DEVELOPMENT OF A MINING EXPLOSION DATABASE FOR SOUTHERN ASIA

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ABSTRACT

We have recently initiated the development of a high-quality mining explosion database for southern Asia consisting of detailed mining information together with seismograms recorded from mine blasts in India, Pakistan, and the surrounding regions. The database will be used to support the location, detection, and discrimination of mining explosions from earthquakes and nuclear explosions in this region. The preliminary development of the database has been completed in three research tasks: (1) collection and integration of mining data, (2) acquisition and analyses of seismic data, and (3) location, ground truth classification, and characterization of the mine blasts.

The mining database developed for this study currently contains over 240 mines and mineral deposits in southern Asia. These data include information on location, geology, commodities, production, mineralogy, references, operator, mining explosion resources, and additional parameters that were integrated into a single, digital database. The current focus of the database is on the Indian states of Andhra Pradesh and Rajasthan, and during the next phase of the project, we plan to expand the focus to other Indian states as well as Pakistan, Iran, and other regions.

We collected waveform data from several stations in southern Asia including HYB, GBA, NIL, and other proprietary data sources. We applied the waveform correlation method (Harris, 1991) on data collected from these stations during two months. For example, at HYB, the GEOSCOPE station in central India, a simple STA/LTA detector determined 413 detections, of which over 96% of the events occurred within daytime hours, for data acquired between 1 November and 31 December 1999. The detected events were then correlated down to a threshold of 0.7 resulting in several small clusters and one very large one. We have also developed and employed a detector to highlight events with short-period Rayleigh waves (*Rg*), which are often visible on mine blast seismograms in central and southern India.

Using single-station/array location techniques, we found several mines with blasts that contribute to the regional seismicity. In southern India, we located events in the Bellary-Hospet and Kudremukh iron-ore districts. In central India, we located events, with m_b magnitudes ranging from 1.6 to 2.6, originating from different mines in the extensive Godavari Valley Coal Field. Finally, in the northeastern Indian state of Rajasthan, we determined locations for events with $m_b \sim 3$ at the Rampura Agucha open pit zinc mine. These locations, waveforms, overhead imagery, and other information have all been incorporated into the mining explosion database. This resource may be of increasing importance now that stringent regulations on foreign mining interests in southern Asia have been relaxed, paving the way for larger mines in the region.

OBJECTIVE

The objective of our project is to develop a research database for southern Asia that will consist of detailed mining information together with seismograms recorded from mine blasts in India, Pakistan, and the surrounding regions. The database will be used to support the location and detection of mining explosions in this region and to increase opportunities for high-quality ground truth data. The preliminary development of the database has been completed in three research tasks:

- Collection and integration of data for mining districts and mine operations within southern Asia including location, geology, commodities, production, mineralogy, references, operator, mining explosion resources, and additional parameters into a single, digital database,
- Collection of seismic waveforms from mining explosions for inclusion in the database, and
- Analysis of these data for ground truth classification and mining statistics.

The results of the initial phase of this research are described in the following sections of this paper. Our results show that ground truth information, essential for monitoring efforts in southern Asia, can be compiled from these and additional data into a single comprehensive mining explosion database.

RESEARCH ACCOMPLISHED

Mining Database Development

Dr. Tom Weaver of Los Alamos National Laboratory previously compiled an extensive unpublished database of over 18000 mines and mineral deposits (henceforth called the Weaver database) from around the world. The Weaver database has information on 132 mines and districts in our study region. We used this database as an initial reference in our development of a mining explosion database for southern Asia. The information in the Weaver database includes mine location, geology, commodities, production, mineralogy, references, operator, opening, and closing dates. For some mines, he had compiled all of the above-mentioned data, while in other cases he had determined only an approximate location and mine name.

We have determined additional sources of information from within the international and local mining community to update and complete the Weaver database, as needed. Reviews of historical literature on economic geology and resources in India, Pakistan and Burma (Mehdiratta, 1962) were conducted together with web- and paper-based literature searches for information on mineral resources, production and exports for the following countries: Afghanistan, Bangladesh, Bhutan, China (western section), India (all states), Iran (eastern section), Myanmar (Burma), Pakistan, Sri Lanka, Tajikistan, Turkmenistan, Uzbekistan, and Nepal. The amount of readily available information for mineral resources in each of these countries and their states varied considerably. For instance, a number of Indian states had active and well-maintained web sites that summarized natural resources and identified specific commodities. Other countries, such as Afghanistan, had little representation except for reviews available in the journal *Annual Mining Review* (1996-1999). Lists of commodities and resources for each state were compiled and used to search for journal articles pertaining to mining activities in the countries of interest. Several hundred-journal articles were researched and used to identify mine names, mine districts, commodities, states and countries. On this basis, an updated mines database was developed containing the fields shown in Figure 1.

