

# **Appendix II**

## **Improved Seismic Locations and Location Techniques**

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# 1 Introduction

The accuracy of absolute locations are controlled by several factors, including the network geometry, available P- and S-wave arrivals, the clarity of the P- and S-wave onsets (i.e. presence or absence of noise), whether or not there is superposition of P- and S-waves from different events in the same seismogram, and the assumed velocity model. All these factors together with inadequate knowledge of the velocity structure can introduce random error as well as systematic biases into the location obtained.

In current mining practice an improvement in the absolute location is achieved by accounting for the heterogeneity of the existing 1-D model by inclusion of a station correction, which eliminates the velocity anomalies between the source and station. Initially, a mean P-wave velocity is assumed for all seismic stations in the network, and by adding a velocity correction to each seismic station, the travel time residual (error) will be reduced. The station corrections are found by trial and error, using seismic events that are assumed to occur in certain positions because of localised underground damage. The use of the above method is limited because it cannot account for all 3D variations of the velocity structure in the mine.

The focus of this report is to analyse critically several implementations of relative location methods in mining seismology. The following sections review the details of the relative location technique (locating events in relation to a single master event) and the group location technique, in which multiple master events are used.

## 1.1 Relative location techniques for single master events

One type of relative location technique is to compute the hypocentre relative to the known hypocentral location of a *master event*. This location method uses two events, the location of the first event named the master event, and the second event, which is located using the coordinates of the master event. If the separation between the two hypocentres is small compared to the hypocentre-station distance, then the ray paths between both source regions and the seismic stations will be similar.

The relative location approach has the advantage of eliminating travel time anomalies resulting from velocity heterogeneity. An improvement in relative location is achieved without improvement in the velocity model. For a cluster of events the problem of location error reduction is addressed by improvement of the relative location errors between nearby events.

Dramatic improvements in relative locations in seismic clusters have been reported in the earthquake seismology literature, even though the true location of the entire cluster could remain poorly constrained (i.e. the events are well located in relation to each other, revealing an improved seismic image of an active structure, but there could still be similar biases in all the locations, resulting in a net shift away from the true location of the cluster). An improvement of the true cluster location is achieved by using non-seismic information to help locate the master events (e.g. a mining blast, or observed damage that is assumed to be close to the event).

The accuracy achieved by the relative location will depend on the accuracy of the master event location. A shift of the master event will induce an equal shift of the second event. The application of the technique must comply with the assumption that both the master (event 1) and secondary events occur in the same region.

The arrival times for the two events for the  $i$ th station are:

$$T_{1i}^A = t_{o1} + T_{1i} + e_{1i} \quad (1.1)$$

$$T_{2i}^A = t_{o2} + T_{2i} + e_{2i} \quad (1.2)$$

where  $T_{1i}^A$  is the arrival time for event 1 (master event) at station  $i$ ,  $t_{o1}$  is the origin time of event 1,  $T_{1i}$  is the travel time to station  $i$ , and  $e_{1i}$  is the observation error or time residual. The travel time for the second event is defined in a similar manner (see equation 1.2). The observational error is mostly caused by a difference between the true rockmass velocity and the velocity model used in the location procedure.

If event 2 is close to event 1 (master event), the standard procedure of the first order Taylor series expansion is applied to  $T_{2i}$ . The travel time of event 2 is approximated by the travel time of event 1 plus of the travel time correction,  $\Delta T$ , as follows:

$$T_{2i}^A = t_{o2} + (T_{1i} + \Delta T) + e_{2i} \quad (1.3)$$

$$\Delta T = f'_x dx + f'_y dy + f'_z dz \quad (1.4)$$

$$\begin{aligned} f'_x &= (x_{o1} - x_i)/(V_i d_{1i}) \\ f'_y &= (y_{o1} - y_i)/(V_i d_{1i}) \\ f'_z &= (z_{o1} - z_i)/(V_i d_{1i}) \end{aligned} \quad (1.5)$$

$$d_{1i} = [(x_{o1} - x_i)^2 + (y_{o1} - y_i)^2 + (z_{o1} - z_i)^2]^{1/2} \quad (1.6)$$

In the above equations,  $V_i$  are the assumed velocities for the ray path between event 1 and the  $i$ th station,  $d_{1i}$  is the distance between event 1 (master event) and the  $i$ th station,  $(x_i, y_i, z_i)$  denotes the coordinates of the  $i$ th station,  $(x_{o1}, y_{o1}, z_{o1})$  denotes coordinates of event 1,  $(dx, dy, dz)$  denotes the perturbations to the event 2 location and  $f'$  denotes the corresponding set of partial derivatives. The location,  $x_{o1}$ ,  $y_{o1}$ ,  $z_{o1}$ , and  $t_{o1}$  of event 1 (master event) are known. The assumed velocity between source and station,  $V_i$ , can then be replaced with the calculated velocity for the ray path

$$V_{ci} = d_{1i}/(T_{1i}^A - t_{o1}) \quad (1.7)$$

The method proposed here assumes that the distance between the two events is small compared with the distance between source and station. Consequently, the calculated

velocity between source 1 (master event) and the  $i$ th station is approximately the same as the calculated velocity between source 2 and the  $i$ th station. The distance between the second event and the  $i$ th station can be expressed using the coordinate of the first event

$$d_{2i} = [(x_{o1} - x_i + dx')^2 + (y_{o1} - y_i + dy')^2 + (z_{o1} - z_i + dz')^2]^{1/2} \quad (1.8)$$

where  $(dx', dy', dz')$  are the changes required in the location to make the model fit the data better. The residuals at the  $i$ th station for the second event can be expressed using equation 1.2:

$$e_{2i} = T_{2i}^A - t_{o2} - d_{2i}/V_{ci} \quad (1.9)$$

The third term in the equation above expresses the travel time of the second event using calculated velocity of the first event (master event, see equation 6) and the distance between event 2 and the  $i$ th station is determined from equation 5. The misfit function is defined using the norm  $L1$  as follows (Method 1):

$$E = \sum |e_{2i}| \quad (1.10)$$

The norm  $L1$  is used to reduce the effect of phase misidentification. The minimum of the misfit function is found using the Simplex Method. The minimum is reached very quickly, because a location of the master event is used as the starting point of inversion. Notice that the calculated velocity,  $V_{ci}$ , is known only for the stations that record both events. Therefore, if only the second event is recorded at a station, the assumed velocity  $V_i$  is used. The last step of an inversion process calculates the distance between the two events  $(dx', dy', dz')$ .

The master event location method can be formulated differently (Method 2). The misfit function is defined by subtracting equation 1.2 from equation 1.1

$$e_i = e_{1i} - e_{2i} = (T_{1i}^A - T_{2i}^A) + (t_{o1} - t_{o2}) - (T_{1i} - T_{2i}) \quad (1.11)$$

where the first term is the arrival time difference, the second term is the origin time difference and the third term is travel time difference. The difference  $e_{1i} - e_{2i}$  clearly indicates that the travel time anomaly, which resulted from velocity heterogeneity, has been removed. A similar misfit function can be obtained by subtracting equation 1.3 from equation 1.1:

$$e_i = e_{1i} - e_{2i} = (T_{1i}^A - T_{2i}^A) + (t_{o1} - t_{o2}) + (f'_x dx + f'_y dy + f'_z dz) \quad (1.12)$$

The third term in the equation above is an approximated difference between travel times.

When the same seismic station records event 1 (master event) and event 2, it is said that the events are connected or linked. In most cases events occurring close to each other will be recorded by the same set of stations, and method 2 includes only stations

that recorded both events. Notice that it is possible for two events to have only a few common observations. We choose not to use this relocation method if less than five stations record both event 1 (master event) and event 2. In such instances, we can revert to Method 1 above.

In the ISSI implementation of the relative location method, extra effort was made to make the software intuitive and simple. Relocations of seismic events are thus done in the following five steps:

- Select a polygon where high precision location is needed. This is usually the volume around an active stope or active geological feature such as a fault or dyke;
- Locate the seismic event using the absolute location algorithm and the P- and/or S-arrival times (the seismological processing software provides, as default, locations obtained using the P-wave and/or S-wave arrival time and/or the directions and azimuths obtained from the P-wave polarity. The method of location that is based on the above input parameters is called the *absolute* location to distinguish it from the *relative* location, which is a separate process carried out afterwards.);
- Select a master event in the volume of interest (a perfect master event is the event whose location is known, for example a production blast, although records of blasts are seldom available in the area of interest. In most cases, the master event has to be selected from records of the available seismic events, thus the master event can be any event that is located with a higher confidence level than the other events in the volume of interest).
- Apply the relative location algorithm using the selected master event, and the absolute event locations in the volume of interest.
- Compare the absolute and relative location data using the XDI graphics tool to establish (qualitatively) whether there is any bias in the relocated data.

In the examples studied in this report the following criteria were used to select master events:

- the level of seismic noise is small in comparison to amplitude of the first arrival of P-wave and S-wave;
- event is recorded by more than 10 stations;
- all P-wave arrivals are sharp;
- at least a few first arrivals of the S-wave are sharp and can be used by the absolute seismic location algorithm;
- including or omitting one or two stations from the location should not change the location significantly;
- at least one or two stations should be relatively close to the seismic source so that source directions and azimuths can be used as additional constraints parameters in the absolute location algorithm.

There are two options in the implemented relocation software: to use the relative location algorithm in real time processing or in batch mode at the end of the day.

### 1.1.1 Comparison of methods 1 and 2

Method 1 uses the observed velocity of the master event (event 1) to locate event 2. The advantage of method 1 arises in the two following circumstances:

- event 2 is recorded by a smaller number of stations than event 1;
- event 2 is recorded, in addition to the stations common with event 1, by several stations that did not record event 1.

In the first case, a good location for event 1 will help to locate a smaller event observed only by a few stations. In the second case the connection between event 1 and event 2 is supported by the additional arrival times, which are not recorded for event 1. Those additional arrivals use the fixed (or assumed) P-wave and S-wave velocities. However, with the right selection of master events, the second case should never happen, because it is expected that the master event should be recorded by an equal or larger number of stations than is the case for event 2.

Method 2 uses the misfit function with differential arrival time, differential origin times, and differential travel time between the two events. Those differences naturally remove all ray path heterogeneity, because the anomalies affect both events in the same way. The origin time of event 2 does not have to be calculated as the differential origin time can be removed from the inversion process. The misfit function is suitable for using delay times between events; this is the additional strong benefit of method 2.

## 1.2 Group location technique

The group location technique relocates large numbers of events with high resolution, and the approach has the advantage of eliminating travel time anomalies resulting from velocity heterogeneity. Recently, a double difference location method was developed (Waldhauser and Ellsworth, 2000) to locate a group of seismic events when hypocentral separation between two earthquakes is small compared to the hypocentre-station distance. The double difference method has the capability of revealing much sharper seismic images than classic joint hypocenter determination (JHD, e.g. Pujol 2000). As such it is more useful than the relative location technique discussed above in delimiting geological features. The group location method uses P- and S-wave arrival times and the associated quality factors.

The residual between the observed and theoretical differential travel time between the two events are given by:

$$\Delta e_k^{ij} = (T_k^i - T_k^j)_{obs} - (T_k^i - T_k^j)_{theoretical} \quad (1.13)$$

The subscripts  $i$  and  $j$  refer to the two events, and  $k$  to the station. The first term measures the observed wave travel time differences between events  $i$  and  $j$ , the second term measures the theoretical wave travel time difference between the two events. The difference between the observed and theoretical differences is known as the *double difference*, which gives the technique its name.

The double difference equation can be expressed, using the changes in the relative hypocentral parameters between the two events  $i$  and  $j$ , as:

$$\Delta e_k^{ij} = f_{kx}^i \Delta x^i + f_{ky}^i \Delta y^i + f_{kz}^i \Delta z^i - f_{kx}^j \Delta x^j - f_{ky}^j \Delta y^j - f_{kz}^j \Delta z^j + \Delta t_0^i - \Delta t_0^j \quad (1.14)$$

Where  $\Delta x^i, \Delta y^i, \Delta z^i, \Delta t^i, \Delta x^j, \Delta y^j, \Delta z^j, \Delta t^j$  are the changes in relative hypocentral parameters, and  $f^i, f^j$  are the partial derivatives of the travel time.

The group location is organized in two steps. In the first step, a cluster is formed between linked events, and then in the second step the events within the cluster are relocated. Before the clusters can be determined, several parameters controlling the grouping have to be selected. These parameters filter out data unsuitable for relocation. The output of grouping consists of the number of events that will participate in relocation and parameters of the groups. The output of the relocation is new coordinates for the selected seismic events.

## 1.2.1 Description of input parameters for processing

Travel time anomalies caused by the unknown velocity of seismic waves variations could be effectively eliminated by relocating the group of seismic events simultaneously. This technique needs several input parameters, which are described below.

### 1.2.1.1 Maximum number of groups

This parameter defines the maximum number of groups of events, which will be processed. This number should not be too big to avoid allocation of unnecessarily large arrays in computer memory. This parameter can also be used to delete groups containing small numbers of events. An optimal value is found by trial and error, and the recommended value for the first try is 30 groups.

### 1.2.1.2 Maximum separation between events

This is the maximum permissible distance between a pair of events. It is assumed that two events located at a distance smaller than this distance will have similar waveforms and similar ray paths, hence similar velocities, between source and seismic recording site. The recommended value for the first try is the average distance between neighbouring events.

### 1.2.1.3 Maximum number of neighbours for event

This is the maximum number of events connected to an event of interest within maximum separation distance between events described above. An optimal value is found by trial and error, and the recommended value for the first try is 8 or more.

### 1.2.1.4 Minimum number of sites per pair

This is the minimal number of sites used per pair of the events or minimum number of links necessary to define a neighbour. This number also depends on the site's configuration, and an optimal value must be found by trial and error. If the minimum number of sites per pair is less than 8 then it could happen that some events have no data common to the same stations to perform the relocation. To avoid this problem, the number of sites recording each event must be sufficiently large, and experience shows that 8 or more stations produce acceptable results.

### 1.2.1.5 Maximum number of sites per pair

This is the maximum number of sites used per pair of events, and it places a limit on the number of pairs that can be formed given the input criteria defined. If the number is too

large (i.e. larger than 20), then the grouping process can lead to groups so large that the computation is very lengthy. The optimal value depends on the event cluster of interest, and should be found by trial and error. The recommended value for the first try is from 10 to 16 pairs.

