The use of waveform similarity to define planes of mining-induced seismic events

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Abstract

Mining-induced seismicity results from a complex interaction of ambient and mining-induced stresses acting on a rock mass that has been intersected by a variety of geological weaknesses and discontinuities. A major challenge is to improve mine design methodology by identifying the geological features that are seismically active and then changing the direction of mining to reduce the potential for shear slip on these features. In this paper we classify seismic events with similar waveforms (doublets) into multiplets, relocate them simultaneously using arrival-time differences based on cross-correlations between all event pairs and then identify the orientation of the most likely plane on which the events are located. Identification of multiplets has been automated, even including events that have not previously been located. In contrast to the conventional 'master' event method, no single master event is used: each event is a 'master' event for each other event. The absolute location of each multiplet is stabilised by using all manually selected arrival times. Vectors are drawn between all pairs of events and Principal Component Analysis applied to obtain the orientation of the most likely plane of the events in each multiplet. We tested this method on seismic data recorded underground at a site in Blyvooruitzicht Gold Mine, South Africa, in which a strike stabilising pillar has been mined from one end with the aid of precondition blasting. We found that 39% of events that were previously located in a diffuse cloud within a mine pillar, were formed into three distinct multiplets. Two multiplets were oriented parallel to directions of dominant mining-induced stresses, i.e., along the long axis of the pillar and parallel to the active mining face, and the third along a pervasive joint set. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: waveform; mining-induced seismicity; stress multiplet location method

1. Introduction

The Witwatersrand gold deposits in South Africa are typically narrow, less than 1 m in width, and shallow-dipping, but can extend for many kilometres horizontally. As ore is removed, the stresses that were previously carried by the ore body are then transferred onto the remaining unmined ground, resulting in huge vertical stress ahead of actively mined faces and stationary abutments. Within an elastic rock mass, vertical stresses ahead of deep-level stopes exceed the strength of the rock by far and are relaxed by rock failure. The resulting fractures follow the shape, in plan, of the mining outline.

The rock mass is cut through by a number of geological weaknesses in the form of bedding planes, faults, dykes, joints and quartz veins. Although seis-

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micity can be associated with failure of previously unfractured rock (Ortlepp, 1978), geological discontinuities, large and small, play an important role. The largest mining-induced seismic events are usually associated with faults and dykes (Gay et al., 1984). On a smaller scale, minor faults and joints also control seismicity (Rorke and Roering, 1984).

One method of controlling seismicity is therefore to reduce stresses induced on geological features by approaching them at an oblique angle. Unfortunately, sets of discontinuities at different angles are common and it is not practical, and often not possible, to mine obliquely to all geological discontinuities. It is therefore important to identify those discontinuities that are most easily mobilised by mining. In practice, it is not easy to use seismic locations only to identify the most active structures as seismicity often locates on the intersection of two or more structures and the best location accuracy requires a very dense network of seismometers. Seismic mechanisms can be used to identify the causative structure if more than one is in the vicinity, but this has only occasionally been achieved (Spottiswoode, 1984). Accurate relative locations can provide the orientation of geological structures (Urbancic et al., 1993).

Events that locate close together with similar mechanisms generate similar waveforms and are called doublets (e.g., Poupinet et al., 1984) and can be relocated very accurately with respect to one another (e.g., Ito, 1985; Deichmann and Garcia-Fernandez, 1992). Groups of doublets can be called multiplets (Fremont and Malone, 1987; Moriya et al., 1996). In this paper we extend the doublet relative location procedure and introduce multiplet relocation using arrival-time differences for all possible event pairs simultaneously. We then looked for the 'best' plane though each event multiplet.

Michelini and Bolt (1986) have applied a technique called a 'method of principal parameters' for finding the orientation of active fault planes inferred from an aftershock sequence. Fehler et al. (1987) proposed the 'three-point method' to infer the planes of events locations. This method assumes that the earthquakes occur over pre-existing planes (fault planes) and defines each plane by the triangles formed by each set of three locations. Their method was applied to microearthquakes induced by hydraulic injection into crystalline rock. Urban-

cic et al. (1993) applied the Principal Component Analysis to mining-induced seismic events. They found good agreement with focal mechanisms, in-situ stress measurements and structural mapping.

In this paper we investigate the spatial distributions of seismic events using Principal Component Analysis and introduce a 'two-point' method in which the plane of locations is identified from the assemblage of vectors between event pairs. The Principal Component is then the normal to this plane. As each multiplet can be related to a single genesis, or mechanism, we use the term 'family' when referring to the events in a multiplet as a group.

