A hybrid location methodology

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Synopsis

The aim of the hybrid location method is to improve seismic event locations by reducing the effects of errors in the wave velocity of ray paths between each event and each recording site. We report on further enhancements made to the hybrid location algorithm, which is based on the double-difference method developed by Spottiswoode and Milev[1] and Waldhauser and Ellsworth[2]. The term 'double-difference' refers to the residuals between the observed and theoretical travel-time differences and are obtained using either picked arrival times or various measures of time differences obtained from waveform pairs. These residuals are minimized for pairs of earthquakes at each station while linking together all observed event-station pairs.

An important enhancement is that the double-difference term uses the median arrival time residuals to reduce the effect of outliers on the system of equations. In addition, the hybrid locations are further constrained by considering events of known locations, in this case along lines of development blasts.

We relocated some 20 000 previously located seismic events in the Driefontein 5E area; 5 800 of these events were considered to have been development blasts and we constrained their locations to lie on the straight lines joining about 2 150 survey pegs from the mine's database. Relocated events were shown to distribute more closely around advancing faces than had been the case before relocation. Wave velocities from the development blasts show evidence of anisotropy.

Introduction

The position in 3-D space or 'location' of a seismic event is the most fundamental parameter because all other parameters (e.g. magnitude and seismic moment) are derived from it. The identification and interpretation of seismically active features is dependent on accurate locations. In addition, the integration of seismic data with modelling for improved estimates of future seismicity requires accurate locations (e.g. Spottiswoode[3]). However, event locations are subject to a number of sources of error, resulting in scattering of the hypocentres. These sources of errors are a result of inconsistent phase picking, poor recognition of wave phases, network geometry and inhomogeneities in the rock mass, resulting in the travel times being too slow or too fast. This last source of error is of particular relevance to this paper because the main objective of the location methods discussed (relative and hybrid) is to reduce the effects of errors in velocity structure.

At present, the seismic velocity structure within mine seismic networks is typically based on trial-and-error schemes designed to reduce error estimates and to move events closer to active mining or to geological features. On occasion, P- and S-wave velocities have been obtained from calibration blasts. Ideally large (~50 kg) well-tamped charges are set off close to a geophone to obtain the event origin time. The results are usually interpreted in terms of a constant velocity model. In this paper we will use events that we considered to be development blast events to constrain locations and also to provide insights into the velocity structure in the study area.

Relocating event locations to reduce hypocentral scattering is currently a hot topic in both global seismology and mining seismology, and a numbers of methods have been proposed[5]. Most of these methods are based on the time residuals and velocity model, and consider clusters of events. These so-called relative methods utilize the arrival-time differences between a reference or master event and nearby events. The arrival times are adjusted by corrections for each arrival time based on time residuals from a chosen master event. These adjusted arrival times are then used to locate events close to the master event.

This paper focuses on improving the 'double-difference' method developed by Spottiswoode and Milev[1], Waldhauser and Ellsworth[2] and Spottiswoode and Linzer[4]. The term 'double-difference' refers to the residuals between the observed and theoretical travel-time differences and are obtained using either picked arrival times or various measures of

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time differences obtained from waveform pairs. These residuals are minimized for pairs of earthquakes at each station while linking together all observed event-station pairs.

The enhancements are as follows:

- All recorded events in the database are used as master events. Previously Spottiswoode and Milev[1] used only groups of similar events called multiplets
- All sites that record events are used, not just the recording sites common to all the events in the data-set
- The location of every event is influenced by all nearby events
- Events with additional constraints on their locations, such as development blasts, are used to constrain the hybrid locations. Events from blasting during tunnel development are forced to lie along lines between survey points along these tunnels. Exact locations would have been preferable, but could not be easily determined
- The median of the distribution of residuals is used to weight the data. Experience gained by Andersen (Linzer)[6] and Spottiswoode and Linzer[4] suggests that use of median corrections is both more stable and more accurate, even while the location of individual events is based on weighted least-squares minimization
- The data recorded from closer geophones is given a greater weight, when absolute locations are computed using classical methods, to reduce errors caused by velocity errors from long ray paths.

Spottiswoode and Milev[1] used seismograms from about 300 events whereas, in this paper, an event catalogue consisting of about 20 000 events recorded at six or more sites was used. Only the P- and S-wave arrival times as picked by the mine for routine locations were used.

Theory

Absolute location method

Most absolute location methods are based on the classic Geiger[7] formulation. These methods involve minimizing the sum of the squared residuals (or differences) between the observed and theoretical arrival times. For event i recorded at sites $k = 1,...,n$ the residual is given by:

$$r_{ik} = T_{ik}^{obs} - T_{ik}^{th} \qquad [1]$$

and the sum of the squared residuals to be minimized is:

$$\sum_{k=1}^{n} \left(r_{ik}\right)^2 = \sum_{k=1}^{n} \left(T_{ik}^{obs} - T_{ik}^{th}\right)^2 . \qquad [2]$$

The observed arrival times T_{ik}^{obs} are the phase picks of the P- and S-waves of the seismogram and the theoretical arrival times T_{ik}^{th} are calculated using:

$$T_{ik}^{th}\left(x_{oi}, y_{oi}, z_{oi}\right) = t_{oi} + t_{ik} \qquad [3]$$

where t_{oi} is the origin time of the event hypocentre and the term t_{ik} is the travel time between the hypocentre and recording station k. The travel time is calculated using d_{ik}/v_{ik} where d_{ik} is the distance between the hypocentre (x_{oi}, y_{oi}, z_{oi}) of event i and recording station k and v_{ic} is the velocity assumed for the wave phase along the ray path.

