SEISMIC MONITORING OF BLASTING ACTIVITY IN RUSSIA

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ABSTRACT

Two significant mining regions in Russia lie near Novosibirsk and at the Kursk Magnetic Anomaly. A small percentage of events from these areas trigger the International Monitoring System (IMS). We have studied IMS recordings of events from these areas with the main goal of better understanding how these blasts are detonated and how these events will be most effectively monitored using IMS data. We have collected ground-truth information on the mining blasts and crustal structure in the area to facilitate modeling of the events. We have focused on sifting out from further consideration routine mining events and identifying detonation anomalies. We define master traces to represent tight clusters of mining events and to be used to identify anomalous events. We have examined recordings of events from eight significant event clusters in the 500-km-long Kuzbass/Abakan mining trend near Novosibirsk. The recordings were made by the IMS station ZAL. We see significant variations in the P onset and early coda between different events in clusters. We have found strong evidence of a detonation anomaly in just one of the events (out of 178 examined). Differences in the onset wave trains are attributed largely to differences in the firing patterns.

Time independent spectral modulations have been observed in seismic signals produced by delay-fired mining events in mining regions throughout the world. The Novosibirsk trend is no exception to this rule. Delay-fired events in many mining regions, such as Kuzbass/Abakan, are also commonly associated with enhanced long-period (2- to 8-s) surface waves. The mine blasts in Russian mining regions appear, seismically, to resemble large blasts recorded in other regions (such as Wyoming). Techniques found to be effective in Wyoming, reviewed by Hedlin *et al*., 2002 and Stump *et al*., 2002, are expected to perform well when applied to recordings from the Novosibirsk and Kursk mining areas.

OBJECTIVE

Seismic recordings of mine blasts in the Kursk and Novosibirsk regions of Russia made by stations in the IMS hold a wealth of information about how these events were detonated. Our main objective is to use these data to learn how mining events can be successfully, and routinely, discriminated from single explosions and earthquakes. We seek evidence from the seismic recordings of anomalous, sympathetic detonations that might be confused with hidden nuclear tests. We use simulations of mine blasts, based on ground-truth data, to model the recorded waveforms and explore the utility of these events for obscuring instantaneous detonations.

RESEARCH ACCOMPLISHED

Briefly, our research has involved IMS recordings of mine blasts near Novosibirsk and near Kursk, Russia. We have obtained ground truth data for a small subset of blasts in the Novosibirsk area and have used this information for modeling seismic waves at regional distances from these events. In this section we present a brief overview of progress toward our main objectives.

IMS recordings of Novosibirsk region events

Dataset: Only one IMS seismic station lies within 500 km of the Novosibirsk mining trend (Figure 1). This station, ZAL, has provided, by far, the most informative recordings of events in this trend. Consequently, data from this station have played a central role in our analysis. We have collected ZAL recordings of events that span the entire 500-km mining trend. This trend comprises over 70 mines; however, it includes several very active clusters of mines (Figure 2). We have received *a priori* identifications of over 200 blasts in this trend and have collected recordings of 178 events. We also have *a priori* identifications of 58 earthquakes. Ground truth data on these events was provided by V. Khalturin (Lamont-Doherty Earth Observatory -- LDEO).

Routine Screening: We have found recordings made at more distant IMS stations, and the regional network KNET, have a more limited value for describing mining events in this region and screening them from further consideration. Routine screening of events from this trend involves quantification of spectral rugosity, such as that displayed in Figure 3. The screening also compares mid-period amplitudes with short-period amplitudes recorded at the nearby IMS station ZAL. A comparison of short- and mid-period wave amplitudes is shown in Figure 4.

Possible Detonation Anomaly: The amplitude screening software described above identified one event, recorded at a range of 103 km from ZAL, as an outlier with greater than expected P wave amplitudes when compared with the surface waves (Figure 4). The recordings of this event made at ZAL are shown in Figure 5. Ground truth data have been unavailable for this event although the seismic data suggests a detonation anomaly occurred ~ 3 seconds into the blast sequence.