2. Method

Mine seismic networks can record thousands of triggered seismic events associated with many different mine workings and geological features. Our method of multiplet locations was motivated by a number of considerations.

(1) Event locations are normally based on manually selected P- and S-wave arrival times. Automatic arrival-time picking is also used, but is prone to large errors. We would like to obtain robust locations even for events that have not previously been well located.

(2) Pairs of events that write similar seismograms and therefore are likely to have similar mechanisms should be automatically matched. Such pairs are called doublets.

(3) Identical locations and moment tensors will generate identical waveforms at frequencies much less than the corner frequency. Deviations from similarity at the corner frequency and higher will result from differences in the direction of propagation of slip. Such effects must be minimised.

(4) Computational demands for comparing a large number of events with one another can be reduced by excluding event pairs that are 'obviously' different. In our case we rejected event pairs that were too dissimilar in location, peak amplitudes, energy envelopes, P- and S-wave amplitudes or P- and S-wave phases.

(5) Doublets should be linked together to form multiplets of similar events.

(6) Locations should then be based on arrival-time differences obtained from cross-correlation analyses on all doublets. The absolute location of the events
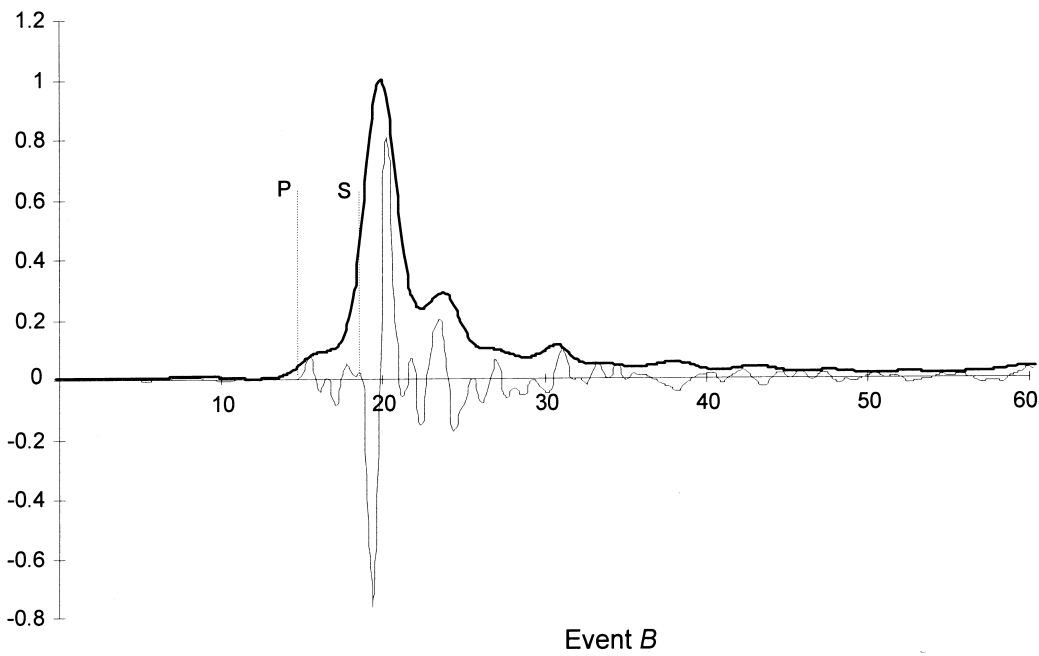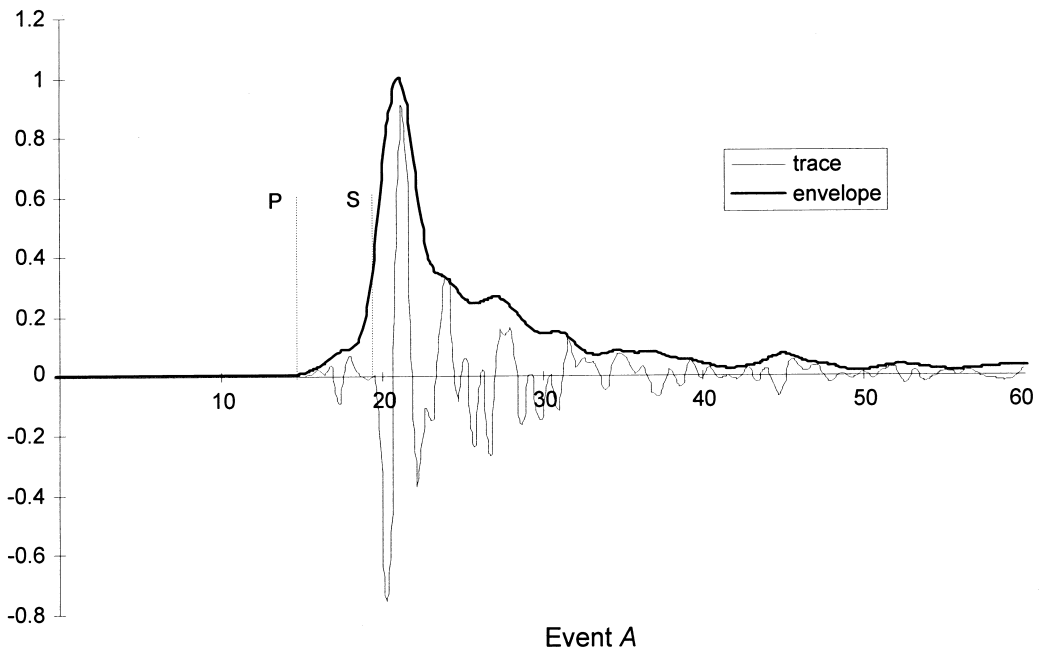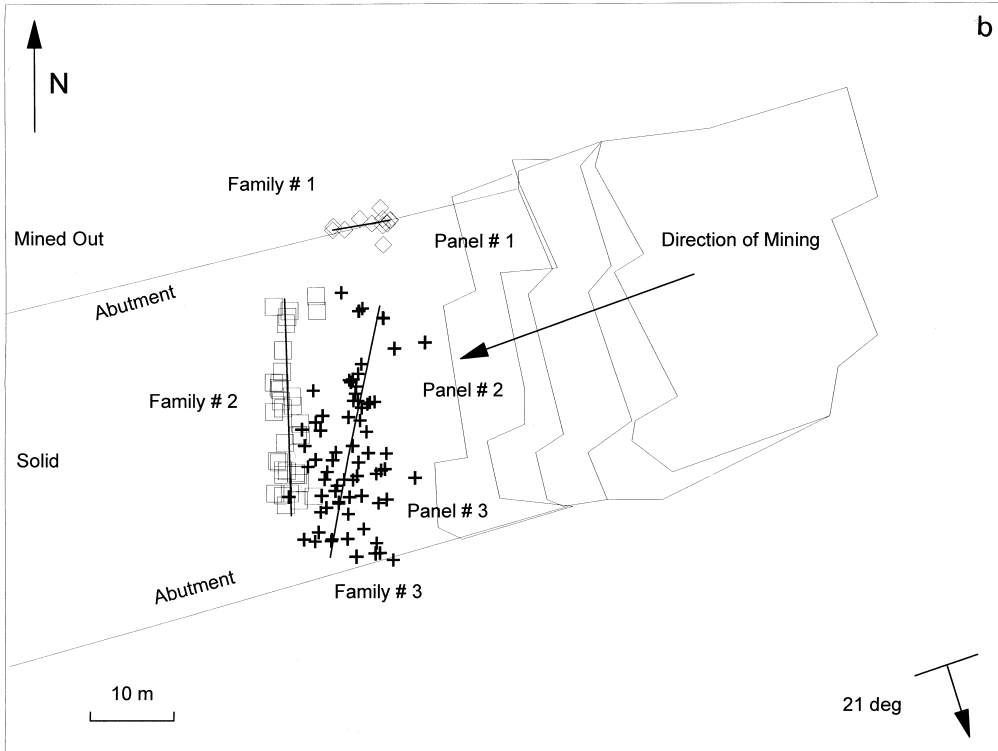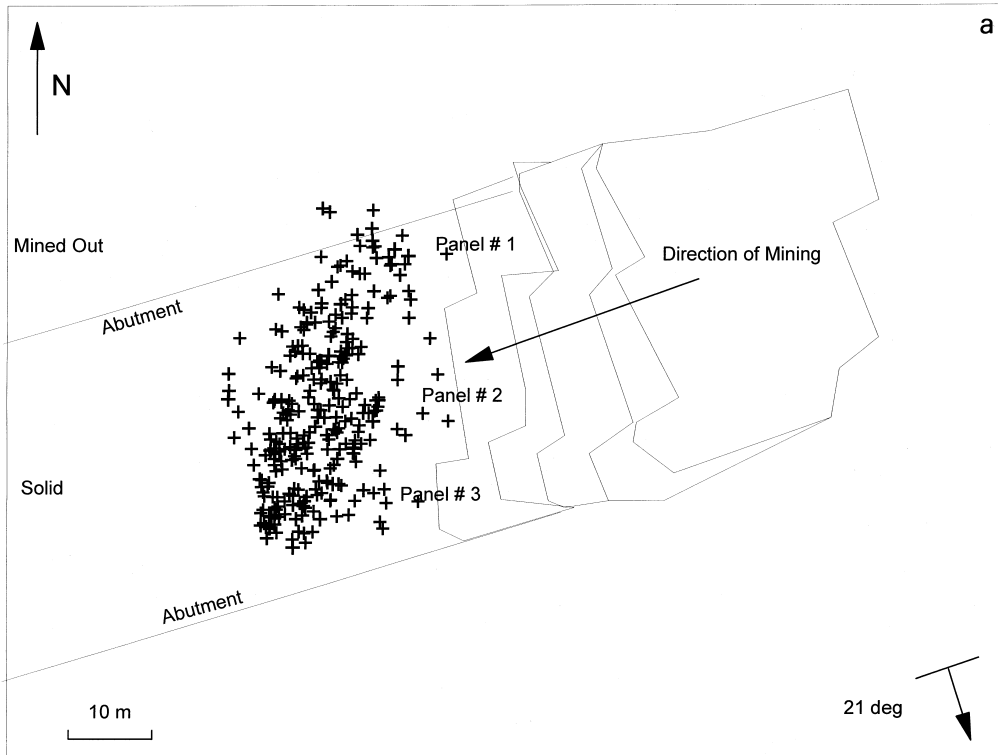
Fig. 1. Pair of seismograms from Family 1 and their energy envelopes: Event A; 28 Jan. 1995; $t_0 = 12:24:39$; $X = 36385$; $Y = 22177$; $Z = -2183$; $M = -0.97$; Event B; 6 Jan. 1995; $t_0 = 23:44:51$; $X = 36378$; $Y = 22177$; $Z = -2184$; $M = -1.26$.
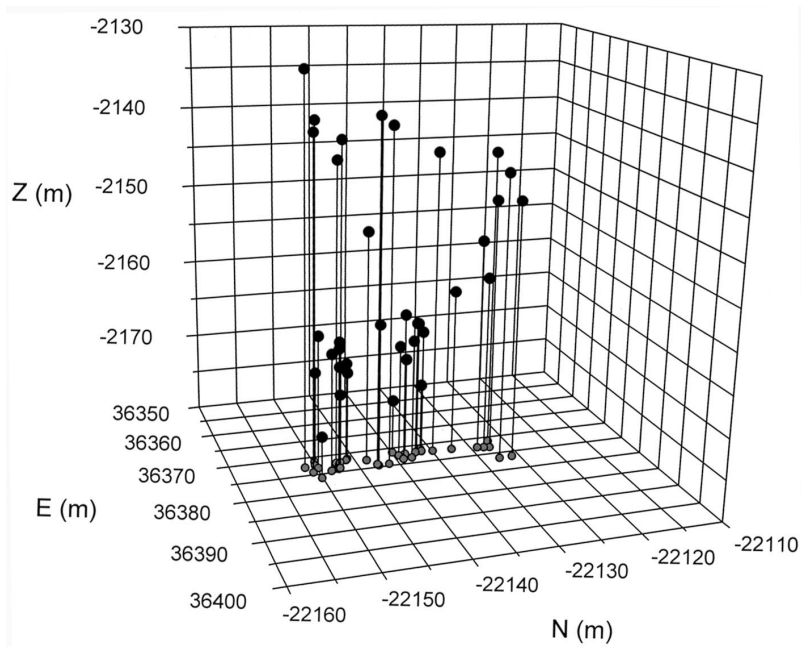
Fig. 3. A 3D view of events distribution with their horizontal projection for Family 3.

