Trail Mountain Mine: A Case Study for Improving Locations of Mining-Induced Seismicity with Double-Difference Relocation

Eleanor Sonley, Postdoctoral Fellow
Department of Mining Engineering
University of Utah
Salt Lake City, UT

Kristine L. Pankow, Assistant Director
University of Utah Seismograph Stations
University of Utah
Salt Lake City, UT

Michael K. McCarter, Professor
Department of Mining Engineering
University of Utah
Salt Lake City, UT

ABSTRACT

In October 2000, temporary seismographic stations were installed above the Trail Mountain Mine, Emery County, Utah, USA to supplement a regional network. Over seven months, 1826 mining-induced seismic events were recorded with a magnitude range of M 0 to M 2.2 (Arabasz et al., 2002, 2005). Routine event locations for this dataset cluster around the longwall mining activity during the recording interval. However, applying a double difference relocation technique to the routine locations significantly improves the correlation between mining activity and event location. The resulting relocations depend greatly on station distribution and the number of arrival time picks.

We use this dense temporary array to assess station distribution requirements for applying the double difference technique at other mines by systematically removing data from available stations, thus simulating sparser networks. The insight gained using the Trail Mountain dataset is used to develop a metric for assessing the usefulness of above-mine networks and to develop a tool for expanding seismic network coverage. To verify the appropriateness of these tools for wider application, we examine data from two additional mines located in the western United States.

Improving the relative locations of mining-induced seismic events highlights the association of these events with active portions of the mine. Clusters, regions of quiescence and relative timing of events can be used by mine operators to assess hazard, optimize production, and evaluate performance of mine plans. The lessons learned from this study may be used in future network design to improve accuracy of event locations at other mines.

INTRODUCTION

One methodology for assessing the ground response induced by coal extraction is monitoring of mining-induced seismicity (MIS), both in space and time. The level of detection and location of events is controlled by the scale of the seismic network. In-mine network sensors are located close to where the MIS is emanating; this allows for both detection of small events and the potential for accurate event locations. However, in-mine systems are often quite expensive to acquire, maintain, and operate. As an alternative, it has been shown that both a localized above mine-array (Arabasz

et al., 2002, 2005; Swanson et al., 2008) and the application of double difference relocation methodologies using above mine networks (Pechmann et al., 2008; Pankow et al., 2008) can provide a fairly detailed picture of the MIS. Above mine networks have the advantage of being less expensive and easier to maintain. However, given the distance from active mining, the magnitude detection threshold and uncertainties in event location are usually larger than for an in-mine system.

In this paper, we examine the combined effects of seismic network distribution and the double difference relocation technique *hypoDD* (Waldhauser and Ellsworth, 2000) for improving MIS locations. In particular, we focus on the Trail Mountain Mine, where a previous study (Arabasz et al., 2002, 2005) deployed an array of nine temporary stations in the vicinity of active mining. By systematically removing arrival time picks from one and then multiple stations in the Trail Mountain network, we explore the tradeoffs between various network geometries and gain insight into optimal ways to link events for use in *hypoDD*. Using this knowledge, we develop a metric for assessing the usefulness of various above-mine network geometries. We then expand on the usefulness metric and develop a tool to assess the optimal location for additional stations to be used to further improve MIS locations using *hypoDD*. To verify that the tools and insight developed and learned from the Trail Mountain dataset are widely applicable, we also look at data from two additional mines located in the western United States.

DATA

The primary dataset for this study is a subset of the University of Utah Seismograph Stations (UUSS) catalog and the related travel-time pick data, observed in the Wasatch Plateau and Bookcliffs region of central Utah. We concentrate on the time period from January 2000 to July 2008 when approximately 13,000 seismic events ($0.1 < M_c < 4.5$) were located in polygons that circumscribe the active mining areas in central Utah (after Arabasz et al., 1997; Figure 1). Arabasz and Pechmann (2001) concluded that >98% of the seismic events occurring within these defined polygons are MIS.

From this larger dataset, we look at three subsets. The main subset includes seismic events located near the Trail Mountain
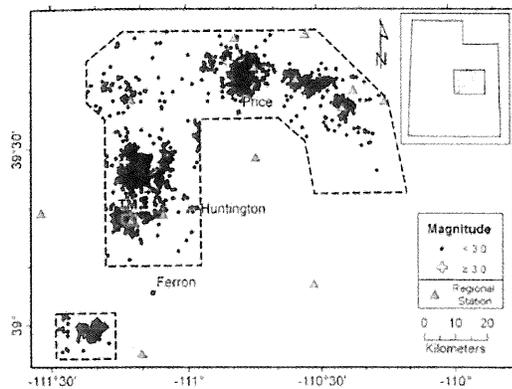
Figure 1. The Wasatch Plateau and Bookcliffs coal-mining polygons (after Arabasz et al., 1997) of central Utah. Seismic events recorded between January 2000 and July 2008. White crosses M ≥ 3.0 seismic events; solid circles M < 3. Triangles show locations of UUSS regional seismic stations. The permit area of Trail Mountain Mine (TM) is also shown.

