channels (Figure 3). The region is 200 km

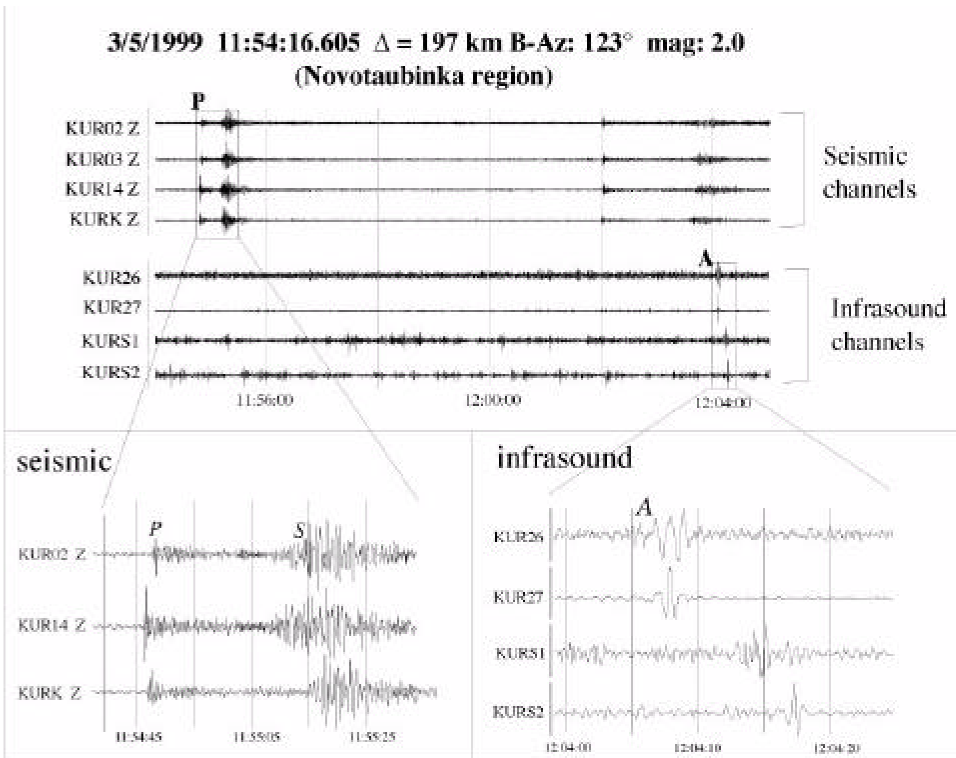

Figure 3. (top) Showing selected seismic and infrasound waveforms recorded at Kurchatov from an event at the Novotaubinka mining region (about 195 km SE of the network). P-wave travel time at KUR02 is 31.7 s, and infrasound (A) travel time at KUR26 is 629 s. This travel time corresponds to 330 m/s acoustic speed. No second infrasound arrival is detected at this distance and direction of propagation. (bottom) Close-up displays of selected seismic and infrasound channels (labelled) are shown.

southeast of the Kurchatov cross-array. The signals from the Novotaubinka region exhibit one single arrival at an apparent phase velocity of 330 m/s. For the same period of data, we have detected 122 events from the Kuzbass region in seismic channels at Kurchatov. The Altay-Sayan Experimental and Methodical Seismological Expedition (ASEMSE) collected ground truth information for 10 events from the Kuzbass and Abakan regions for this time period (Table 1). Signals from all those events are recorded in seismic channels at Kurchatov and the International Monitoring System (IMS) broadband station at Yeltsovka (ELT) (Figure 4). No corresponding infrasound detection is found. The Kuzbass mining area is about 700 km northeast of the Kurchatov cross-array, and about 120 km from the ELT station.