The updated mines database contains information on over 230 mines and mineral deposits in southern Asia and is a deliverable for this project in various formats. For some mining localities, geographic coordinates were available, while the coordinates (Figure 2) for approximately 50 of the mines were identified by cross-referencing the local municipality names with the name of the mine or district. The locations of the mines from the original Weaver database are shown as red diamonds, while updates to the database completed during the initial stages of this research project are presented as white diamonds.

Due to the very large number of references, mines and mineral deposits in the region (there are over 5000 active mines in the Indian state of Andhra Pradesh alone (http://www.andhrapradesh.com)), we determined that the scope of the initial research phase should be limited to populating the database for regions where we have access to seismic data. For example, Andhra Pradesh, India was a primary focus of the research as station HYB often records

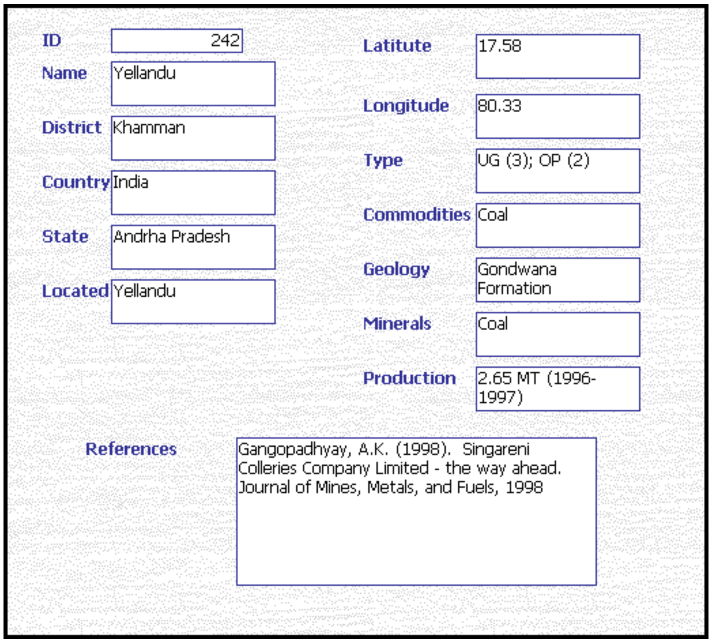

Figure 1. Example of an entry in our southern Asia mining database for a coalmine in Andhra Pradesh. The fields in the database include mine and district name, country, state, nearest town, latitude, longitude, type of mining, commodities, geology, extracted minerals and resources, production values, and references. The Yellandu mine is part of the Godavari Valley coal field in western Andhra Pradesh. The mine consists of three underground inclines and 2 open pit cast mines.

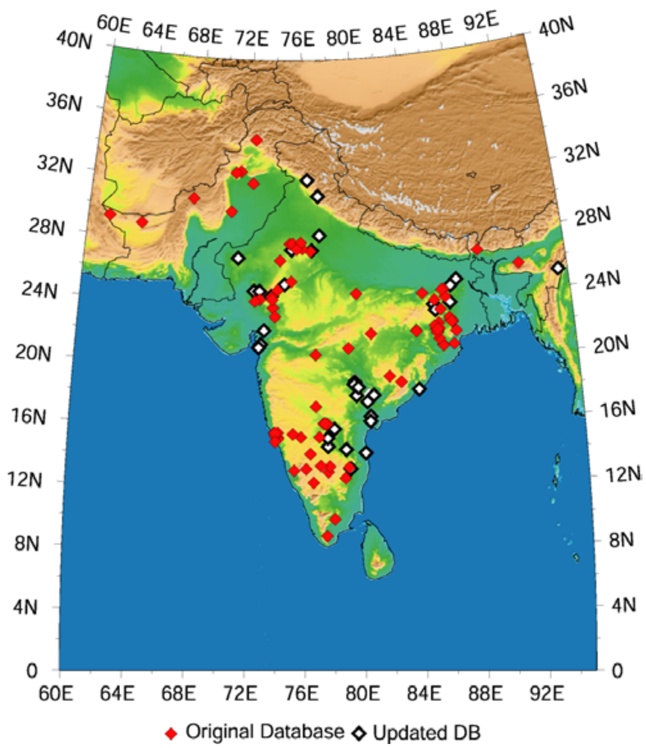

Figure 2. Locations of mines and mineral deposits in southern Asia as listed in the original Weaver database (red diamonds) and with the recent update (white diamonds) performed during the current research project.

mining explosions, some of which are presented in subsequent sections of this report. The current version of the database includes all mines and mining districts identified in Andhra Pradesh and Rajasthan using the method described above. All reference citations used to identify the mine/district have been entered in the appropriate record in the "reference" field of the database. In addition to the Andhra Pradesh and Rajasthan mines, the new version of the updated database also includes the identifications of mines in the Indian states of Assam, Manipur, Bihar (Jharkhand), Goa, Gujarat, Haryana, Himachal Pradesh, and Jammu & Kashmir. All remaining Indian states, and all other countries have had mines identified, but neither their identities nor their supporting references have been entered into the current database. We will complete the development of this database during the next stage of the project.

