DETECTION METHODS FOR MINING EXPLOSIONS IN SOUTHERN ASIA

Ileana M. Tibuleac[1], James Britton[1], David B. Harris[2], Terri Hauk[2], Heather Hooper[1] and Jessie L. Bonner[1]

Weston Geophysical Corporation[1] and Lawrence Livermore National Laboratory[2]

Sponsored by National Nuclear Security Administration
Office of Nonproliferation Research and Engineering
Office of Defense Nuclear Nonproliferation

Contract No. DE-FG02-01-ER83341[1] and W-7405-ENG-48[2]

ABSTRACT

Weston Geophysical maintains a high-quality seismic research database for southern Asia consisting of detailed mining information together with seismograms recorded from mine blasts in northwestern India, southern Pakistan and the surrounding regions. This digital mining database contains data on more than 260 mines and mineral deposits in southern Asia, including information on location, geology, commodities, production, mineralogy, references, operator, and mining explosion resources. The waveform data consists of seismograms from several stations in southern Asia including NIL, ABKT, HYB, and GBA, in addition to data from proprietary stations.

We have employed complementary techniques to detect probable mining explosions. First, we applied the waveform correlation method (Harris, 1991) to data recorded in 2002 at each station of interest. Six clusters of mining events were detected between May and October 2002 near stations in southern, central and northwestern India. Second, a short-period Rayleigh wave (*Rg*) detector (Tibuleac and Britton; 2004, Britton et al, 2003) was developed for quarry-blast/shallow source, near-regional events. The *Rg* detector was integrated into a semi-automatic event-detection and -location algorithm and applied on continuous data. The algorithm uses improved three-component frequency-wavenumber (*fk*3C) single-station location techniques. We obtained better detection results and back azimuth estimates using nonlinear pre-filtering. We present continuous detection results from two proprietary stations in March and April 2001.

We are in the process of obtaining satellite imagery for the areas covering the locations of the mining clusters. The imagery, event locations, station locations, and information on the mines are stored in an ArcView 8.3 geographic information system (GIS) database in which the digital seismic waveform data are linked. The database is updated as more mining clusters are detected and supplemental information (satellite imagery, mining information) is received.

OBJECTIVES

The objectives of this research are to catalog the mining resources of southern Asia and to compile mine information together with mining explosion waveforms into a single digital database.

RESEARCH ACCOMPLISHED

Mine Database

Continuous broadband waveform data were obtained from the IRIS/IDA stations ABKT, NIL, and PALK. HYB waveforms were obtained from the Geoscope Network, and GBA waveforms were obtained through the Atomic Weapons Exchange (AWE) in the United Kingdom. The locations of these stations are shown in Figure 1, with proprietary stations indicated by P1 and P2 on the map and in this paper. Table 1 shows the dates of continuous data segments obtained from these stations.

In addition to obtaining continuous waveform data, information on the mines and mining districts surrounding these stations is being compiled. Supplemental information, such as satellite imagery, is imported into the database to aid in determining ground truth for the locations of detected mine blasts.

Table 1. Stations for which continuous data have been obtained

Station	Network	Dates	Segment Length [days]	Lat (deg)	Lon (deg)
ABKT	IRIS/IDA	4/9/02 - 10/22/02	196	37.9	58.1
NIL	IRIS/IDA	7/2/98 - 3/3/99	244	33.7	73.2
HYB	GEOSCOPE	4/21/99 - 5/20/99	30	17.4	78.5
GBA	GEOSCOPE	2/1/1996 – 2/7/1996	7	13.6	77.4
P1	Proprietary	3/19/01 - 12/31/02	652	NW	India
P2	Proprietary	3/29/01 - 8/8/01	132	Southern	India