The standard approach to solving Equation [2] is described in most textbooks (e.g. Gibowicz and Kijko[8]) and involves assuming an initial value for the focal parameters that are being solved for and applying the first-order Taylor expansion to linearize the equation.

The approach described thus far assumes that all observed arrival times T_{i1}^{obs}, T_{i2}^{obs},..., T_{in}^{obs} are equally reliable. Unfortunately, this is often not the case for data recorded in the mining environment because mining voids (stopes, tunnels, etc.) and inhomogeneities in the rock mass affect the ray paths, resulting in errors in the travel times. Other sources of error are caused by the network geometry and picking inconsistencies. To counteract these error sources, weighting schemes are often applied to downgrade the arrival times that are considered less reliable than the others.

Relative locations

Another approach often used to reduce the travel time anomalies resulting from velocity model uncertainties is the relative location method, also known as the 'master event' or arrival time difference (ATD) method. The relative methods are applicable when the hypocentral separation between two events is small compared to the event-station distance and the scale length of the velocity heterogeneities[2]. If these conditions are met, the ray paths between the source region and a common station are similar along almost the entire ray path and the difference in travel times for two events observed at one station can be attributed to the spatial offset between the events. This method does, however, depend on there being accurately located reference events, i.e. an event with known hypocentre and origin time.

Several variants of the relative location method are presented in the literature. In the master event method, each event in the spatial cluster is relocated relative to one event. The disadvantage of this is that selection of the master event is subjective and errors in master event can lead to biased solutions. The master event method is also limited spatially because all events in the cluster must correlate with the master event.

Got *et al.*[9] improved the method by determining cross-correlation time delays for all possible event pairs. These were then combined into a system of linear equations and solved using least-squares methods to obtain the hypocentroid separations. (The hypocentroid differs from the hypocentre in that it represents the centre of the rupture volume, whereas the hypocentre indicates the start of the rupture). The method is limited however because it cannot relocate uncorrelated clusters relative to each other.

Double-difference methods

Waldhauser and Ellsworth[2] extended the relative method further by considering both the P- and S-wave differential travel times derived from cross-spectral methods with travel time differences calculated from catalogue data for pairs of events. The method simultaneously determines inter-event distances between clusters of correlated events while determining the relative locations of other clusters and uncorrelated events.

Waldhauser and Ellsworth[2] defined the residual between the observed and calculated travel times between the two events i and j recorded at site k as:

$$r_{ijk} = \left(t_{ik} - t_{jk}\right)^{obs} - \left(t_{ik} - t_{jk}\right)^{th} \quad [4]$$

and referred to the term on the right-hand side of the equation as the 'double difference'. Equation [4] can be rewritten by regrouping the travel times as:

$$r_{ijk} = \left(t_{ik}^{obs} - t_{ik}^{th}\right) - \left(t_{jk}^{obs} - t_{jk}^{th}\right) \quad [5]$$

This step may seem trivial, but is useful in the description of the hybrid method later in the paper.

Waldhauser and Ellsworth[2] applied *a priori* quality weights to the arrival times, expressing the precision of the cross-correlation measurements, quality and consistency with which the first-motion arrival times are determined on a routine basis, and the relative accuracy between the two data-sets. Their solution procedure involves two steps: first iterate using the *a priori* quality weights until a stable solution is obtained, and then iterate further with reweighting of the data. The data are reweighted by multiplying the *a priori* quality weights with weights that depend on the misfit of the data from the previous iteration and on the offset between events (to downweight event pairs with large inter-event differences).

Hybrid location method

The hybrid location method is so called because it is a combination of the double difference method and absolute methods. The method was first proposed by Spottiswoode and Milev[1], extended by Spottiswoode and Linzer[4] and is developed further in this paper. In addition, the method described in this paper is similar to that used by Andersen (now Linzer)[5] and Andersen and Spottiswoode[10] for moment tensor inversions.

The advantages of the hybrid location method when compared with the relative method are as follows:

- In effect, all events act as master events: there is no need to select individual events as master events
- All sites that record events are used
- Events are influenced by, and influence, nearby events
- Events with known or constrained locations will keep a control on the absolute locations of all events Development blasts are such events, either with known locations in three dimensions or constrained to lie along a tunnel
- Very large data-sets can be used because the amount of memory required is proportional to the number of events
- The only parameters needed are four weighting factors and one characteristic distance described below.

For events i and j recorded at site k, the residual is defined as:

$$\begin{aligned}\left(r_{ijk}\right)^2 &= w^{ABS}\left[T_{ik}^{obs} - T_{ik}^{th}\right]^2 \\ &+ w^{2D}\left[\left(T_{ik}^{obs} - T_{ik}^{th}\right) - median\left(T_{jk}^{obs} - T_{jk}^{th}\right)\right]^2 \\ &+ \sum_2 w^{LINE}\left[d_i / v_k\right]^2 = w^{ABS}A_{ik} + w^{2D}B_{ijk} \\ &+ w^{LINE}C_{ik} + w^{LINE}D_{ik}\end{aligned} \quad [6]$$

where $A_{ik} = [T_{ik}^{obs} - T_{ik}^{th}]^2$,
$B_{ijk} = [(T_{ik}^{obs} - T_{ik}^{th}) - median(T_{jk}^{obs} - T_{jk}^{th})]^2$,
$C_{ik} = [d_i/v_k]^2$ and
$D_{ik} = [d_i/v_k]^2$

and d_i is the distance of event i from either of two planes through the tunnel for a development blast, and v_k is the velocity assumed for the wave phase along the ray path.