Data Sources for Mine Blast Waveforms

We have collected waveform data from stations in southern Asia in order to determine the contribution of mining explosions to regional seismograms. Table I shows the stations for which data have been collected to populate the database. We examined data from HYB (Table 1), a three-component station in central India that is part of the GEOSCOPE network. We have also compiled seismic data for the Gauribidanur Seismic Array (GBA) in central India. This medium aperture seismic array has twenty short-period seismometers arranged as two perpendicular arms (i.e., a cross array) and was operated by the Atomic Weapons Research Establishment (AWRE) of the United Kingdom between 04 March 1979 and 27 July 1996. Finally, we have permitted access to additional proprietary data sources in southern Asia for which we have examined the waveform data for mine blasts. During the next research stage, we will seek additional stations and sources of seismic waveform data.

Table 1. Stations in southern Asia for which waveforms were processed for mine blast detection.

STATION	LOCATION	TYPE	NETWORK	LATITUDE	LONGITUDE	OPERATION DATES
HYB	Hyderabad, India	3C	GEOSCOPE	17.417	78.553	15 Jan 1989 - present
GBA	Gauribidanur, India	Array	AWRE	13.6042	77.4361	04 Mar 1979- 27 July 1996

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Location Methodology

In regions with few seismic stations and small ($m_b < 4$) sized events, traditional location methods cannot always satisfy the location accuracy requirements for monitoring. This leads to location algorithms based on observations made at single stations and/or arrays. To locate an event with a single station, the slowness vector for the various seismic phases recorded (e.g., *Pn, Pg*) must be estimated. For a single three-component (3-C) station, the horizontal projection of the slowness vector is the backazimuth, and the vertical projection gives the angle of incidence that can be converted to an apparent phase given a known receiver crustal structure. In contrast to typical location routines for moderate-sized events that use a single scalar observable for one component of ground motion, this method incorporates the important information from all three components of the ground motion. For arrays, the backazimuth is derived from estimates of the slowness vector determined by fitting a plane to many sensor arrival times with the array using a correlation technique (Tibuleac and Herrin, 1997) or by beamforming (Ruud *et al*., 1998). The epicentral distance is calculated from the differences in travel times between secondary and primary phases (e.g., *Lg-Pn* or *Lg-Pg*). Given the station-to-source azimuth (backazimuth) and the epicentral distance, the epicenter location can be determined using standard geometric formulae.

The mining explosions in India are, in fact, small-sized events, and few seismic stations are available. We developed a single-station location technique capable of locating such events. Our method begins with adopting a model for the region surrounding the station. Reiter *et al*. (2001) developed a *P*-wave velocity model for India and Pakistan (called WINPAK3D), which was used to obtain velocity profiles near each station. The velocity profile was then used to estimate the *Pn* and *Pg* travel times as a function of distance from each station. We assumed a constant velocity of 3.5 km/s to calculate the *Lg* travel times as a function of distance, and note that this velocity will be refined as more data are analyzed in this region. The epicentral distance was then calculated by equating the observed difference between the *Lg* and *Pn/Pg* arrival times to the predicted travel time difference. Once the backazimuth is estimated, either for 3-C stations or the GBA array (using the f-k routines of Matseis (Young, 1997)), the source is located and compared to known locations from the mining database.

For example, stations HYB and GBA are located in the shield region of India where WINPAK3D velocity structure is based upon previous studies (Priestley *et al*., 2001). These researchers have shown the crustal structure in this region is relatively simple and can be approximated by two layers over a mantle half space (Figure 3). Using the standard refraction equation for a three-layer model (Burger, 1992), we derived an equation for epicentral distance (x) as a function of the *Lg-Pn* travel time distance ($\Delta_{Lg\text{-}Pn}$):

$$x = 6.25\ (\Delta_{Lg\text{-}Pn}) + 53 \quad \text{for } 1.7° < x < \sim 5° \qquad (1)$$