Mine from October 2000 to April 2001 (permit area shown, Figure 2). This subset is unique due to a nine station temporary array placed in the vicinity of the mine (Arabasz et al., 2002, 2005). The purpose of the temporary array was to assess potential ground-shaking effects at the nearby Joe's Valley Dam (McGarr and Fletcher, 2005; Fletcher and McGarr, 2005). The nine temporary stations (eight of which are shown in Figure 2) are located within a 6 km radius of the active portions of the mine. This localized network allowed detection and location of smaller magnitude events with greater accuracy than would have been achievable with the larger-scale regional network. Routine locations of the seismic activity recorded by the local array closely conform to the mining activity (Figure 2). The east-west oriented prominent limbs bracket the active longwall panels and a dense cluster to the east represents an increase in overburden depth. Thinner linear features reflect residual seismicity above previous workings.

Two additional subsets of events analyzed in this study are located near mines that will remain anonymous. Stations in the vicinity of each of these mines are less in number and at greater distances from the active workings than those of the temporary array at Trail Mountain. However, these two subsets are more representative of UUSS monitoring of MIS in central Utah than the Trail Mountain dataset. Mine X has a single station near the active portion of the mine, but most other stations are quite distant (>8 km). Over a three year period, ~1000 events were recorded ($0.3 < M_c < 3.1$) within the mine permit area. In contrast, the nearest station to Mine Y is 9 km from the mining activity. Over an eight-year period only 294 events were recorded ($0.6 < M_c < 3.1$) within this mine permit area.

EVENT LOCATION METHODS

Routine Locations

Seismic events in Utah and Yellowstone National Park, both naturally occurring and induced, are routinely located by UUSS utilizing continuously recorded data, available in real-time at >230
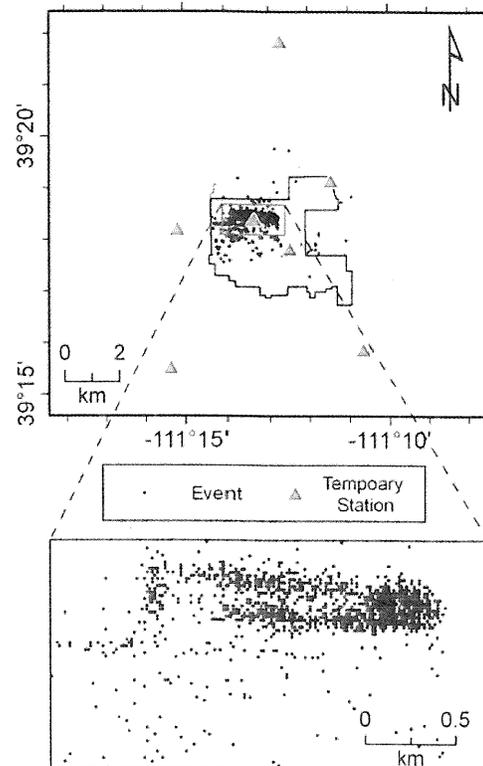
Figure 2. UUSS routine locations for seismic events occurring near the Trail Mountain Mine (outline is the permit area). Temporary array stations are represented by triangles. Note that one station is off the map to the southeast and in the center of the permit area two stations are co-located.

stations. Routine locations are determined using HYPOINVERSE (Klein, 2002), a methodology that minimizes travel time residuals (the difference between an observed P- or S-arrival time and a theoretical time calculated utilizing a one dimensional velocity model) from individual earthquakes recorded at many stations. The output of this inversion is a hypocenter (latitude, longitude, depth) and origin time with associated horizontal and vertical errors. In routine locations determined for the mining area of central Utah, MIS is located using a general velocity model for the Wasatch Plateau. For more refined locations, models for specific areas, such as Trail Mountain or Willow Creek, are used.