Ground Truth

One explosion for which we have received ground truth information occurred at the Sibirginsky Open Pit Coal Mine on July 28, 2001 (Figures 2 and 6). This pit is located in the Kuzbass mining region near the center of the trend. The information was obtained by Vitaly Khalturin (LDEO), who also witnessed the blast. The blast was used to fracture the consolidated sediment layer above the coal seam and did not involve casting. The diagram in Figure 6 shows the complexity of this event. The shot sequence was initiated at the north end and included 57 rows ranging from 2 shots to 30 with a total of 666 shots involving 520,380 kg of explosives in the entire blast. Shots in most rows were detonated simultaneously with 50 msec delays between rows. The 50 msec delays in this figure are shown by the “X” marks. Some rows were split into two segments by a 20-msec delay in the middle. These shorter delays occurred at the “=” marks. The entire blast shot spanned 2.9 seconds. The event was assigned an energy class of 7.7 and a local magnitude of 2.8. Shot depths ranged from 16 to 28 meters. The salient features of this blast are that large numbers of shots are detonated simultaneously. Ground truth on other blasts indicates that this kind of blast is commonly used in this region.

Modeling

Routine Blast Following numerous authors, we model fracture and cast blasts in the Novosibirsk area assuming linear superimposition. The result of one simulation is shown in Figure 7. The shot grid used for this calculation consists of 50 rows of 10 shots each. All shots in each row are detonated simultaneously with rows separated in time by 50 msec and in space by 5 m. The velocity model used in these simulations was based on the work of Solovyev, *et al*. (2000). The modeling indicates that events that do not involve casting will produce spectral modulations below 10 Hz substantial surface waves as observed in most recordings made at regional distances by the IMS station ZAL.

Although the ground truth information that prompted this calculation comes from the plans for the shot, and has not been verified through observation of the actual event, it has been useful in that it shows us how complicated these events are and gives us a physical explanation of the observed spectral modulations.

Anomalous Blasts: We have presented observational evidence for a significant near-simultaneous detonation anomaly in a mine blast near the IMS station ZAL. Events such as these have single-fire characteristics and might prove to be problematic in a discrimination analysis (Stump *et al*., 2002). In our study of anomalous events in this region, we look specifically at blast patterns that are known to be used in this area and estimate the yield that can be detonated simultaneously, and remain hidden, during the mine sequence. One example is based on the routine blast grid considered in Figure 6. In Figure 8 we show a suite of vertical component synthetics generated using this blast grid with instantaneous, over-buried, charges detonated immediately beneath. The charges vary from 100,000 to 500,000 kg. Further details on this calculation are provided in the figure caption.

Blasting at the Kursk Magnetic Anomaly

In 1987, mines at the Kursk Magnetic Anomaly (KMA) provided 10% of the world's iron from rich bands of ore. Prior to 1995, KMA was one of the most significant mining areas in Russia. The largest blasts (> 300 tons) were conducted in the surface mines at the Lebedinsky, Stoilensky and Mikhailovsky mining combines and are used for casting near-surface material. The ore is covered by sediment, which ranges in thickness from 37 to 500 m (Leith, 1995). Kursk "conventional" blasts, like many blasts in the Novosibirsk region, detonate entire rows of charges simultaneously. This type of blast has been used less frequently since the early 1990s as some blasts were detonated with delays within the rows. Mine blasts are also often detonated in blocks separated by ~ 1 second. Delays within the blocks range from 20 to 50 msec, again, as has been observed in the Novosibirsk region. The completed primary seismic network will place 13 stations within 2000 km of KMA (Figure 9).

Monitoring Priority: Our first objective in our study of Kursk mining activity was to assess the importance of this region to the nuclear explosion monitoring community given mining activity since January 1, 1995. In 1987, the region was responsible for up to half of the large (> 300 tons) non-coal mining blasts in the Former Soviet Union (FSU). As reviewed by Leith, the economic down-turn in the early 1990s led to fewer, and smaller, blasts in this region. A list of reviewed events from an area including the three mining combines from January 1, 1995, to the present returned just one event (Figure 10). The event occurred in 2001 on February 2 and was assigned a body wave magnitude of 3.2. We have no ground truth for this event. The location error suggests that the event likely occurred at the Mikhailovsky combine. It appears that presently the Kursk region lies a distant second to the Novosibirsk area in terms of significance for treaty monitoring.