The first term in Equation [6] (containing A_{ik}) is the absolute location component, the second term (containing B_{ijk}) has the form of the double difference described by Equation [5], and the third and fourth terms (containing C_{ik} and D_{ik}) are the distance from two planes (oriented vertically and horizontally) that describe the line of the tunnel. The procedure is iterative and the weighting factors (w^{ABS}, w^{2D}, w^{LINE}) control the influence of each term on the system of equations and are recalculated for each iteration.

The absolute weighting factor w^{ABS} controls the influence of the residuals for the absolute location on the system of equations and is composed of three variables:

$$w^{ABS} = w^{STEP} \cdot w^{PHASE} \cdot w^{HYPO} \quad [7]$$

where w^{STEP} runs from 1 to 0.05 (in steps of 0.05) as the iterative scheme progresses, allowing the location method to vary from being purely absolute (at $w^{STEP} = 1$) to having a dominant relative contribution (at $w^{STEP} = 0.05$). The second variable w^{PHASE} depends on the phases used in the location, with P-wave residuals having a higher weighting that the S-wave residuals because the P arrivals are generally more consistently picked than the S arrivals: for P waves $w^{PHASE} = 1$ and for S waves $w^{PHASE} = 0.5$. w^{HYPO} is a weighting factor that is unity at close hypocentral distances, decaying inversely with distance at large hypocentral distances. This is used in an attempt to balance the adverse effects of small errors in wave velocities at large distances, introducing large time residuals and location errors.

The double-difference weighting factor w^{2D} allows the double-difference residual to be introduced gradually into the system of equations and is given by:

$$w^{2D} = \left(1 - w^{STEP}\right) \cdot w^{PHASE} \quad [8]$$

where $(1-w^{STEP})$ runs from 0 to 0.95 (in steps of 0.05) for each iteration. This allows the double-difference residual to be introduced gradually into the system. w^{HYPO} is not applied to double-difference residuals because the effect of velocity errors along long ray paths is cancelled out.

w^{LINE} is the weighting factor controlling the impact of the lines of development blasts on the system of equations and restricts the locations of the blasts to lines.

Note that the second term of Equation [6] (containing B_{jk}) consists of the difference between the arrival time residuals of event i and the median arrival time residuals of event j. The median is used rather than the mean because the median is less sensitive to outliers and because a large number of master events are used. A weighted median is used, where weights are equal to $w^{PAIR} = e^{-(Di/Dh)^2}$: Di is the inter-event distance and Dh is a proportion of average hypocentral distance. (A value of Dh = 80m ≈ 5% of average hypocentral distance was used in this study). Median-based weighting schemes have also shown success in the moment tensor inversion method developed by Andersen (Linzer)[6].

The arrival-time differences between all pairs of events are used to obtain hybrid locations by minimizing the weighted sum of squares of all arrival-time differences. Minimization is done using the standard Gauss-Newton method[11]. In general, this method results in the number of

arrival-time differences increasing as $N(N-1)/2$, where N is the number of events whereas, for the classical master event method, the number of arrival-time differences increase as $(N-1)$. Because this N^2 scaling is the time-consuming inner loop of the operation, it was appropriate to reduce it. In the present study, we reduced to $N(N-1)/2$ to $M(N-1)$, where M events, earlier and later than the current event, are searched until $\Sigma w^{PAIR} > 250$. This provides an amply statistical population, while keeping the run-times reasonable, namely about 1.5 hours for 20 000 events.

Group location method

At the same time as the work reported here and previously[4], a group location method was developed by Cichowicz[12]. Results of the group and hybrid location method have not yet been compared.

Case study

The No 5E shaft area of Driefontein Gold Mine is being mined on the Carbon Leader Reef through a system of closely-spaced dip pillars at a depth of about 3 000 m below surface. This area is the subject of research to optimize the pillar design[3]. Klokow *et al.*[13] found that the seismicity per area mined occasionally increased at spans of about 100 m and remained high until the final design span of 140 m and pillars 40 m wide. The 5E area is covered by an extensive mine seismic network and more than 10 geophones trigger for events with local magnitude greater than 0. Despite this dense coverage, detailed relationships between the spatial distribution of seismicity and mining are hampered by location errors that often make it difficult to attribute seismicity to geological features, lead-lags, east or west faces or to either side of pillars. Clearly, any improvements in the quality of the seismic locations would be of great benefit in studying the relationship between mining and seismicity.

Selection of seismic events

We used a data set of more than 37 000 seismic events that were recorded and located in this area between October 1997 and November 2003. The data file of 55 Mb included P- and S-wave arrival times as written by the mine's 'XTRIGQRY' data extraction program. Most of these events were mining induced, associated with the extensive stoping in the area. However, numerous small events were associated with blasting during development of off-reef excavations, such as cross-cuts and footwall drives.

Richardson and Jordan[14] showed that events associated with advancing development had moment-magnitude M(Mo) < 0.5 in a study of nearby mines. They labelled these events type 'A' events and interpreted them as 'fracture-dominated' rupture events, as against the normal type 'B' 'friction-dominated' slip events. This bimodal classification scheme was first mentioned by Ebrahim-Trollope and Glazer[15]. We presented several lines of evidence[3,5] that the events described by Richardson and Jordan[14] were the actual development blasts, and they will be called 'blasts' in this study. Whether these events are the actual blasts or induced events as suggested by Richardson and Jordan, is immaterial in this study because the vast majority of induced events would occur within only a few metres of the tunnel face. As will be seen below, these events locate many tens of metres away from the tunnels and therefore our process of restricting them to locate on the tunnels would reduce the overall location error. Our procedure for distinguishing blast events from mining-induced events is described below.