#### **1.2.1.6 Set mean shift to zero**

This parameter constrains the mean shift of all seismic events in a group during its relocation to zero, i.e. there is no net shift of the cluster in any direction during the relocation. This helps to reduce any bias that may arise as a result of the relocation. The rationale behind this constraint is that all absolute location errors are random, that the locations are more or less in the correct position, and that there are no systematic location errors present. When the constraint is set, the mean coordinates of the entire group of absolute locations must be identical to the mean coordinates of the relocated group of events.

set\_mean\_shift\_to\_zero = 1: constraint is applied  
set\_mean\_shift\_to\_zero = 0: constraint is not applied

Experience has shown that set\_mean\_shift\_to\_zero = 1 gives the more stable corrections to relocation, thereby largely eliminating any biases that may have crept in during the relocation.

### **1.2.2 Utility of group location method**

Once the event clusters have been relocated, the results are displayed for inspection and qualitative evaluation. The user has the option to either continue relocating the events for better results, or to input new group location parameters. Since this is a somewhat more complex and computer-intensive method than the relative location method, the algorithm has not been extended to relocations in real time. At present, the group location method can only be used for off-line processing.

## **2 Case studies**

### **2.1 Trial relative location – small dataset**

When using the relative location method described in Section 1.2, Method 2 is preferred because of its intrinsic advantages. Is it true that the pattern of seismicity obtained using the relative location method would be more realistic than the one obtained using the standard absolute location methods? This is the central focus of the chapter.

A group of ten small seismic events, which occurred over a period of 40 seconds with magnitudes ranging from  $M_L$  -1.1 to -0.5, was selected for this case study. Each event was recorded by at least 7 stations, with some events being recorded by up to 10 stations. The hypocentre-station distance varied from approximately 250 to 1250 m. The absolute location method placed all the events relatively close to each other in the same region, i.e. they formed a cluster.

One of events (Event 5) was selected as the master event, which was recorded by 7 seismic stations. Initially, Event 5 was located using the absolute method with an assumed P-wave velocity of 5500m/s and S-wave velocity of 3500 m/s, giving a small residual (error of location) of 16 m. The first test was to relocate Event 5 using the same

Event 5 as the master event. As expected, a relative location put this event in the exact same position as the absolute method, which serves as an indication that the approach works correctly. Table 2.1.1 shows calculated velocities for Event 5 as used in the relocation procedures. The calculated and assumed velocities give the same location of the event.

**Table. 2.1.1 Calculated velocities of the master event.**

Master event, Ev5 $V_p = 5500\text{m/s}$		Residuals = 16m $V_s = 3500\text{ m/s}$	
Site id	Distance [m]	$V_p$ [m/s]	$V_s$ [m/s]
1	252	5463	3703
6	500	5377	3462
12	567	5754	3729
9	594	5275	3555
16	871	5518	3595
33	918	5478	3572
18	1209	5563	3605

The full comparison between absolute locations and relative locations is presented in Table 2.1.2. The absolute location time residuals are always much larger than those for the relative location (column 6). The location error was reduced more than twice (e.g.20m to 9m, 25 to 12m, 32 to 10m etc.). The smaller residuals indicate the higher precision of the location since the Simplex Method is used to find the minimum of the misfit function in both location methods.

The last column of Table 2.1.2 shows the residuals obtained using the calculated velocities of the master event and the relative location coordinates. The result suggests that, for this master event, relative location does not improve absolute location coordinates. This result was expected, because the master event has the same precision of absolute location as the relocated event.

Table 2.1.3 shows calculated velocities between sources and stations. Column three lists the calculated velocities at the seismic station with site id=9. At this station the master event has the smallest calculated velocity. The calculated velocities of the master event are in order from the smallest (column three) to the largest (column eight). The same order of velocities is observed in most relocated events. The exception is station 1 (fifth column). This station is located relatively close to the seismic event; therefore even a small error in estimation of the origin time of the master event has a large influence on the estimation of the calculated velocities. Table 2.1.3 gives substantial insight to the process of relocation. The high order of regularity of the velocities suggests that the relative location of a group of events is much better than the result obtained using the absolute location method.

**Table 2.1.2: Comparison of absolute and relative locations and their residuals**

Event	Location Method, Master Event No.	X [m]	Y [m]	Z [m]	E [m]	E2 [m]
Ev1	Absolute	16154	939	2913	19	-
	Ev5, Rel.	16135	1052	2895	12	57
Ev2	Absolute	16163	1002	2810	14	-
	Ev5, Rel.	16138	1037	2893	7	9
Ev3	Absolute	16171	963	2900	32	-
	Ev7, Rel.	16144	1028	2882	10	39
Ev4	Absolute	16177	981	2866	20	-
	Ev5, Rel.	16139	1029	2864	9	20
Ev6	Ev7 Absolute	16132	1049	1049	16	
	Ev7, Rel.	16132	1049	1049	16	
Ev7	Absolute	16182	987	2856	25	-
	Ev6, Rel.	16142	1043	2905	12	23
Ev8	Absolute	16173	1011	2879	27	-
	Ev5, Rel.	16143	1018	2857	14	41
Ev9	Absolute	16169	1013	2948	32	
	Ev7, Rel.	16141	1037	2895	8	27
Ev10	Absolute	16147	1070	3017	21	-
	Ev7, Rel.	16134	1042	2905	18	33

The absolute event locations are scattered through a volume of 45m by 131m by 138m. After applying relative location method 2 to relocate the events, the volume was reduced to 12m by 34m by 48m, which represents a 98% reduction in the size of the volume enclosing the cluster of events. This conforms to the observations of Jones and Stewart (1997) who say that all relocated events should show tighter clustering (i.e. less scattering) than that obtained by absolute location methods. This means that:

- The relative location method produced the expected tighter clustering, thereby reducing random location scattering and improving the relative positions of the group of events;
- The relative residuals are smaller than the absolute residuals, i.e. that the location error was reduced by a factor of two to three;
- The calculated velocities from source to station show a systematic pattern in most cases, which proves that by calculating the correct velocities the master event systematically improves the relative location of another event;
- It is expected that the ten small events emitted by the rock mass during the 40-second period should come from a relatively compact volume, which has been demonstrated by the 98% reduction in the volume occupied by the relocated events.

The exercise was repeated with another master event, and in this case, the cluster volume was reduced to 8m by 24m by 55m, representing a 99% decrease in cluster volume. However, the change of the master event induced a shift in the group location, which suggests that there are occasions when the choice of the master event may result in a systematic bias in the relocations. Because of this shift it is difficult to say at this stage which relocation exercise has produced the better result.

**Table 2.1.3: Velocity of the P-wave between source and station.**

Event	No. of Connections	Vp [m/s]					
		Id 9 594m	Id 6 500m	Id 1 252m	Id 16 871m	Id 18 1209m	Id 12 567m
Master	7	5275	5377	5463	5519	5561	5754
Ev1	5	5099	5027	-	5277	5427	5322
Ev2	5	5296	5399	5653	5533	-	5691
Ev3	7	5076	5131	5015	5375	5463	5355
Ev4	5	5129	5214	5422	5435	-	5529
Ev7	6	5170	5312	5205	5415	5504	5472
Ev8	5	5103	5237	-	5383	5460	5530
Ev9	7	5121	5180	5102	5416	5471	5514
Ev10	7	5126	5152	5110	5428	5481	5528

### 2.1.1 Discussion and conclusion

This exercise was performed on a small dataset of ten small events, which were expected to have emanated from a small rockmass volume because they all occurred within a time interval of 40 seconds. This means that they should be strongly clustered, but it is not expected that they should reveal a seismogenically active structure within the rockmass because there may not be one, and secondly, this data is insufficient to reveal such a structure. Despite these shortcomings, the exercise demonstrates that relative relocations do result in a material improvement in the relative positions of hypocentres with respect to each other, and that the cluster volume is dramatically decreased, in line with expectations. The exercise shows a second important point: the choice of master event may result in systematic bias in the relocation of the cluster with respect to the absolute locations. At this stage there is no way of knowing whether the absolute locations show random scatter, or whether there is a systematic bias in these locations as well. A means to assess this objectively will have to be found.

### 2.2 Relative location of large datasets with one master event

This case study investigates the potential of relocating a large dataset using one master event. A cluster containing 991 events is presented in Figure 2.2.1. The master event was chosen from the data according to the criteria listed in Section 1.1, and its location was determined using an absolute location algorithm. The event hypocentre was fixed in the local coordinate system at  $x = 25991\text{m}$ ,  $y = -5294\text{m}$ , and  $z = 3545\text{m}$ .

A volume of similarity around the hypocenter position of the master event must be defined. This volume is controlled by several disparate factors and assumptions, making it difficult to develop a standard methodology, which will always capture all of them. The main factor is geological complexity, which affects the velocity of the seismic waves. There is no simple way to capture all velocity variations in the rockmass. The ISS software provides an estimation of the similarity volume by displaying its radius using a variable named *similarity\_size*. The similarity size is estimated using a percentage of average hypocentral distance and a useful rule of thumb in which:

$$\begin{aligned} \text{Similarity size} &= 0.15 \text{ average hypocentral distance} + \text{location residual} \\ \text{or :} & \\ \text{Similarity size} &= \text{velocity of seismic wave} / \text{dominant frequency in the signal} \end{aligned} \quad (1.15)$$

This is the estimated maximum event separation beyond which the seismic event signals become dissimilar for the volume under consideration. The user can modify the similarity size by judgment if any additional information about geological structure is available by simply entering the estimated value as an input parameter. The ellipsoid in Figure 2.2.1 (B) represents an area inside the similarity radius of 500 m, estimated for this case study. The triangles represent positions of the seismic stations used for location. The dot colours represent the relative time of occurrence of the seismic events - blue through green to red for events that occurred the earliest to the latest respectively.

Figure 2.2.1 shows the relocation result using a relative location method with one master event. Because of the density of the plotted events, it is not possible to show which event is the master event, the reader should accept that it lies in the centre of the similarity ellipsoid shown. The similarity size criterion limits relocations to only those events whose absolute locations lie within 500m of the master event. The events lying outside this limit were not relocated, and therefore not replotted in Figures 2.2.1 (B) and 2.2.1 (D). The best results of relocation should be achieved for events located closest to the master event, because these events should have the greatest similarity to the master event. This is true especially for a medium with a complex structure that effects P- or S-wave velocities, and that may contain structures close to each other that produce dissimilar events. However, if the medium is relatively homogeneous around the master event, then event relocations inside the similarity radius should all be of similar quality. In real life, the velocity model is usually unknown, and geological structure complexity cannot be easily accounted for in velocity model variations. The solution to this problem lies in selecting several master events uniformly distributed through the volume of interest.

The volume of the absolutely located cluster in Figure 2.2.1 (A) is estimated at  $30 \times 20 \times 25 = 15000$  units, while that of the relocated cluster in Figure 2.2.1 (B) is  $19 \times 7 \times 10 = 1330$  units, representing a 91% reduction in cluster volume. Jones and Stewart (1997) assert that all good relocations result in increased clustering, which is certainly the case in this experiment.

## 2.2.1 Conclusions

Since there is as yet no comprehensive methodology for estimating similarity size, operator intervention is still necessary in estimating a size using one or both simple rules of thumb above together with an estimation of the effects of geological complexity of the area under consideration. This process is therefore not automated at present.

It is concluded that:

- The positions of events inside the similarity ellipsoid closest to the master event have changed;
- The relocated events have formed one distinctive cluster, while a few scattered outlier events have remained outliers;

- The cluster is extended in one direction (see Figure 2.2.1) suggesting a linear feature in the rockmass;
- Relocated events do not symmetrically collapse around the master event in any artificial way, therefore the shape of the cluster probably reflects a real seismic pattern which should be given further attention during the risk assessment and risk management process;
- The volume of the relocated cluster is estimated to be about 9% of the original cluster volume, and if the heuristic of Jones and Stewart (1997) is correct, then the relocations are of considerably better quality than the absolute locations;

This work required extensive operator intervention and analysis, and is presently not automatable.

