SEISMO-ACOUSTIC ANALYSIS IN THE ZALESOVO REGION OF CENTRAL ASIA

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ABSTRACT

Interactive seismo-acoustic data analysis was conducted on a one-month dataset to describe the station characteristics of the International Monitoring System (IMS) seismic station ZALV (Zalesovo, Russian Federation) located in central Asia. Specific study objectives included: the location of all local and regional seismic events observed by the station, including single station events; identification of seismic sources routinely observed at the station; background noise characterization; and identification of any biases in station azimuth, time, and slowness, etc. Additionally, these data provided a baseline for a separate study for evaluation, tuning, and enhancement of automatic and interactive processing functions at the International Data Centre (IDC). The compiled seismic catalog was used to identify infrasound detections on the co-sited IMS infrasound station I46RU that theoretically could be associated with these seismic events. For seismic events with proposed associated infrasound detections, the events were first relocated using both seismic and infrasound detections. Active mine sites located in the area of the seismic events were identified using Google Earth. Each event in the integrated seismo-acoustic catalog was relocated with epicenters fixed at the nearest mine source location and results evaluated.

Thirty days (16 February–15 March 2008) of continuous IMS waveform data from the co-sited seismic array ZALV and from the infrasound array I46RU were analyzed in this study. Approximately 800 seismic events at an epicentral distance less than 20° from station ZALV were human-analyst reviewed, including phase identification and event location. Twelve clusters of seismicity were identified. Infrasound detections were associated with approximately 200 of the events and appear to originate from roughly 50 mining complexes, the majority of which are located within 500 kilometers of Zalesovo. A small subset of the infrasound signals were observed on the seismic waveforms. No prominent noise sources on seismic station ZALV were observed in this data set. For regional events, ZALV shows good response across the full-frequency spectrum. Trends in observed biases were catalogued for each station based on azimuthal distribution. The biases for each cluster were determined by averaging residuals for each measurement (time, azimuth, velocity) and comparing them to the iasp91 travel time tables routinely used during production of the Reviewed Event Bulletin (REB). *Rg* phases at ZALV can often have large (late) time residuals, but are usually very clear on the waveform records.

OBJECTIVES

The objective of this study was to interactively review one month of data to describe station characteristics of the IMS seismic station ZALV and its co-located IMS infrasound station I46RU. Here, we focused on: (1) the location of all local and regional seismic events observed on ZALV, including events located using only a single station; (2) identification of routinely observed seismic sources; (3) background noise characterization; and (4) identification of waveform characteristics including any biases in station azimuth, time, and slowness, etc. Additionally, during this project, notes were kept on the thresholds necessary at ZALV for a given event to be recorded at other stations, trends in azimuth and velocity (slowness), optimal filter bands for analysis, and any timing errors. The compiled seismic catalog was then used to identify infrasound detections on the co-sited IMS infrasound station I46RU that could be associated with these seismic events. Mine sites located in the area of the seismic events were identified using Google Earth satellite imagery.

RESEARCH ACCOMPLISHED

Identification of Sources of Observed Seismic Activity

The first objective was to locate all seismic events (including single station events) observable on station ZALV. A total of thirty days of data were reviewed (February 16, 2008 thru March 15, 2008). Routine IDC analysis processing software, related configuration parameters, and database tables, including automated seismic detections and events, were provided by the IDC for this study. IDC's version of the Analyst Review Station (ARS) software package was the primary tool used for waveform review, phase identification, and location purposes. For routine frequency-wavenumber (F-K) processing, XfkDisplay and the multi-band F-K module from the program Geotool were used. Seismic data analysis for this study was performed by displaying the waveforms in a five minute window and manually scrolling page-by-page. In most cases, waveform filtering was performed on a nearly constant basis. A 1–5 Hz bandpass, causal, Butterworth filter was the primary filter used during analysis. This filter preserves, in most cases, the predominant frequencies of many teleseismic arrivals, while providing enough frequency content of regional arrivals to lead the analyst to further investigation. Extremely high frequency events are not very common at ZALV, although a few were observed, located mainly west of the station. The surface solution from the location program was used when only one station observed the events.

An intermittent, recurring noise burst was observed on the study dataset on seismic station ZALV. The noise bursts have an emergent onset and are incoherent; determination of the noise source was not possible. An example of noise bursts is shown in Figure 1. Two to three of these bursts per day were observed on average in this particular data set and the impact on analysis was minimal.