Ground truth: Prof Spivak (IDG) has provided a catalog of blasts at the Lebedinsky, Stoilensky and Mikhailovsky combines in the Kursk region with yield above 100 tons and a list of underground events with yield above 10 tons.

Screening methods: Two permanent and six temporary seismic stations located at KMA recorded 12 blasts from August through September 1995 and recorded spectral modulations. Our analysis of IMS data to assess the utility of these modulations, and energy partitioning, for routine screening of events from this region is ongoing.

CONCLUSIONS AND RECOMMENDATIONS

Events in the Novosibirsk region do not commonly trigger IMS sensors. Events that do should be readily screened out using techniques developed for large mine blasts in Wyoming. These events routinely produce spectral modulations and long-period surface waves that are due to the long duration of the delay-fired shot sequence. We have found evidence for one detonation anomaly in this region based on the seismic data. Routine monitoring of this region will have to rely heavily on the IMS station ZAL.

Significant progress in the study of mining blasts in the Novosibirsk region will require more accurate ground truth data on the mine blasts as well as an improved velocity model of the region. A calibration experiment in this area would provide much-needed basic empirical data that could be used to further our understanding of single and delay-fired events in the mining trend. Such knowledge will be required to provide a physical basis for establishing a dividing line between normal and abnormal events of the sort considered in this paper.

Presently, the Kursk region does not appear to pose a significant concern for the monitoring community. A return to simultaneous detonation of large numbers of charges, or a return to higher yield and more frequent blasting, would raise the profile of this mining region considerably.

ACKNOWLEDGEMENTS

Vitaly Khalturin provided information on blasts and earthquakes in the vicinity of Novosibirsk. David Yang provided Green's functions for the simulations of blasts in the Novosibirsk region. We thank Bill Leith, who assisted by putting our group into contact with the IDG group, including Alexander Spivak, and for providing his report on mining in the Kursk region.

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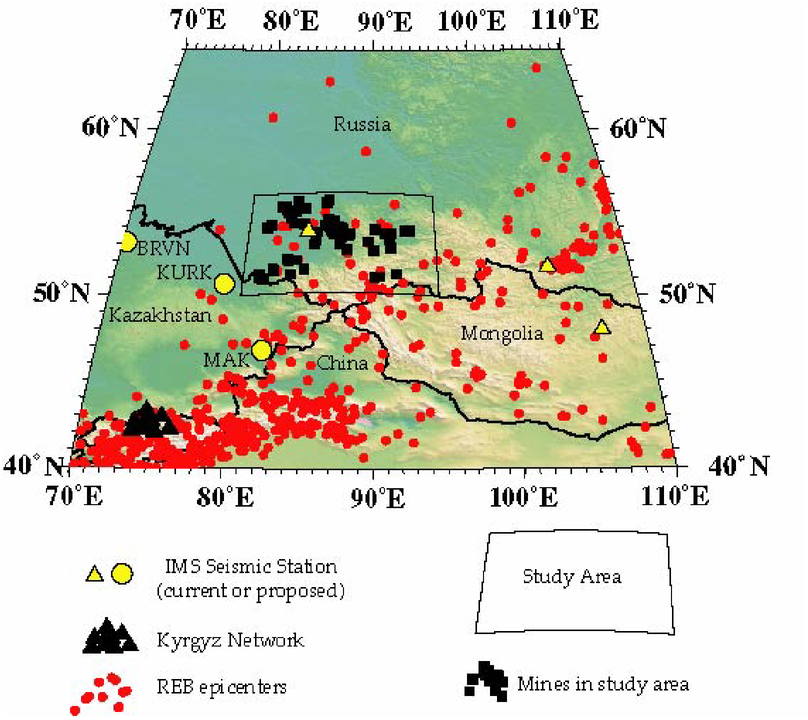

Figure 1. Seismic events reported in the reviewed event bulletin between 1/1/95 and 2/20/2000 are plotted with seismic stations in Central Asia near the study area. The study area includes 72+ surface and underground mines in the Altai-Sayan mining trend.