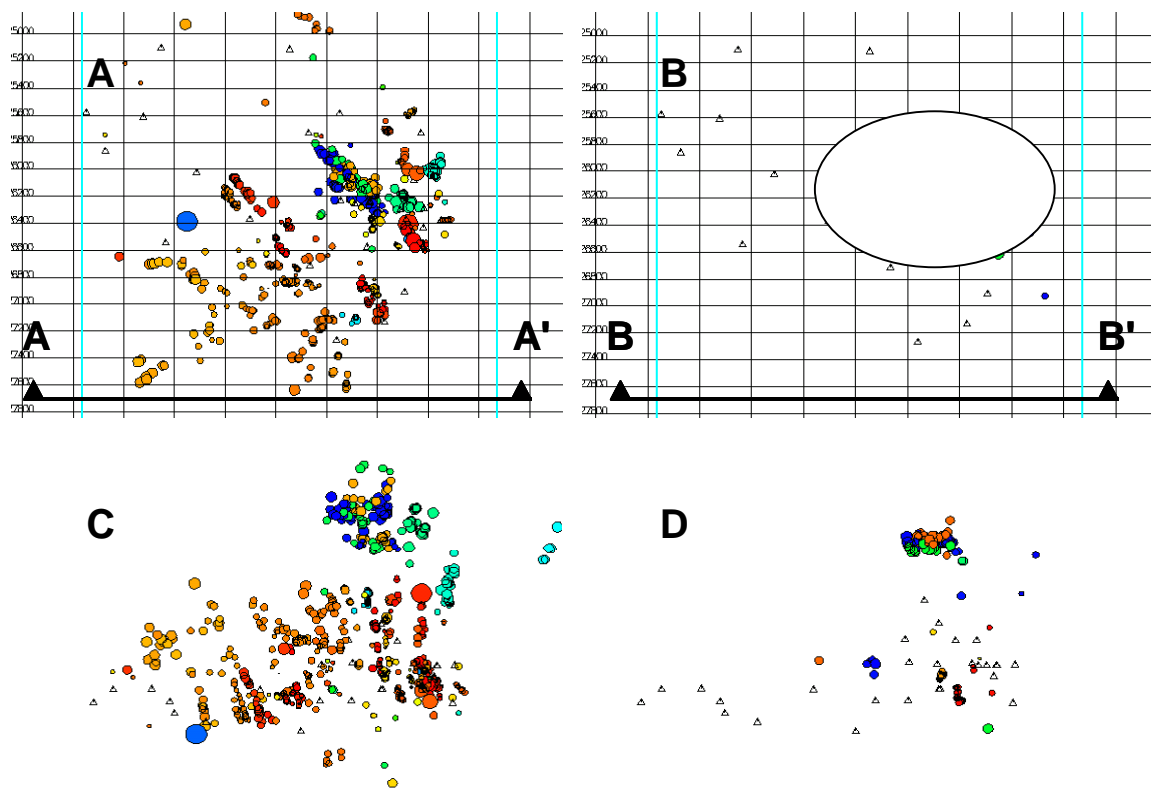
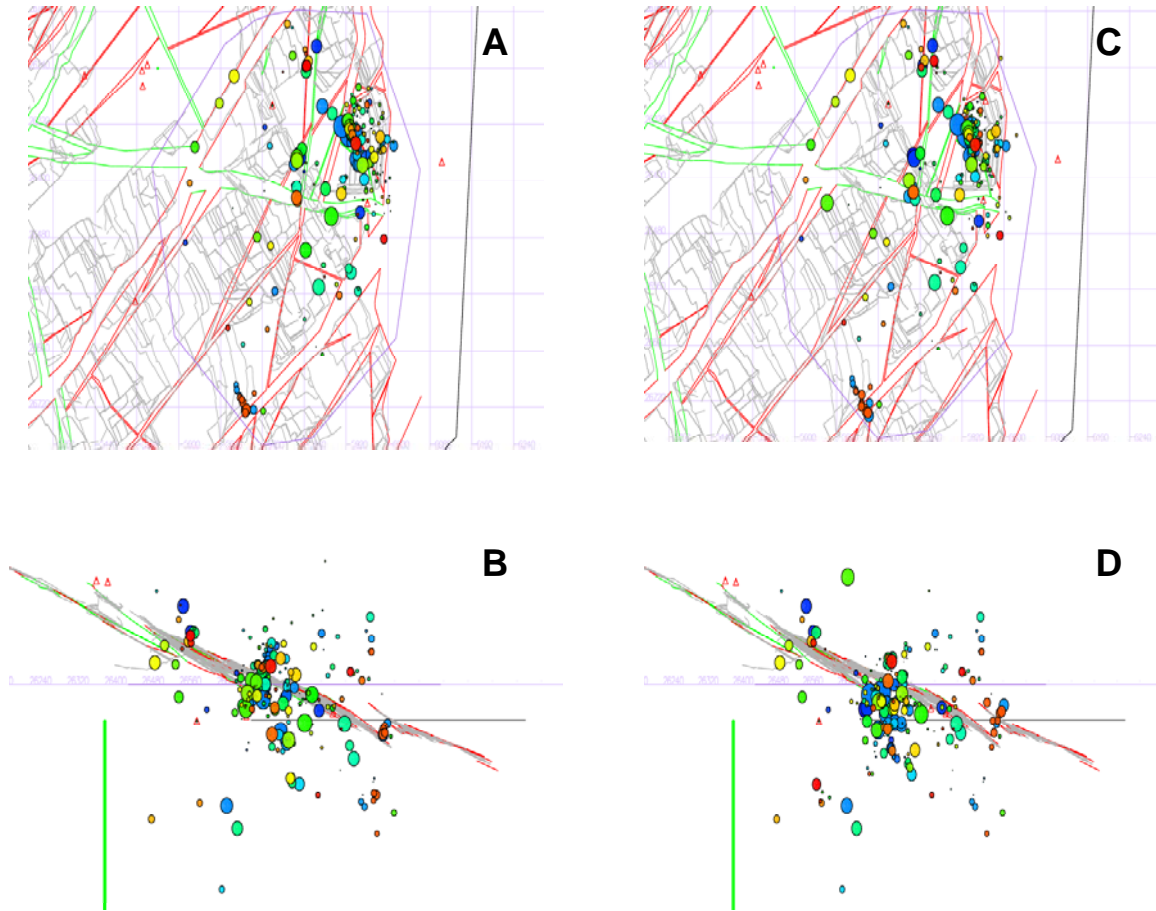


Figure 2.2.1 (A) Plan of absolute event locations, (B) Plan of relative locations using one master event, (C) Section A-A' of absolute location data, (D) Section B-B' of relative location data.

## 2.3 Relative location with several master events

The objective of this section is to present a case where the relative location method is used as a practical tool for interpretation of the seismicity pattern in a real life situation. For the case a study polygon 500m x 500m was selected. The polygon chosen contains a dataset of 249 events recorded over a period of three days. Of these, the seismograms from more than twenty events satisfied the criteria defined in Section 1.1

for master events, and were thus selected as master events. Several tests were run with different similarity sizes, varying from 35m to 88m, suggested by the software. The similarity sizes are considered too small because only a small fraction of the events in the polygon were relocated. The final example similarity size was fixed at 200m for all master events, and for this size, most events were relocated, different parts of the polygon being covered by the different master events.



**Figure 2.3.1: Comparison of absolute and relative locations of seismic events using multiple master events**

Figure 2.3.1 shows the absolute locations of seismic events recorded over a three-day period in plan view (A) and vertical section (B). The circles represent the location of seismic events, the size of the circle is proportional to magnitude, and magnitudes vary from 0.5 to 2.0. The circle colours represent time of seismic event; blue for events that occurred on the first day, green the second day, and red to the third day of the period. The seismicity pattern obtained using the relative location technique is presented on the right side of Figure 2.3.1 (C and D) for the plan and section respectively. Figure 2.3.1 additionally displays dykes, faults and face positions. A comparison of Figure 2.3.1 (A) and (C) shows that the relative location using multiple master events leads to insignificant changes in the horizontal coordinates of the seismic events. The sections in Figure 2.3.1 (B) and (D) show significant differences when compared. The center of seismic activity was shifted substantially (about 50 m) toward the footwall. For some events, the vertical coordinates changed as much as 150m. This shows that the vertical

coordinate was weakly determined (probably as a result of most geophones lying close to the reef plane), and that geophones far removed from the reef plane are necessary to improve the error in the vertical coordinate determination.

### **2.3.1 Discussion and conclusion**

Detailed analysis shows that the relative location technique improves the relative positions of the events in the relocated group. The center of seismic activity was shifted substantially (about 50 m) toward the footwall, to an expected position of center of seismic activity. In this case, the location scatter is not isotropic (locations were well constrained in the x- and y-directions), because most of the location error is in the z-direction. It is a clear indication that the current seismic array needs geophones installed away from the reef, either on surface, or at greater depth. The cluster volume has not changed significantly, a very different result to that obtained in the case study using one master event.

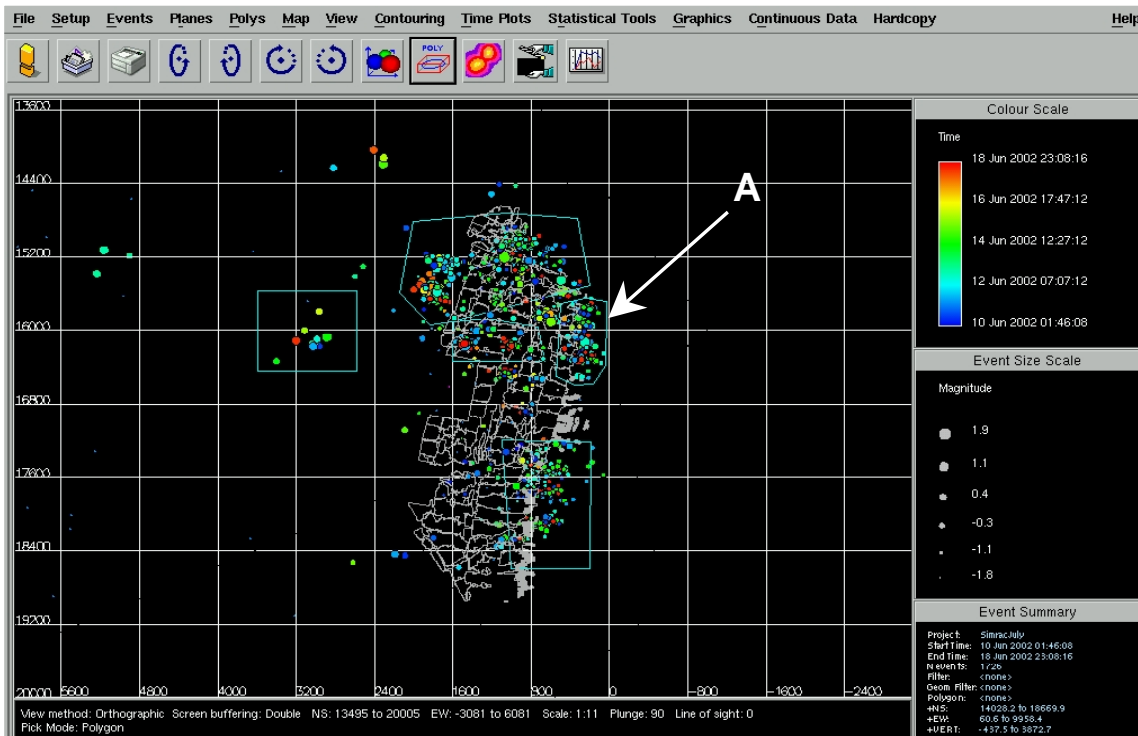
### 3 Group location example tutorial

The group location tutorial laid out below is a step-by-step lesson, designed to teach the fundamentals of relocation. It has been implemented as part of XDI in the ISS software. There are two objectives of the report: to show the all advantages of the method and to present the detailed procedure of application of the method. The data are from a deep level gold mine, containing 1726 seismic events recorded from 10 June 2002 to 18 June 2002 (see Figure 2.3.2). Most events were recorded by 6 seismic stations, but the bigger events were recorded by up to 13 stations.

#### 3.1 Example A: Location using default set of input parameters.

##### 3.1.1 Step 1

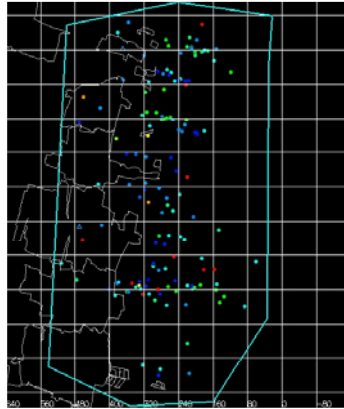
Try to separate some clusters of events. Figure 3.1.1 shows five distinct clusters of seismic events. Polygon is drawn around each cluster. The division of data into several clusters is not obligatory, but significantly increases the efficiency of the method. The selection of polygons for each cluster is not strictly regulated; often each cluster can be subdivided, although this will not affect the final relocation significantly. For best results, it is recommended that the relocation method be applied to each cluster independently.



**Figure 3.1.1: Seismic catalogue recorded over a period of 8 days in a deep level gold mine with several cluster groups outlined by polygons**

### 3.1.2 Step 2

Select the cluster/polygon by clicking button “Poly” in the bar menu. The left mouse has to be moved to polygon border, so the “ Polygon” menu will appear, then click on “Select Polygon”. From data presented on Figure 3.1.2 the polygon marked A is chosen for analysis in this tutorial. Detailed inspection of Figure 3.1.2 shows that several sub-clusters could be selected inside the polygon. The implications of further sub-division of the seismic events into smaller clusters will be covered later in this section.



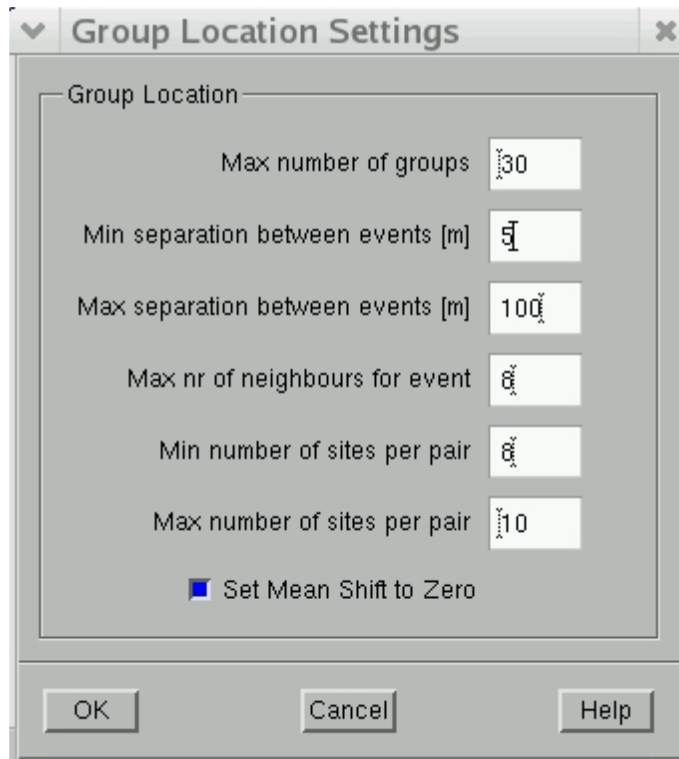
**Figure 3.1.2: Selected polygon with several clusters containing a total of 138 seismic events**

### 3.1.3 Step 3.

Select “Event” from bar menu, and then choose “Group Location”. A window with dialogue will appear as shown in Figure 3.1.3. The definition of each controlling parameter appears in Section 1.2.1 above. Click button “OK” to go to the next stage. In the bottom of the screen the information “Initialising group location, please be patient” will be displayed. This process takes from a few seconds to a few minutes, depending on the number of seismic events.

### 3.1.4 Step 4

The results of grouping will be seen in a new, pop-up window shown in Figure 3.1.4. The information provided shows that the selected polygon contains 138 events, and that 65 of the 138 events are included in the relocation process. These 65 events are split into three groups, each containing 34, 26, and 5 events respectively. Each event has to be connected with other events in the group in order to form links. A link between two events is defined if events belong to the same group and the same seismic station records both events. Each link represents an equation with 8 unknowns  $dx, dy, dz, dt$  for event one and  $dx, dy, dz, dt$  for event two, see equation 1.14). In this example group 1 (consisting of 34 events) has 908 possible links and this relates to a set of  $908 * 8 = 7264$  linear equations, which have to be solved to obtain the relocation results. Relocation was done using damped least square inversion (see Waldhauser and Ellsworth, 2000).