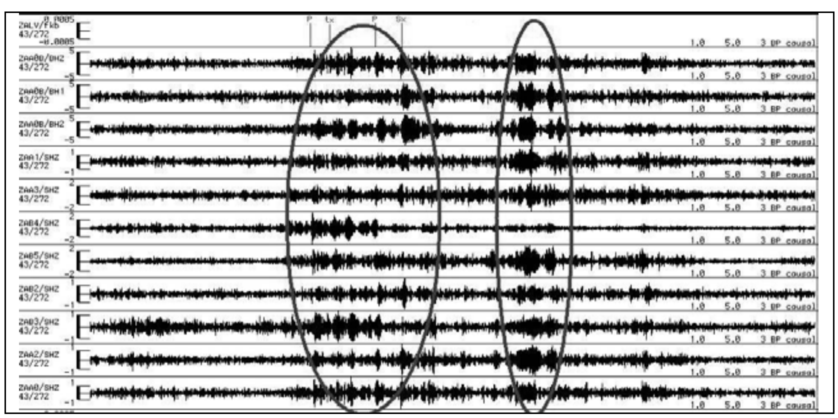

Figure 1. ARS screenshot showing an example of noise bursts observed periodically on station ZALV (prominent noise shown in ellipses).

Identification of regional phases was difficult for this station. Most events occurred near the *Pn*/*Pg* and *Sn*/*Lg* crossover distance. Thus, discerning whether a *P*-type phase was a *Pn* or *Pg*, or if the *S*-type phase was an *Sn* or *Lg* was problematic. Oftentimes the energy from phases in this distance range is mixed, resulting in less than optimal F-

K calculations. The shape of the envelope was often a determining factor since F-K values were generally mixed. The degree of confidence in the locations is still high however, since the phases have nearly identical travel-times in this distance range. When events were at located distances offering good separation of the phases, the determination was far less difficult. The key seismic phase used to identify events during this study was the ZALV *Lg* arrival as the *P*-type phases were particularly difficult to identify. For *Rg* phases, it was difficult to achieve F-K results that are consistent with theoretical velocities.

Routine analysis at the IDC included data from the Zalesovo array beginning on January 15, 2007. From the station start in IDC operations (January 15, 2007) through December 31, 2007, ZALV initial *P*-type arrivals were associated to 11,143 of the 27,506 (40.5%) of the events in the REB (Figure 2). ZALV records many different types of seismic phases, including regional and teleseismic signals, originating from all areas of the globe. Small clusters of local seismic events are commonly observed on the ZALV waveforms, many of which are presumed to be mining-related explosions.