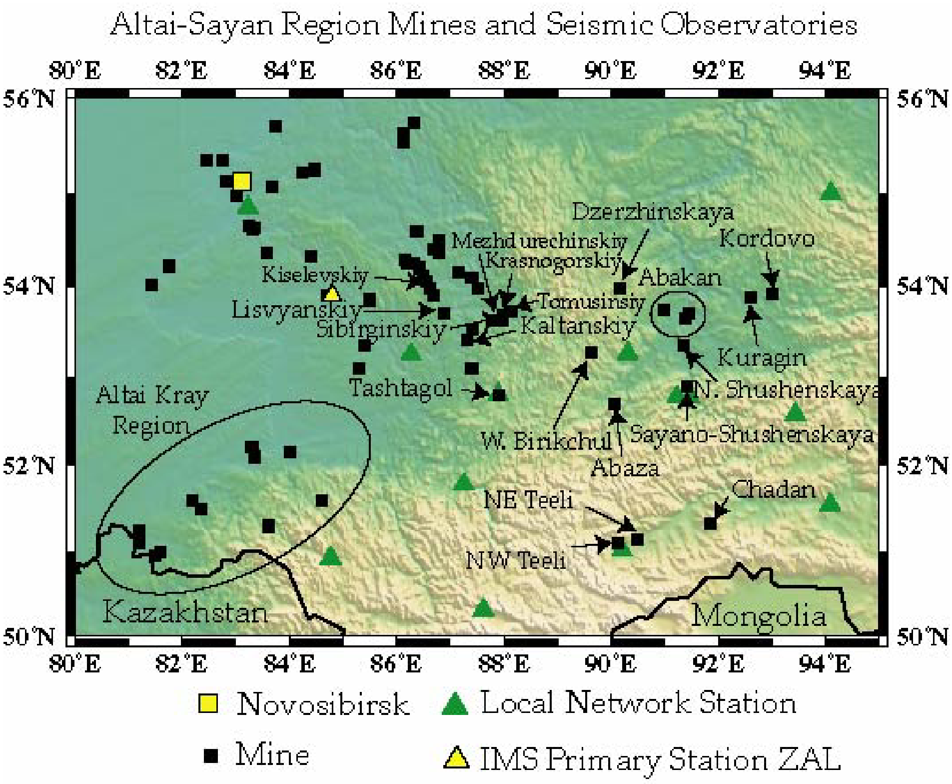

Figure 2. Mines located in the Altai-Sayan mining region. Most mines are located to the east of Novosibirsk, Russia, and are located less than 559 km from the IMS primary 3-component seismic station at Zalesovo. Blast yield and frequency are strongly dependent on the area of the mine. The Altai Kray mining region is responsible for relatively few number of small blasts. Significant blasting is common in the Kuzbass region near the center of the map. The mining region is monitored closely by stations in the Altai-Sayan Seismological Expedition regional network.