Mining geometry: stoping and development

The study area is accessed through hangingwall cross-cuts developed from the 5E shaft[13]. These cross-cuts passed through the reef, branched into footwall drives, again into footwall cross-cuts to reef, before turning back into the dip gullies (raises) from which the stoping commenced. The access cross-cuts and haulages are approximately 3.5 m by 3.5 m in section. They were advanced through full-face blasting using slow fuses. Individual charges resulted in small seismic events, recorded by the mine network with local magnitude less than zero.

Stoping then took place from the raises outwards until final dip-aligned pillars were left (Figure 1). The outlines were digitized off a 1:1000 mine plan. As expected, seismicity tended to group around the final high-stressed pillars, as shown in Figure 1(b).

As mentioned above, seismic events identified as development blast events were constrained to lie along the lines between survey pegs placed along the tunnels created

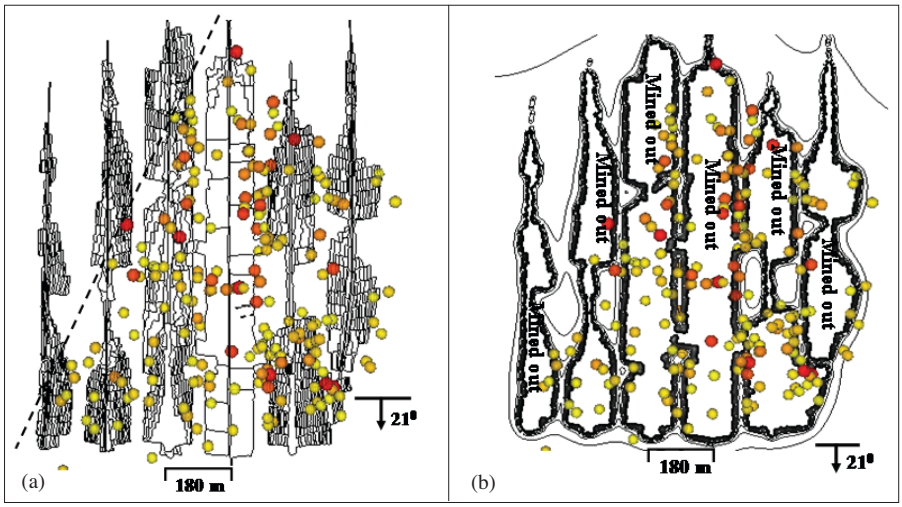

Figure 1—(a) Stoping and seismicity (M>≈2). Data west of Y=-9800 (dashed line) were missing from our data-set. (b) Pillars are highlighted using stress contours from boundary element 'elastic' numerical modelling

by the blasting. Tunnel coordinates were defined here using line segments joining the survey pegs placed along the tunnels. Survey peg data were obtained in spreadsheet format and converted into simple ASCII files for use in this study. The file structure contained peg name, back-sight peg name, spatial coordinates and date of installation. Of the 6 135 pegs that were placed in the 5 Shaft area, 2 150 were identified as off-reef development pegs through a manual search for terms such as 'X/C' or 'FW DRIVE' in the description of each peg. Although this process was simplified by using the sort function provided by a spreadsheet program, such a search could be automated for the production environment by writing appropriate software. The positions of these pegs are shown in Figure 2.

In a separate exercise, on-reef pegs were identified by terms such as 'STOPE', 'GULLY' or 'REEF DRIVE'. We checked that coordinates of the on-reef pegs were in agreement with the digitized face positions graphically, using views similar to those shown in Figure 2.

The entire procedure of separating on-reef from off-reef peg data was made easy by the good quality of the data and was considered to be worthwhile because procedures that we developed here could be used in many mining situations.

Identification of tunnel blast and induced events

As this present study considers seismicity induced by stoping and seismicity from tunnel development blasting, we need to separate tunnel events from induced events. The following selection procedure was applied:

- Events more than 100 m from lines joining any previously installed pegs and more than 200 m from any previous mining face were rejected. Events which were recorded by fewer than six sites were also rejected
- Following the suggestion of Richardson and Jordan[14] as applied by Spottiswoode[3], the development blast events were identified as those with moment-magnitude less than 0.5 (M(Mo)<0.5) and that located within 100 m and within 30 s of another similarly small event. 5 800 events were identified in this way as blast events
- Induced seismic events were the events that were not identified as tunnel events and that located less than 200 m from any previous mining face. 14 001 events were identified as induced events.

Results

Hybrid locations were then obtained with tunnel events being restrained to lie along the lines described by the closest tunnels. Figure 3 shows locations, in plan and section, of these events as given by the mine's catalogue and as relocated in this study.

The tunnel events as shown in Figure 3 fall on lines between pegs shown in Figure 2. A few exceptions can be seen, which result from no specific precaution against events falling on extensions of lines between pegs being applied.

A natural extension of restraining locations to the tunnels is to provide data that can be used to improve our knowledge of the (P-wave and S-wave) velocity structure within the mine seismic network. Results will be shown in the next section.