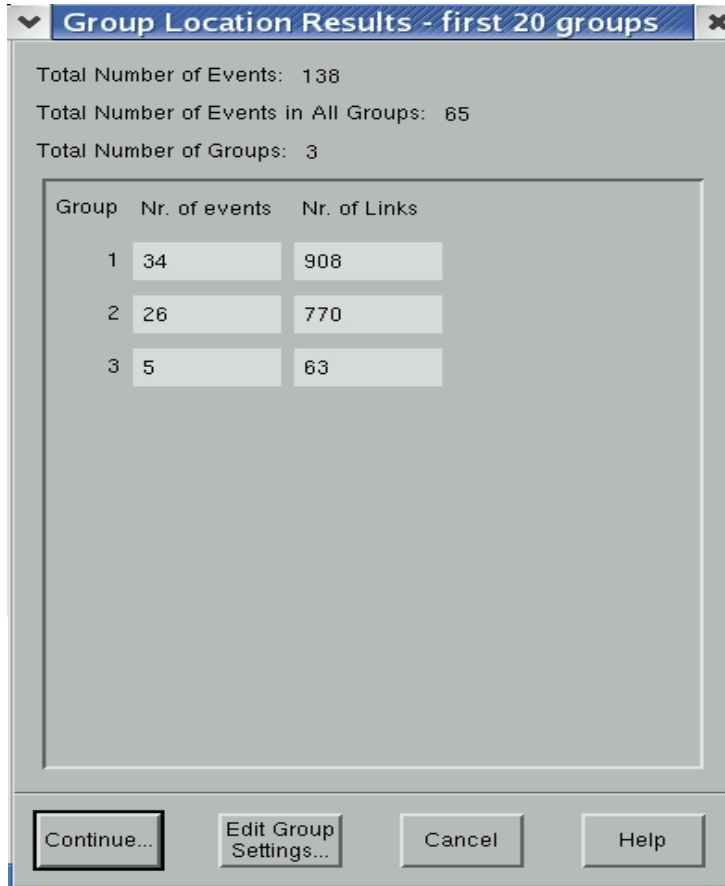
**Figure 3.1.3: Dialog box for determining group location parameters**

### 3.1.5 Step 5

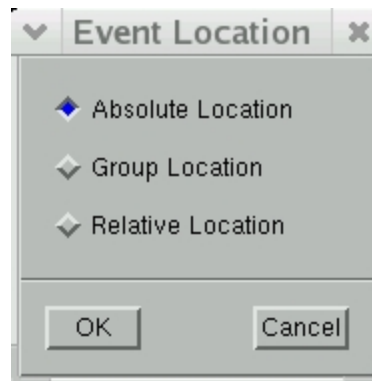
If for some reason the parameter settings are unacceptable (e.g. too many links, or too few events involved in the relocation), click on “Edit Group Settings” to go back to Figure 3.1.3. For accepted group parameters, click on the button “Continue” to perform the relocation. The software will then display “Calculating group location, please be patient” at the bottom of the screen. Once the relocation process is complete, a small window will appear with options for displaying the relocated seismicity pattern. The relocation process with the parameter settings given in Figure 3.1.4 used only 65 of the 138 events, which indicates that the parameter settings were not optimal. To include more events into the relocation, parameter values in Figure 3.1.3 should be changed, or the polygon should be subdivided further. The strength of the group location lies in simultaneous relocation of the largest possible number of seismic events in each cluster, within reasonable limits. The balance between subdividing the polygon further or altering the relocation parameters has to be found individually for each specific dataset. The implications of this are that as yet, this method will not be able to be applied automatically because considerable operator judgment and intervention is still necessary to optimise the relocations.

### 3.1.6 Step 6

Switching between toggle buttons shown in Figure 3.1.5 allows visual comparison of results between relative location and absolute location methods. Figure 3.1.6 shows the result of relocation using the default parameters shown in Figure 3.1.3.



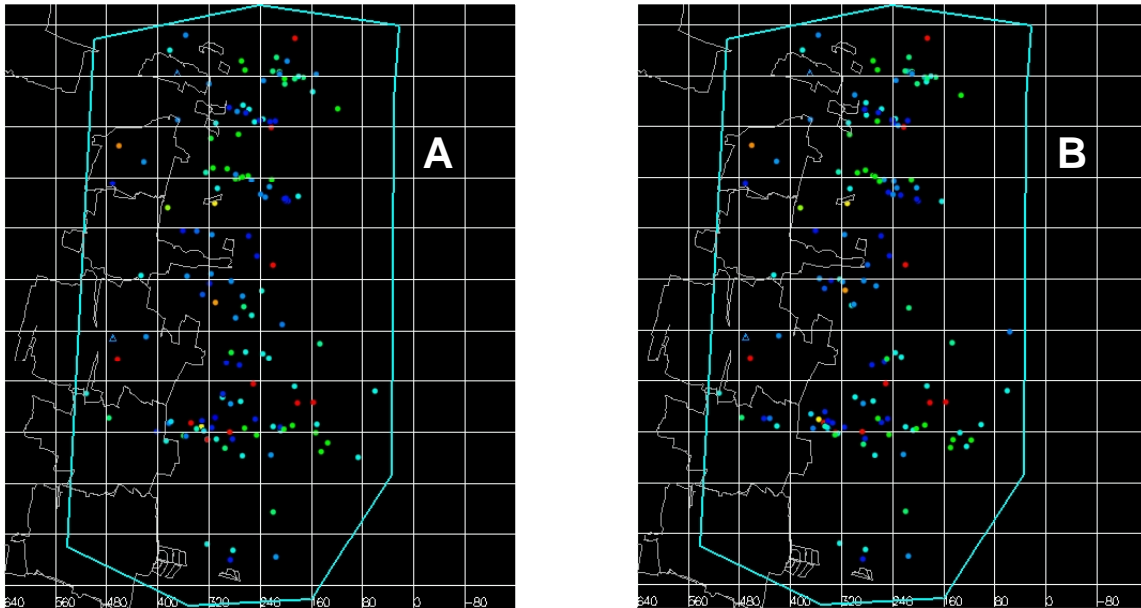
**Figure 3.1.4: Result of parameter settings**



**Figure 3.1.5: Toggle button for choice of location results to be viewed**

At this point, the first cycle of the relocation process is complete, with events in the selected polygon being processed using the default set of the parameters. Note that there is an improvement in the plan clustering of the events, although it is expected that the relocation could be improved by adjusting input parameters shown in Figure 2.3.4. The following examples will show how to choose the best parameters for data from a

polygon. In each example, the value of only one parameter at a time should be modified. This approach to relocation will give better insight into the effect of changing each parameter.

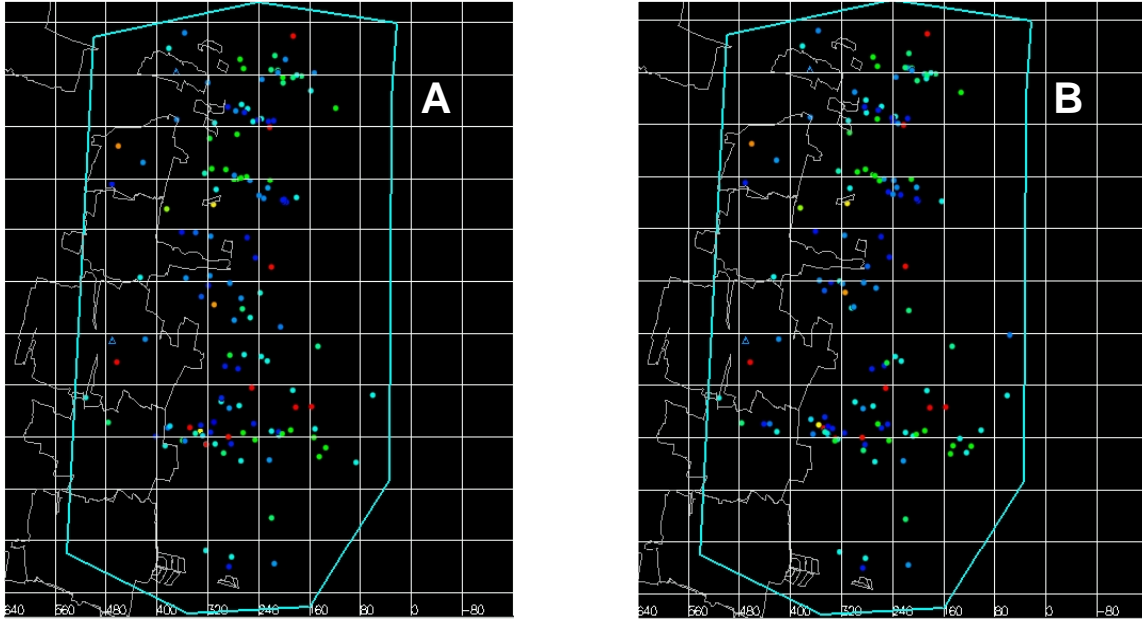


**Figure 3.1.6: (A) Absolute locations, and (B) Relative locations using the default input parameters for group locations**

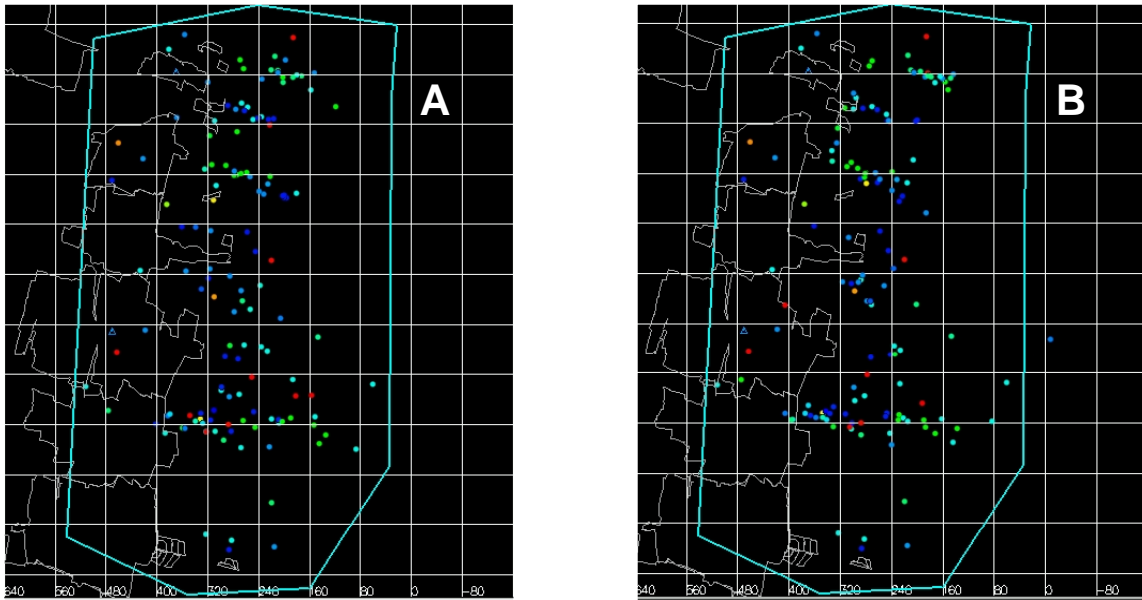
### **3.2 Example B: Minimum number of sites per pair reset to six**

In Example A above, the parameter called “minimal number of sites per pair” was set at eight. This setting significantly restricts the number of events that could be included in the relocation process because each event has to have been located with information from at least eight seismic stations. The majority of the events in the polygon had been located using information from only six stations, and cases when pairs of two neighbouring events had been located by information from at least eight stations happened relatively infrequently, in this case for only 65 events. The parameter “minimal number of sites per pair” should be changed to six, to include a larger number of events in the relocation. The results of grouping and the relocation process are shown in Figure 3.2.1.

The relocation process uses some 108 events out of a total 138 events, and this is considered an acceptable proportion. However, the question arises about the quality of relocation, as it is apparent in Figure 3.2.1 that there is not significantly improved clustering. In this case there are many events that are not so well linked, and in order to improve the results of relocation a value of “maximal number of sites per pair” should be increased. In that scenario some pairs will be linked weakly but others strongly.



**Figure 3.2.1: (A) Absolute locations, and (B) Relative relocations using the default parameters with number of sites used for each absolute location reduced to six**



**Figure 3.3.1: (A) Absolute locations, and (B) Relative locations with input parameter "maximum number of sites per pair" set at thirteen.**

### **3.3 Example C: Maximum number of sites per pair reset to thirteen**

In Example A, the value of parameter “max number of sites per pair” was set at 10, and as the biggest events were recorded by 13 stations, these events should be processed using “max number of sites per pair” = 13. The result of relocation is shown on Figure 3.3.1.

### **3.4 Example D: Maximum number of neighbours reset to sixteen**

A value of “Maximal number of neighbours for event” in previous examples was eight. Further improvement of relocation result can be obtained by increasing maximal number of neighbours for event, and this example runs the relocation process with a value of sixteen.

The result of the relocation is shown on Figure 3.4.1, and it is the best result thus far. Detailed inspections of the seismicity pattern show that after relocation the clusters of events are much clearer than for the absolute locations. The left side of Section B-B' in Figure 3.4.1 strongly suggests that the seismic events cluster on a plane, indicating the presence of a seismically active geological feature. A measure of the planarity of this cluster should be applied, because it is not always possible to recognise that events are clustered in a plane in a perspective projection.