Best beams of infrasound arrivals calculated by slant stacking the traces for a given slowness grid show that the predicted azimuth is slightly off from the seismologically calculated azimuth (Figure 5). For a set of selected events

Table 1: Mining blasts in the Kuzbass and Abakan Regions with Ground Truth Data

Date yr-mo-dd	Time hh:mm:ss	Lat (°N)	Lon (°E)	K	mb	Yield (ton)	name
99-03-03	08:21:38.9	53.85	88.10	9.2	3.59		Oldgerasky
99-03-05	10:45:22.60	53.60	91.37	9.3	3.64		Abakan-2
99-03-06	06:38:39.10	54.32	86.78	8.8	3.41	239.4	Karakansky
99-03-07	10:57:14.80	54.45	86.88	9.0	3.50		Kolmogovsky-2
99-03-10	09:48:52.00	53.71	87.86	9.4	3.68		Krasnogorsky
99-03-12	08:59:46.90	54.53	86.60	8.6	3.32		Kolmogorovsky-1
99-03-19	10:51:12.30	54.08	87.39	8.7	3.36	194.1	Badaevsky
99-03-24	09:11:57.70	53.71	87.83	9.3	3.64	209.4	Sibirginsky
99-03-30	06:55:31.80	53.85	88.15	8.9	3.45		Oldgerasky
99-03-31	09:03:11.60	54.54	86.62	8.9	3.45		Kolmogorovsky

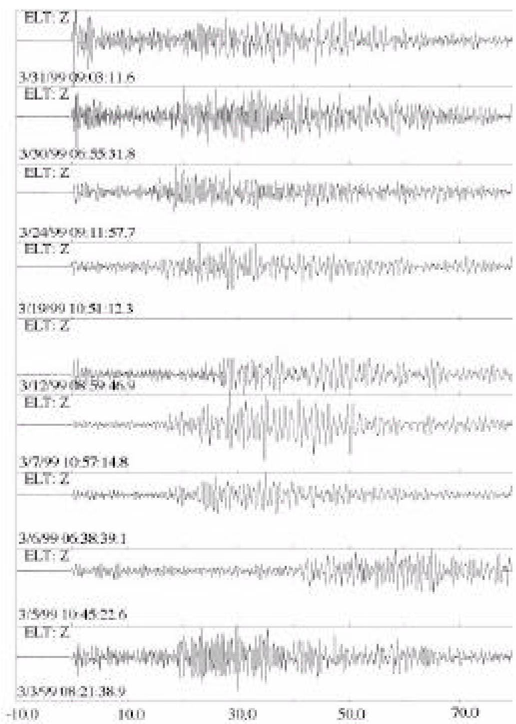

Figure 4. Waveforms of mining events listed in Table 1 recorded at ELT. Records are bandpass filtered at 1-5 Hz. Only vertical component data are shown. P-waves are aligned at 0.0. Origin times are shown in the box.

from one month of data from the Ekibastuz area, maximum power occurs when the traces for first infrasound arrivals are aligned with an average horizontal phase slowness of 3.76± 0.41 s/km (equivalent velocity of 266 m/s) and a back-azimuth of 303°± 5.5 (Figure 6). Although the average best-beam azimuth varies within 3° to 7° from the seismically predicted azimuth, the phase velocity emerges slightly slower than the nominal sound velocity of 330 m/s.

To ascertain whether the size of the mining blasts helps in detecting infrasound signals, we calculated the magnitude of the Ekibastuz events from seismic channels using a *Lg*-based regional magnitude formula (Nuttli, 1973). For Ekibastuz events, the magnitudes of all mining blasts detected range between 1.3 and 2.8, with a mean value of 2.0. The distribution resembles a Gaussian with a standard deviation of 0.30. The magnitude distribution of events that are only detected by infrasound channels also exhibits similar variations (mean 1.9 and standard deviation 0.26),