should be stabilised by using all available arrival times.

(7) The number of knowns will increase as N^2 while the number of unknowns is $4N$, where N is the number of events. For large values of N, we then have a large amount of redundancy and outliers can easily be identified and rejected.

(8) Principal Component Analysis should then be used to identify planarity of events in each family.

These objectives were met by a set of four computer programs developed for this study. We use the names of the programs here because they perform distinct functions and the names are useful for understanding these functions: ENVEL generates energy envelopes; CCM writes cross-correlation matrices; MULT identifies multiplets and performs locations; and PCA performs Principal Component Analysis. In practice, these programs can be automatically queued.

ENVEL calculates envelopes for all waveforms. The energy envelope is the sum of kinetic and potential energies, where the potential energy is the quadrature function calculated from a 90 degrees phase shift in the frequency domain. We low-pass filter the energy function and store the lowest Fourier components of this function to facilitate later cross-correlation. Fig. 1 illustrates two similar events and the square root of the energy envelopes as recorded by one geophone.

CCM generates cross-correlation matrices between all event pairs that are sufficiently similar. As similarity between events can be measured in many different ways and it is desirable to speed up this time-critical process, we considered five stages of similarity and rejected dissimilar pairs at each stage. The five stages of comparison for each event pair were: location of the events, when available; peak amplitude at each pair of seismograms; envelopes for

Fig. 2. (a) Plan view showing a pillar being mined at Blyvooruitzicht Gold Mine together with seismic locations based on manually selected P and S arrival times. Three working faces, or panels, were mined simultaneously along the dip length of the pillar. (b) Plan view with the positions of families and PCA best-fit plane after applying the relocation procedure. The PCA plane is drawn through the centre of gravity of the locations.
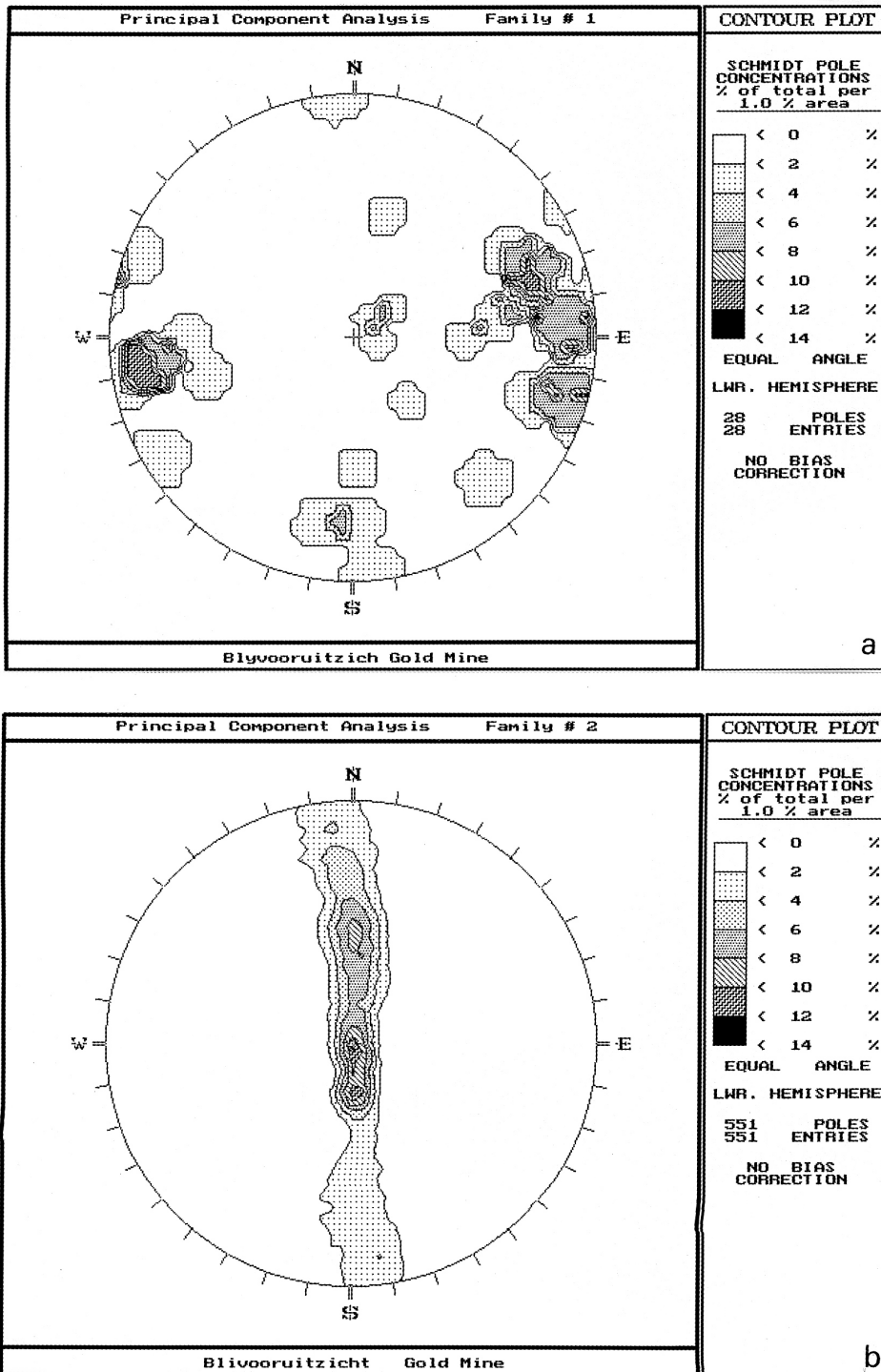
Fig. 4. (a, b, c) Contours of vectors drawn between pairs of events using a lower hemisphere projection: (a) corresponds to Family 1, (b) to Family 2, and (c) to Family 3, as identified in Fig. 2b.
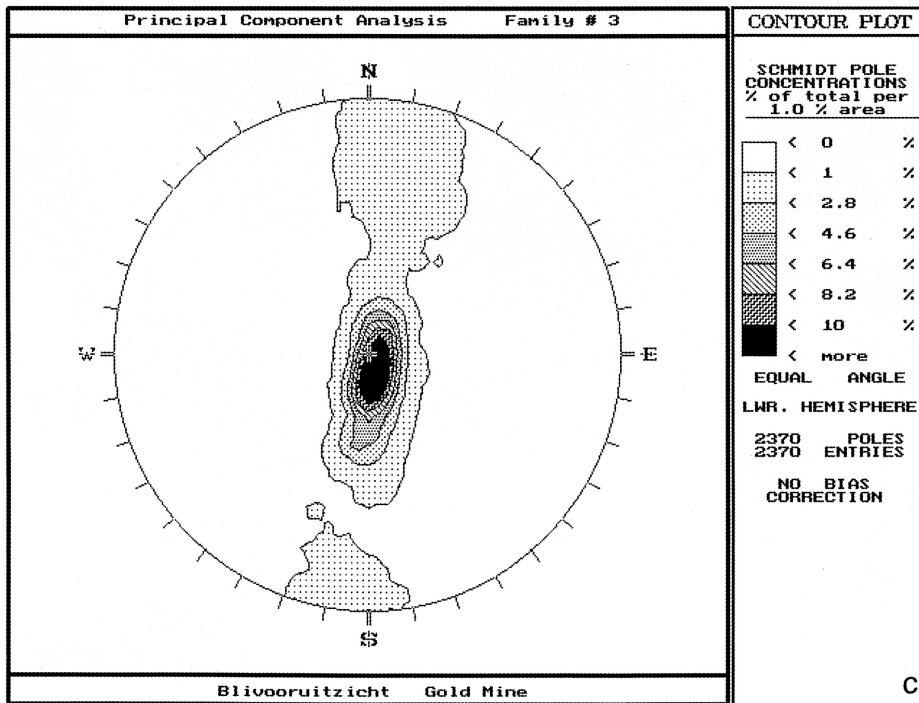
Fig. 4 (continued).