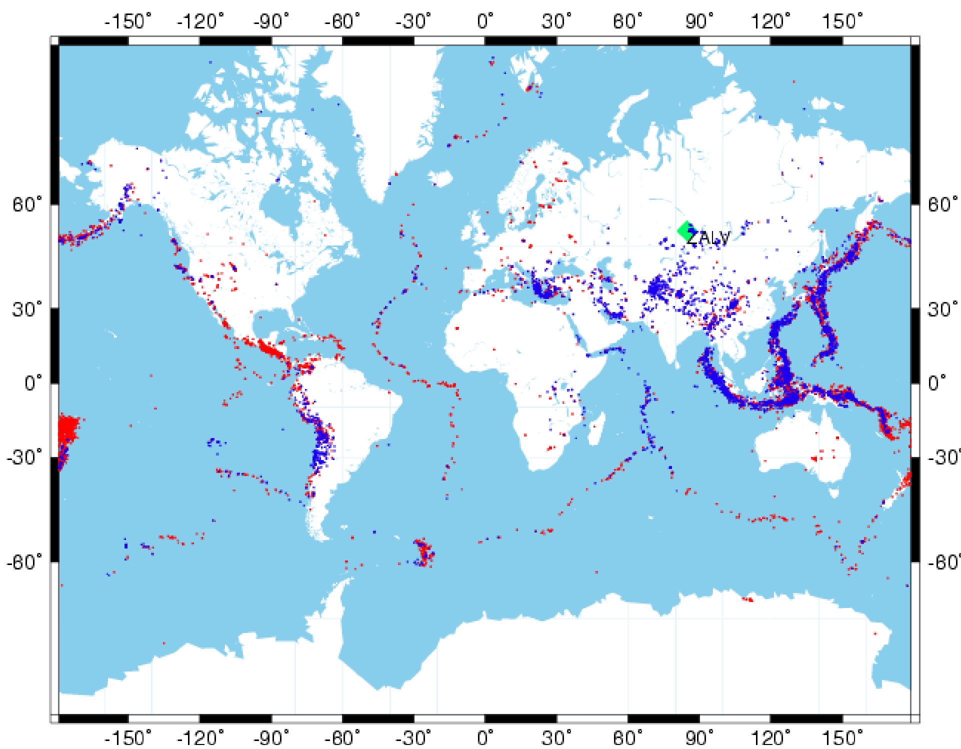

Figure 2. Map showing station ZALV *P*-type phase contributions to the 2008 REB. Events with an associated ZALV *P*-phase arrival are plotted in blue and events without a ZALV *P*-phase are plotted in red.

For the thirty-day dataset reviewed, approximately 800 seismic events occurring within an epicentral distance of less than twenty degrees from the ZALV seismic array were located during this study. Each of the events was human analyst reviewed, including phase identification and event location. Twelve clusters of seismic events (Figure 3) were identified, based on geographic and temporal distribution, during the seismic phase of this study, and later refined when detailed infrasound analysis was incorporated. The majority of the seismic events in these clusters are presumed to be mining-related explosions. Attributes used to characterize clusters at this stage were temporal distribution, Google Earth imagery, and waveform characteristics. Time-of-day and day-of-week pattern histograms were prepared for each cluster; however, space limitations prevent showing these intermediate results here.

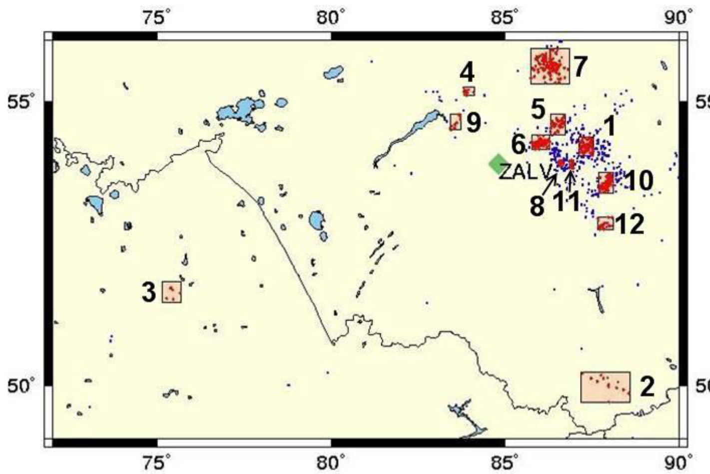

Figure 3. Map of events located in the vicinity of IMS station ZALV. Peach boxes with red dots denote cluster events; other events are shown as blue dots.

Table 1. Identified Seismic Clusters

Cluster Number	Event Count
1	51
2	14
3	5
4	10
5	35
6	61
7	115
8	15
9	9
10	67
11	18
12	17