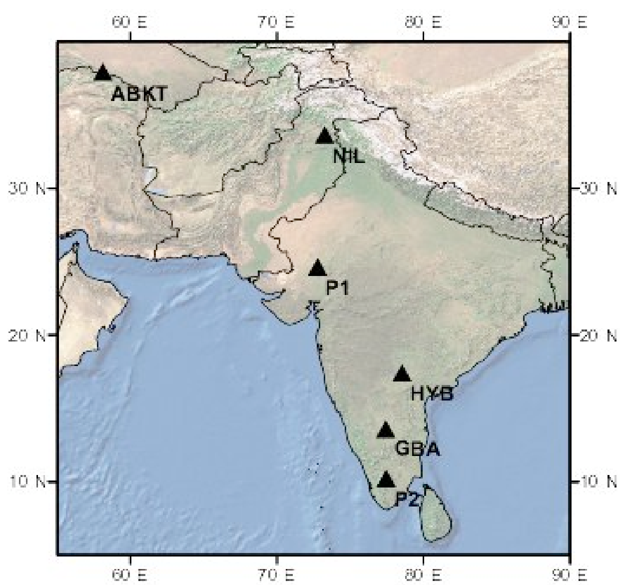

Figure 1. Location of IRIS/IDA (ABKT and NIL) stations, Geoscope station HYB, station GBA, formerly operated by the Atomic Weapons Establishment (AWE) at Blacknest, UK, and proprietary stations P1 and P2.

Detection of Mining Events from Continuous Data

Waveform correlation techniques. Two methods for detecting mine blasts are employed in this research. The first is the waveform correlation method (Harris, 1991). This method has been used on data from HYB, ABKT, GBA, NIL and the proprietary stations P1 and P2 (see also Britton *et al*., 2003 for an example of previous results at station P2). A simple STA/LTA detector was applied to twelve months of continuous data from proprietary station P1 as an initialization for the waveform correlation. Over 2000 detections were made for this period and the detected waveforms were correlated to a threshold of 0.7 into clusters of two or more events each. We developed subspace detectors for the six largest clusters (Table 2). These detectors were used to reprocess six months of the P1 dataset in order to find additional events in the six clusters. Events in these clusters are initially examined by eye, and if the events appear to be mine blasts (based on the presence of the *Rg* phase or repeated occurrence during daylight hours) then the events in the cluster are located. Figure 2 shows the locations of the clusters relative to P1. Figure 3 shows the detections, sorted by time of day, for a six-month period for each cluster. Figure 4 shows an example of events from each cluster.

Table 2. P1 cluster parameters. *P* and *Rg* back azimuth sample standard deviation was calculated only for events with detected *Rg* arrivals.

Cluster	Latitude (deg)	Longitude (deg)	Initial No. events	No. events used for cluster location	No. events with detected *Rg* arrivals	*P* back azimuth Sample Std. Dev (deg)	*Rg* back azimuth Sample Std. Dev. (deg)
2	25.1	74.9	88	39	33	11.2	11.5
3	23.5	73.6	30	14	5	10.3	6.23
4	24.4	73.8	22	16	16	7.4	7.1
5	22.9	73.5	35	16	-	14.2	-
6	24.4	73.9	12	7	4	4.1	8.7
7	24.8	73.7	21	6	4	12.3	12.2
Total events			208	98			

Only events detected by an analyst and with signal-to-noise ratio (SNR) greater than 1 were used for cluster location estimates. We calculated SNR as the ratio between the maximum *P* amplitude in a 3-sec window and twice the standard deviation of the noise (Der and Shumway, 1999) in a 10-sec window preceding the signal. The largest location outliers were discarded from each cluster. *P* and *Lg* arrival times were picked by an analyst, an *Rg* detector was applied and the events were located using semi-automatic methods similar to those described in the next section (Britton *et al.*, 2003). Median values for latitude and longitude were calculated for each cluster. A comparison between the *Rg* and *P* back azimuth residuals for 98 events with *Rg* arrivals from five clusters in northwestern India recorded at station P1 is presented in Figure 5. We observe (Table 2) that sample standard deviations of back azimuth estimates using the *Rg* detector are comparable or better than single station *P* back azimuth estimates for all clusters (except for the four events in Cluster 6). A possible explanation is that the *Rg* phase often has larger amplitude than the *P* phase.

