The performance of Brunswick Mine's rockburst support system during a severe seismic episode

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Synopsis

At Brunswick Mine, an increase in the number of seismically-related falls of ground and in particular rockbursts occurred during 1999. This was due to the ever-increasing stress levels in the remaining ore reserves, mining in difficult highly stressed areas and in particular troublesome geological features.

In conjunction with the Noranda Technology Centre, development of rockburst support systems started at the Brunswick Mine in 1996 and efforts were accelerated in 1999. A support package consisting of #6 gauge chain link mesh, #0 gauge heavy mesh straps, and a 1 m by 1 m pattern of modified conebolts was developed. The conebolts were modified to enable mixing of the resin anchoring.

Two major rockbursts occurred during an intense seismic episode at the Brunswick Mine from October 13th to 17th , 2000. The area was evacuated approximately four hours before the first burst hit, and remained closed during the seismic 'flurry†'. The first damaging activity occurred around midnight on Friday the 13th, and a second damaging episode occurred on the 17th that included a local Richter Magnitude 2.7 event. The second rockburst had dimensions of approximately 5 m by 5 m by 20 m or 2150 tonnes of massive sulphide material (density 4300 kg/m^3). The first failure area was more extensive, caving approximately six metres of an intersection back with the lateral extent not safely measurable. This paper briefly describes the mining conditions that led to the bursting, the seismic response of the region, the mechanisms thought to have caused the bursts, and a yielding support system which had been partially installed before the burst.

Introduction

Noranda's Brunswick Mine, is a large massive sulphide deposit which produces zinc-lead-copper-silver. The mine is situated in northern New Brunswick, Canada, 27 kilometres south-west of the town of Bathurst. The deposit has been mined continuously since 1964 with an overall extraction of over 70%. In December 1999, remaining reserves were estimated at 37 million tonnes grading 8.64% zinc, 3.40% lead, 0.38% copper, and 102 grams/tonne silver. The current production is at a rate of 9400 tonnes per day using longhole open stoping with delayed backfilling.

The deposit strikes to the south and dips steeply to the west at about 75°. It has a multi-lens orebody with an overall strike length of about 1.2 km and depths up to 1.2 km below surface. At Brunswick, the principal stress direction is sub-horizontal east/west (~1.9 times the vertical), with the intermediate principal stress being sub-horizontal north/south (on strike) at about 1.6 times the vertical, and the minor principal stress being vertical approximately equal to the weight of the overburden.

A distinct contrast exists between the meta-sediment country rock sequences and the massive sulphide deposit. The hangingwall rocks tend to be highly laminated, chloritic rocks with unconfined compressive strengths in the 30 to 40 MPa range, the footwall sequence is also highly laminated but slightly stronger with strengths up to 70 MPa. The massive sulphide material (lead/zinc rich ore, or pyrite/pyrhotite rich waste) generally has unconfined compressive strengths exceeding 200 MPa. Typical joint spacing in the sulphides is in terms of metres, with the rock being very competent and brittle. Stress fracturing however is a very common feature and can seriously degrade the local rockmass quality.

Seismic monitoring at the mine

The mine's microseismic array consists of 29 triaxial sensors and 18 uniaxial sensors distributed throughout the underground workings. The uniaxial sensors are from the mine's previous MP250 array and are only

†Local term analogous to a snow 'flurry', referring to a very high seismic event rate over a relatively short duration

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used for source location purposes. The data acquisition hardware is the ISS system developed in South Africa, and analysis software varies from standard spreadsheet applications to custom designed CAD viewers and commercial processing software. The Brunswick network records in the order of 25000 events per annum with local Richter Magnitudes (M_L) in the order of –3 to 3 (seismic energies of a few joules to approximately 10^8 joules). Location errors typically are in the 5 to 10 m range, with tight clustering often observed on small isolated pillars (Simser and Andrieux[1]), and in high stress mining abutments.

The system is connected to locally developed telephone pager routines that automatically send a page when an event exceeds a M_L of –0.5. In addition, systematic checks of seismic activity are completed at least twice per day, after the 06:00 a.m. centralized blast (mostly development rounds) and the 18:00 main production blast time. Event rates typically rise sharply after stope blasts in the near surrounds, but there is a much weaker correlation between blast time and relatively large seismic events. Time/space clustering of activity is the main tool used to determine pro-active closures of work places, while source parameter information is largely used for rock mass characterization, tracking the response to mining, and understanding the seismic source mechanisms throughout the mine (Simser[2], Simser and Andrieux[3], Alcott[4]). The underground workings are serviced with a leaky feeder radio system allowing rapid communication between the workforce and engineering support staff. The mine's ground control department has a person designated as 'on-call' 24 hours per day with a home computer able to access the mine's seismic data. Underground tremors are routinely 'called in' by the underground workers for verification by the ground control group.