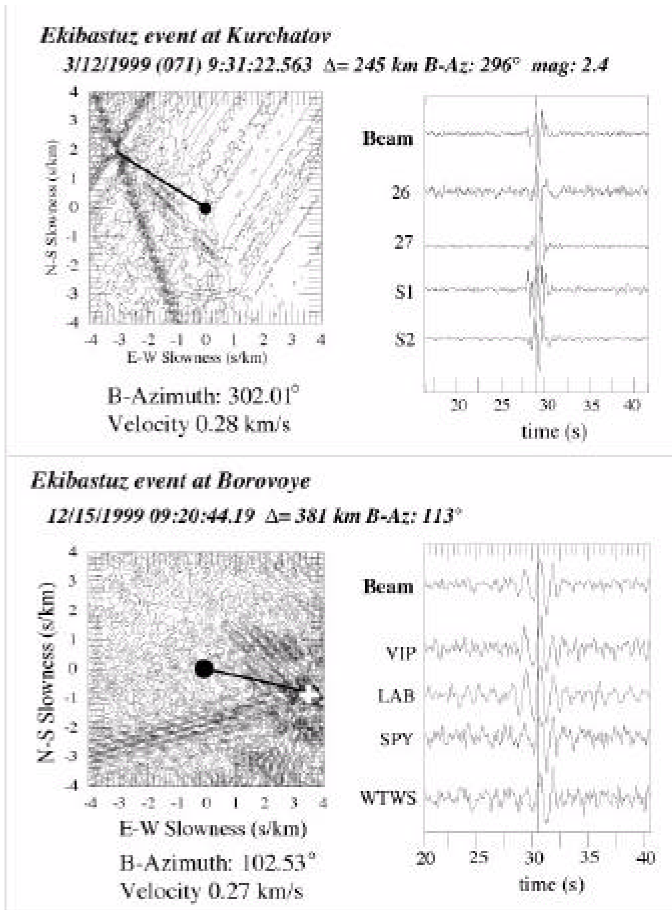

Figure 5. (top) Best beam (right) and contour plot of normalized maximum beam power (left) for an Ekibastuz event recorded at Kurchatov. The waveforms are that of Figure 2. Predicted azimuthal direction is about 7° off of seismologically calculated azimuth. (bottom) Same plot for another event from Ekibastuz recorded at Borovoye. The waveforms are that of Figure 6. In this case, the predicted azimuth is off by 5° from the seismological one. Solid circle is the location of the array, + is the predicted source, and thick solid line is the azimuthal direction. Times are relative to the beginning of the processed window length.

indicating that the magnitudes of seismic signals do not play a significant role in infrasound detection. Should magnitude contribute to infrasound detection, we would have seen a positively biased distribution of magnitude where the higher ends of distribution would only be coincident, not the lower ends.

Seismic and Infrasound Observations at Borovoye

For two months of data from the Borovoye seismic and infrasound array (December 1999 - January 2000), we have detected 161 coal mine events from the Ekibastuz area in seismic channels. The corresponding infrasound detection is low -- only four. The Ekibastuz mining region is about 300 km southeast of the array. The infrasound wavetrains from Ekibastuz are simple, comprising a wave packet of 3-5 s long (Figure 7). The infrasound travel time is about 1150 s, which corresponds to an apparent group velocity of 300 m/s. For recordings at Borovoye, no second arrivals are seen in the infrasound channels for any events from Ekibastuz.

For the same months of data, we have positively identified six events from the Kokchetav mining region, located about 60 km northwest of the Borovoye array. The infrasound travel time is about 10.5 s, giving an apparent group

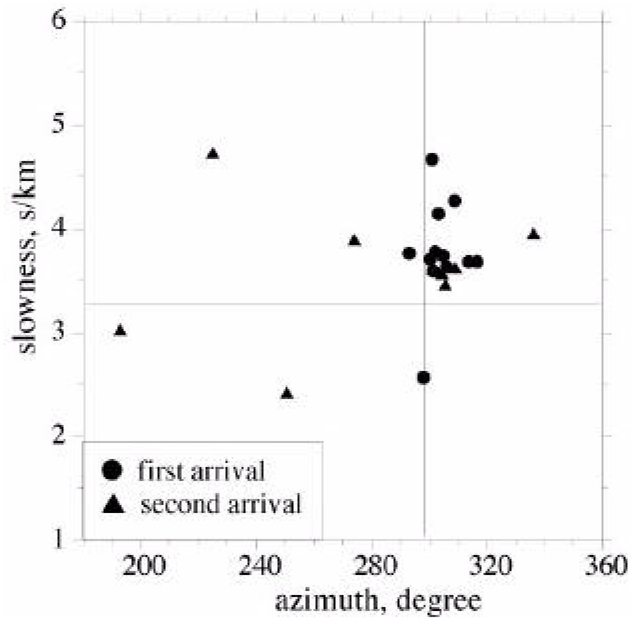

Figure 6. Plot showing predicted azimuth and slowness values from best beam analyses of infrasound arrivals from the Ekibastuz mining region. Circles depict measurements from first infrasound arrivals, and triangles from second arrivals, when present. The plot is made from 17 quality records where signal-to-noise ratio is greater than 3.The mean slowness of first arrivals is 3.76± 0.41 s/km (equivalent velocity 266 m/s) and azimuthal value is 303.2°± 5.5. The mean slowness and azimuth values for second arrivals are not determined because of large outliers in the data.