Double Difference Relocation

Many methods have been explored to improve the accuracy of seismic event locations. In this study, we will use the double difference relocation technique *hypoDD* (Waldhauser and Ellsworth, 2000; Waldhauser, 2001). Like other double difference methodologies the advantage of *hypoDD* is that it minimizes the effect of the velocity model. If two routine event locations are relatively close to one other, the difference in the observed travel times from each event to the same station is a function of the difference in their respective locations only. This difference can be used to find the relative locations of the events by minimizing the residuals of double difference (t_{DD}) travel times:

$$t_{DD} = \Delta t_{obs} - \Delta t_{theory} \qquad\qquad (1)$$

where Δt_{obs} is the difference in observed travel times, and Δt_{theory} is the difference in travel times computed through a one-dimensional velocity model. Due to the closeness of the two events, the ray paths traveled to the station will be nearly identical, and any travel time discrepancies produced by the difference between the velocity model and the real earth will be the same for both paths. Thus, the effects of small-scale inaccuracies in the velocity model are largely eliminated. In this inversion, what is being solved for is not an absolute location in space and time, but the relative locations between events used to form the double difference travel times. Note that even though an absolute location is output from *hypoDD*, the precision in the methodology is in the relative spacing between relocated events. For MIS it has been shown that accurate (<200 m) absolute locations can be achieved by vector-shifting the relative locations using ground truth information (Pechmann et al., 2008; Pankow et al., 2008).

As with routine locations, *hypoDD* requires reliable travel-time picks. One method for improving arrival time pick accuracy is with cross-correlation (e.g. Rowe et al., 2002; Schaff et al., 2004). *hypoDD* was developed to utilize analyst picks, cross-correlation data, or both (Waldhauser and Ellsworth, 2000; Waldhauser, 2001). In this study, analyst picks were solely used because a cross-correlation analysis of the Trail Mountain data indicated that no significant alteration to the travel-time picks (~2 counts or 0.02s) was warranted.

One of the major assumptions when using *hypoDD* is that the hypocentral separation between the two events is small compared to the event-station separation and the scale length of velocity heterogeneities (Waldhauser and Ellsworth, 2000). This separation distance, also called the linking distance, is a configurable parameter within *hypoDD* and one that we found to significantly influence the resulting locations. In some earthquake studies, this linking parameter has been set to <10 km (e.g. Waldhauser and Ellsworth, 2000; Pankow et al., 2004). Earthquakes tend to originate at depths from 5 – 30 km where average one-dimensional velocity models (and hopefully the real Earth) change little over a 10 km scale length. In contrast, for depths associated with MIS (< 1 km), the average one-dimensional velocity models might have scale lengths <2km. Thus the linking distance must be appropriately chosen for each application of *hypoDD*. In this study, we empirically determined an appropriate linking distance, relative to the size of the initial spatial clusterings of MIS for three case study mines. This linking distance ranged from 60 m to <3 km. Half the width of each initial cluster proved to be a successful rule of thumb for a fourth case study mine (not included in this paper).

A minimum number of common travel-time picks must also be set. Generally, each event pair requires arrival time picks from eight common stations in order for both events to be fully resolved (latitude, longitude, depth and origin time). Following Pankow et al., (2008) we reduce this requirement to six common picks by fixing the depth of each event in the pair to the depth of mining activity (e.g. 600 m for Trail Mountain). Smaller magnitude events are often excluded from hypoDD locations as they have insufficient picks to meet the common pick criteria. Typically, the smaller the magnitude, the fewer stations picked.

STATION USEFULNESS WITHIN A NETWORK

For each seismic event recorded, arrival time picks (both P- and S- wave picks) are made by analysts at the UUSS. The probability that a station will be picked depends on the distance from the event, the magnitude of the event and the noise at the seismic station. The larger the event, the higher the initial amplitude and the larger the amplitude at greater distances. Picks can only be made when the signal amplitude from the earthquake is significantly larger than the noise at the station.

Here we develop a metric for evaluating how useful each station is within the network given a set of seismic events. We use a summation of coefficients reflecting distance, azimuthal gap, and magnitude, over all events with arrival time picks at an individual station. We describe the usefulness, U_j, for n events picked at station j by:

$$U_j = \sum_{n=1}^{N_j} D_j G_n P_n M_n \qquad\qquad (2)$$

where N_j is the total number of events with a travel-time pick at station j, M_n is the coda magnitude, D_j, G_n and P_n are distance, gap and pick coefficients respectively described by:

$$D_j = \begin{cases} 1 & R < TH(M_n) - ST(M_n) \\ 0.5 & R < TH(M_n) + ST(M_n) \\ 0 & R > TH(M_n) + ST(M_n) \end{cases}$$

$$G_n = \begin{cases} 1 & A \le 90^0 \\ 0.75 & A \le 135^0 \\ 0.25 & A \le 180^0 \\ 0 & A > 180^0 \end{cases}$$

$$P_n = \begin{cases} 1 & K \ge 8 \\ \dfrac{K}{8} & K < 8 \end{cases}$$

where R is the hypocentral distance in km, $TH(M_n)$ is the distance threshold given in Table 1 for magnitude M_n, $ST(M_n)$ is the standard deviation given in Table 1 for magnitude M_n, A is the largest angle of non-coverage for event n (Figure 3) and K represents the number of picks for event n.