Using standard group velocities for *Pg* and *Lg* of 6.0 km/s and 3.5 km/s, respectively, we determined the equation for epicentral distance as:

$$x = 8.4\ (\Delta_{Lg\text{-}Pg}) \qquad (2)$$

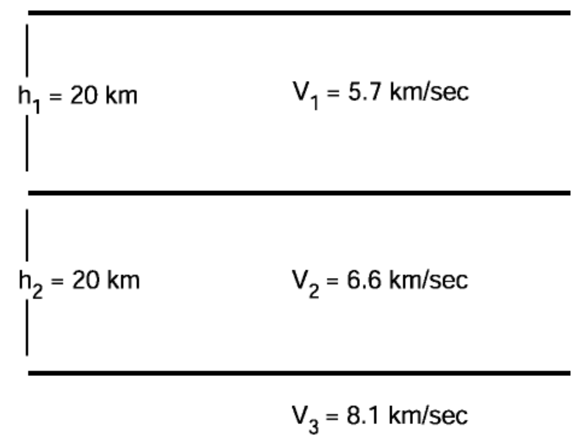

Figure 3. Average WINPAK3D P-wave velocity structure of west-central India.

Regional Mine Blast Seismicity at GBA

GBA data are an excellent source of regional mining explosions as documented by Krishna and Ramesh (2000). They compiled explosion seismograms recorded at GBA from various mines (Figure 4) in India to provide evidence for an upper crustal waveguide for *Pg* with a scattering zone in the upper 15 km of crust. In the upper plots of Figure 5, we provide example seismograms recorded at GBA from the Bellary-Hospet iron-ore region and the Kalyadi copper districts in Karnataka, India. We determined backazimuths for these seismograms by bandpass filtering between 0.8 and 2 Hz (lower plots) and performing *f-k* analyses on the *Rg* arrivals. Locations were determined by converting the *Lg-Pn/Pg* travel time differences to epicentral distances using formulae developed from regional models (Eqs. 1 and 2).

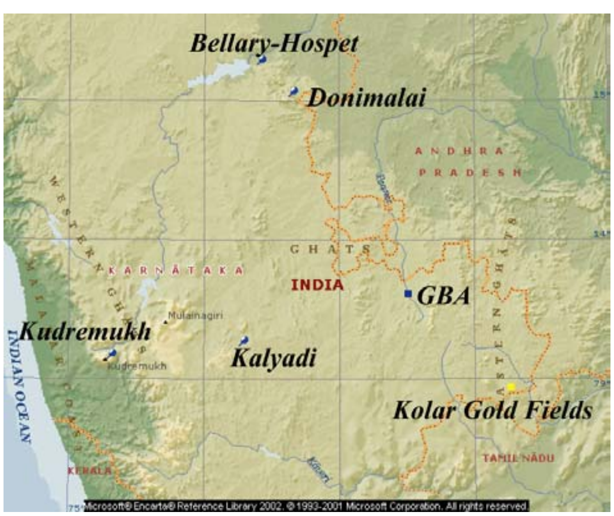

Figure 4. Location of the GBA cross array (star) in the state of Karnataka, India. Also shown are the locations of the Bellary-Hospet, Donimalai, and Kudremukh iron-ore districts and the Kalyadi copper district. The Kolar Gold Field is a deep underground mine complex located near Bangalore, India.