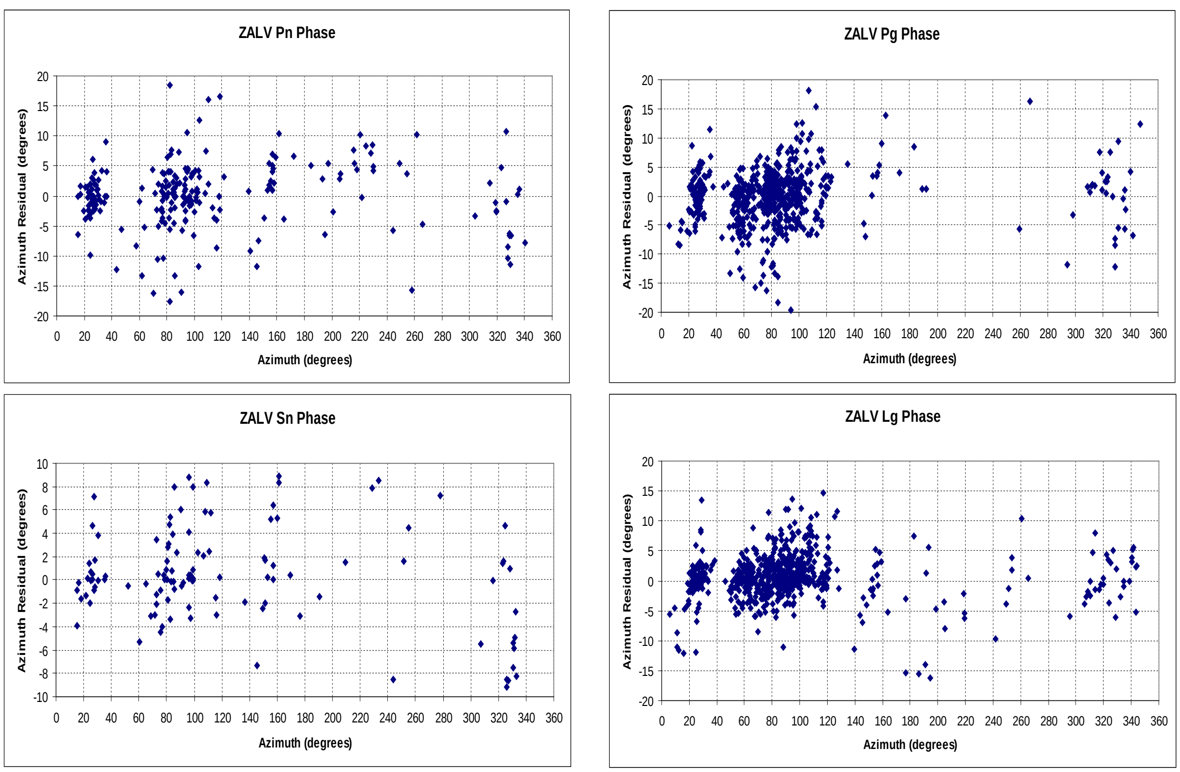

Figure 4. Azimuth residuals versus azimuth for ZALV regional seismic phases for study dataset.

Figure 4 shows the azimuth residuals of regional phases observed at ZALV during analysis of the study data. Figure 5 shows the velocity residuals versus azimuth of regional phases observed at ZALV during analysis of the study data.