In order to determine the distance threshold and standard deviation used in the distance coefficient, each event located within the polygons outlining mining activity in the Wasatch Plateau and Bookcliffs region (Figure 1) between 2006 and 2008 was placed into a bin of 0.5 magnitude units (0-0.5, 0.5-1.0, etc.). For each magnitude bin, the distance between each event and the most distant station with a travel time pick was computed. Mean (*TH*) and standard deviation (*ST*) values are presented in Table 1. *TH* represents the maximum hypocentral distance expected to have a travel-time pick. The standard deviation of each mean was also computed, to provide confidence limits on this assumption. For the gap coefficient, we follow the definitions for epicentral quality in

189

Table 1. Distance Coefficient Parameters.

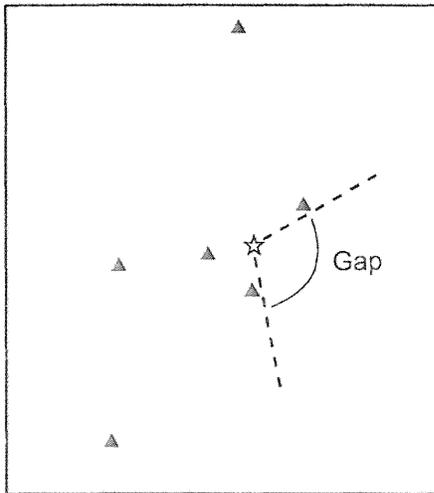| Magnitude (M_n) [Upper Bound]	Distance Threshold (TH) [km]	Standard Deviation (ST) [km]
0.5	25.52	3.97
1.0	42.09	19.53
1.5	66.14	22.47
2.0	82.71	29.88
2.5	105.81	35.32
3.0	149.77	43.89
3.5	160.70	56.85

Figure 3. The largest angle between two stations recording a single seismic event is called the azimuthal gap.

Arabasz et al. (2005). Lower quality translates into lower confidence in the location, therefore more uncertainty in the pairing for *hypoDD*. The limiting value for the pick coefficient is determined by the minimum requirements of *hypoDD*. In order to determine the four unknown location parameters for both events using the double difference, eight common station observations are required. Thus, events with fewer than eight picks are less useful for applications of *hypoDD* and will carry less weight.

The maximum possible value of U_j is equal to the sum of all magnitudes (designated M_t). This is the case when the following four criteria are met: (1) the station is always picked; (2) the distance is less than the calculated threshold (TH in Table 1); (3) the event meets the gap criteria; and (4) the event meets the number of picks criteria. In practice this is rarely the case, as no single station is picked for every event. With somewhat arbitrary levels, we rank the relative contribution of each station within the network for a given set of seismic events. Stations with $U_j > 60\%M_t$ contribute the most to *hypoDD* locations, as at least 60% (most likely more) of the events were picked at station j. If $U_j < 10\%M_t$, then there is little potential for pairs of earthquakes to be picked at this station. Figure 4 shows the application of this metric to the three case studies, Trail Mountain, Mine X and Mine Y.
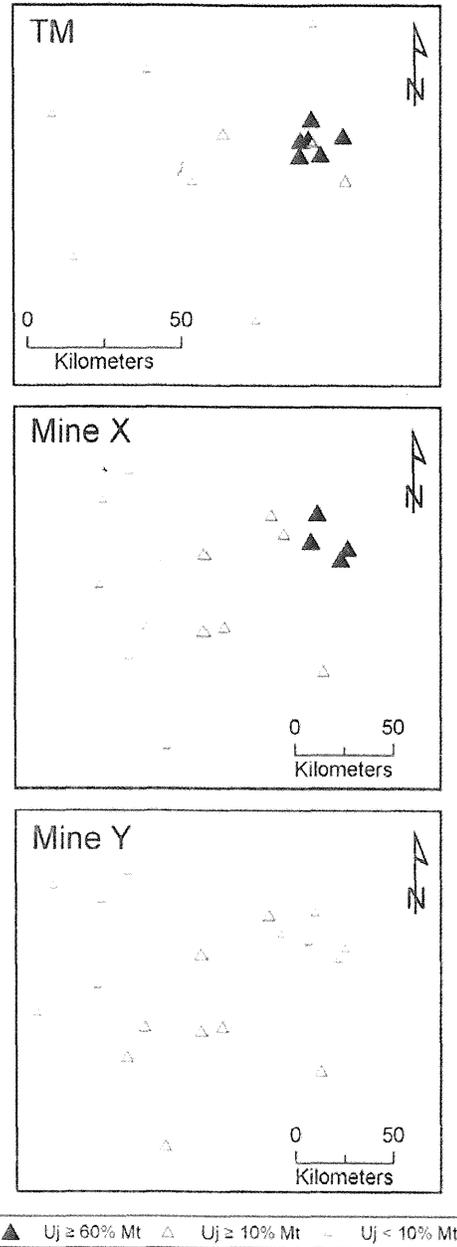