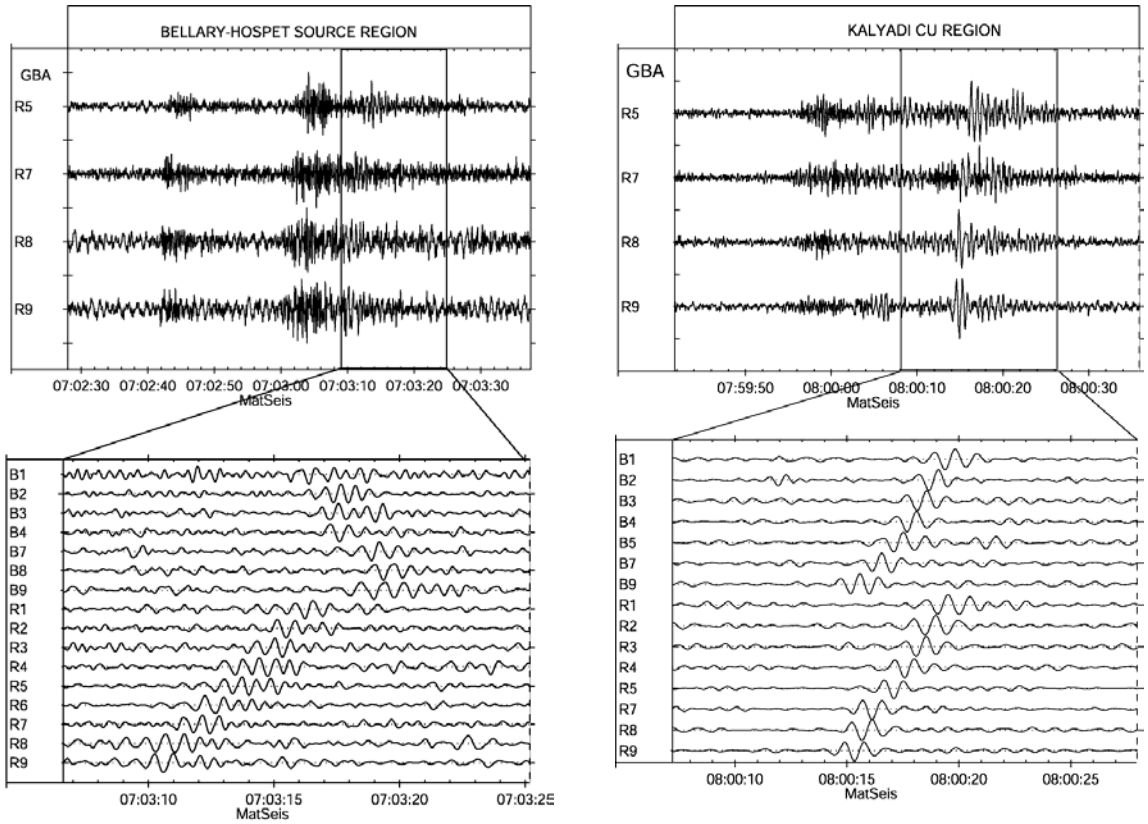

Figure 5. (Upper Left) Seismograms from a mine blast in the Bellary-Hospet iron-ore district recorded on four elements at GBA. (LowerLeft). Bandpass filtered *Rg* arrivals are presented all available seismic elements at GBA. We completed an f-k analysis on the *Rg* to determine a backazimuth of 332° for the explosion. (Upper Right) Seismograms from a suspected mine blast in the region of the Kalyadi copper mines recorded on 4 elements at GBA. (Lower Right). Bandpass filtered *Rg* arrivals are presented for all elements of GBA. The *Rg* signals were processed using f-k techniques to determine a back azimuth of 252° for the explosion.

Regional Mine Blast Seismicity at HYB

We performed the waveform correlation method (Harris, 1991) on two months of data (1 November to 31 December 1999) recorded at station HYB. First, a simple STA/LTA detector performed on the filtered (bandpassed between 1 and 4 Hz) seismic data determined 413 detections for the two months. These were then correlated down to a threshold of 0.7 resulting in several small clusters and one very large cluster. Figure 6 shows the time of day and day of week when the detections occurred. The majority of the detections occured between 04:00 and 11:00 UTC (9:30 AM to 4:30 PM local time) suggesting that most detections at HYB are from mining explosions or daytime construction explosions in the region.

The largest cluster resulted from correlation of simple *Rg* signals from a small mine near station HYB. Four additional clusters were chosen for a more detailed study. Example waveforms for these clusters are shown in Figure 7. The three-component records consist of a small *Pg* signal and large *Lg* and *Rg* arrivals. The seismograms were bandpass filtered between 0.8 and 6 Hz to increase the signal-to-noise ratio (SNR).

For each event in clusters 2, 9, 10, and 12, we measured the *Pg* and *Lg* arrival times, amplitudes, and periods, and determined the backazimuths using the 3-C waveforms. For several of the events, the *Pg* SNR was too low (< 1.5 – 2) for analysis, and thus the event was not analyzed. We used Equation 2 to estimate the epicentral distance based upon the observed *Lg*-*Pg* travel times, and then converted distance and backazimuth to the source latitude and longitude. The locations are plotted in Figure 8.

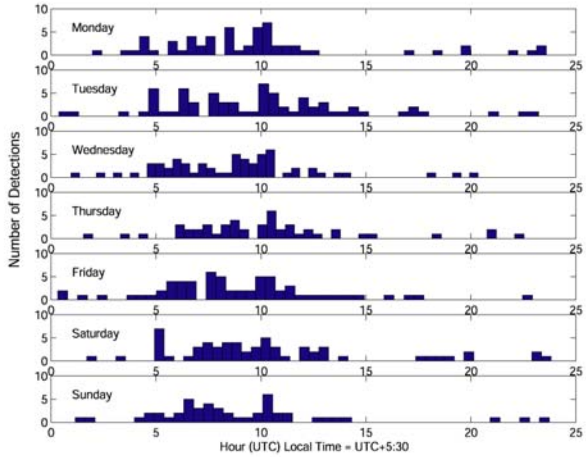

Figure 6. Occurrence times for the 413 detections from the waveform correlation technique performed on 2 months of continuous HYB data.