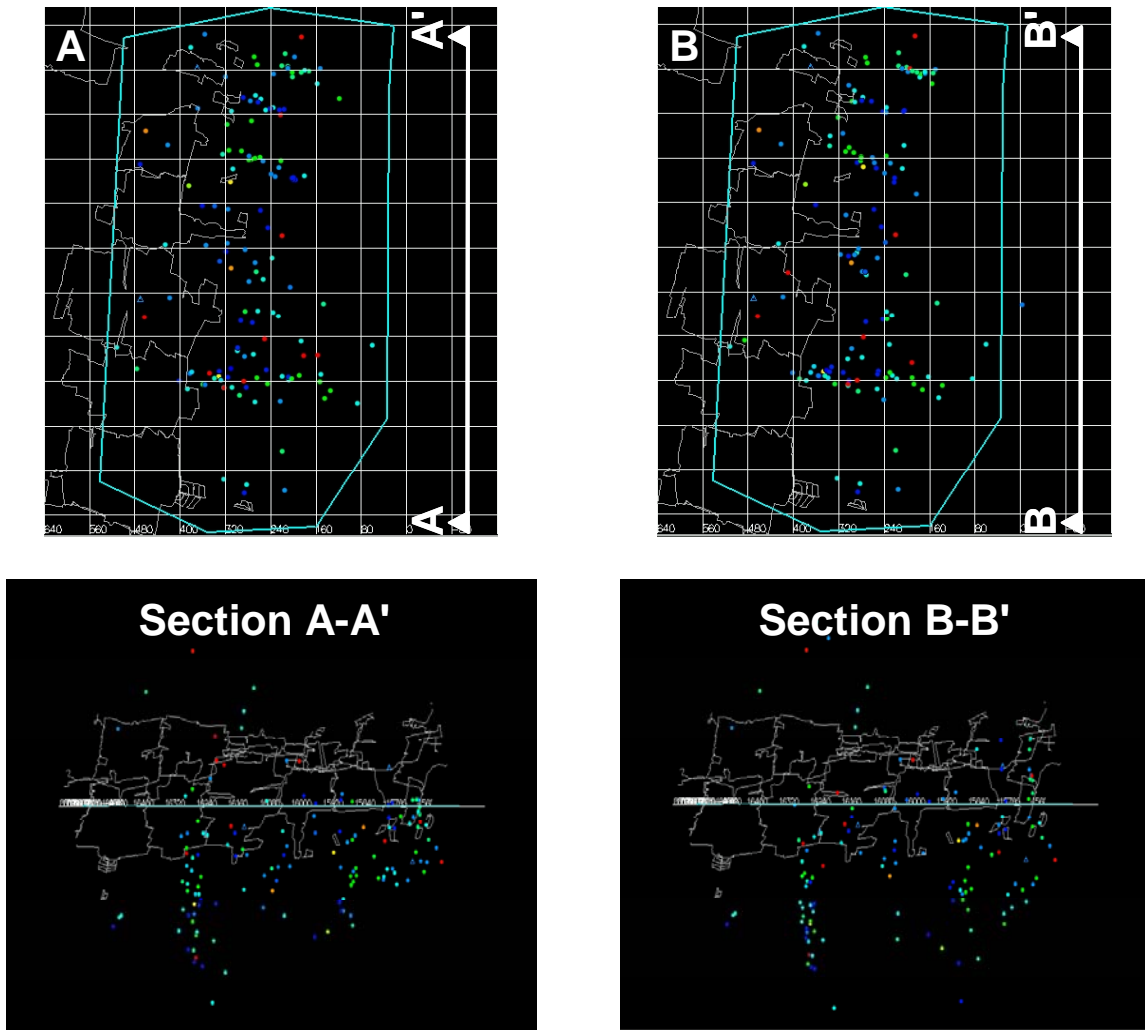
### **3.5 Example E: Maximum separation between events reset to 300m**

The maximum distance (separation) between a pair of events is an important controlling parameter because the further apart events are, the less they are likely to be related in any way. The default value for this parameter is set at 100m, and appears correct for the data set. The size of the polygon is 300 by 800m and most events are less than 100m from each other.

After increasing the value of 100m to 300m almost all the seismic events are included in one cluster -123 events with 12458 links. This situation is not desired, as it is very unlikely that the events spread across the entire polygon area would be influenced by the same velocity anomalies. The result for this relocation is shown in Figure 3.5.1.

### **3.6 Example F: Maximum separation between events reset to 50m**

Here the maximum separation between events has been reduced to 50m. Although this may be desirable from a relative location point of view (only events close to each other will be relocated relative to each other), absolute location scatter may be such that this setting is too small. This appears true in this case because data are split into a relatively large number of clusters, each containing a small number of events. This is not a desirable situation, since each cluster possesses too little information to perform the relocation process effectively. The results appear in Figure 3.6.1.

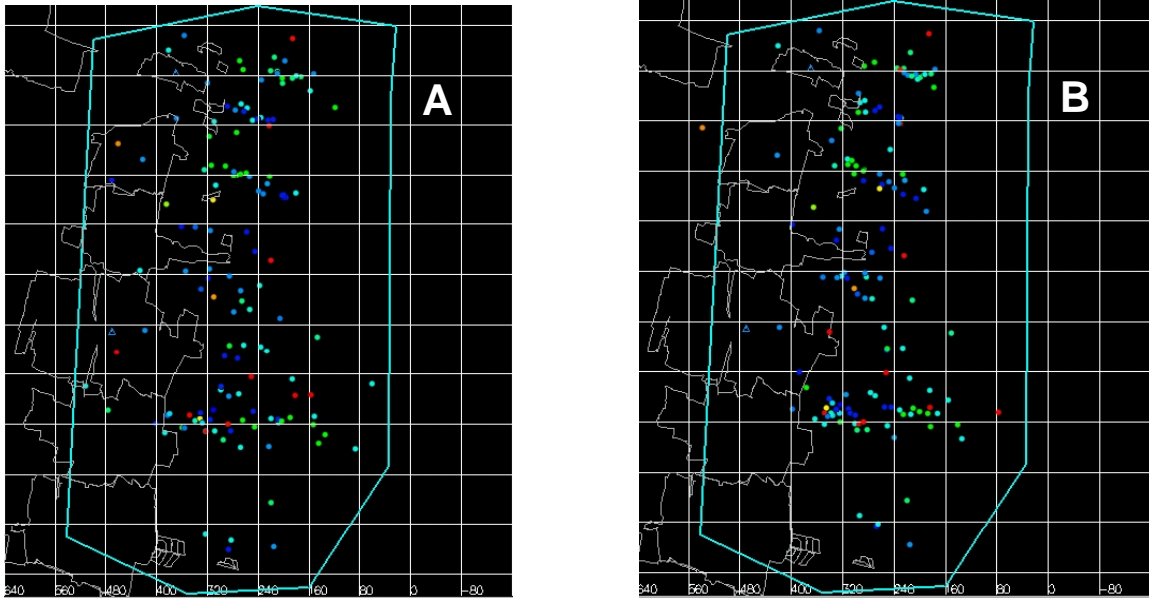


**Figure 3.4.1:** (A) Plan of absolute locations, (B) Relative locations with parameter “maximal number of neighbours” increased from eight to sixteen. The vertical sections show improved clustering in the footwall.

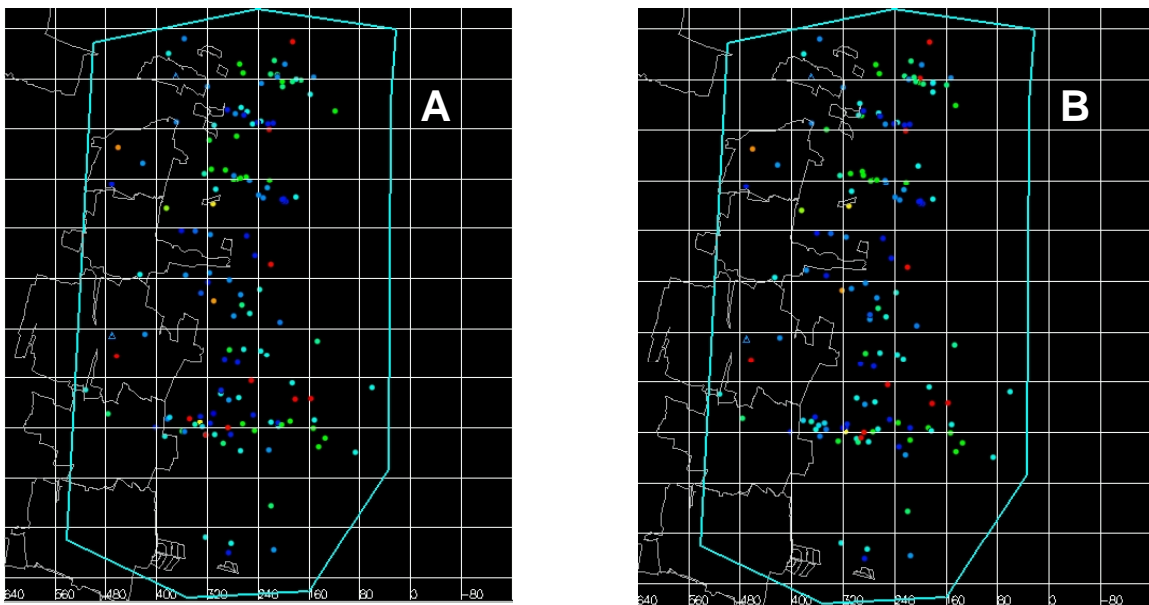
### 3.7 Summary

The group location method is applied to data from a deep level gold mine, and it is shown in several examples that the seismic patterns obtained with the group location algorithm reveal more features than the seismic patterns obtained using absolute locations, because location scatter is minimised. The new method relocates events with higher precision than is possible with traditional techniques. A further benefit is that the relocations effectively eliminate travel time anomalies resulting from velocity heterogeneity in the rockmass, assisting in building a 3-D velocity model for the rockmass. Example D represents the optimal solution, and it shows the main advantages of using the group location method, namely that events are more clustered, revealing seismogenic features in the rock mass. Furthermore a velocity model can be

built for the rock mass, thereby reducing scatter of future absolute locations. The results of the six relocations are summarised in Table 3.7.1 below.



**Figure 3.5.1: (A) Absolute locations, and (B) Relative locations with maximum distance between events reset to 300m.**



**Figure 3.6.1: (A) Absolute locations, and (B) Relative locations with maximum distance between events set at 50m.**

**Table 3.7.1: Summary of Group Location Results**

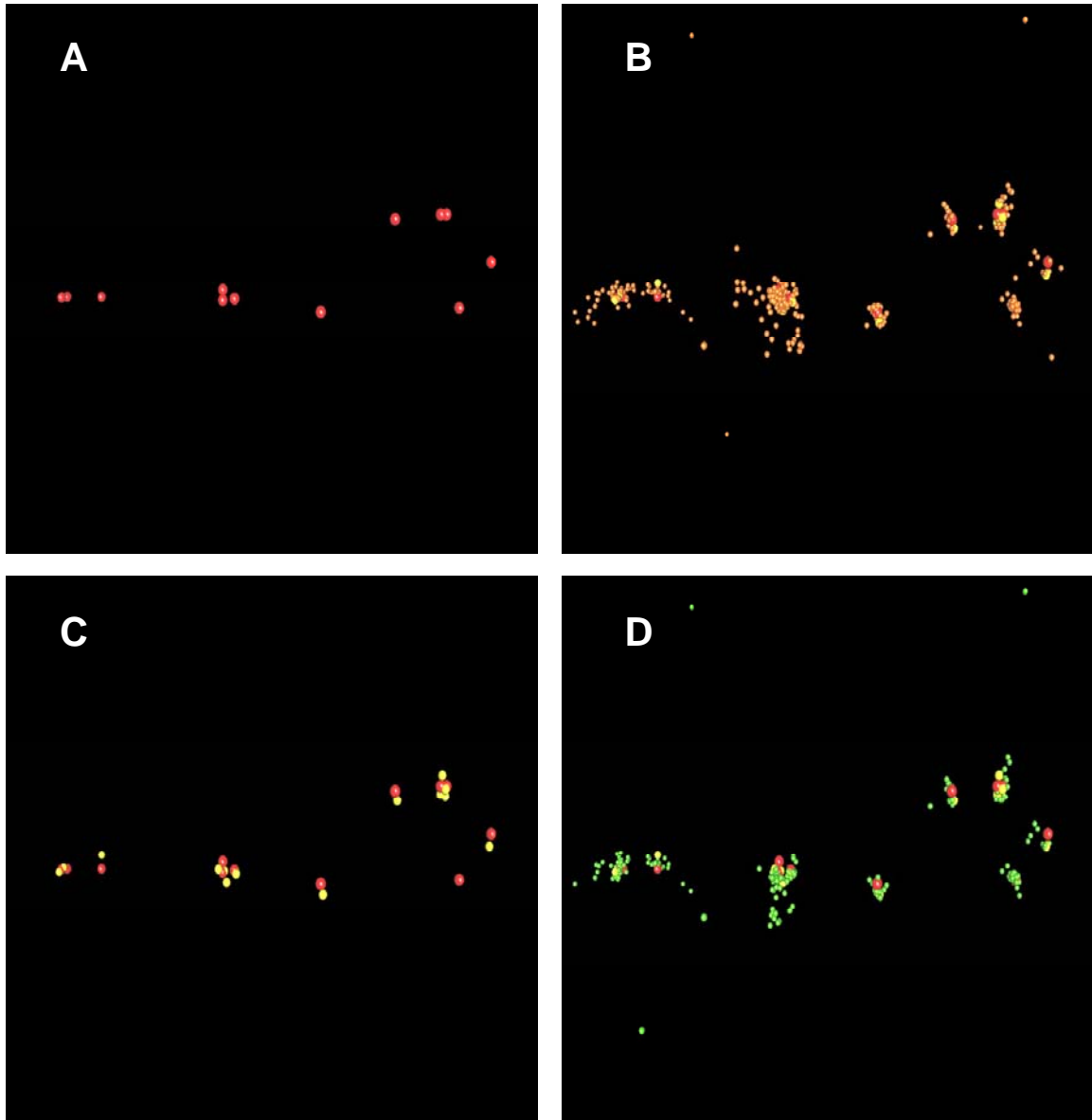
Maximum no. of groups = 30, Min separation between event = 1 m						
Example	Max separation	Max neighbours	Min sites	Max sites	No. relocated events	No. events in group and no. links
A	100	8	8	10	65	34-908
						26-770
						5-63
B	100	8	6	10	108	57-1399
						51-1616
C	100	8	6	30	108	57-1605
						51-1633
D	100	16	6	30	108	57-1733
						51-1909
E	300	16	6	30	123	123-12458
F	50	16	6	30	57	14-211
						11-212
						7-105
						6-117
						5-32
						5-50