Most of the events in Cluster 2 were recorded between 0800 and 1000 UTC (13:30 to 15:30 local time). Less than half of the events in Cluster 3 had SNR > 1. Of these, five events had *Rg* arrivals recorded at times marked by arrows in Figure 3. Further investigation of events in Cluster 3 is necessary to find whether one or several mines are operating in the area. All the events in Cluster 4 had *Rg* arrivals and occurred between 0800 and 1000 UTC (13:30 to 15:30 local time). No *Rg* arrivals were found in Cluster 5 except for an event with SNR lower than 1. The events in Cluster 5 were recorded between 04:00 and 07:00 UTC (09:30 to 12:30 local time) or 1200 and 1500 (17:30 to 20:30 local time). Cluster 5 might be composed of two sub-clusters with different occurrence times. Three events without *Rg* arrivals were located apart from the other four events in Cluster 6 with detected *Rg* phases. Given the long durations of these cluster sequences (Table 2) and the consistency of the origin times, these sources appear to be mines. The fact that events from Clusters 2, 3, 4, 6 and 7 exhibit *Rg* phases, which are consistent with shallow sources such as open-pit mine blasts, supports this interpretation.

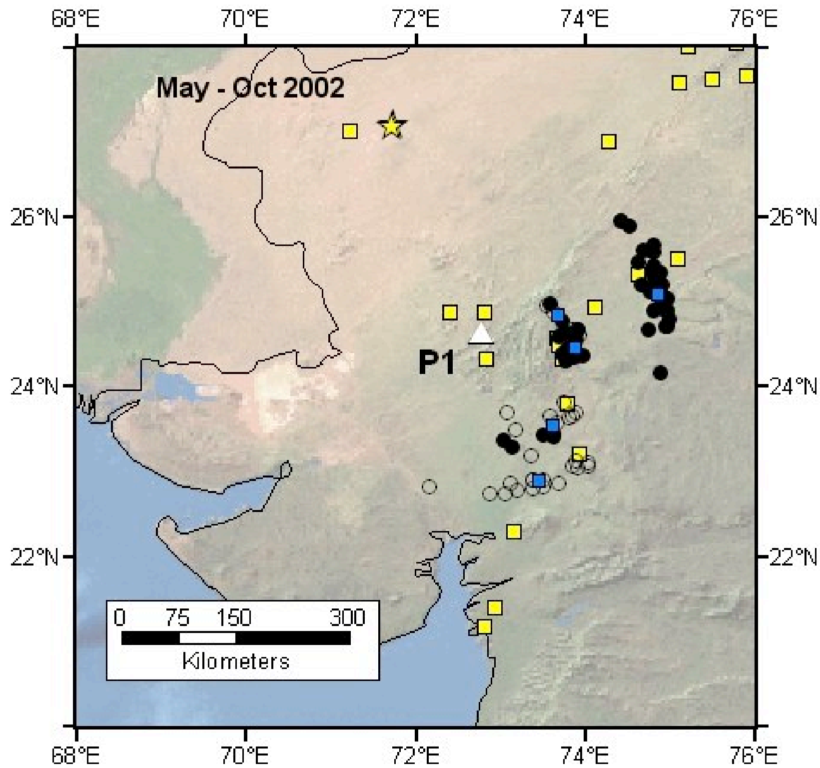

Figure 2. Single-station location of the six largest subspace detection clusters (blue squares) recorded at P1 between May and October 2002. Events for which *Rg* was detected (suspected mine blasts) are plotted as black circles. Yellow squares represent locations of open-mine pits. All the other cluster events are plotted as open circles. The yellow star is the location of the Pokhran test site.