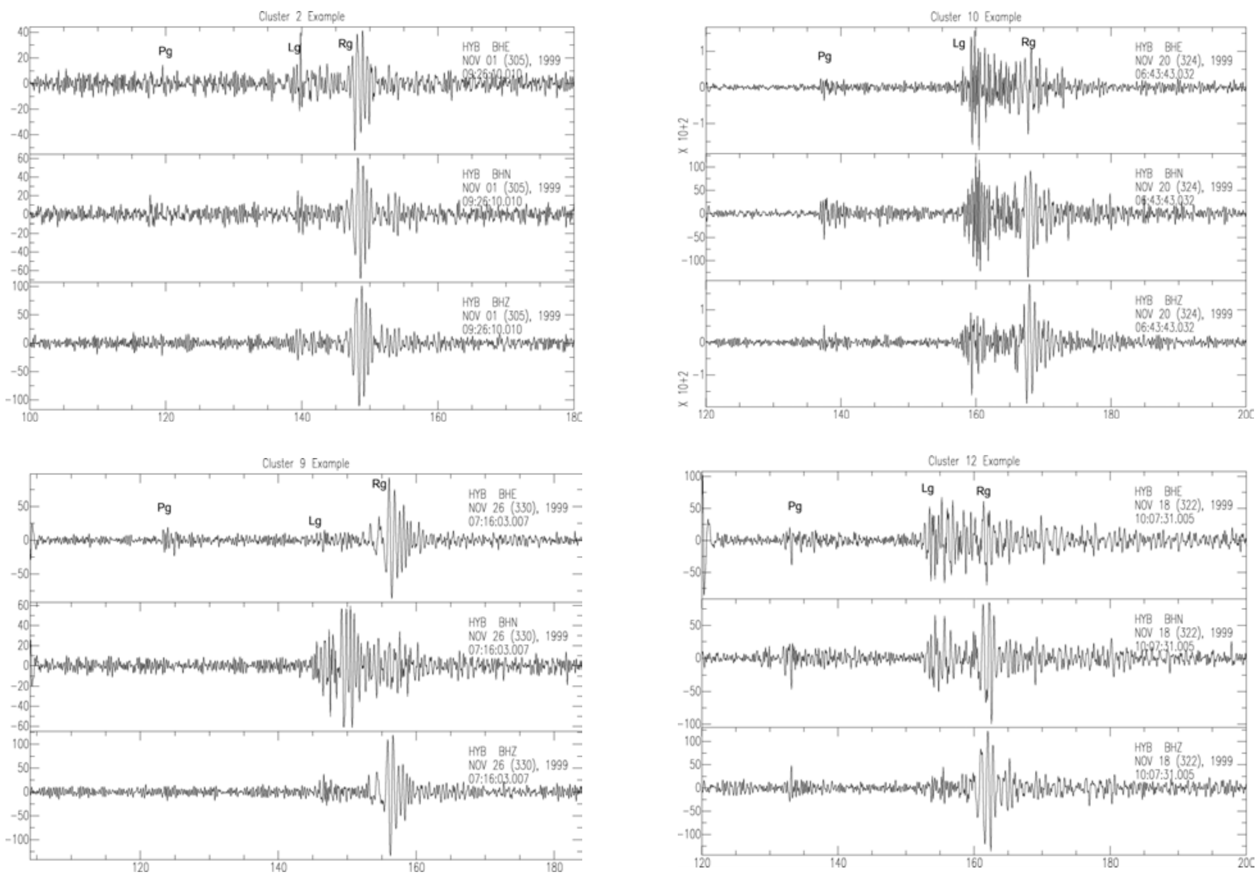

Figure 7. (Upper Left) Three-component seismograms for an event from cluster 2. The traces were bandpass filtered between 0.8 and 4 Hz. (Lower Left) Event from cluster 9. (Upper Right) Event from cluster 10. (Lower Right) Event from cluster 12.