### 3.8 Verifying relative relocations with blast data

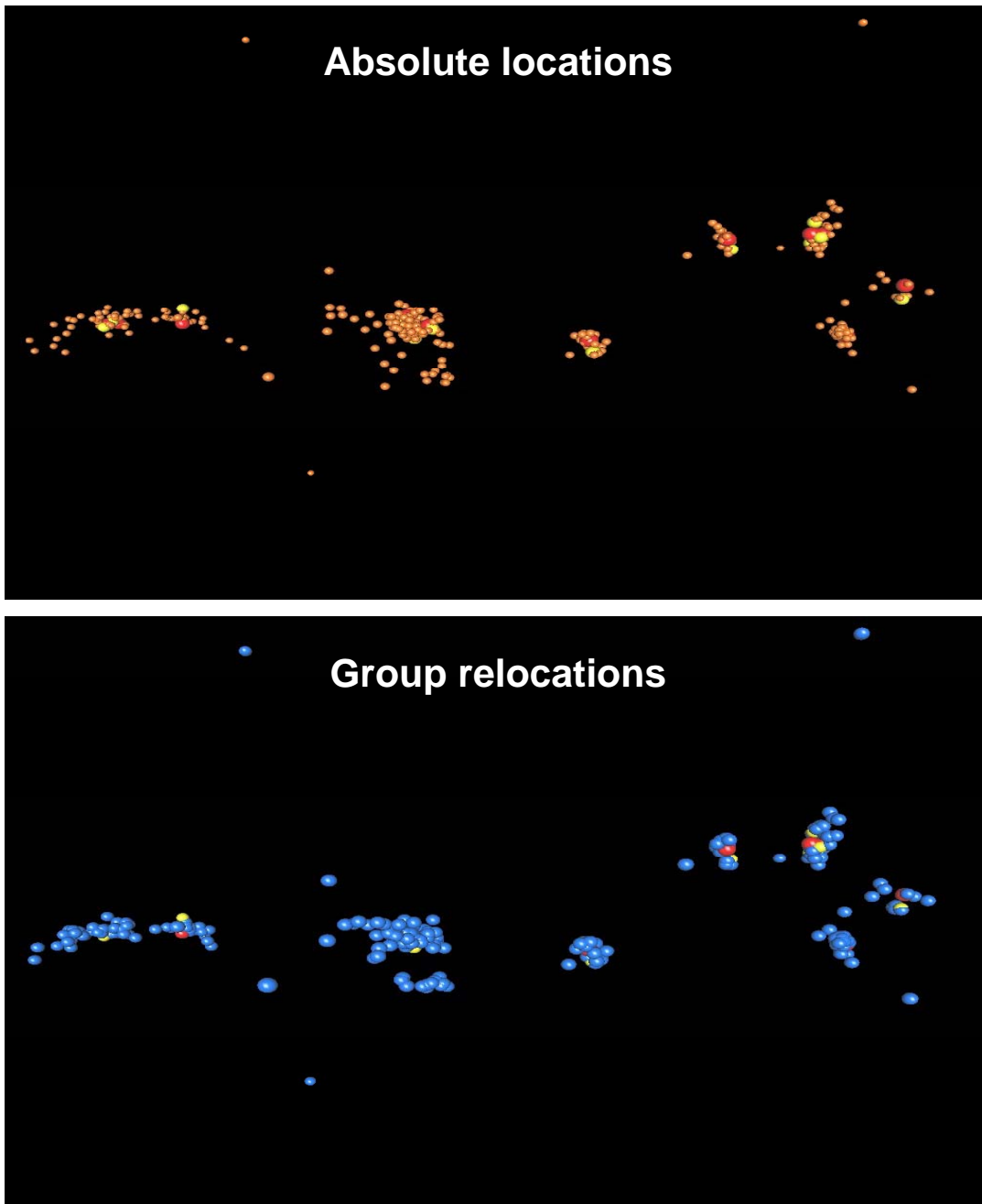
It is a big challenge to locate a seismic event reliably and with high accuracy, hence the measure of success of any relocation should be assessed on the basis of independent information. In the mining situation, blast data with known locations can be used to verify the results from the relative location and group location methods. Figure 3.8.1 (A) shows the known positions of blasting – these are not located blast events, they are merely representations of the x, y, and z coordinate positions of where blasts took place in a mine. Figure 3.8.1 (B) shows the absolute locations of the blasts, derived from seismograms recorded by the system. There is some source scattering caused by the error of location, but in general, the locations are fairly accurate. Because of the scattering, it is difficult to say whether the few source locations remote from the blast positions are mislocated blasts, blast-induced seismicity, or mining-induced seismicity.

The best absolute locations (i.e. those that plotted closest to the known blast positions) were then selected as master events. These are shown in yellow in Figure 3.8.1 (C) and

the known blast positions in red. There are a total of fourteen master events, and each one locates very close to a known blast position. Comparing Figure 3.8.1 (B) with Figure 3.8.1 (D), it can be clearly seen that the relative location moved the positioning of events much closer to the blast locations, which confirms the notion of Jones and Stewart (1997) that good relocations should increase cluster density. The relative locations carried out on the data in Figure 3.8.1 show undoubtedly that the relative location method is a high precision tool for positioning seismic events. Events remote from the blast positions can now be considered to be mining induced seismicity with a greater degree of confidence.



**Figure 3.8.1: (A) Known blast locations (red), (B) Absolute blast locations (orange), (C) Master event (yellow) selection based on those absolute locations closest to known blast locations, and (D) Relative blast relocations (green).**



**Figure 3.8.2: Absolute locations (top, orange) and group relocations (bottom, blue) of blast data – blast positions are shown in red, master event locations shown in yellow, and group relocations shown in blue**

Figure 3.8.2 shows the result of relocation of the blast data using the group location method. The locations of events are much closer to blast positions than those obtained using the absolute method. Comparing Figures 3.8.1 (D) and 3.8.2, it is clear that the relative relocation method increases clustering, but that the group relocation method is even more effective in refining event locations, based on the increased clustering notion of Jones and Stewart (1997). Events remote from the blast positions are almost certainly mining induced seismicity since it is highly unlikely that time residuals are now sufficiently incorrect to allow such large errors of location. This is confirmed by the fact that their locations do not change significantly during the group relocation process. Finally, there is no apparent systematic bias in either the absolute location, relative relocation, or group relocation results, which suggests that these methods are all highly effective in producing improved location accuracy. Data used in the experiment was obtained from an Australian mine, with a horizontal scale of about 200m.

### **3.9 Conclusion**

New processing methods enable us to improve location of events. The relative location and group location changes the picture of seismicity to that extent, that it should effect interpretation of the seismic pattern, identification of seismogenic features, and ultimately, the decision process. Both single master event and multiple master event methods locate seismic events with much higher precision than the absolute location method.

## **4 Interactive system for velocity calibration**

### **4.1 Initial velocity model**

Previous experience indicates that a new owner of a seismic network often has a problem with selecting a proper velocity model, since a seismic network is usually installed in an area where the velocity model is not known. The velocity calibration tool was developed to build a proper velocity model, thereby improving absolute location and ultimately relative location precision. The advanced location procedures will significantly benefit from a reliable absolute location based on a realistic velocity model. The velocity calibration tool offers the following strategies: calculation of P-wave or S-wave or simultaneous P- and S-wave apparent velocities, but for this to be possible, the location of the seismic event or blast has to be known. The main purpose of this section is to calculate the velocities of seismic waves produced by mining blasts.

In the volume of interest, seismic waves are reflected and refracted at material discontinuities. To locate seismic events with optimum precision, the following assumption must be made: body waves propagate through a medium that has a constant apparent velocity (average velocity). However, if the geological setting justifies it, layers or polygons with different velocities can be introduced. The velocities of seismic waves in rock depend on several variables of which the most important are elastic modulus and rock density. Initially, seismic location is obtained by using the default values for the velocity of propagation of seismic waves (see Table 4.1.1). The velocities from the table are nearly always inadequate for obtaining a high precision location of a seismic event but it is an unavoidable starting point for the location process.

**Table 4.1.1: Examples of typical compressional and shear wave velocities (after Press, 1966)**

Material	Vp [ $\times 10^3$ m/s]	Vs [ $\times 10^3$ m/s]
Alluvium	0.5-2.0	
Clay	1.1-2.5	
Quartz	6.0	3.5
Calcite	6.7	3.5
Dolomite	7.4	4
Granite	5	3
Limestone Soft	1.7-4.2	
Limestone Hard	2.8-6.4	
Porous Rocks		
Shale	4.2-1.7(40%)*	
Sandstone	5.0-1.8(40%)	
Limestone	6.2-4.0(20%)	
Dolomite	7.2-4.9(20%)	
Igneous	5.8-5.0	

\*Note: The effect of porosity is indicated by percentages (after Sheriff and Geldart, 1983). The lower velocities for any rock type are the high-porosity members of the set, and the higher velocities are the low-porosity members.

## 4.2 Velocity calibration tool

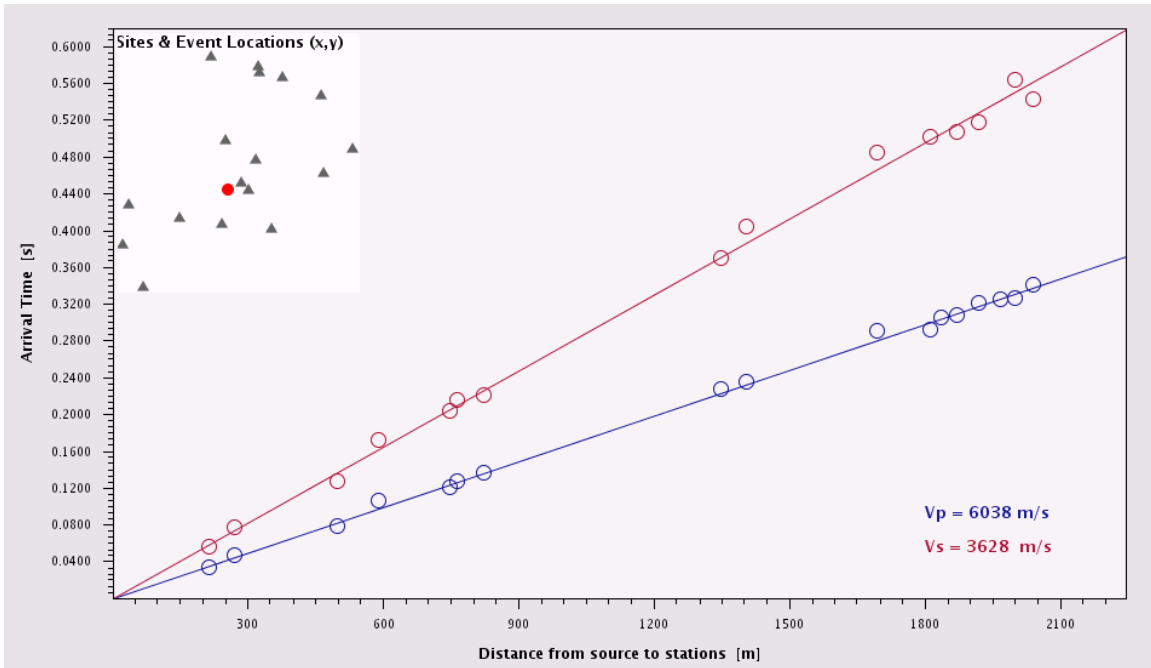
The velocity calibration tool was developed to build a proper velocity model of the volume of interest so as to optimise absolute location error. The velocity calibration tool offers the following calculation possibilities:

- calculation of apparent P-wave velocity (average velocity);
- calculation of apparent S-wave velocity (average velocity);
- simultaneous calculation of apparent P and S-wave velocities (average velocities);
- calculation of apparent velocities between the source and all sites.

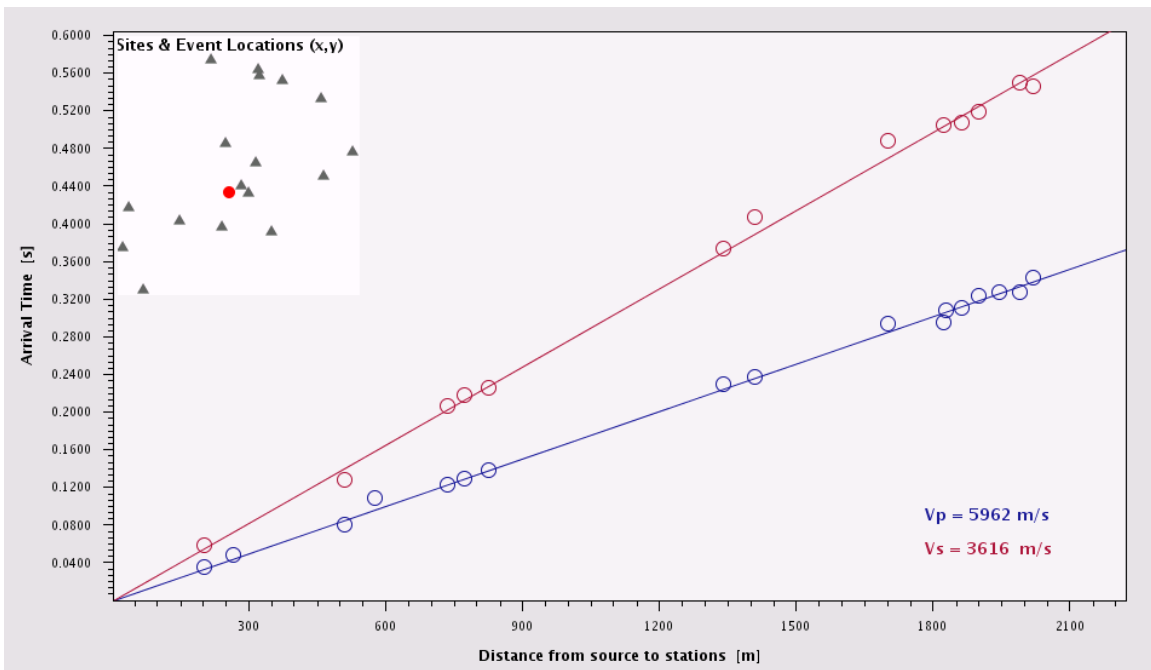
The velocity calibration tool requires the following input data:

- a known location of the mining blast or seismic event;
- seismic station co-ordinates;
- P-wave arrival time and or S-wave arrival time at each station;
- initial velocity model;
- a location obtained using initial velocity model (which will consist of velocities obtained from Table 3.1.1, or from local knowledge of the rock mass).