each pair of seismograms; P- and S-wave amplitudes at each pair of seismograms; and P- and S-wave pulses. During the stage of envelope cross-correlation, the time difference between the two events was used for selection of time window for correlation of the P and S pulses.

Cross-correlation of each phase was performed for ground displacement in the frequency domain. As suggested above, this was done to reduce the effect of differences in the details of the source processes at the corner frequency and above. A noise window before the P-wave arrival was used to define the signal-to-noise ratio in the frequency domain and Wiener filtering (Press et al., 1992) was used to minimise the effect of noisy frequencies.

MULT builds up multiplets of event pairs with a large number of similar phases using Equivalent Classes (Press et al., 1992). Arrival-time differences between all pairs within a multiplet are then used to obtain relative locations by minimising the weighted sum of squares of all arrival-time differences

$$
\begin{aligned}
E = \sum_{cijk} & q_{cijk}[t_{cijk} - (t_{0j} - D_{ij}/V_{cij}) \\
& - (t_{0k} - D_{ik}/V_{cik})]^2 \\
& + \sum_{cij} q'_{cij}[t'_{cij} - (t_{0j} - D_{ij}/V_{cj})]^2
\end{aligned} \tag{1}
$$

where q is a quality factor obtained from cross-correlation factors and amplitudes, q' is a quality factor for picked arrival times (we used $q' \ll q$ so that less weight was given to picked arrivals, especially for distant geophone sites), c is the P or S phase, i is the site number, j and k are the events; the pair is then (j, k), t is the arrival-time differences between event pairs as identified by CCM, t' is the picked arrival times, t_0 is the origin time of each individual event, D is the hypocentral distance and V_c is P or S velocity. It was found that blasts were located with 5 m accuracy using constant velocities of $V_P = 5860$ m/s and $V_S = 3748$ m/s.

Minimisation is done using the standard Gauss–Newton method (Press et al., 1992). Whereas the number of arrival-time differences increase as

$(N − 1)$ for the classical master event method, in our method the number of arrival-time differences increase as $N*(N − 1)/2$, where N is the number of events. For a large value of N, this can result in a high level of redundancy and we rejected data with errors that exceeded three standard deviations.