velocity of 310 m/s. Records from these events are seen in both seismic and infrasound channels. The infrasound waveforms comprise multiple pulses with about 2- to 3-s duration (Figure 8). ASEME collected the ground truth information for 49 events from the Kuzbass and Abakan regions for this time period. We have detected 36 events in seismic channels out of these 49 events. The Kuzbass mining region is about 1150 km east of the network. No corresponding infrasound signals have been positively identified.

Ground Truth Data From Large Mining Blasts in the Kuzbass and Abakan Regions

The Kuzbass and Abakan regions in southwestern Siberia conduct large mining operations. These mining regions are probably the largest that routinely conduct mining operations in Eurasia. The average size of the blasts is over 3 on the seismic magnitude scale. We obtained ground truth data for several mining blasts in the Kuzbass and Abakan regions for 1999-2000. ASEMSE located 367 blasts using data from regional seismic stations (Figure 9). The events located by ASEMSE have location errors ranging from about 5-10 km.

CONCLUSIONS AND RECOMMENDATIONS

Infrasound and seismic data recorded at the Kurchatov and Borovoye arrays from the Ekibastuz, Nobotuabinka, Kokchetav, Kuzbass, and Abakan mining regions have been analyzed. At Kurchatov, this data period covers March of 1999, and at Borovoye, it covers December, 1999 - January, 2000. Results indicate high infrasound detection capability for large aperture arrays. The Ekibastuz mine produces 4-6 seismic detections per day, while there are 2-3 detections from the Kuzbass and Abakan mining region. For Ekibastuz events, about 65% of events that are detected by seismic channels are seen by infrasound channels at Kurchatov, while less than 1% of seismically