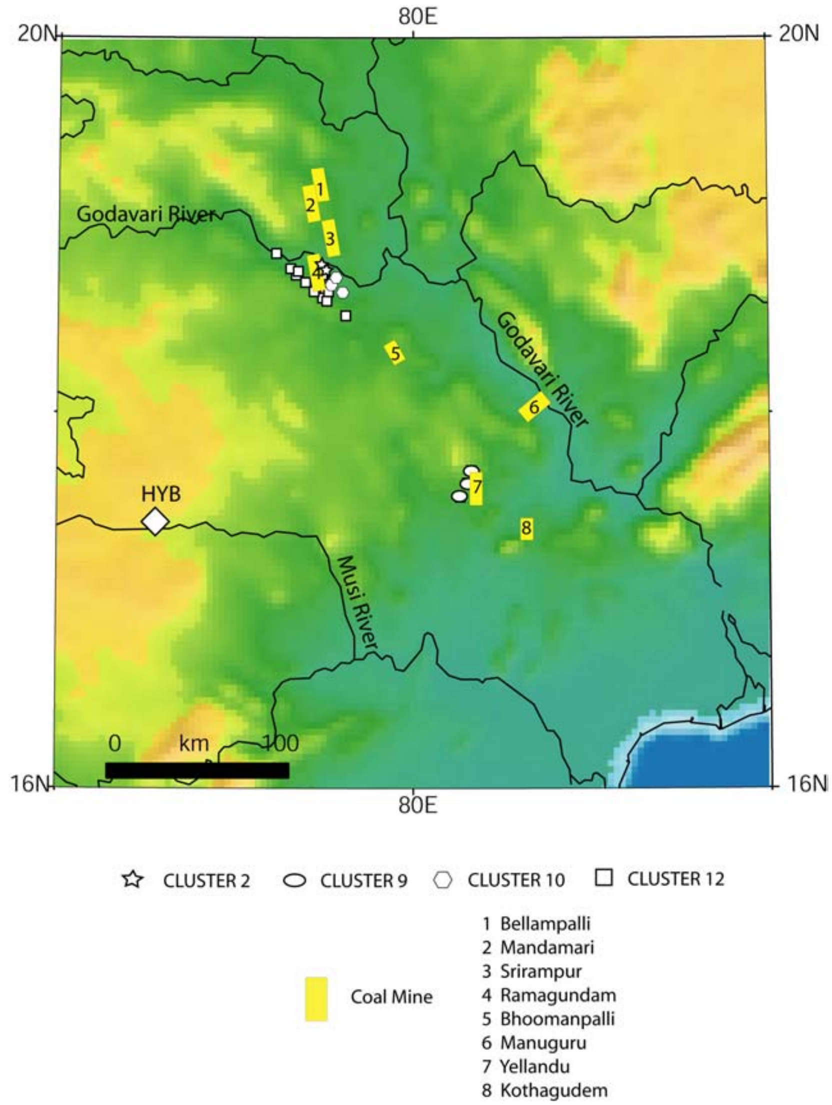

Figure 8. Single-station (HYB) locations for the events in clusters 2, 9, 10, and 12. Also shown are the known locations of mines in the Godavari Valley Coalfield.

The locations of coal mines in the Godavari Valley Coal Field (GVCF) are presented in Figure 8 in relation to the event cluster locations. Coal was first discovered in the GCVF in 1871 near the village of Yellandu, in the state of Andhra Pradesh. The coal is found in the northwest-southeast trending, fault-bounded Gondwana basin in Carbonaceous-aged sediments, and the Godavari River cuts across these sediments in a northwest to southeast direction as seen in Figure 8. The mines and processing infrastructure in the coal fields are presently operated by the state-owned Singareni Collieries Company Limited (SCCL), and the coal bearing strata are located in 3 districts of Andhra Pradesh: Adilabad, Karminagar, and Khamman. Mines in the region consist of both underground and opencast surface operations. In total, there are 62 underground mines and 11 open-pit mines in GVCF (Gangopadhyay, 1998).

The Yellandu mine of the GCVF is the source of the cluster 9 mining explosions as seen in Figure 8. Because of low SNR for the Pg arrivals, only 3 of the 6 events from the cluster could be located. We used 25-meter resolution satellite imagery to identify the opencast pits at Yellandu. We do not have blaster confirmation of the individual pit for the cluster 9 events; however, our event locations and the center of the mine differ on average by less than 10 km. The range of $m_b(Pg)$ magnitudes for the explosions in cluster 9 was 1.5 to 2.4.

The locations for clusters 2, 10, and 12 are near the Ramagundam mines of the Karminagar district as seen on the 25-meter resolution satellite imagery (Figure 9). The scatter in the locations is oriented along a NW-SE arc projected from HYB and is caused by uncertainties in backazimuth projection (±6°). The Ramagundam mine is the most productive mining region of the GVCF, with four opencast mines. Given the scatter in the azimuth data, it is difficult to pinpoint the individual pits responsible for the clusters. The m_b (*Lg*) magnitudes for clusters 2, 10, and 12 ranged from 1.5 to 2.0, 1.6 to 2.6, and 1.7 to 2.6, respectively.