The purpose of restraining locations of *tunnel* events is principally to improve the locations of the *induced* events so that they can be more readily interpreted in terms of mining and geological features. Figure 4 shows a comparison between catalogue and relocated locations for the larger events. There is insufficient detail at this scale to comment

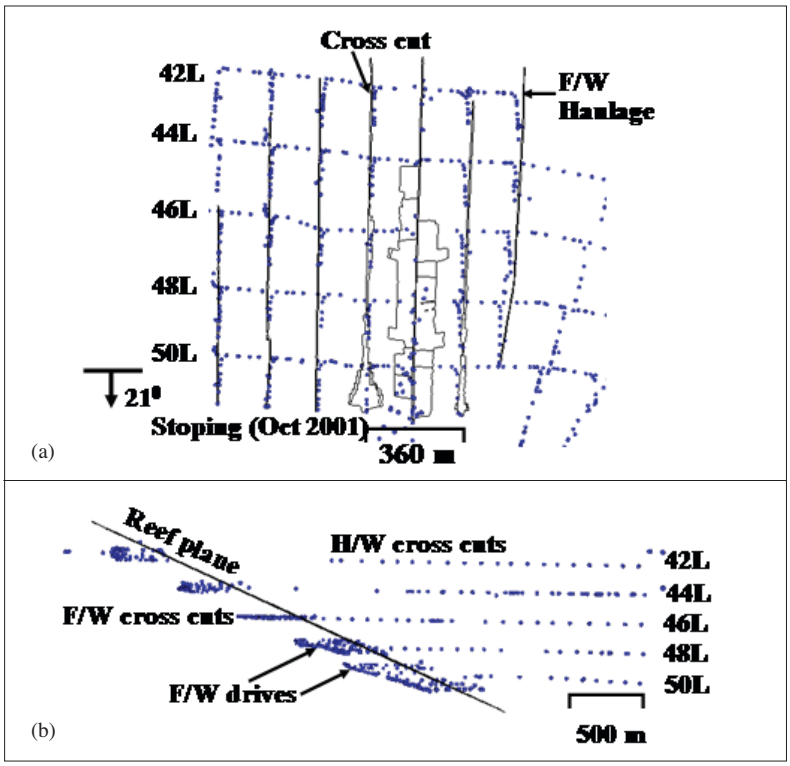

Figure 2—Plot of off-reef tunnel pegs used in this study and face positions in October 2001. (a) is a plan view and (b) is a perspective view looking along the 46 Level Reef intersection

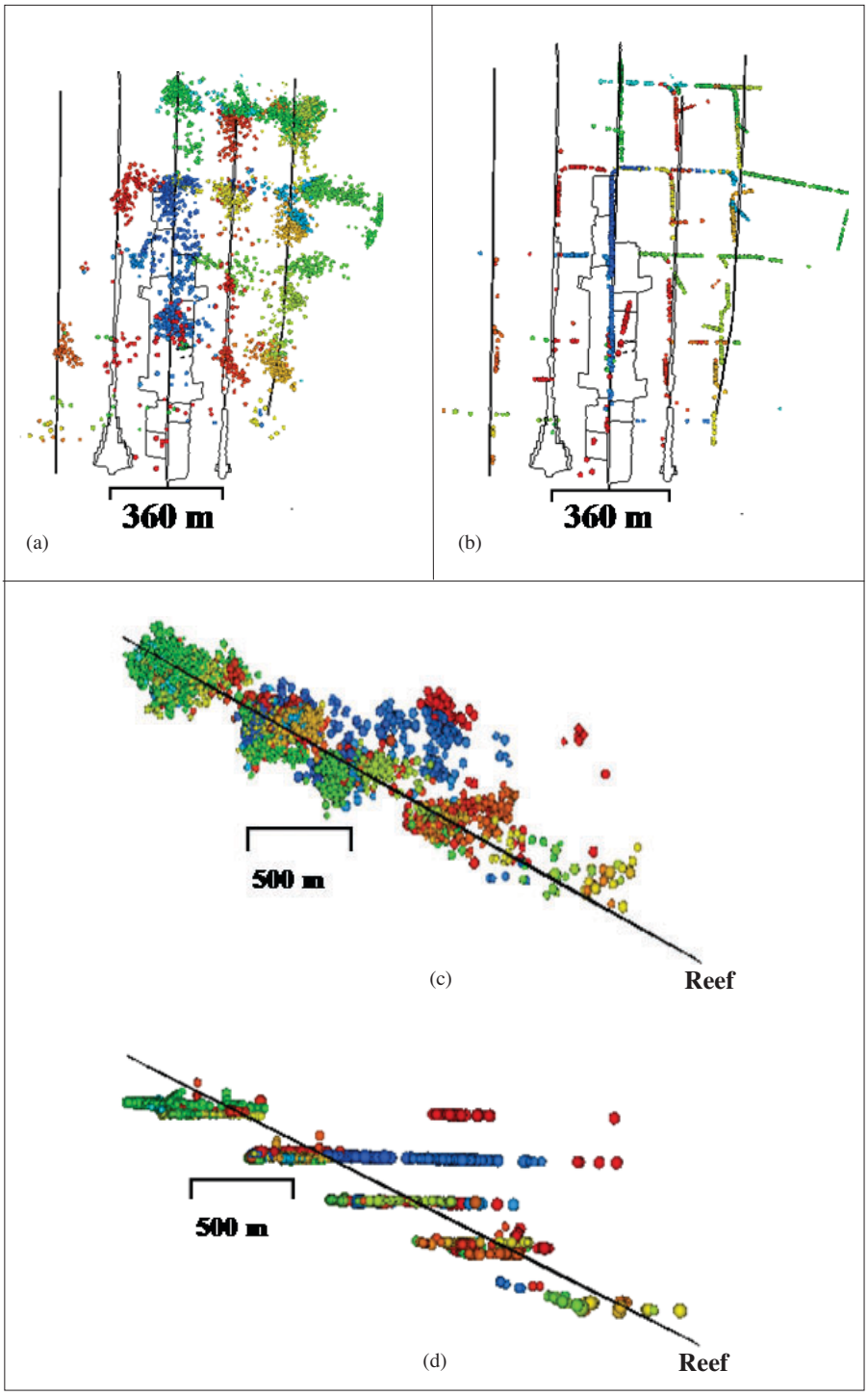

Figure 3—Locations, in plan (a) and (b) and section (c) and (d), of tunnel blast events as per mine catalogue (a) and (c) and after relocation (b) and (d)