Figure 4. Station usefulness for the three case study mines. Trail Mountain (TM) had a local seismic monitoring network. Six stations have usefulness parameters $U_j > 60\%M_t$. Mine X is representative of the best currently available seismic monitoring network in central Utah. Four stations have usefulness parameters $U_j > 60\%M_t$. Mine Y is located in an area of sparse seismic network coverage. No stations have $U_j > 60\%M_t$.

SIMULATING NETWORK IMPROVEMENT

Consider an existing seismic network where an additional station is being added to improve seismic event locations using *hypoDD*. A visual comparison of the three case study mines (Figure 4) indicates the relative usefulness of the existing network, but does not indicate where additional monitoring stations should be placed. To address this, a Monte Carlo simulation has been developed, expanding upon

the previous discussion on the usefulness metric, to evaluate the most advantageous new station locations.

In order to simulate station usefulness, a catalog of event locations is required to simulate distances and picks. To demonstrate, we use the eight most commonly picked stations from the Crandall Canyon Mine dataset (see Pechmann et al., 2008). The total magnitude sum (M_t) in this case is 381. Four hundred evenly spaced hypothetical stations are added one at a time to the original network (making 400 separate cases of 9 stations in the new network). U_j is computed for each station in the new network, and the values of U_j at each new station are contoured in Figure 5. We have not used the actual pick data for Crandall Canyon in the simulation as these data do not exist for each simulated station. Instead, we consider randomly assigned pick probabilities for the 400 simulated stations. Probabilities are assigned with a 75% chance that a station will be picked if the distance is less than the threshold distance for the magnitude of the event (see Table 1) and a 10% probability of being picked if the distance is greater than the threshold. This is an attempt to simulate noise and the human contribution to routine picks. This methodology can be applied anywhere an existing network is present.

RESULTS AND DISCUSSION

Final Relative Locations

HypoDD relative locations (Figure 6) for the three case study mines described above indicate various levels of improvements in locating mining-induced seismicity. In most cases patterns not previously obvious are elucidated. The dense network at Trail Mountain yields excellent routine locations that show much of the structure (Figure 2). *HypoDD* further defines the east-west oriented longwall panels and lineations in the dense cluster located to the east (compare Figure 6A to Figure 2). At Mine X (Figure 6b), the diffuse spatial clusters collapse into northwest-southeast lineaments (as seen on the figure) roughly paralleling mining activity. At Mine Y (Figure 6c), less detail is visible, but again we see a collapse of the scatter in event locations into a more well-defined cluster. In this case, the network was not sufficient to elucidate mining activity, but there is an improved correlation to the mine permit area (permit area not shown to maintain anonymity).