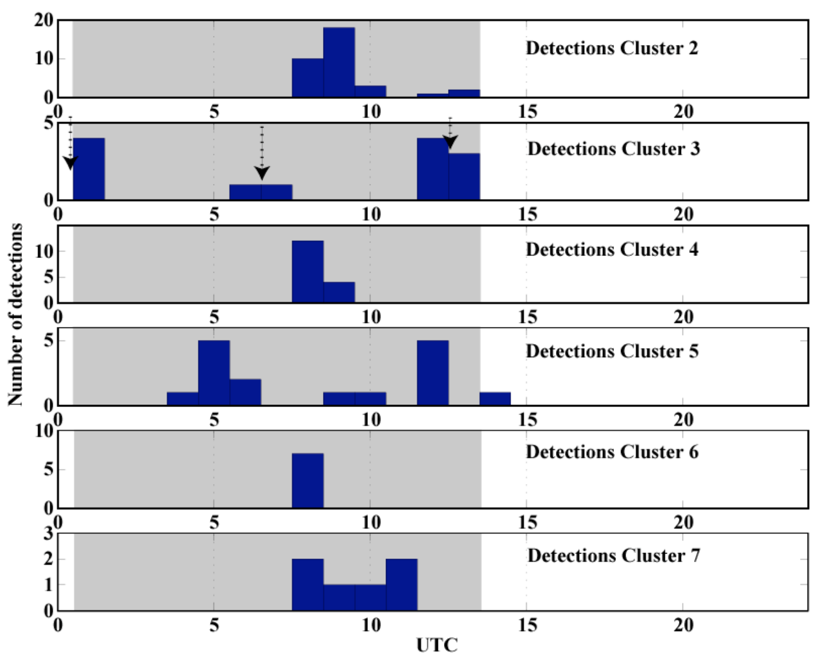

Figure 3. Clusters 2 to 7 event detections at station P1 sorted by time of day. Local time equals UTC plus 5.5 hours. Daylight hours (0600 to 1900 local time are highlighted). The arrows represent occurrence times for the Cluster 3 events with *Rg* arrivals.

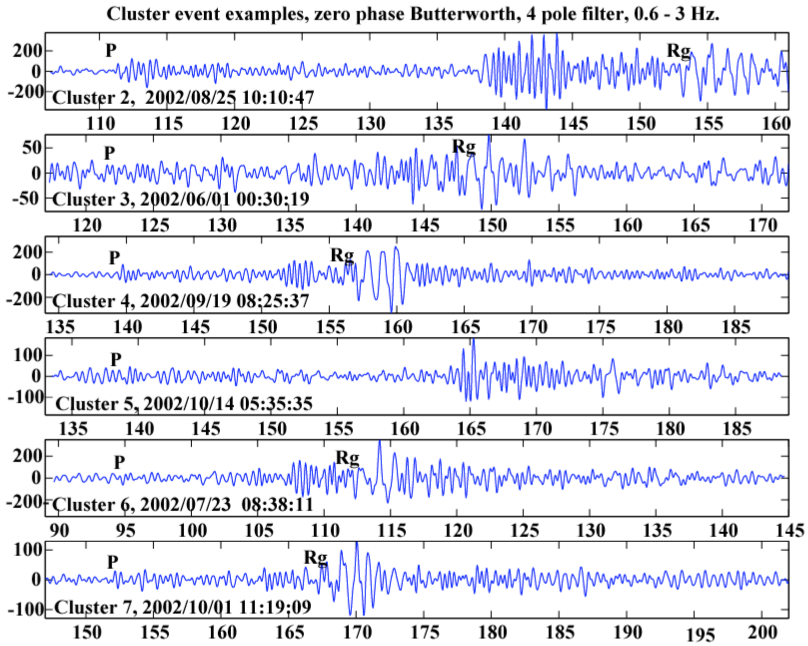

Figure 4. Examples of events from the six clusters, recorded at P1.