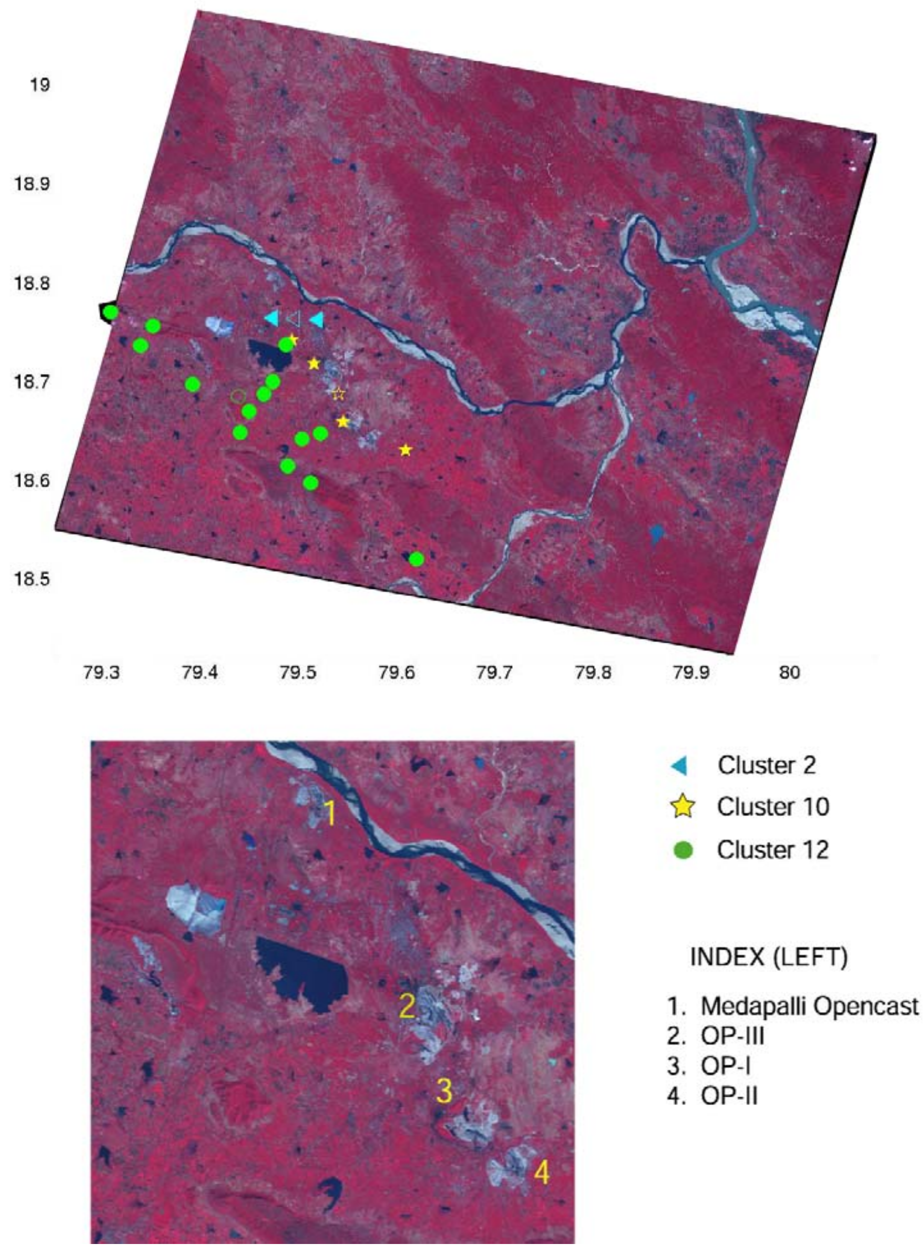

Figure 9. (Top) Locations for events in clusters 2, 10, and 12 shown as closed triangles, stars, and circles, respectively, overlain on a 25-meter resolution Spot photo. The average location for each cluster is shown as the open symbol. (Bottom) Inset from top figure showing locations of the open pits of the Ramagundam mine.

CONCLUSIONS AND RECOMMENDATIONS

Our research has uncovered new sources of mining information for southern Asia, allowing us to update the Weaver mining database. We have separated mining explosions from the background seismicity in India using the waveform correlation technique (Harris, 1991) and identified iron ore, copper and coal mining blasts in southern India and production shots in zinc mines in northwestern India. Our single-station event characterization method has the capability to locate mine blasts and other near-regional events in India to within 10-15 km of the ground truth locations. This level of accuracy allows us to determine the mine conducting the blasting, but does not allow us to pinpoint the actual pit with certainty. We recognize the mining explosions recorded thus far are small events ($1.5 < m_b < 2.9$) and do not offer optimal examples of ground truth data. However, the mining explosion database will be expanded significantly during the next phase of the project to include more recent sources of data that could reveal larger mining explosions in the region.

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