In general, *hypoDD* relative locations clarify structure within the seismicity that may not be as obvious from routine locations. The resolution is a function of seismic network geometry. The networks composed of more and better distributed stations provide the clearest resolution. Resolution is a function of both good starting locations determined from the routine analysis, which has similar network requirements as *hypoDD*, and a large number of double differences formed at common stations that constrain the inversion. However, before associating these high resolution images with the mining environment, ground truth information (underground location of one or more actual events that are seismically recorded) is essential to shift the events from relative locations to absolute locations. Note that the final error is a function of both the precision of the relative locations and error associate with shifting all events using a single vector. In the case of the Trail Mountain dataset, plan-view accuracies of shifted *hypoDD* relative locations are on the order of 100m or less. For arrays with lower station usefulness (Mine X and Mine Y), the error is considerably larger.
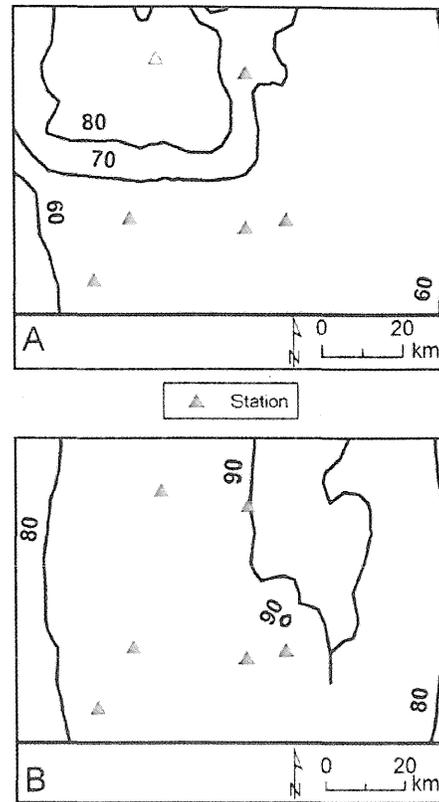

Figure 5. Contours of station usefulness, U_j, for a simulated network near the Crandall Canyon Mine. Existing stations shaded triangles. Proposed new station open triangle. (A) shows that the initial network would be more successful at utilizing the capabilities of *hypoDD* were a station placed in the northwest corner. (B) shows the results from the second iteration for this network, after a station was added to the northwest corner. Because there are now six stations with $U_j > 60\% M_t$, additional stations are not required.

Station Distribution

In each of the case studies examined, the main difference is the distribution of seismic monitoring stations. To demonstrate that station distribution is indeed the most critical factor, we systematically remove one and then multiple stations from the Trail Mountain dataset and then re-apply *hypoDD* using the modified network. Some events are lost in the routine location stage because there are insufficient picks to perform a routine location. Similarly, many events no longer meet the required number of common picks for *hypoDD* and are also lost. In the case shown in Figure 7A, the station immediately above the mine activity was eliminated from all calculations. Fewer events (1027 of 1781) were located, due to a reduced number of common picks, but many of the features seen in Figure 6A are retained. Both linear features bracketing the active panels are tighter and the dense cluster to the east is still apparent, though some of the internal structure is lost. Removing other stations, one at a time, yields similar results indicating that no single station is dominating the location results.
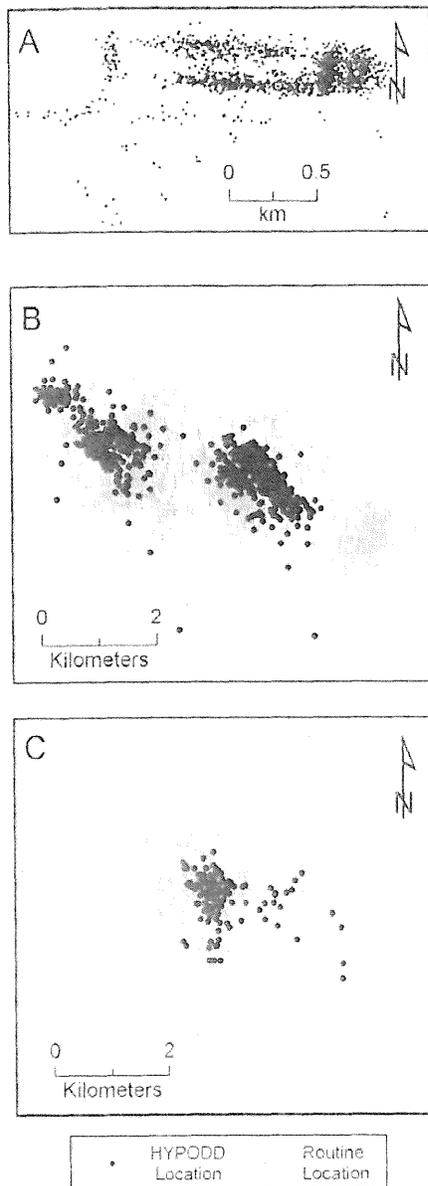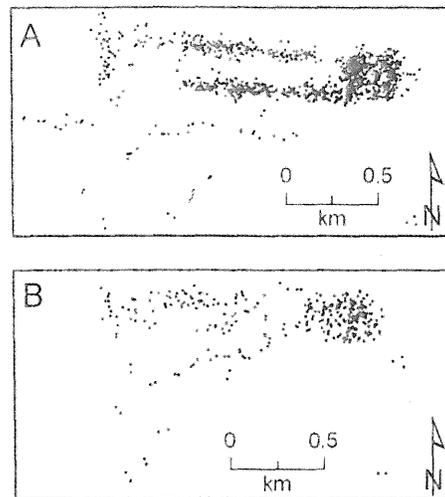
191

Figure 7. *HypoDD* locations using subsets of the Trail Mountain dataset generated by simulating different network geometries. (A) results using a modified network that does not include the station directly above mining activity. (B) results from a modified network that includes the station directly above mining activity, but does not include three nearby temporary array stations.