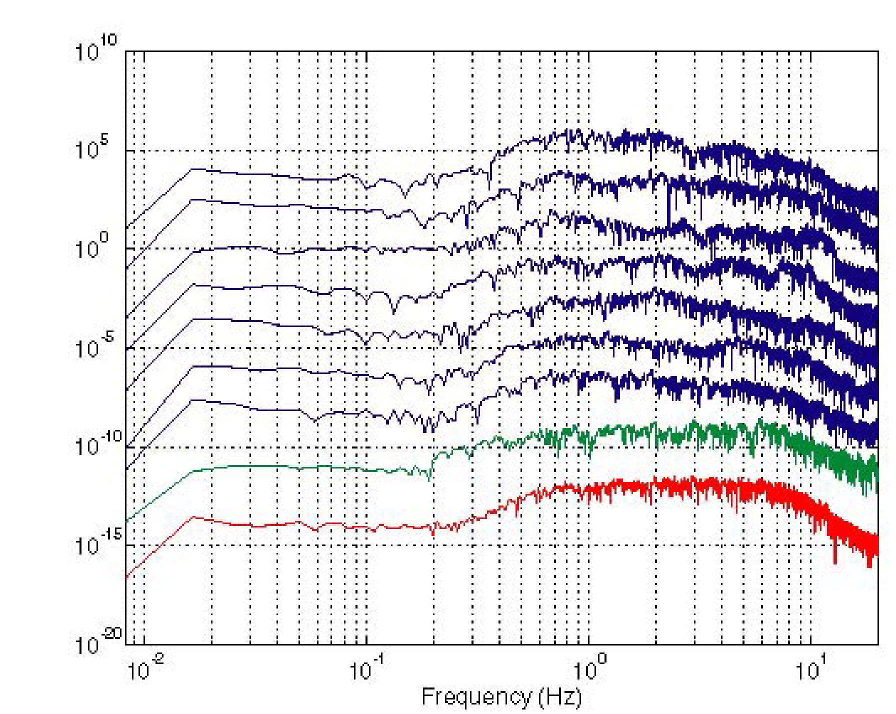

Figure 3. Vertical component spectra from events in the Sibirginsky cluster. Modeling indicates that the observed spectral modulations are due to shot finiteness in time and not directly due to inter-row or inter-shot delays. The lowest trace in this figure was taken from a recording of an earthquake located near the cluster. The second lowest spectrum is from the event shown in Figure 6.

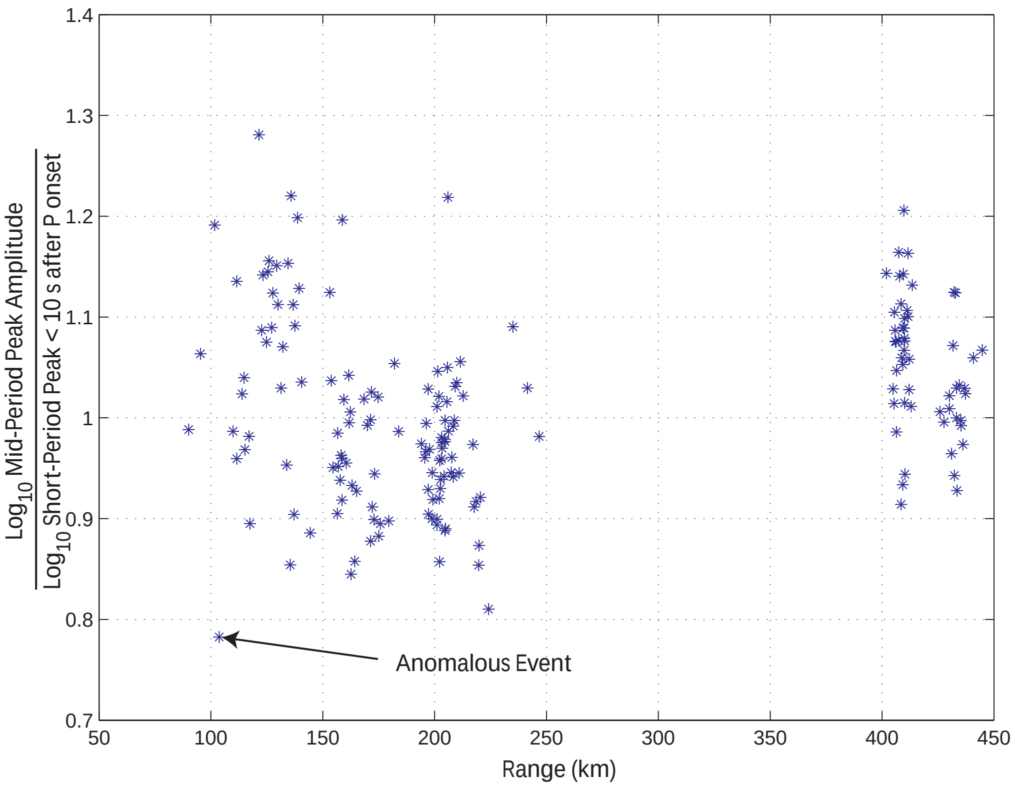

Figure 4. Of 178 mining events considered in the 500-km-long mining trend near Novosibirsk, one was automatically identified as anomalous by software that compares peak, high-frequency amplitudes recorded within 10 s of the P onset on the short-period channel at ZAL with mid-period peak amplitudes at times when the surface waves are expected.