on changed locations and a part of Figure 4 is zoomed and shown in Figure 5 for one month's data and all magnitudes.

Here is an interpretation of the seismicity patterns shown in Figure 5, with reference to the seismicity within the areas shown as ellipses.

A: These tiny events were blasts associated with off-reef development, and were brought into a smaller region during relocation

B: Another group of events that were identified as being associated with development. They relocated under the mined-out area in plan and are not visible in Figure 5(b)

C,D,E: Seismicity associated with stoping from the raise on line 29, the right-most stoping shown in this Figure. The relocated data in Figure 5(b) are clearly both more clustered parallel to the face and even plot closer to the face than in the equivalent catalogue data shown in Figure 5 (a).

The seismic patterns associated with stoping from the central raise in Figure 5, on line 28, have shown less

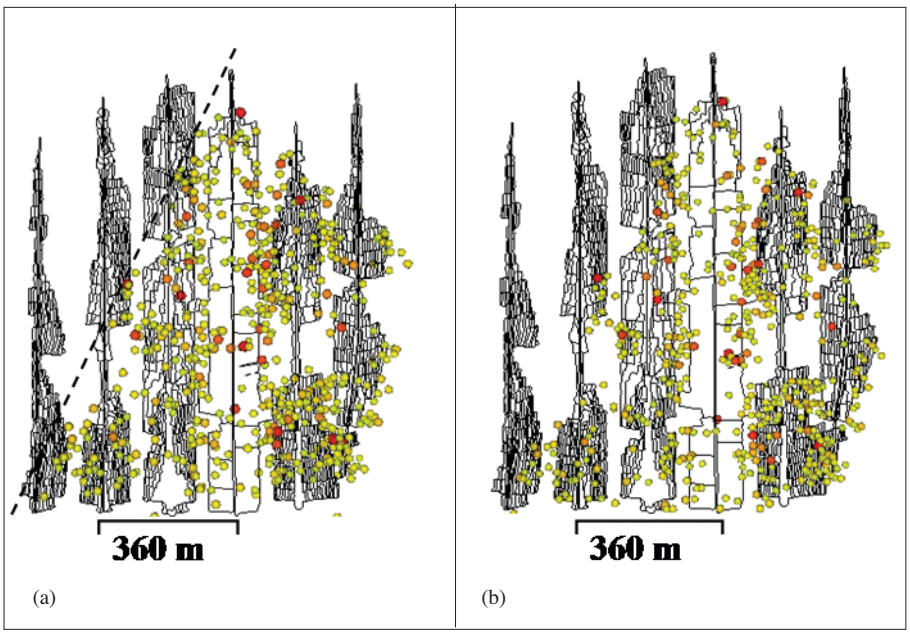

Figure 4—Locations, in plan (a) of M>≈2 seismic events as reported in the mine catalogue (b) after relocation

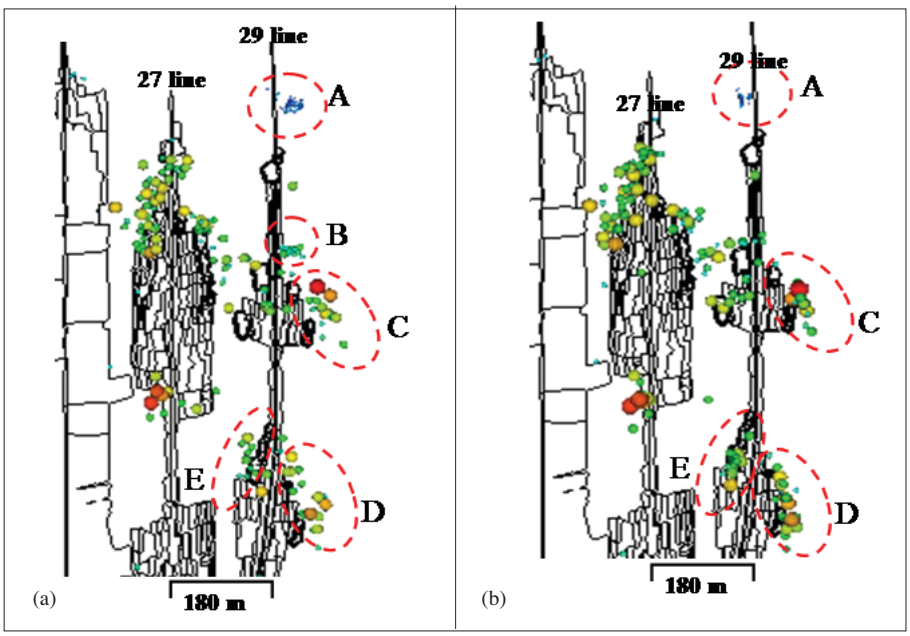

Figure 5—All seismic events during the month of March 2003, together with face positions up to this date. As before, catalogue data are shown in (a) and relocated data in (b). Areas of mining during this month are shown by contours but can only just be seen underneath the events. The appearance of the seismicity in the labelled areas is discussed in the text

consistent change than shown in mining from raise on line 29.