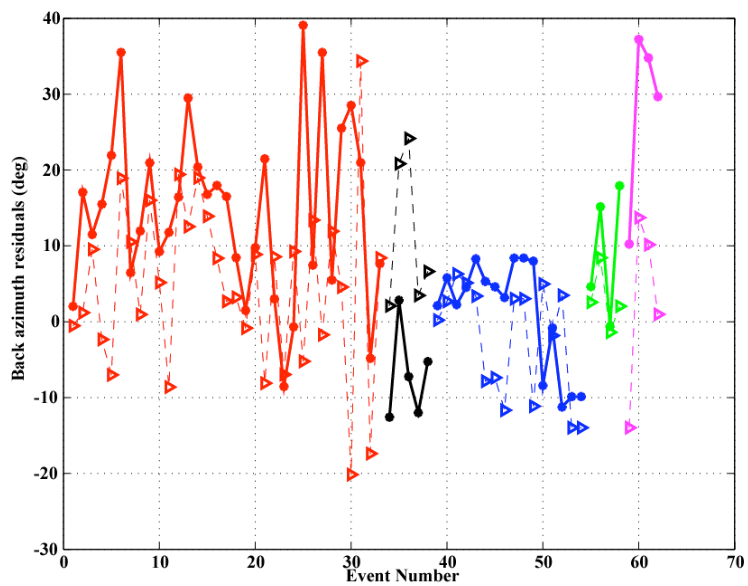

Figure 5. *P* back azimuth residuals (dotted line with triangles) and *Rg* back azimuth residuals (continuous line with stars). The residuals were calculated relative to the cluster estimated back azimuth. Events 1 to 33 are from Cluster 2 (red), events 34 to 38 are from Cluster 3 (black), events 39 to 54 are from Cluster 4 (blue), events 55 to 58 are from Cluster 6 (green) and events 59 to 62 are from Cluster 7 (magenta).

Semi-automatic detection of possible mining events from continuous data using an Rg detector. An alternate approach to the waveform correlation method is to continuously scan the station data for *Rg* arrivals without reference to known events. The presence of *Rg* on waveforms indicates shallow source depth, and when it is detected repeatedly during daytime hours, it is often an indication of mining operations. At this point we use only the *P* back azimuth in location algorithms. However, estimates of *Rg* back azimuth could be used for location of events with low SNR first arrival and large *Rg* amplitude. Thus, a complementary method used to detect small shallow events (possible mine blasts) is the automatic *Rg* detector (Tibuleac and Britton, 2004; Britton *et al.*, 2003; Chael, 1997). When applied after non-linear pre-filtering, the *Rg* detector code, using both polarization and amplitude information, produced back azimuth estimates comparable to the frequency to wavenumber three-component (*fk*3C) single station *P* back azimuth estimates when tested on clusters of well-located events in India (see also Figure 5 in this study).

Continuous data processing algorithms. The *Rg* detector was incorporated into routines for semi-automatic analysis of continuous data. A first arrival (*P*) detector and the *Rg* detection algorithm were applied to 10-min files. The *P* detector code was designed for three-component data using an algorithm similar to the *Rg* detector, modified for first arrival detection, and using a combination of Fourier and non-linear pre-filtering techniques. So far, the *P* detector has only been used for qualitative information purposes. Based on previous studies (Britton *et al.*, 2003), we decided to use non-linear pre-filtering before *Rg* detection. The non-linearly filtered data consists of coefficients of a Continuous Wavelet Transform using the 'Meyer' wavelet. Due to its similarity to a sinc function, the Fourier transform of a Meyer wavelet is a boxcar, centered on the analyst-chosen period (1 sec for this region).

Once a detection was declared, we applied the WAVELET1.0 picker developed at Weston Geophysical by Tibuleac *et al.*, (2003), to estimate *P* and *Lg* phase arrival times. Epicentral distance was estimated from the *P* and *Lg* arrival time difference using empirical, station specific formulas for station P1, and using the SSLOC3D single-station location method (Leidig *et al.*, 2003) for station P2. The first arrival back azimuth was estimated using the *fk*3C method adapted from MatSeis (Harris and Young, 1997). Improvements to the *fk*3C method include: 1) non-linear pre-filtering using a 'bior3.7' wavelet centered on the analyst-chosen *P* period. 2) *fk* analysis in a sliding 1 sec window with a step of 0.5 sec, performed within 5 sec of the detected *P* arrival to obtain the most stable back azimuth value estimation. Starting 2 min. before the detected *P* arrival, 10 min. of waveforms were stored in the database for each event, using specific MATLAB–to–SAC conversion routines.

Detection results for proprietary station P1. The detection algorithms were applied to continuous data from station P1 recorded for 15 days in March and April 2001. The analysis resulted in 282 detected local events. Of these events, 35 had *Rg* arrivals and were classified as possible explosions (orange circles in Figure 6). All the events with detected *Rg* arrivals were located to the northeast of P1, in the direction of known local mines (yellow squares), except for five events located in the seismically active Bhuj region, near the Basantgarh Copper Mine. Examples of possible explosions recorded from northeast of station P1 are presented in Figure 7. The upper plot presents a suspected explosion, recorded on 8 April 2001, 08:31, followed by a similar, lower magnitude event, 43 sec later. Another typical event with an *Rg* arrival, recorded on 5 April 2001, 08:13, also classified as a possible explosion, is presented in Figure 7, lower plot.