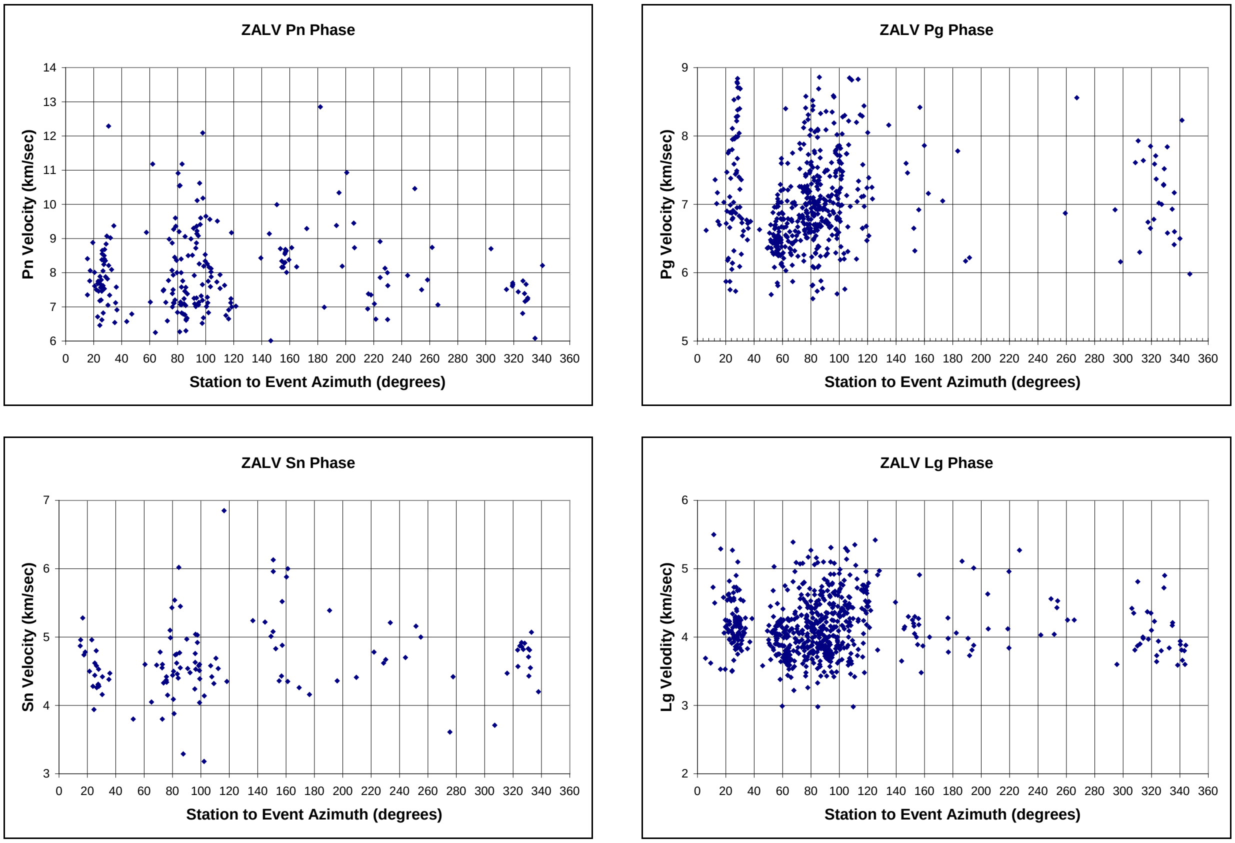

Figure 5. Velocity residuals versus azimuth for ZALV regional phases for study dataset.

Figure 6 shows the travel time of regional phases recorded at ZALV during the course of this study. The iasp91 travel-time tables were used to compute origin times in this study.

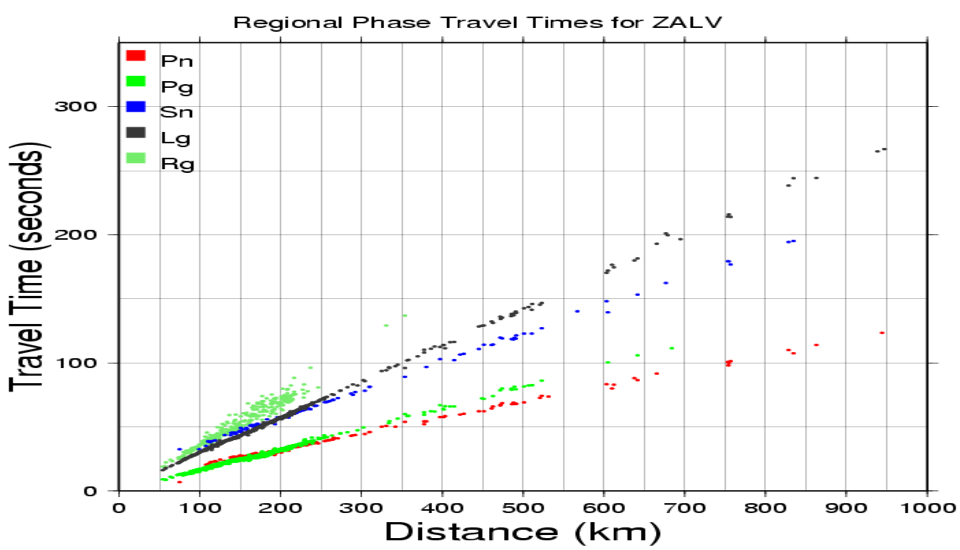

Figure 6. Plot of regional phase travel times for regional phases at ZALV.

There were several dozen observations of infrasound signals recorded on the seismometers at ZALV. The arrival time and azimuth of the acoustic signal on the co-sited infrasound station (I46RU) match the observations on the seismic channels. Sample waveforms showing the acoustic signal recorded on the seismic sensors from two representative events are shown in Figure 7. Identification and study of acoustic signals observed on seismic waveforms was not an objective of this study, thus the number of observations is likely low. The presumed associated source mine locations are well distributed in azimuth from ZALV and originate from many different mines. However, not all mines identified in this study had acoustic signals observed on the seismic channels.

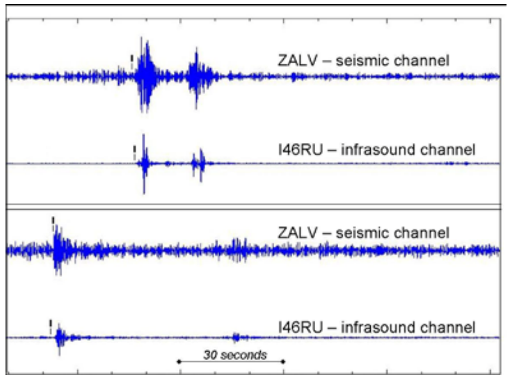

Figure 7. Two examples of infrasound signals observed on the seismic sensors at station ZALV. All waveforms are bandpass filtered between 2–5 Hz. Waveforms are not time aligned.