Figure 4.2.1 shows a linear travel time curve, derived from the arrival times recorded at different points as a function of distance from the seismic source. Seismic velocities within the medium can be computed from the slope of the least squares best fit line, and this value represents the apparent velocity for the volume of interest.



**Figure 4.2.1: Velocity model for one event (red circle in inset) and seventeen seismic stations (grey triangles in inset) and input velocities  $V_p=6000 \text{ m/s}$  and  $V_s=3500 \text{ m/s}$**



**Figure 4.2.2: The same calibration as Figure 3.2.1, this time with input velocities  $V_p=5925 \text{ m/s}$ , and  $V_s=3650 \text{ m/s}$**

**Table 4.2.2: Two examples of use of velocity calibration tool**

Model [m/s]	Location [x,y,z] and Residuals [m]	Apparent P-wave Velocity [m/s]	Apparent S-wave Velocity [m/s]	Apparent P- and S-wave velocities
Vp=6000 Vs=3500	(977,650,3132) 38m (3.0%)	Vp= 6038 -	- Vs =3645	Vp=6038 Vs =3628
Vp=5925 Vs=3650	(967,641,3095) 26m, (2.0%)	Vp =6016 -	- Vs 3625	Vp=5962 Vs =3616

The same data inputs excepting the input P- and S-wave velocities were used for both calibrations. It is tempting to select the second result because the location residual is smaller than the first. However, the correct choice can only be made when the position of the seismic event is already known.

Typically, a mine blast will serve as a known seismic event position (face positions and access development face positions will be known beforehand), although the time of initiation of the blast will be unknown. Despite this, the tool can still be used effectively. It is suggested that the seismic system is triggered when the blast is initiated electronically, because this would provide the unknown blast time, making the analysis more effective. The tool can also be applied in the case where the location of damage caused by a seismic event is known; if damage is used, only damage caused by the ground motion in the source volume should be used. Using the location of a fall of ground induced by a seismic event could lead to a significant error because the event itself may be remote from the damage.

The larger the deviation of the station arrival times from the best-fit line, the larger the travel time residual. Even for an event with unknown location, the velocity calibration tool is useful to identify stations with large travel time residuals. These stations have a different apparent velocity, which is usually associated with a local geological condition.

Figures 4.2.1 and 4.2.2 contain most of the features of the velocity calibration tool (excluding the relocation feature). Apparent velocity, velocities between source and station, or any other velocity, which the user thinks is the right one are transferred to the event structure. A user can then relocate a seismic event with the new velocity model. Finding the best velocity model, which accounts for the different geological settings and ray paths is an iterative process. It remains difficult to automate, as only the user knows a local geological structure, but effective means of doing this should be investigated.

Users might be tempted to utilize the calculated velocities between source and stations in order to obtain the smallest residuals. This is incorrect, and will not produce an improved location. It is better to use an apparent velocity (average velocity), which is more representative of the volume of interest, and to build an apparent velocity model for the volume of interest for seismic events coming from all points in the volume.

## 5 Automatic P- and S-wave pick algorithms

The next important aspect for precise locations is to obtain the correct P- and S-wave arrival times. At present this task is nearly always performed manually because human operators are much more flexible and capable of making correct choices than any algorithm presently available. There is also a perception that manual picking provides

better quality processing than automatic processing, which is often true, but developments in the near future should reverse this. The disadvantages of the manual approach are as follows:

- P- and S-wave arrival time biases may creep into the data because of operator preferences (cases when automatic processing yields a chaotic seismic pattern but manual processing produces more coherent clusters in seismic patterns should be carefully investigated, because it is obvious that an operator processing seismic data will select those P- and S-wave onsets that place the location of the seismic event close to the anticipated place - closer to a reef or closer to an active slope. As a result manual processing produces nice clusters in seismic patterns but this is not unbiased processing);
- The bias and the error in picking arrival times by eye varies from person to person, so systematic biases may accumulate because of a change in personnel engaged in the work. It is impossible to avoid subjective bias in reading seismograms, some people tend to pick out arrival times earlier than the actual one, and others tend to pick a later arrival time (where they are sure the P-wave has arrived). It is impossible to make an objective estimate of the errors involved in human bias.
- Manual arrival time identification is slow and expensive, thereby severely limiting capacity to handle large volumes of seismic data;
- Limitation of data handling capability restricts the potential for seismic prediction in real time to almost zero;
- Constant checks of arrival time picks need to be undertaken, taking up valuable man-hours for data quality checks, and limiting time for seismic interpretation, risk assessment, and risk management.

An effective automatic P- and S-picking algorithm will not only provide the solution to all these problems, but also provide further impetus in the drive toward real-time prediction.

## **5.1 Effectiveness of automatic algorithms**

The most popular P-wave detection algorithm is the STA/LTA (ratio of short-term average to long-term average). STAs are sensitive to rapid increases in the amplitude of a signal, while LTAs measure the local background amplitude. The ratio of the STA to the LTA is therefore a measure of the signal to noise ratio. How to accurately and rapidly process the huge volume of incoming waveforms is the most challenging task in monitoring seismicity in mines. The object of the task is to evaluate the effectiveness of currently implemented algorithms for automatic picking of the P- and S - waves. A recent implementation of a P-wave picking algorithm is described. The algorithm constructs, almost in real time, the multi-dimensional prediction model of seismic noise.

Seismic networks for mines are designed to record as many seismic events as nature and instrumentation permit and they produce an extensive volume of data. The collected seismic data contain a wealth of information about the dynamical process in the rock mass. Automatic processing is the only way to fully utilize the information obtained from networks. The core of automatic processing is picking of the P- and S-wave arrival times. Automatic location and estimation of seismic source parameters are advanced numerical procedures, but the quality of the results depends very strongly on the quality of the picked P-and S- wave arrival times.

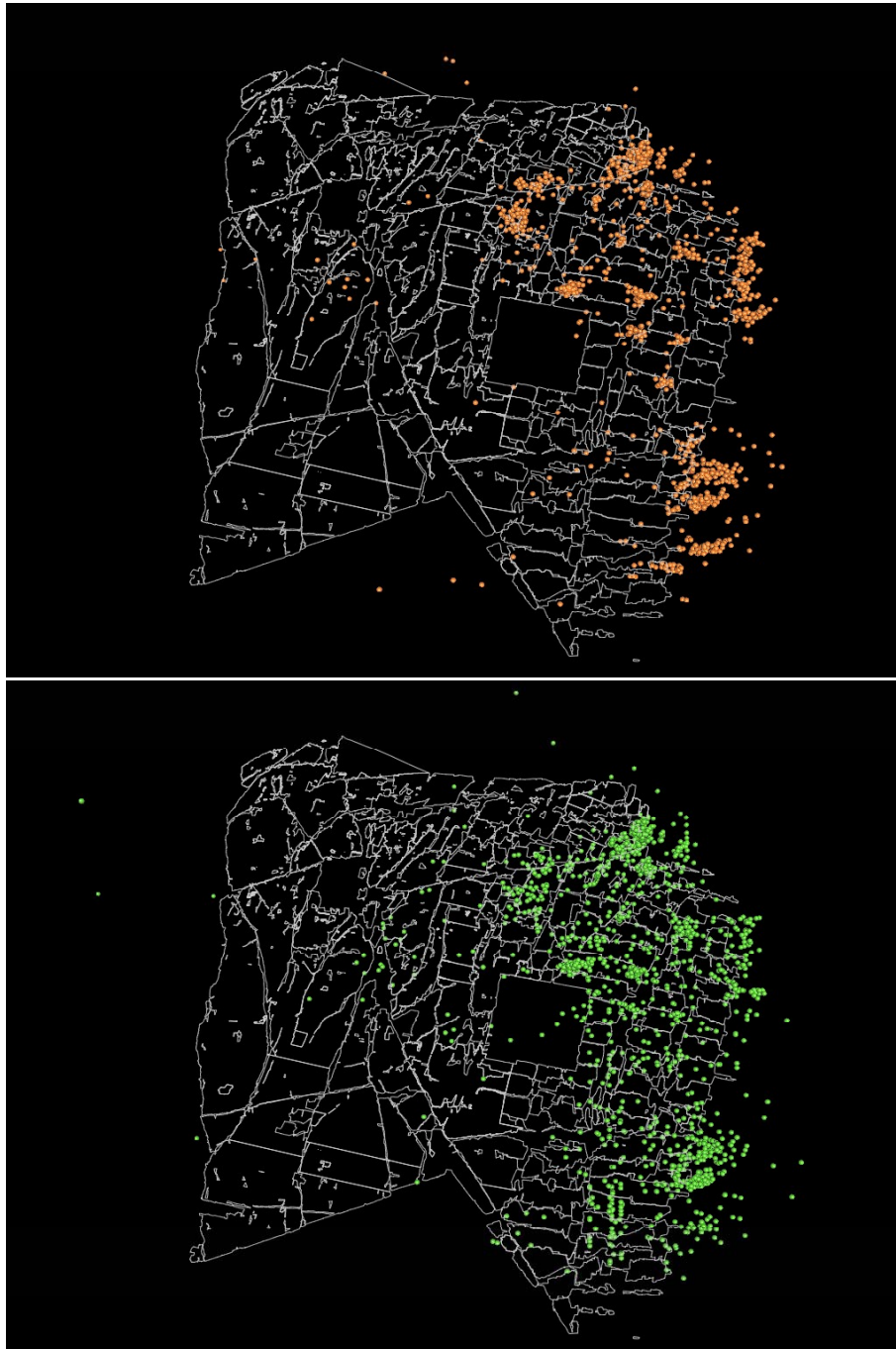
The first question that has to be answered is: what percentage of seismic data is processed reliably? This simple question does not have a simple answer. The ratio of the seismic signal to noise is the most important parameter that determines the quality of the automatic processing. However, that parameter can vary significantly for the same event recorded by different stations. Therefore the ratio is important for the characterization of the performance of the numerical algorithm for picking of the P- or S-wave arrivals but does not answer the question. The practical answer comes out of a statistical analysis of a large volume of seismic data and personal experience.

A series of experiments were conducted where the locations of seismic events were calculated using P- and S-wave arrivals obtained manually and automatically (see Figure 5.1.1). Several hundred records of seismic events from a deep level gold mine were processed with the 27 seismic stations covering an area of 3000m by 2000m. An experienced person did manual processing. In the first step, seismic events recorded by at least 5 stations were selected. The visual comparison of seismicity patterns indicates remarkable similarity between automatic and manual results, since all clusters of seismic events are located in the same positions. Therefore the rock mechanics service responsible for interpretation of seismic patterns may base decisions on the results of automatic processing.

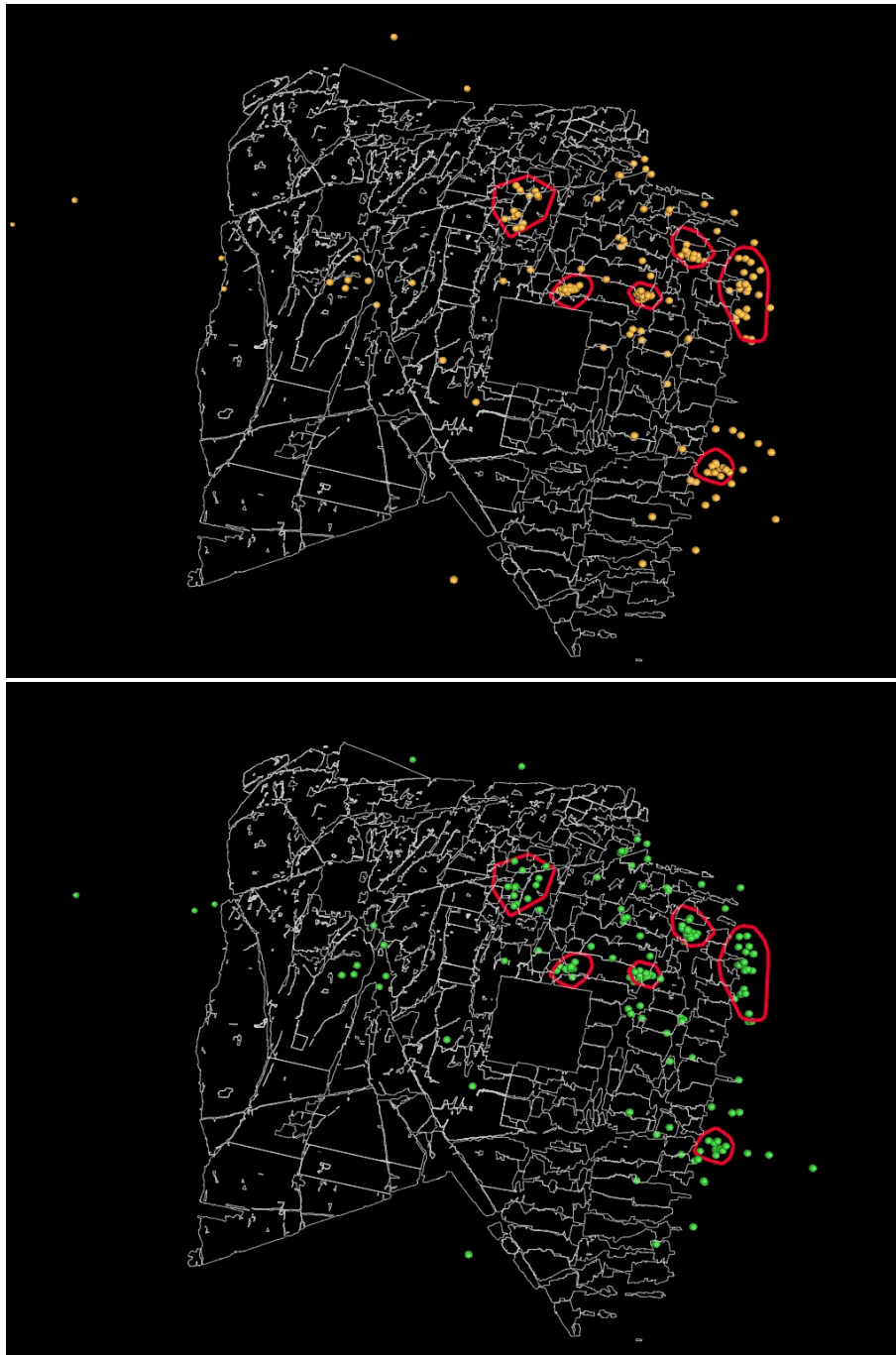
In mining practice a seismic event for which residuals equal 3% of the average hypocentral distance is classified as a well-located event (this amounts to a spatial error of approximately 30m if the event is 1000m from the station). In the case study under consideration, 60% of automatically processed events were located within 70m of the manually processed locations. The location difference of 70 m is equal to 6% of the average hypocentral-station distance. Therefore, the difference of 6% is the average hypocentral distance between automatically and manually processed events. Although these results are only marginally acceptable, they represent an achievement in comparison to results from automatic picking algorithms only a few years ago.