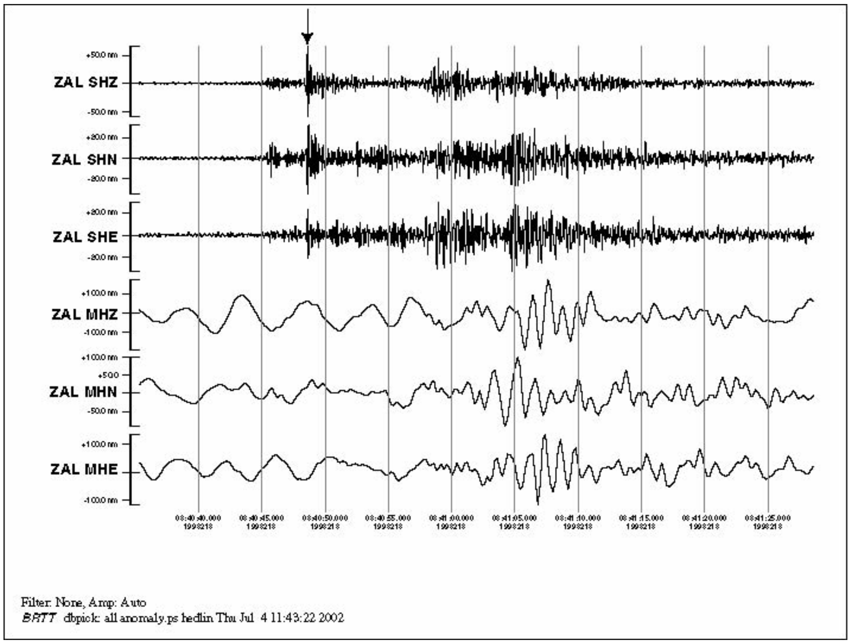

Figure 5. The short- and mid-period recordings made at ZAL of the event highlighted in Figure 4 are shown above. A possibl y is shown ~ 3 seconds after the P wave onset. Ground truth data

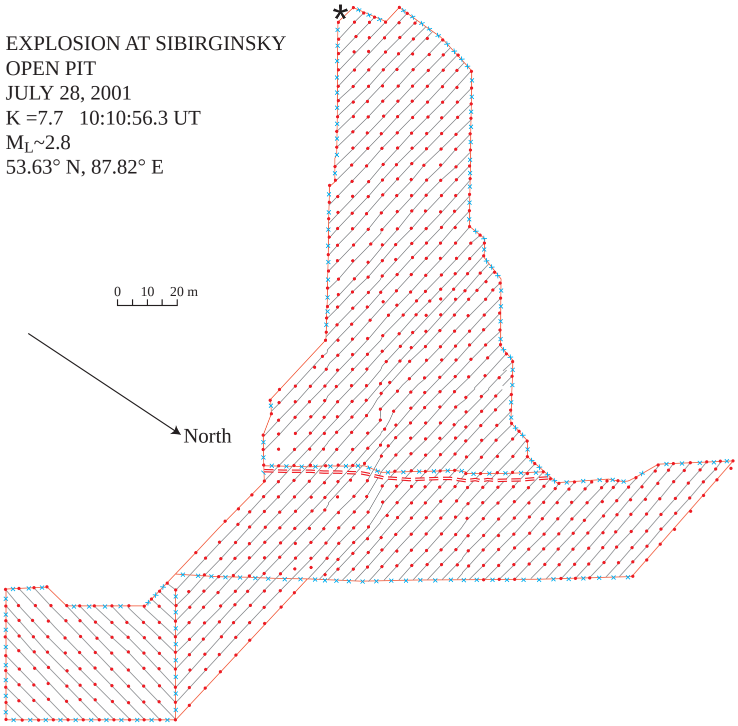

Figure 6. Blast grid for one event at the Sibirginsky open-pit coal mine. The blast was used to fracture the overburden. The blast sequence was initiated at the "*" at the upper limit of the grid. Inter-row delays were 50 msec and are represented by the "X" marks. Some rows were detonated with a single 20 msec delay ("=") sign.