Association of Infrasound Detections with Seismic Event Catalog

Using the compiled seismic catalog, we identified all signals in the IDC-provided infrasound detection database from the co-sited IMS infrasound station I46RU that theoretically could be associated with these seismic events. For seismic events with proposed associated infrasound detections, the events were first relocated using both seismic and infrasound detections. The event epicenters were plotted using Google Earth; we then searched the imagery for possible mining sources. The nearest town name was used to identify the mines. Events believed to be associated with a mining source were relocated, with the event location fixed to the center of the mining activity. Celerity was checked at this stage and iterative adjustments made to event associations, or mine locations. There were several cases of mines located close to one another. Infrasound detections were determined to be associated with approximately 200 of the seismic catalog events (~25%) and appear to originate from roughly 50 mining complexes (Figure 8 and Table 2). About 80% of the events moved less than 20 km when relocated using both seismic and acoustic data and associated to a mine site. The majority of the identified mine complexes are located within 500 kilometers of Zalesovo. Figure 9 is a detailed map of the mine sites located within several hundred kilometers of the IMS arrays I46RU/ZALV.

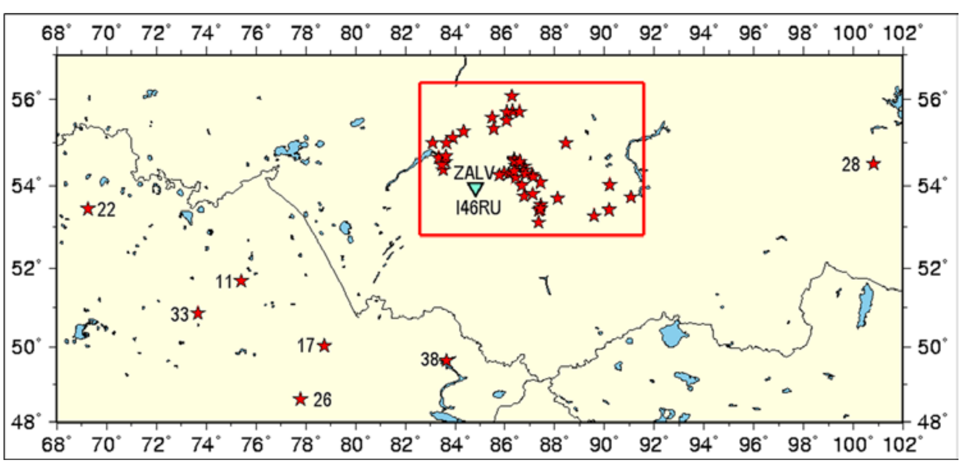

Figure 8. Map showing the source locations (mine complexes) identified using combined seismic and infrasound event locations within the one month dataset (red stars). Inverted triangle shows IMS station locations. The red box is the detail area shown in Figure 9. The labels are keyed to Table 2.

Table 2. Mine complex locations

ID	Nearest Town	Count	ID	Nearest Town	Count	ID	Nearest Town	Count
1	Bachatkiy	9	**18**	Karakan	10	**35**	Nov. Put	4
2	Barzas	4	**19**	Kedrovka	5	**36**	Novokuznetsk	2
3	Belogorsk	1	**20**	Khakassia	1	**37**	Novosibirisk	2
4	Belova	2	**21**	Kiselevsk	14	**38**	Oktjabrskij	1
5	Berezovskiy	8	**22**	Kokchetav	1	**39**	Rudnichnyy	3
6	Bol Kedrovka	1	**23**	Krasnobrodskiy	12	**40**	Salair	3
7	Bol'sheyamnoye	1	**24**	Krasnoyarka	1	**41**	Sartaki	4
8	Chernogorsk	6	**25**	Kyrgay	2	**42**	Simanovo	5
9	Chernyy Kaltan	1	**26**	KZ221	1	**43**	Sorsk	2
10	Dunaevka	2	**27**	Lekarstvennoye	1	**44**	Sukharinka	1
11	Ekibastuz	1	**28**	Listvyakana	1	**45**	Svet	10
12	Gornyy	9	**29**	Mayskiy	2	**46**	Toguchin	1
13	Gramoteino	2	**30**	Medvedskoye	1	**47**	Urgun	1
14	Gur'evsk	2	**31**	Mezhdurechensk	31	**48**	Uspenka	1
15	Iskitim	2	**32**	Mokhovo	1	**49**	Ust Chem	3
16	Kaltan	2	**33**	Molodezhnoye	2	**50**	Vershina Tei	2
17	Kara Zhyra	1	**34**	Nov. Gorodok	1	**51**	Yerunakova	9
						52	Zhernovo	11