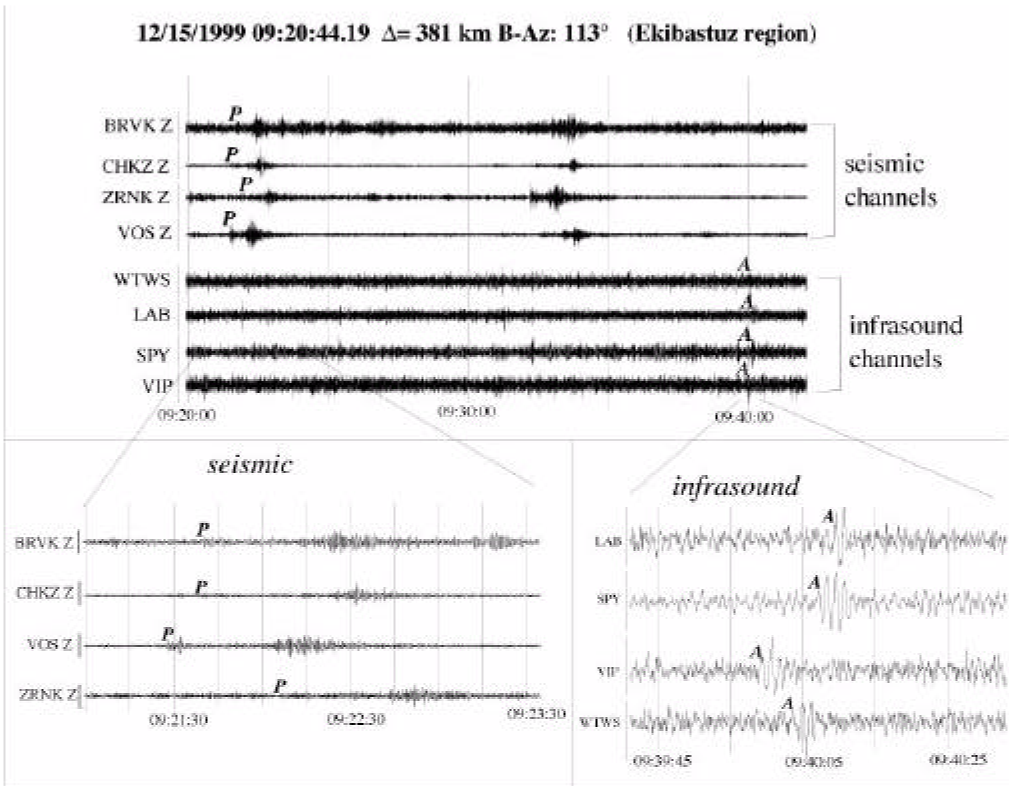

Figure 7. (top) showing selected seismic and infrasound recordings for an event from the Ekibastuz mining area recorded at Borovoye. The P-wave travel time at BRVK is 54.6 s, and the corresponding infrasound (A) travel time at LAB is 1163.8 s. This travel time corresponds to 300 m/s apparent acoustic speed. Bottom figure displays close-up views of selected seismic and infrasound arrivals (labelled).

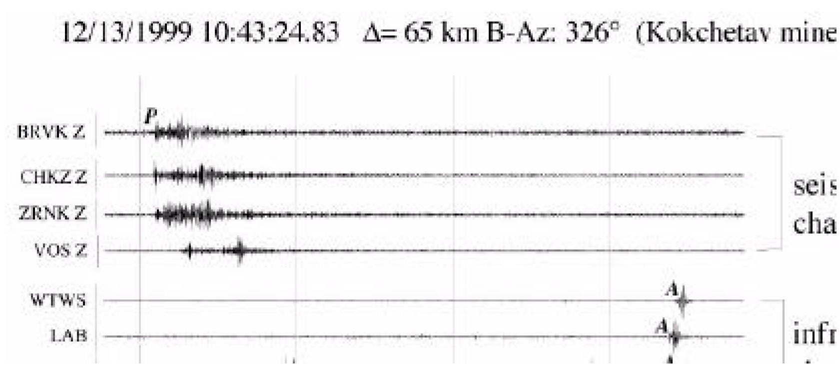

Figure 8. Plot showing selected seismic and infrasound waveforms recorded at Borovoye for an event from the Kokchetav mining region (65 km NW of the array). The P-wave travel time at BRVK is 10.7 s, and the corresponding infrasound (A) travel time at LAB is 208 s. This travel time gives an apparent acoustic velocity of 310 m/s.

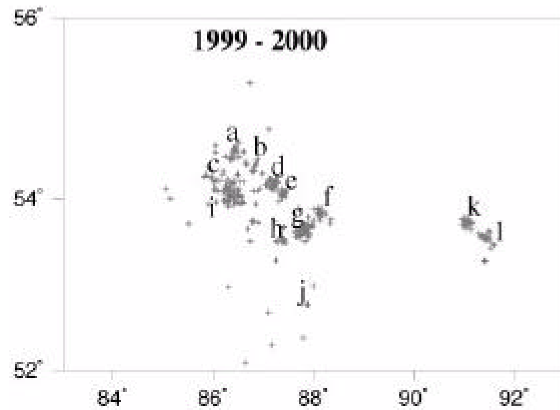

Figure 9. Mining events from the Kuzbass and Abakan regions during 1999-2000. Events were located by the ASEMSE group. Large mines are indicated by clusters of events. a: Kolmogorovsky-1, b: Kolmogorovsky-2, c: Kiselevsk, d: Taldinisky, e: Badaevsky, f: Oldgerasky, g: Mezhdurechensk, h: Kaltansky, i: Listvyansky, j: Tashtagol, k: Abakan-1, l: Abakan-2.

detected events from Ekibastuz are associated with infrasound channels at Borovoye. This may be related to wind direction and directivity of blasts. A simple ray tracing scheme using an appropriate atmospheric model for this region indicates that the first arrival propagates through the troposphere and is followed 60 s later by a stratospheric arrival. Such phenomenon of wave propagation is not seen in any channels that are located against the zonal wind direction. A second arrival appears in the infrasound sensor about 60s after the first arrival for Ekibastuz events that are recorded at Kurchatov. The second arrival, when present, also shows multiples pulses in the recordings, indicating strong positive sound speed gradients in the troposphere and, especially, in the upper stratosphere. Array analyses for data from the Ekibastuz, Novotaubinka, and Kokchetav regions show that predicted azimuthal direction is about 3°-7° off from the seismologically calculated azimuth.

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