Station Usefulness

Applying the station usefulness metric (equation 2) to the three case studies (see Figure 4) helps to quantify the lessons learned by removing stations from the Trail Mountain dataset. We see that stations within ~15 km of the MIS are generally more useful than more distant stations. An exception to this is the co-located stations above the Trail Mountain Mine. Rarely are both of these stations picked for a given event, which artificially lowers U_j at these two stations. From the three case studies, we classify the networks into three classes of relative success. *Successful* networks for implementing *hypoDD* include six stations with $U_j > 60\%M_t$ and at least two additional stations with $U_j > 10\%M_t$. At this level of success, we expect to image detail structure correlated with aspects of the mine, such as individual panels and changes in overburden, as shown for Trail Mountain in Figure 6A. *Moderately successful* networks include one station with $U_j > 60\%M_t$ plus at least seven stations with $U_j > 10\%M_t$. At this level of success, we expect to image the gross features associated with mining, as shown for Mine X in Figure 6b. *Marginally successful* networks include at least eight stations with $U_j > 10\%M_t$. At this level of success, we expect to image well-defined clusters—a general improvement over the routine locations, as shown for Mine Y in Figure 6c. Areas where the station distribution fails to meet the above-defined marginal category are not considered viable for *hypoDD*.

Simulating Network Improvement

Using the station usefulness metric and the previously described Monte Carlo simulation provides a mechanism for adding stations to an existing network in order to improve the results found using *hypoDD*. Contours with the highest values of U_j represent regions where a new station would be most advantageous. In the Crandall Canyon example (Figure 5A), the northwest corner requires an additional station, largely to close the gap. Locations for additional

Figure 6. *HypoDD* locations for seismic events near (A) Trail Mountain, (B) Mine X, and (C) Mine Y. Circles show the *hypoDD* locations. Crosses routine HYPOINVERSE locations. The routine locations for Trail Mountain are shown in Figure 2.

If we further reduce the available number of stations, by removing three nearby temporary array stations for a given *hypoDD* inversion, we produce the locations depicted in Figure 7B. Many fewer (320 of 1781) events are located, as most small magnitude events no longer have a sufficient number of picks. The limbs have become disperse and are not necessarily recognizable as surrounding the active panels. The eastern cluster remains, but again is much more diffuse. This procedure was repeated with the general result that the loss of definition was found to be essentially the same for all network configurations reduced by three stations.

192

stations can be identified by running the simulation iteratively. In the case shown in Figure 5B, the second iteration indicates that after adding a station to the northwest corner (Figure 5A) the network meets the highest level of success as seen in the Trail Mountain Mine dataset (six stations with $U_j > 60\%M_1$ and at least two additional stations with $U_j > 10\%M_1$) and no additional stations are required.

CONCLUSIONS

We have seen that with different levels of seismic monitoring, different levels of success in producing relative locations using *hypoDD* are achieved. At Trail Mountain, where a dense temporary array of seismic stations was available, details such as seismic activity bracketing the active longwall panels and dense clustering at increased overburden depth were visible. Where a less dense monitoring network is available, such is the case at Mines X and Y, less detail, but still improved clustering is achieved utilizing *hypoDD*. In order to evaluate the existing network, a metric was developed to indicate the dependence of the network on each individual station. This metric can also be used to simulate the addition of one or more new stations to improve the monitoring capabilities.

When the station distribution is sufficient, precise mining-induced seismicity locations achieved with *hypoDD* provide an improved relationship between MIS and mining activities. Making use of these precise locations is beyond the scope of the current study, but improved accuracy should prove to be a useful tool in mine planning and hazard assessment.

ACKNOWLEDGMENT

REFERENCES

1. Arabasz, W.J., S.J. Nava, M.K. McCarter, K.L. Pankow, J.C. Pechmann, J. Ake, and A. McGarr, 2005. Coal-Mining Seismicity and Ground-Shaking Hazard: A Case Study in the Trail Mountain Area, Emery County, Utah. Bulletin of the Seismological Society of America, vol 95, pp. 18-30.