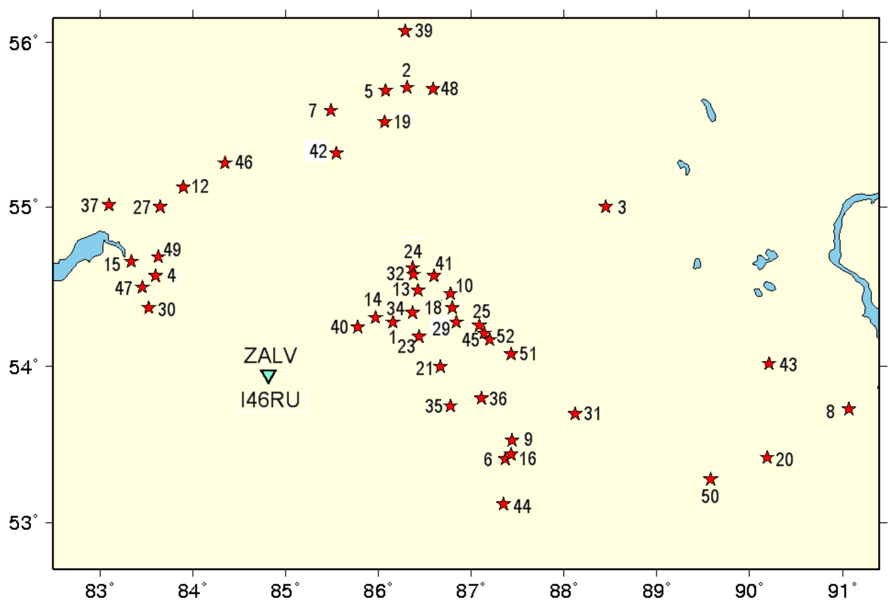

Figure 9. Detailed map (red box in Figure 8) showing mine sites (red stars) identified during study located near IMS stations ZALV/I46RU (inverted triangle). The labels are keyed to Table 2.

For those mine complexes with ten or more events associated, we provide time-of-day (GMT) and day-of-week histograms (Figure 10). Although not conclusive, these histograms support a mining-related source for the seismic events. All events shown here occurred during daytime hours at these mine sources and no events occurred on Sundays.