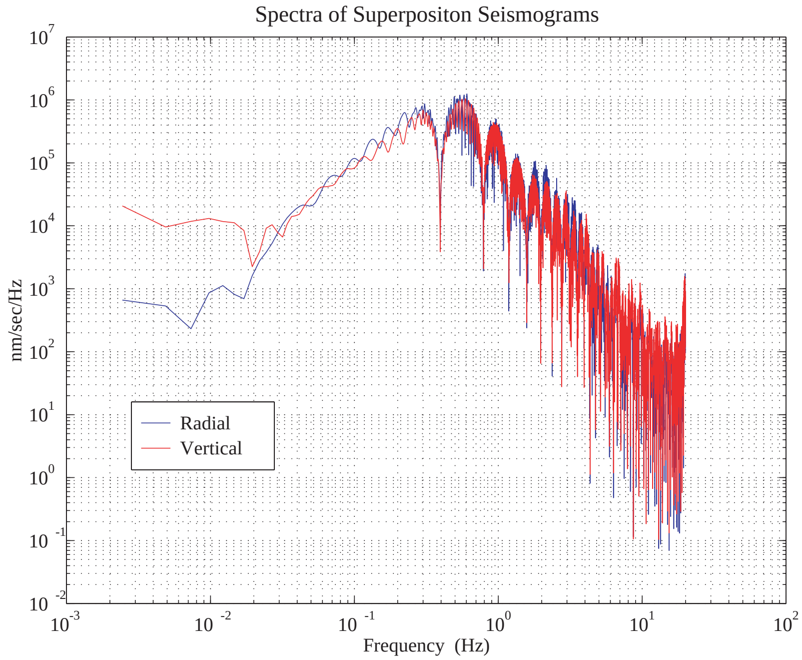

Figure 7. Vertical and radial component spectra from a simulated fracture shot at the Sibirginsky coal mine in the Kuzbass. The synthetics were calculated at a range of 200 km (the distance from the mine to ZAL). The generic event comprises 50 rows of 10 shots each. Time delays between rows are 50 msec, all shots in each row are detonated simultaneously. The inter-row delays produce spectral modulations starting at 20 Hz. Modulations seen at lower frequencies in this simulation are due to the duration of the shot. Similar modulations are commonly observed in recorded data at the IMS station ZAL. The superposition spectra shown above were calculated using the Mineseis package provided by David Yang (LANL).