2. Arabasz, W.J., S.J. Nava, M.K. McCarter, and K.L. Pankow, 2002. Ground-Motion Recording and Analysis of Mining-Induced Seismicity in the Trail Mountain Area, Emery County, Utah. Final Report, prepared for State of Utah School and Institutional Trust Lands Administration.

3. Swanson, P., C. Stewart, and W. Koontz, 2008. Monitoring Coal Mine Seismicity with an Automated Wireless Digital Strong-Motion Network. In: Proceedings of 27th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV, pp. 79-86.

4. Pechmann, J.C., W.J. Arabasz, K.L. Pankow, R. Burlacu, and M.K. McCarter, 2008. Seismological Report on the 6 August 2007 Crandall Canyon Mine Collapse in Utah. Seismological Research Letters, vol, 79, pp. 620-636.

5. Pankow, K.L., M.K. McCarter, W.J. Arabasz, and R. Burlacu, 2008. Coal-Mining Induced Seismicity in Utah – Improving Spatial Resolution Using Double Difference Relocations. In: Proceedings of 27th International Conference on Ground Control in Mining, West Virginia University, Morgantown, WV, pp. 91-97.

6. Waldhauser, F. and W.L. Ellsworth, 2000. A Double Difference Earthquake Location Algorithm: Method and Application to the Northern Hayward Fault, California. Bulletin of the Seismological Society of America, vol 90, pp1353-1368.

7. Arabasz, W.J., Nava, S.J., and Phelps, W.T, 1997. Mining seismicity in the Wasatch Plateau and Book Cliffs coal mining districts, Utah, USA, *in* Gibowicz, S.J., and Lasocki, S., editors, Rockbursts and Seismicity in Mines, Proceedings of the 4th International Symposium on Rockbursts and Seismicity in Mines, Krakow, Poland: Rotterdam, A. A. Balkema, p. 111–116.

8. Arabasz, W.J. and J.C. Pechmann, 2001. Seismic Characterization of Coal-mining Seismicity in Utah for CBTB Monitoring. Technical Report URCL-CR-143772, Lawrence Livermore National Laboratory, Livermore, California, LLNL Research Agreement No. B344836, 120 pp. Accessible online at www.seis.utah.edu/Reports/llnl2001

9. McGarr, A. and J.B. Fletcher, 2005. Development of Ground-Motion Prediction Equations Relevant to Shallow Mining-Induced Seismicity in the Trail Mountain Area, Emery County, Utah. Bulletin of the Seismological Society of America, vol. 95, pp. 31-47.

10. Fletcher, J.B. and A. McGarr, 2005. Moment Tensor Inversion of Ground Motion from Mining-Induced Earthquakes, Trail Mountain, Utah. Bulletin of the Seismological Society of America, vol, 95, pp. 48-57.

11. Klein, F.W., 2002. User's Guide to HYPOINVERSE-2000, a Fortran Program to Solve for Earthquake Locations and Magnitudes. USGS Open report 02-171.

12. Waldhauser, F., 2001. hypoDD – A Program to Compute Double Difference Hypocenter Locations (hypoDD version 1.0, 3/2001). USGS open report 01-113

13. Row, C.A., R.C. Aster, B. Borchers, and C.J. Young, (2002). An Automatic, Adaptive Algorithm for Refining Phase Picks in Large Seismic Data Sets. Bulletin of the Seismological Society of America, vol 92, pp. 1660-1674.

14. Schaff, D.P., G.H.R. Bokelmann, W.L. Ellsworth, E. Zanzerkia, F. Waldhauser, and G.C. Beroza, (2004). Optimizing Correlation Techniques for Improved Earthquake Location. Bulletin of the Seismological Society of America, vol 94, pp. 705-721.

15. Pankow, K.L., W.J. Arabasz, S.J. Nava, and J.C. Pechmann, 2004. Triggered Seismicity in Utah from the 3 November 2002 Denali Fault Earthquake. Bulletin of the Seismological Society of America, vol 94, pp. S332-S347.

Proceedings
28th International Conference on Ground Control in Mining

Edited by

Syd S. Peng[1]
Thomas Barczak[3]
Chris Mark[3]
Steve Tadolini[2]
Gerry Finfinger[4]
Keith Heasley[1]
Yi Luo[1]

1. West Virginia University, Mining Engineering Department, Morgantown, WV
2. Minova Americas, Georgetown, KY
3. NIOSH-Pittsburgh Research Lab, Pittsburgh, PA
4. NIOSH, Pittsburgh, PA

July 28-30, 2009
Lakeview Scanticon Resort & Conference, Morgantown, WV, USA