Detection results for proprietary station P2. The detection algorithms were applied to continuous data from station P2 recorded for 24 days in March and April, 2001. The analysis resulted in 156 detected local events. Of these events, 40 had *Rg* arrivals and were classified as possible explosions. The majority of the events with detected *Rg* arrivals were located to the northwest, in the direction of known local mines described by Britton *et al*, (2003). An example of suspected explosion detected northeast of station P2 on 3 April 2001, 09:12, is presented in Figure 8.

GIS Database

Waveforms of mine blasts detected by the waveform correlation and *Rg* detection methods are linked through hypertext transfer protocol (http) to an ArcView 8.3 geographic information system (GIS) database containing information on event location, satellite imagery, regional geology, station information, and mine information. An example is shown in Figure 9.

Event locations are added to the mining activity tables. When the suspected mine blasts do not occur near known mines contained in the database, a literature search for mines in that area is initiated. Satellite imagery in the area of the event location aids in providing ground-truth locations for the mining events. Often, the event locations lie within 10 km of an observed pit. The images are geo-referenced and can be readily incorporated into GIS maps. The database now contains satellite imagery for four mining districts showing the locations of at least a half dozen open pit mines. We have been unable to obtain any blast confirmations from the southern Asia mines; therefore satellite imagery has become our main source of ground truth.

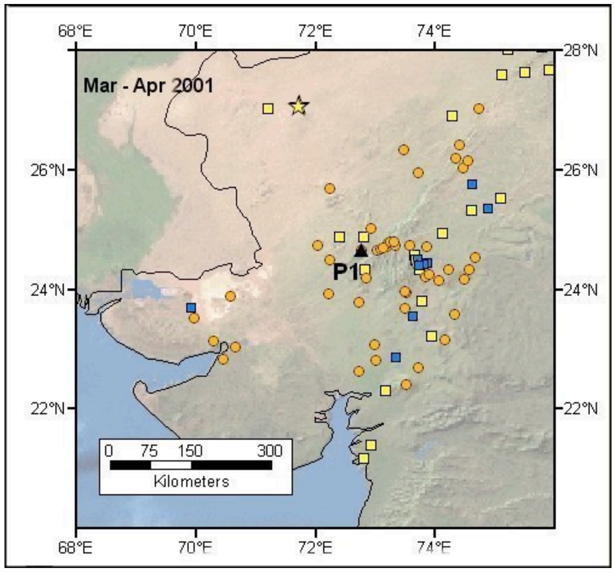

Figure 6. Location of suspected mine blasts (events with *Rg* arrivals) detected in March and April 2001 at station P1. Events for which *Rg* was detected (suspected mine blasts) are plotted as orange circles. Yellow squares represent locations of open-mine pits. Locations of event clusters estimated using waveform correlation methods are represented as blue squares.