Detailed analysis reveals that automatic processing produces more scattered events than the manual process does. Some seismic clusters obtained with manual processing are more compact than the corresponding clusters obtained with automatic processing. An automatic pick algorithm in tandem with an automatic relocation algorithm now brings reliable automatic seismic data processing within reach. There is still much work to do, but the potential benefits of a fully automated location algorithm incorporating a robust relocation algorithm together with an automatic velocity model would reward research and development efforts in this direction handsomely.

In the second experiment only events recorded by 8 stations were selected from the above data set (see Figure 5.1.2). This experiment has much fewer seismic events and more detailed analysis is possible. The first impression is that several features of seismic clusters are indistinguishable. This does not imply that all events automatically processed were processed perfectly, as there are still some events where automatic processing fails despite a good signal to noise ratio. Each case has its logical explanation why manual processing gives a different result than the automatic algorithm, and a list compiled from experience with the automatic picker are discussed below.



**Figure 5.1.1: Locations of seismic events were calculated using P-and S-wave arrivals obtained manually (top) and automatically (bottom); seismic events recorded by at least 5 stations. Note that both sets of locations are absolute locations.**



**Figure 5.1.2. Locations of seismic events were calculated using P-and S-wave arrivals obtained manually (top) and automatically (bottom); seismic events recorded by at least 8 stations. Note that both sets of locations are absolute locations.**

## 5.2 Current status of automatic location algorithm

Experiences with the automatic algorithm are listed below:

- sometimes a small burst of noise, recorded on all three components, is stored in the same buffer with the seismogram. This is easily identified by the operator, and is ignored during manual processing, but automatic processing will treat the noise burst as a P-wave arrival;
- when two events are recorded in one buffer, manual operators easily separate them but automatic processing usually takes the first event P- wave arrival and the second event S-wave arrival;
- lack of automatic identification of non-operational components, hence meaningless picks from non-functioning stations may be included in the location, resulting in a large location error.

Further progress will require substantial effort to improve the quality of automatic picking, because it still requires substantial operator intervention for quality control and verification. A new automatic picking method will have to be developed and implemented. The requirements for such an automatic picker should be as follows:

- automatic pick errors must be reduced to one in one hundred thousand, if it is required that only one in ten thousand 12-station events are mislocated;
- the picker must be able to distinguish between one or two events in the buffer, issue a warning, and cancel the S-pick in two-event cases;
- review the potential for reliable locations using P-arrivals only;
- develop ways of discarding S-arrival picks if these are inconsistent with other seismic data;
- apply existing algorithms for P- and S-arrival inconsistency minimisation and/or removal in seismic data;
- develop a simple software algorithm that excludes data from non-functioning seismic stations in the automatic location;
- noise bursts must be either removed electronically, or improved station installation and maintenance procedures should be implemented.

In conclusion, automatic arrival picking produces satisfactory results (in comparison to current manual absolute locations) for events recorded by six or more stations, since a seismic signal recorded by six stations usually has a sufficiently good signal to noise ratio that permits a reliable P-pick on all, or nearly all stations. The results are marginally satisfactory for 5-station events, which means that current algorithms need to be improved further. In order to improve automatic seismic location error, a relative relocation must be implemented to remove or at least minimise arrival time inconsistencies in the seismic dataset. Manually operated algorithms are already available, and have been demonstrated, it is now only a matter of time before reliable automatic algorithms become available.

### 5.3 New developments in automatic P-wave picking

During the course of this research, the STA/LTA detector was replaced by a more advanced method, originally developed by Cichowicz and Kopystynski (1975). To determine the onset time of a P-wave, the three-dimensional Auto Regressive (AR), model is used. The AR model captures information about signal amplitude and spectral content and their change with time is expressed in AR coefficients.

The typical seismic signal consists of noise, the P-wave signal, and the S-wave signal. The P-wave picker focuses only on the first part of seismogram (see equation 1) where only seismic noise,  $x_t^1$ , and P-wave,  $x_t^2$ , are recorded. The P-wave merges in at time  $t = p$ ,

$$x_t = \begin{cases} x_t^1 & \text{for } t = 0, 1, \dots, p-1 \\ x_t^1 + x_t^2 & \text{for } t = p, p+1, \dots, q \end{cases} \quad (5.1)$$

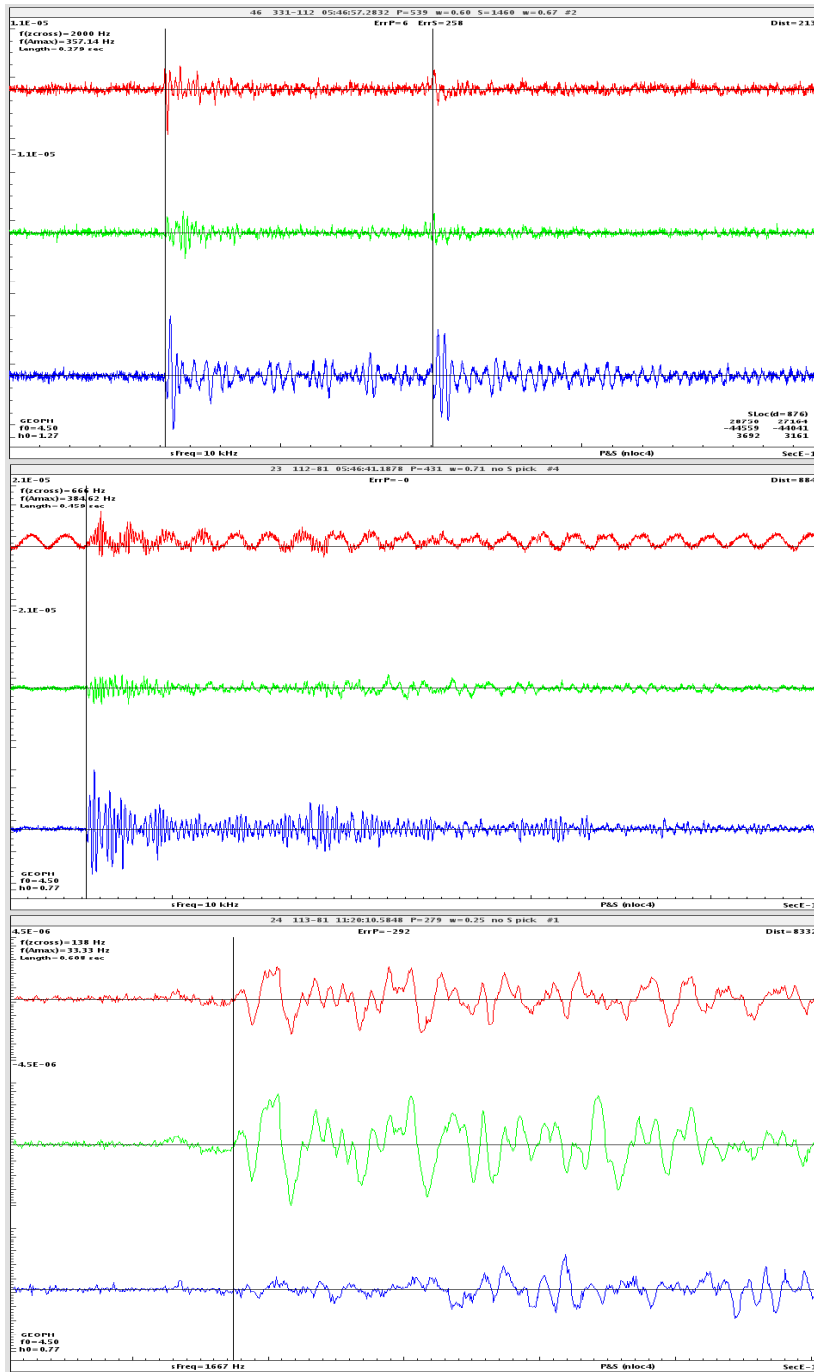
The noise signal can be regarded as a stationary signal so the AR model can easily express the characteristics of the noise. Let us assume, as was done by Wiener (1949), that for time  $t = 0, 1, 2, \dots$  one could determine the stationary process with the discrete time samples  $\{x_t\}$ . The model construction is based on the assumption that from the linear combination of  $m+1$  discrete signal values  $x_t, x_{t-1}, x_{t-2}, \dots, x_{t-m}$ , one could determine the approximate value of  $x_{t+1}$ :

$$z_{t+1} = a_0 x_t + a_1 x_{t-1} + a_2 x_{t-2} + \dots + a_m x_{t-m} \quad (5.2)$$

The signal  $z_{t+1}$  approximates the observed signal  $x_{t+1}$  in the best way when the mean quadratic deviation of coefficients  $a_0, a_1, a_2, \dots, a_m$  reaches its smallest possible value. The AR coefficients model the deterministic part of the  $x_t$  signal. The non-deterministic time series  $e_t = x_t - z_t$  is supposed to be a Gaussian process with constant mean and variance. Now it is possible to determine an unknown time  $t=p$ . Several simple statistical algorithms have to be applied to signal  $e_t$  in order to detect the onset of the P-wave.

Sleeman and van Eck (1999) implemented a similar P-wave picker. In their implementations some 70% of the manual picks were automatically estimated within a 90% confidence interval. This was a significant improvement compared to the old STA/LTA picker. Our implementation goes one step further (see: Cichowicz and Kopystynski, 1974). The multi-channel filtering process is applied to three-component data, which is a generalisation of the above one-channel filtering technique. The P-wave arrival time should be common for the X, Y, and Z components recorded at a station. In most cases the noises on the three components have similar spectral characteristics and onsets of the oscillations are synchronized. Those features justify construction of the noise model using the following equation:

$$z_{t+1}^l = \sum_{k=1}^N \sum_{s=0}^m a_s^{kl} x_{t-s}^k \quad (5.3)$$



**Figure 5.3.1. Three examples of application of multi-dimensional AR model for picking P-wave arrivals in difficult seismograms. The P-wave arrivals are all preceded by strong non-monotonic noise. The STA/LTA detection algorithm failed in all the above examples.**

In equation 5.3  $N$  is the channel number,  $m$  is the filter length,  $a_s$  are coefficients of multi-dimension models and  $x$  is the multi-dimensional signal. The predictive power of the multi-dimensional model (equation 5.3) is much stronger than the predictive power of the single dimension model (equation 5.2).

The results of P-wave detection by the three-dimensional AR model appear in Figure 5.3.1. The P-wave arrivals are preceded by a strong non-monotonic noise. The top example from Figure 5.3.1 shows high frequency noise with several relatively strong spikes. Each spike would be interpreted as an arrival of the new signal by the STA/LAT algorithm, but the multi-dimensional AR detector ignores all of them. The second example (see Figure 5.3.1 middle) shows 50Hz noise in one component. It is well known that the STA/LTA detector often fails to detect P-wave arrivals in this environment. The third example (see Figure 5.3.1 bottom) is the most difficult one. A strong, low frequency impulse is observed before the P-wave arrival, but the AT detector picks the P-wave in the right place. Although the impulse is recorded by all three components the shape of the pulse differs from component to component. The STA/LTA detection algorithm is ineffective in all the above examples.

## 5.4 Discussion

The problem that still has to be addressed is the reliable processing of events recorded by only four or five stations. In order to do this a new algorithm has to be implemented and tested. Sometimes, a series of events occurs in a very short interval of time, such as a seismic event that occurs during blasting time (when the blast signals as well as the seismic traces are being recorded by the system), or a small foreshock occurring just before the main event. The waveforms from these different events will be placed in one buffer if they are sufficiently close to each other in time. A method for automatic event separation in this case has not been developed yet, but it is a possible task. The AR method shows great promise in obtaining reliable P-wave onsets, even in difficult seismograms, and work to implement this picker in seismic location software should continue.

## 6 Conclusions

This report covers the development and implementation of relative location techniques to improve seismic locations. Relocations using single and multiple master events have been demonstrated firstly, for well-located seismic events as master events, and secondly, using blasts with known coordinates. Both show the effectiveness of the techniques in reducing cluster volume (thereby sharpening images of seismically active features in the rockmass), as well as in removing systematic absolute location biases, such as weak constraints in the vertical direction because the geophones are arranged more or less on a plane below the reef horizon. Group locations using the double difference algorithm have also demonstrated their effectiveness. There is as yet no objective way of determining reductions in location error excepting:

- If clusters are smaller in the relocated dataset, then the notion of James and Stewart (1997) suggests that the relative locations are better quality than the absolute locations, although there is no indication that the relocated events are near their true locations;

- Optimisation of relocation input parameters (demonstrated in tutorials in the report) results in an optimal relocations that will be fairly insensitive to further manipulation of the inputs;
- Verifying seismic locations using blast data with known locations as master events.

These relocation techniques still require considerable operator intervention; hence they have not been automated, although this possibility should be investigated.

Automated location methodologies and their results have been demonstrated in the report. The Cichowicz – Kopystynski algorithm is demonstrated as being more effective than the popular Short Term Average / Long Term Average (STA/LTA) algorithm, especially in cases where significant noise is present in the seismograms. The automatic algorithms show reasonably good results for events recorded by eight stations, and it is possible that their effectiveness could be considerably enhanced by automatically relocating the events using one of the relocation methodologies discussed in the text. This suggests a new research direction aimed at making automatic location algorithms effective by adding automatic relocation methodologies to improve the results, thus relieving operators of manual relocation, and perhaps significantly reducing the location quality control workload.

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