Eq. 1 does not make any allowances for the difference between the hypocentral and centroid locations. Hypocentral locations are based on arrival times and represent the initiation of rapid slip. Arrival-time differences that are based on cross-correlation between event pairs, measure temporal and spatial differences in the event centroids, the 'centre of gravity' of each event. We minimised the effect of this error on relative locations by using a very low quality, or weighting, factor for picked arrival times.

Having found families of similar events we derived the planes of location by PCA. Initially we performed PCA using the 'three-point method' (Fehler et al., 1987) in which the normal to the 'best' plane is found from normals to the triangles formed by all combinations of three events at a time. The existence of location errors require that small and flat triangles must be rejected. As this rejection procedure seemed rather arbitrary and the number of surviving triangles for our largest multiplet exceeded the maximum allowed by the contouring software that we used, we developed a 'two-point' method based on the assemblage of vectors between each pair of events.

In our 'two-point' method, we searched all directions in the lower hemisphere, in one degree intervals in dip and strike and measured the angle between this direction and each vector formed between event pairs. The Principal Component was then taken as the centre of the smallest solid angle that included at least 50% of the normals to the vectors.

3. Results and discussion

We tested this method on seismic data recorded underground at a site in Blyvooruitzicht Gold Mine, South Africa, in which a strike stabilising pillar has been mined from one end with the aid of precondition blasting (Kullmann et al., 1996). Events were recorded at twelve geophones grouped into six sites using a Portable Seismic System (PSS) (Pattrick et al., 1990). The geophones are grouted at the ends of boreholes drilled about 10 m into the rock mass from tunnel sidewalls and the ground motion was digitised at 10,000 samples per second. We considered 297 consecutive events with magnitudes in the range $−1.0 \leq M_L \leq 1.0$.

Handley et al. (1996), attempted to model seismograms from seismic events in the same pillar and found that the extensive mining around the pillar resulted in complex waveforms that are not amenable to mechanism solutions based on a homogeneous rock mass. They modelled the stopes as voids using a finite-difference program and found improved, but still very imperfect, fit between the observed and modelled seismograms. We suggest that it is almost inevitable that the most intense mining-induced seismicity takes place within altered rock close to mining voids and therefore is not amenable to inversion using assumptions of rock mass homogeneity.

Fig. 2a shows a plan view of the site and the 300 seismic events associated with the mining that occurred in the first quarter of 1995. The locations were calculated using hand-picked P and S arrival times.

Fig. 2b shows the same events after grouping into multiplets and relocation using MULT with a cut-off value for the cross-correlation factor of 0.8. Some 39% of the events were grouped into three multiplets with five or more events. Smaller multiplets are not amenable to PCA and are not shown in Fig. 2b. We found 0.8 as an optimal cut-off for this data set. The smaller cut-off values than 0.8 resulted in one large dominant multiplet and a number of much smaller multiplets. For cut-off values larger than 0.8 too many events were rejected. It can be seen that the three families presented in Fig. 2b are well separated. We now relate them to mining and geological features.

Family 1 consisted of ten events that formed a subvertical plane with a strike parallel to the up-dip edge of the pillar. Fractures in this position and with this orientation are expected from the stresses acting along the edge of the pillar and are exposed during the regular face advance. Some of these fractures date from the previous mining up-dip of the pillar, as evidenced from rusting of exposed pyrites. This fracturing relaxes the stresses on the up-dip side of the pillar.

Family 2 consisted of 35 events on a plan parallel to the face of panel 2. This panel mines the core of the pillar. This is the most highly stressed portion of

the pillar and mining is likely to result in rock failure deeper into the pillar.

Family 3 consisted of 72 members, the largest family of this site. The strike direction of this family of events is parallel to the existing joint system and to the overall orientation of the three panels together. The kinks, or leads and lags, between panels facilitate removal of the rock. Fig. 3 is a 3D section that shows the vertical planarity of this multiplet.

The contours of density of vectors for the families are presented in Fig. 4 (a, b, c, respectively). Family 1 has fewer members and is therefore less well defined than the other families. The planes through families 2 and 3 were very well defined and almost vertical.

The improved resolution of the seismic events shown in Fig. 2b over the original locations in Fig. 2a could be attributed to three factors. Firstly, the identification of events into distinct families. Without the different symbols used in Fig. 2b, separation of families 2 and 3 would not be as convincing. Secondly, not all the events fell into these three families. Thirdly, the original locations were subject to errors of less 5 m, as estimated from RMS errors and confirmed from errors in the location of known blasts. The RMS errors in the relative locations were typically less than 2 m.