Velocity structure

One of the advantages of restraining seismic events to known tunnels is that the P-wave and S-wave velocity structure within the mine seismic network can be determined.

All the locations reported above were based on the assumption that all P waves travelled at a constant velocity of V_P = 6 359 m/s and all S waves travelled at V_S = 3 747 m/s. These figures were derived from the locations determined by applying the hybrid method to tunnel blast events only, using over 77 000 distances and travel times, by repeated use of apparent velocities after starting with V_P = 6 500 m/s and V_S = 3 650 m/s as used by the mine network.

Figure 6 shows the distribution of P-wave velocity, for all ray paths, recorded by the seven most commonly used recording stations. Velocities to some of the sites are very clearly faster than velocities to others. The distribution is bimodal with peaks at approximately 6 250 m/s and 6 550 m/s. The reason for these strong velocity variations, even bimodality, is not known at this stage in the research. In an attempt to find the cause of these large, but consistent,

velocity variations, the velocities were compared to geophone depths in Figure 7 and to the average angle of the ray paths between every event and each geophone in Figure 8.

Figure 7 shows the variation of P- and S-wave velocity with increasing depth. The P-wave velocity decreased with increasing geophone depth, whereas the S-wave velocity remained more or less constant. This is contrary to the general observation that seismic velocities increase with depth. One explanation might be that the shallower geophones are in the Ventersdorp Lavas and therefore that ray paths to shallower geophones would travel through the faster lavas.

The data in Figure 8 are compatible with another explanation, namely that ray paths travelling in directions closer to vertical travel faster than those travelling sub-horizontally. The best-fit line in Figure 8 suggests horizontal V_P = 6 030 m/s and vertical V_P = 6 572 m/s. As these data were generated from locations using the constant velocities mentioned above (V_P = 6 359 m/s and VS = 3 747 m/s), the final 'best' model would involve some iteration and testing. It is easy to apply an anisotropic velocity model when calculating locations.

The concept of vertical ray paths being faster than horizontal ray paths is compatible with:

- The k-ratio (horizontal / vertical virgin stress) in most of the gold mining districts is less than 1, on average about 0.5. In general, P waves travel faster along directions of higher stress
- Sub-horizontal ray paths more often travel close to the stoping in this area and therefore pass through, or close to, fractured or low-stress rock.

The almost total lack of dependence of S-wave velocities on depth or ray-path angle should be the subject of further research.

Discussions and conclusions

We suggest that the use of double differences and constraining development blasts to lie on tunnels provide better locations than those normally achieved within mine networks. This involved two processes that we believe are new to mine seismic locations:

- Consistently identifying large numbers of seismic events as development blasts. We used survey pegs to define segments of tunnels in space and time. We then constrained development blast events to tunnel segments developed prior to the date of peg installation. Events were identified as blasts in terms of their size, inter-event spacing and time differences, proximity to tunnels and distance from mining faces. Determining the location of development blast events involved estimation of two unknowns, namely origin time and the position along each tunnel. Locations normally involve determining four unknowns, three in space and one in time
- Development and application of a hybrid location method. This consisted of applying the double difference method with each event as the master for each nearby event and with some contributions from absolute locations to reduce any tendency of the locations to drift. Median values of the error residuals of the master events were used to guard against outliers.

We relocated some 20 000 previously located seismic events in the Driefontein 5E area; 5 800 of these events were development blasts and we constrained their locations to lie on the straight lines joining about 2 150 survey pegs from the mine's database. Relocated events were shown to distribute more closely around advancing faces than had been the case before relocation.

A brief analysis of the average apparent velocities between all of the development events and the geophones showed that P-wave velocities varied strongly to different geophones. The P-wave velocities were apparently faster to shallower geophones and also faster for ray paths inclined closer to the vertical. The effect was barely noticeable for S-wave velocities. This effect should be further investigated.

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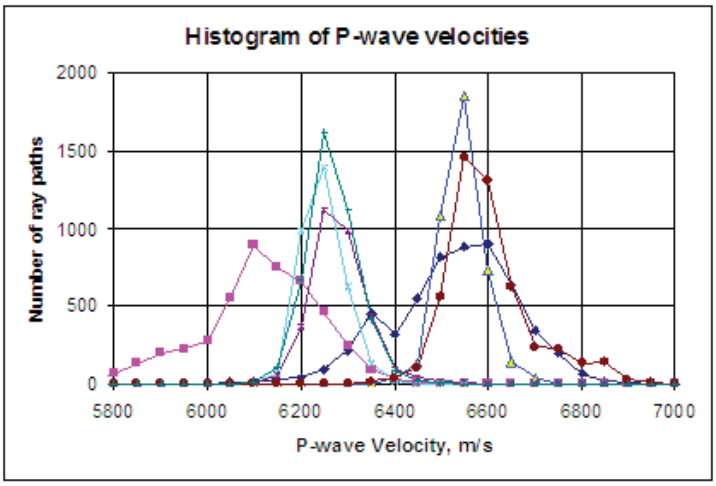

Figure 6—Distribution of P-wave velocity for all ray paths to the seven geophones which most commonly recorded development blasts