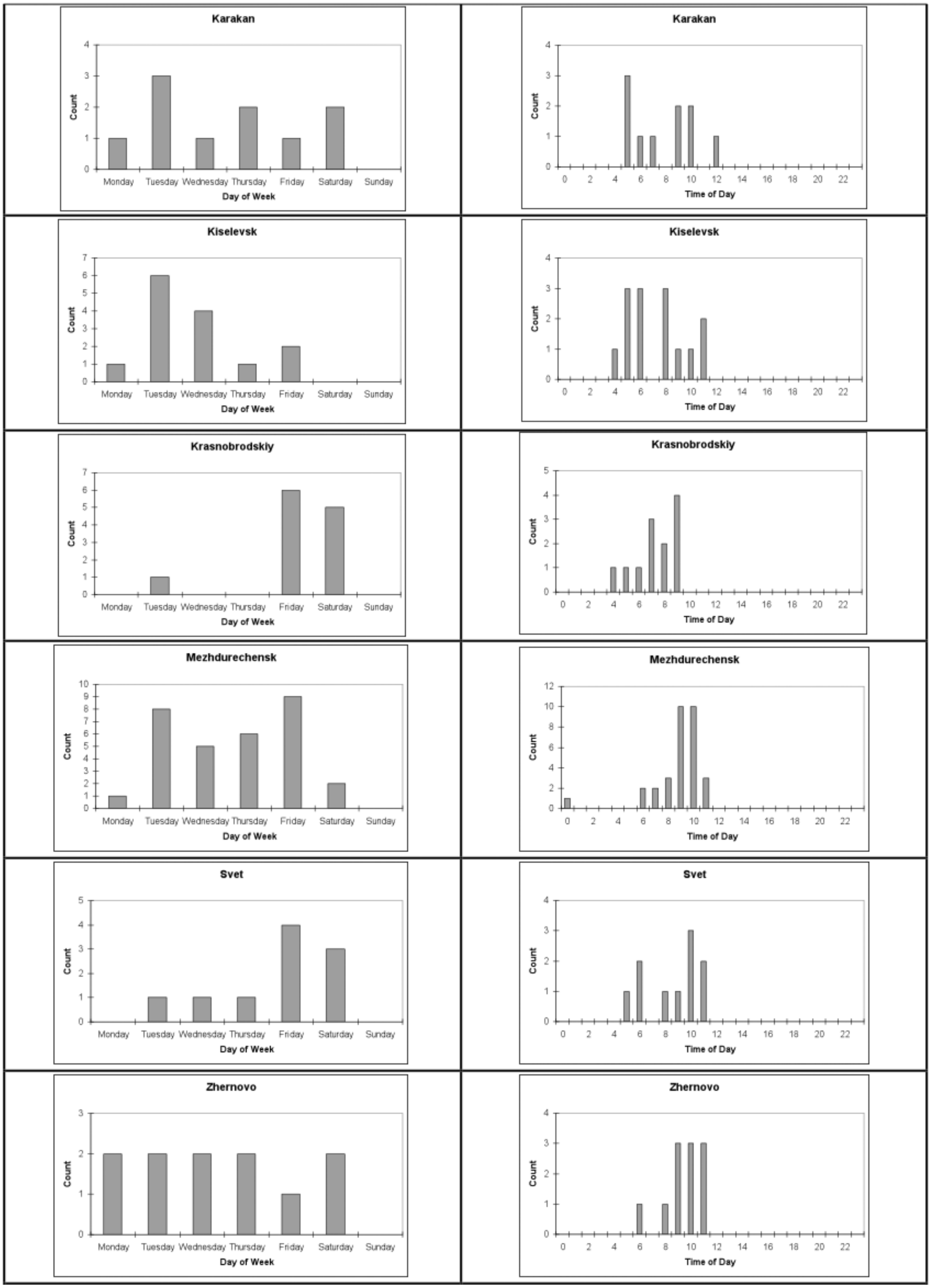

Figure 10. Temporal histograms of selected mine complexes.

CONCLUSIONS AND RECOMMENDATIONS

The ZALV array is a vast improvement for CTBT monitoring purposes over the previously operational three-component IMS station ZAL. The ability to calculate reliable azimuth and slowness estimates from the array improves regional and global monitoring capability. Most teleseismic signals recorded on station ZALV appear to have lower frequency content than on neighboring station MKAR, although for many teleseismic events the path is quite similar. For regional events, ZALV shows good response across the full-frequency spectrum. *Rg* phases at ZALV can often have large (late) time residuals (based on the iasp91 velocity model), but are usually very clear on the waveforms. The reviewed dataset will be used as a benchmark baseline for tuning automated processing software.

A high-quality human-analyzed 800-event seismic catalog was used as a starting point to identify infrasound detections observed on the IMS infrasound station I46RU. Events were reprocessed and located using both infrasound detections (azimuth defining only; not time defining in locations) and seismic detections (time and azimuth defining as appropriate). Each epicenter was reviewed using Google Earth to attempt to identify nearby mines as potential sources of these signals. When a mine complex was identified near the epicenter, the event was reprocessed with its location fixed at the center of the mine complex. Over 200 events from the master catalog had infrasound detections associated, leading to identification of over 50 source mines. While not a substitute for field validation of ground truth events, the compiled dataset could potentially be used in explosion discrimination studies.

As data from the IMS infrasound network are integrated into routine processing, the IDC inevitably must deal with review of a growing number of events detected at one or more infrasound stations. A portion of this study focused on association of infrasound signals with seismic events occurring in a very active mining region surrounding the IMS infrasound array, I46RU. The reference database of characteristic signals from the identified sources can be used for tuning and validating algorithms in automatic station and network processing, and by IDC analysts during the interactive review process.

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Maps in this document were produced using the program Generic Mapping Tools (Wessel and Smith, 1998).

The views expressed herein are those of the authors and do not necessarily reflect the views of the CTBTO Preparatory Commission.

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Wessel, P. and W. Smith (1998). New, improved version of Generic Mapping Tools released, *EOS Trans. Amer. Geophys. U*. 79: 579.