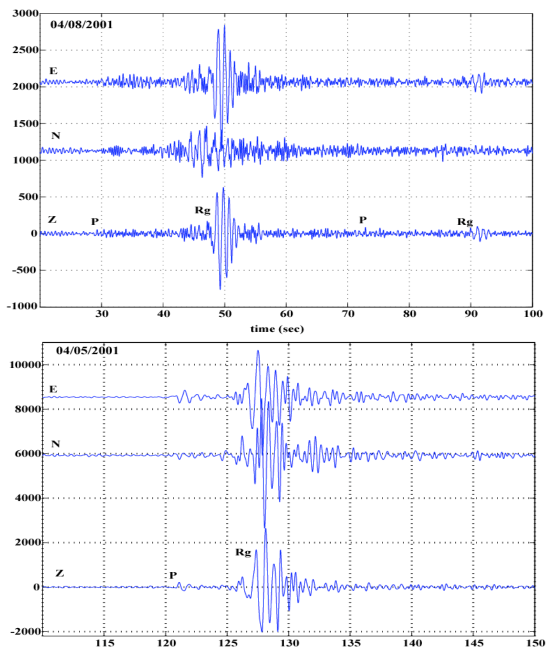

Figure 7. Upper plot: Zero-phase Butterworth 4 pole, 0.6-.5 Hz filtered waveforms for the 8 April 2001, 08:31:49 and 08:32:32 suspected explosions with *Rg* arrivals. The first event (*P* time lag 29 sec) was located 142 km east of P1. First arrival back azimuth was estimated to be 112 deg for the first event, located at 24.2 N and 74.1 E, and 109 deg for the second event, located at 24.3 N and 73.8 E. The *Rg* back azimuth was estimated to be 105 deg for both events. Lower plot: An event recorded at P1 on 5 April 2001, 08:13:12. The estimated location of this event was 24.82 N and 73.21 E, 48 km northeast of P1. First arrival back azimuth was 67 deg, while the *Rg* back azimuth was 63.4 deg.

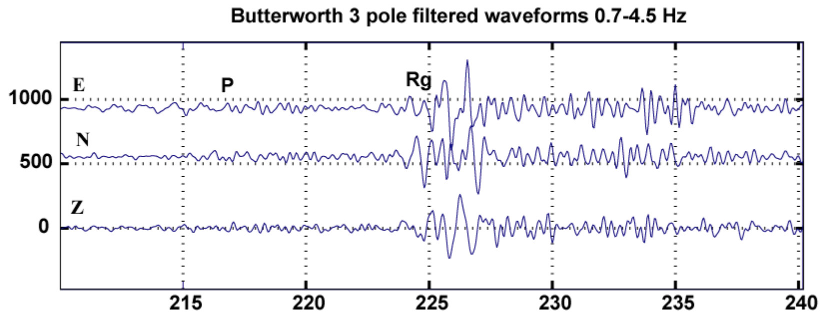

Figure 8. Suspected explosion on 2001/04/03 recorded at 09:12:34, with an estimated location of 10.4 N and 77.7 E, 40 km northeast of P2. Back azimuth was estimated as follows: 57 deg (*P*) and 58 deg (*Rg*).