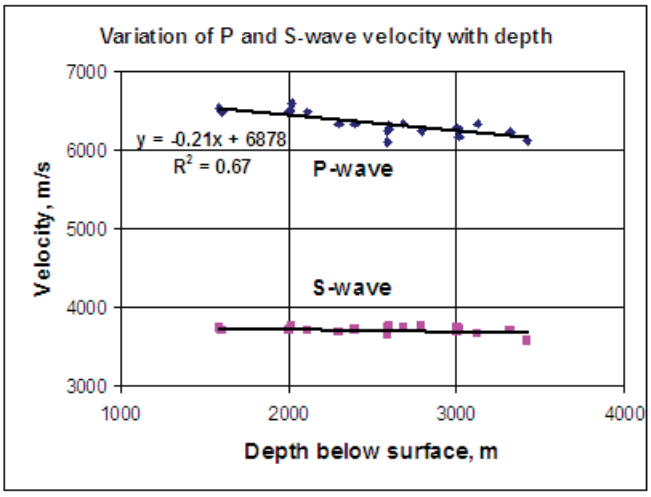

Figure 7—Variation of P- and S-wave velocity with depth

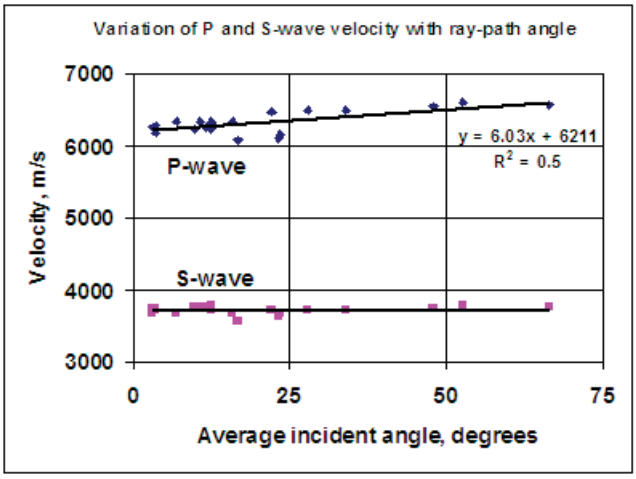

Figure 8—Variation of P- and S-wave velocity with average angle from the vertical (incident angle) of the ray paths

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The South African geologist wins World Young Persons Lecture Compotition*

A young geologist from the University of the Witwatersrand in South Africa is the winner of the first World Young Persons' Lecture Competition, held in London on 21 June. The competition is an initiative of the Institute of Materials, Minerals and Mining (IOM3), aimed at bringing together young scientists and engineers from around the globe and developing their presentation skills. The inaugural event was supported by Rolls-Royce plc.

The winner, Libby Sharman-Harris, was one of five young materials and minerals scientists and engineers who came together at the IOM3 headquarters in London on the evening of 21 June to take part in the final of this new competition. The other participants came from Singapore, Hong Kong, the USA and the UK, and were each national winners of the competition heats in their own country.

Sharman-Harris gave 'a clear and accessible lecture' on the use of sulphur-isotope analysis in understanding the formation of sulphide minerals in the Platreef, Northern Limb, Bushveld Complex, South Africa, a topic related to her Masters degree. She was unanimously declared the winner by the judges, who were impressed with the way she projected herself and answered questions at the end of her presentation. Reflecting on her victory, she said 'I think I was able to get across quite a boring and difficult subject. And this it what it is all about—communication'.

Runner-up in the competition was Johnny Kar-Ho Au, the Hong Kong national winner. Au works for Ove Arup and Partners HK Ltd, and described a technique that aims to prevent corrosion in reinforced concrete with the help of samples that he showed the audience. He said he already felt as though he had won by being able to visit London. In third place was Eric Kan from Singapore, who spoke about the potential of nanocrytalline germanium in flash memory. In his view, the whole event was more a 'sharing session' than a competition.

The judging team was led by Dr Chris Corti, of the World Gold Council, and included Dr Siobhan Matthews, Chair of the IOM3 Younger Members Committee, Dr Mike Hicks of Rolls-Royce and Dr Philip Bischler of the British Nuclear Group. The standard was exceedingly high,'says Bischler. 'There were very few marks between them'.

Dr David Clarke, Head of Technology Strategy at Rolls-Royce plc, spoke on behalf of his company and conveyed his enthusiasm for the competition. 'Materials are desperately important for Rolls Royce and key to what we do. That is why we are sponsoring this event,' he said. ◆

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Top product design receives a disa Design Excellence Award*

The Universal Drill Rig is one of sixteen product designs that received an SABS disa Design Excellence Award at a gala function held at Gallagher Estate recently. The products spanned a variety of industrial sectors such as engineering, mining and machinery, as well as medical, home ware and information technology. This award scheme is an initiative of the SABS Design Institute.

The Universal Drill Rig or Unirig is a simple, flexible, two-boom drill rig intended to mechanize the drilling of development-end tunnels in hard rock mines. It can drill blast holes in the rock face, as well as holes in the hangingwall and side walls for roof bolts. The machine consists of a simple, tack-mounted chassis supporting two booms on cantilevered arms. The arms incorporate unequal pantograph mechanisms in the vertical and horizontal planes to achieve automatic optimum fanning of the drilled holes. The Unirig is powered by water, but a compressed-air version is also available. For more information on this product visit www.hydropwer.co.za

The disa Design Excellence Awards aims to recognize the achievements of South African product designers, while also encouraging local product design and manufacture and promoting international competitiveness of local products. This award scheme has established a proud tradition of promoting indigenous design. For more information on this and other design award schemes, visit www.designinstitute.org.za.. ◆

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