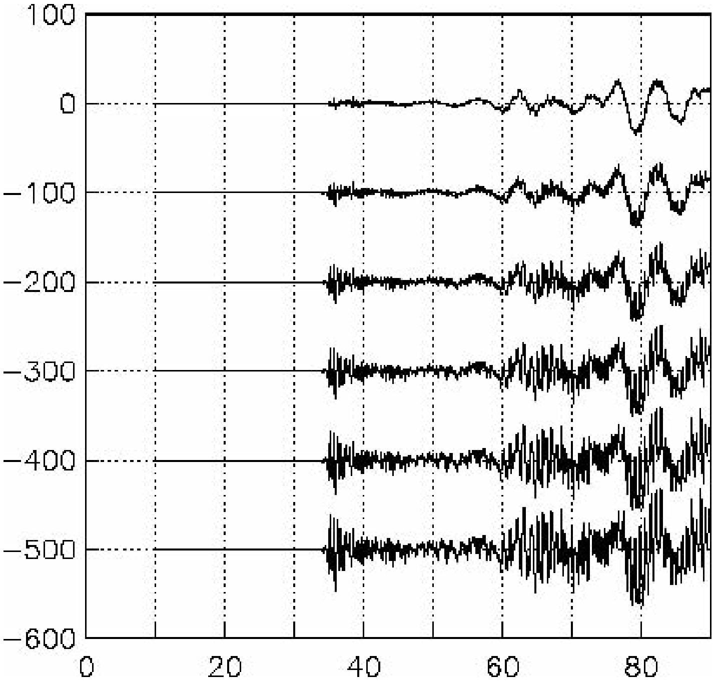

Figure 8. Vertical component synthetics from the generic blast shown in Figure 4 are shown in the upper trace. The delay-fired event is predicted to generate a substantial long-period surface wave. Surface waves are observed commonly at ZAL. The lower five traces are, from top to bottom, the blast detonated with single detonations of 100,000 (top) to 500,000 kg (bottom). The instantaneous charges are buried at depths ranging from 15 to 25 m. The ratio of peak amplitude at long-periods to short periods decreases with increasing yield of the instantaneous shot.

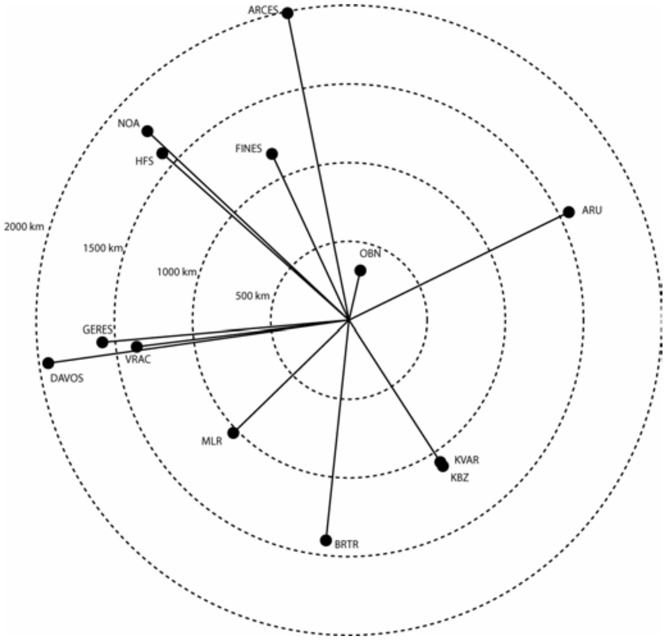

Figure 9. Coverage of the Kursk mining region by stations in the primary IMS seismic network. The closest station, OBN, is located 323 km to the north.

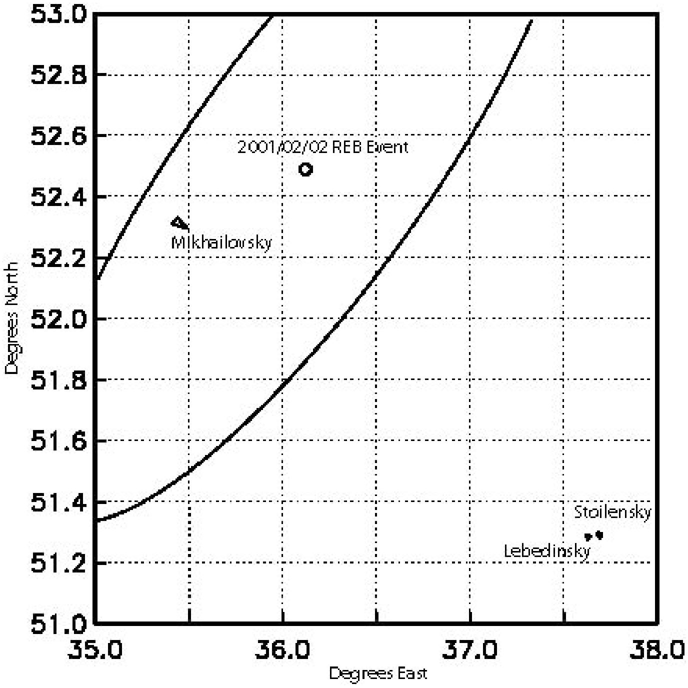

Figure 10. From 1/1/95 to present, a single event at the KMA was reported in the REB. The event location with error ellipse is shown with the mine locations.