4. Conclusions

The results reported in this paper illustrate the capabilities of this new multiplet location method which does not require a master event. This is an extension of the doublet cross-correlation method with a master event. Events were automatically separated into several multiplets. The two-point PCA technique provided a best-fit plane through these locations. The planes of location showed agreement with mining and geological features that could not be anticipated from the original locations.

The methods presented in this paper were developed for mining-induced seismicity, but could be applied directly to the study of local earthquake sequences.

Acknowledgements

References

Deichmann, N., Garcia-Fernandez, M., 1992. Rupture geometry from high-precision relative hypocentre locations in micro-earthquake clusters. Geophys. J. Int. 110, 501–517.

Fehler, M., House, L., Kaieda, H., 1987. Determining planes along which earthquakes occur: Method and application to earthquakes accompanying hydraulic fracturing. J. Geophys. Res. 92, 9407–9414.

Fremont, M.-J., Malone, S.D., 1987. High precision relative locations of earthquakes at Mount St. Helens, Washington. J. Geophys. Res. 92, 10223–10236.

Gay, N.C., Spencer, D., Van Wyk, J.J., Van Der Heever, P.K., 1984. The control of geological and mining parameters on seismicity in the Klerksdorp gold mining district. In: Gay, N.C., Wainwright, E.H. (Eds.), Proc. 1st Int. Congr. Rockbursts and Seismicity in Mines. S. Afr. Inst. Min. Metall., Johannesburg, pp. 107–120.

Handley, M.F., Hildyard, M.W., Spottiswoode, S.M., 1996. The influence of deep mine stopes on seismic waves. In: Abertin, M., Hassany, F., Mitri, H. (Eds.), Proc. 2nd North American Rock Mechanics Symposium: NARMS'96. Balkema, Rotterdam, pp. 499–506.

Ito, A., 1985. High resolution relative hypocenters of similar earthquakes by cross-spectral analysis method. J. Phys. Earth 33, 279–294.

Kullmann, D.H., Stewart, R.D., Grodner, M., 1996. A pillar preconditioning experiment on a deep-level South African gold mine. In: Abertin, M., Hassany, F., Mitri, H. (Eds.), Proc. 2nd North American Rock Mechanics Symposium: NARMS'96. Balkema, Rotterdam, pp. 375–380.

Michelini, A., Bolt, B.A., 1986. Application of principal parameters method to the 1983 Coalinga, California Aftershock sequence. Bull. Seismol. Soc. Am. 76, 409–420.

Moriya, H., Niitsuma, H., Rutledge, J.T., Kaieda, H., 1996. Subsurface stress field determination using multiplets in downhole three-component microseismic measurement. Proc. 2nd North American Rock Mechanics Symposium: NARMS'96. Balkema, Rotterdam, pp. 853–858.

Ortlepp, W.D., 1978. The mechanism of a rockburst. Proc. 19th U.S. Rock Mechanics Symposium, Univ. of Nevada, Reno, pp. 476–483.

Pattrick, K.W., Kelly, A.M., Spottiswoode, S.M., 1990. A portable seismic system or rockburst applications. Int. Deep Mining Conference: Technical Challenges in Deep Level Mining. S. Afr. Inst. Min. Metall., Johannesburg, pp. 1133–1146.

Poupinet, G., Ellsworth, W.L., Frechet, J., 1984. Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras fault, California. J. Geophys. Res. 89, 5719–5731.

Press, W.H., Flannery, B.P., Teukolsky, S.A., Veterling, W.T.,

1992. Numerical Recipes: the Art of Scientific Computing (2nd ed.). Cambridge University Press, Cambridge, 450 pp.

Rorke, A.J., Roering, C., 1984. Source mechanism studies of mine-induced seismic events in a deep-level gold mine. In: Gay, N.C., Wainwright, E.H. (Eds.), Proc. 1st Int. Congr. Rockbursts and Seismicity in Mines. S. Afr. Inst. Min. Metall., Johannesburg, pp. 51–55.

Spottiswoode, S.M., 1984. Source mechanisms of mine tremors at Blyvooruitzicht gold mine. In: Gay, N.C., Wainwright, E.H. (Eds.), Proc. 1st Int. Congr. Rockbursts and Seismicity in Mines. S. Afr. Inst. Min. Metall., Johannesburg, pp. 29–37.

Urbancic, T.I., Trifu, C.-I., Young, P., 1993. Microseismicity derived fault-planes and their relationship to focal mechanism, stress inversion and geologic data. Geophys. Res. Lett. 20, 2475–2478.