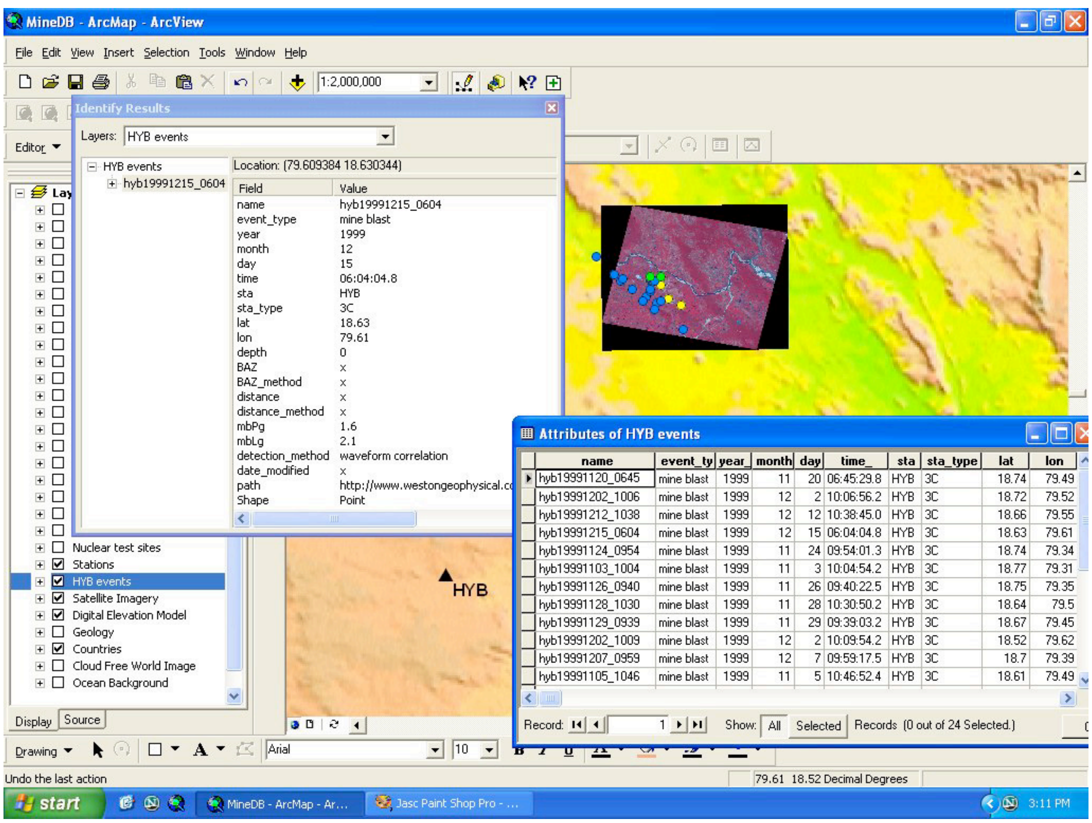

Figure 9. An ArcView interface window showing mining events detected near station HYB (blue, green and yellow circles), overlain satellite imagery and a digital elevation model. A window with event details and links to waveform data (right), and a window showing the attribute table for one of the events (left) are also shown.

CONCLUSIONS AND RECOMMENDATIONS

Information on mining activity around seismic stations in southern Asia is continually being compiled and updated. A combination of techniques, including waveform correlation and continuous data processing algorithms using single-station location methods and an *Rg* detection algorithm, was used to develop the mine database.

Continuous data have been analyzed using the waveform correlation method to detect events associated with nearby mines and mining districts. Waveforms from event clusters detected by the waveform correlation method at station P1 were spatially associated with nearby mines in the database. Additionally, the presence of *Rg* and the occurrence times during daylight hours confirm that these events are mine blasts. We observed that sample standard deviations of cluster back azimuth estimates using the *Rg* detector are comparable to *fk*3C *P* back azimuth estimates. Therefore, using the *Rg* phase back azimuth for event location is a promising alternative using small SNR first arrival back azimuth.

An *Rg* detector was integrated into a semi-automatic event-detection and -location algorithm and applied on continuous data. The algorithm uses improved *fk*3C single-station location techniques. We obtained better detection results and back azimuth estimates using non-linear pre-filtering. We presented continuous detection results at two proprietary stations in March and April 2001.

Detected waveforms are linked to an ArcView 8.3 geographic information system (GIS) database containing information on event location, satellite imagery, regional geology, station information, and mine information.

ACKNOWLEDGMENTS

We express our gratitude to Dr. Delaine Reiter and Mark Leidig for fruitful discussions and help on this project.

REFERENCES

Britton, J. M., D. Harris, I. M. Tibuleac, and J. L. Bonner (2003), Detection of Mining Explosions for a Southern Asia Seismic Database, *Proceedings of the 25th Seismic Research Review-Nuclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. 1, pp. 211-219.

Chael, E. P., (1997), An Automated Rayleigh-Wave Detection Algorithm, *Bull. Seis. Soc. Am*. 87, 157-163.

Der, Z. A. and R. H. Shumway (1999), Phase onset time estimation at regional distances using the CUMSUM algorithm, *Phys. Earth Planet. Int*. 113, 227 –246.

Harris, D.B, (1991), A Waveform Correlation Method for Identifying Quarry Explosions, *Bull. Seis. Soc. Am*. 81, 2395-2419.

Leidig, M., D.T. Reiter, J. L. Bonner, and A. Rodgers, (2004) Applicability of 3D modeling techniques in creating single-station locations: A test case in southern Asia, *Bull. Seis. Soc. Am*. 94, 753-759.

Tibuleac, I. M. and J. M. Britton (2004), An automatic Rg detection algorithm, (in preparation for *Bull. Seis. Soc. Am*).

Tibuleac, I. M., E. T. Herrin, James Britton, R. G. Shumway and A. C. Rosca (2003), Automatic of secondary phase arrivals using wavelet transforms, *Seis. Res. Lett.* 74, 884-892

Harris, M. and C. Young (1997), MatSeis: A Seismic GUI and Toolbox for MATLAB, *Seis. Res. Lett*. 68, 267-269.