General mining layout

The mine has undergone several major mining changes since its inception ranging from cut-and-fill mining to the current long hole open stoping mining method. The production rate was at 10500 tonnes per day but had to be lowered due to difficult ground conditions to the current 9400 tonnes per day (Andrieux and Simser[5]). These difficult mining conditions reached a critical stage in late 1995, and in 1996 many major changes were implemented. The changes include: paste backfill for rapid filling of stopes and lower cycle times; smaller stope sizes, from an average stope size of 75 000 tonnes to 39 000 tonnes; smaller overcuts and fan drilling versus wide overcuts and vertical drilling for smaller in-stope spans; the introduction of shotcrete on a large scale; increased cable bolting; and improvements to the mine seismic monitoring system. Pillarless mining sequences have replaced primary/secondary sequences to avoid trapping high stresses in competent secondary pillars (Andrieux and Simser[5]). Where the sulphide pillars remain relatively 'squat', they can remain highly stressed and seismically active over periods of years. In an example reported by Simser and Andrieux[1], a large-sized secondary stope with a width-to-height ratio of 0.43:1 was shown to have failed. The other secondary pillars in the same zone with width-to-height ratios of 0.67:1, 0.75:1, and 1.2:1 had remained seismically active for periods exceeding five years (and have yet to fail

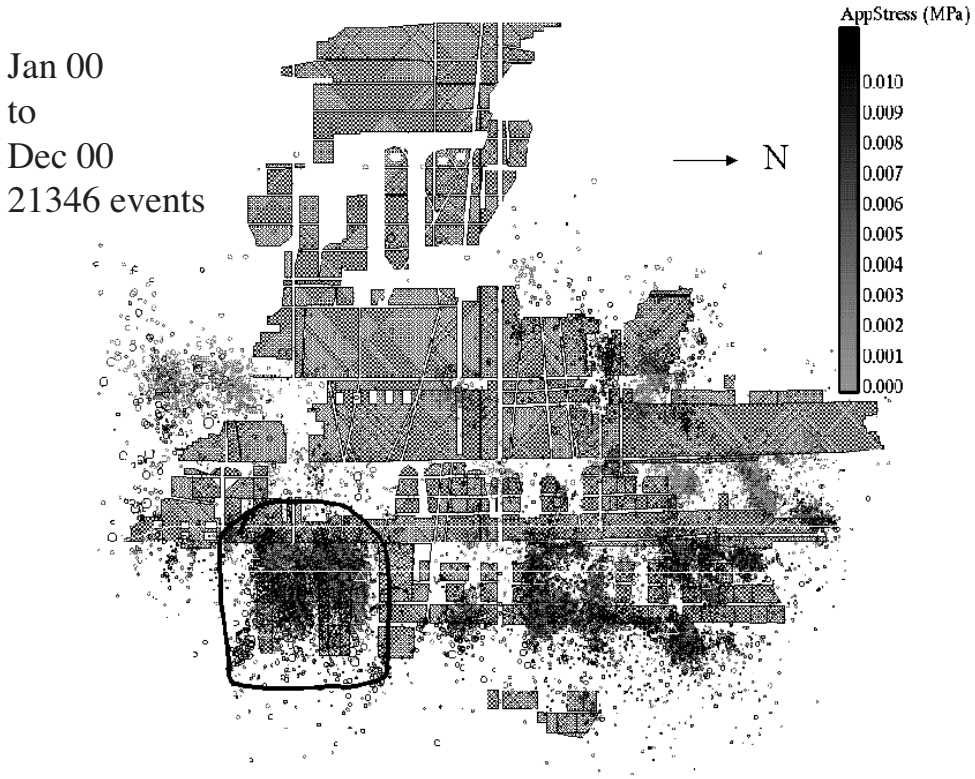

Figure 1—Simplified longitudinal section of the mine looking west. Seismic events shown as circles, size scaled to M_L. The events are from January 2000 to December 2000, for a total of 21346. The hatched areas represent stoping, the circled area is the 1000 South Bulk Zone where the rockbursts occurred. The strike length shown is 1.5 km, the top of the mined out area outcrops on surface, with the deepest mining being 1.2 km below

18/12/00). Figure 1 shows the generalized mine longitudinal section.

Seismic response of the burst region—October 13th to 17th, 2000

The burst area had been seismically active on/off throughout the preceding week, with small magnitude activity clustering in the area and several proactive workplace closures were implemented. Only minor damage had been noted in the area (small-scale cracking in the shotcreted tunnels) due to the activity. On the Friday evening (13th October), a M_L 1.6 seismic event occurred (see Table I), prompting an alarm to the ground control group and the underground worker in the area to 'call in 'the event. This event and the ensuing increase of micro-seismicity prompted the closure of the area. At that time only minor damage was noted, and presumably, the major drift collapse occurred just before midnight.

The dramatic nature of the first observed burst, combined with the general increase in bursting in the area (Simser[6]) prompted a formal shutdown of the zone until a full investigation could be completed. The second major burst occurred on the 17th, presumably concurrent with the M_L 2.7.

Figure 2 shows the simplified longitudinal section of the 1000 South Bulk Zone where the rockbursts occurred. The hangingwall and footwall lens mining is not shown.

Both relatively high horizontal east/west stress and horizontal north/south stress influenced the burst area. Local borehole and raisebore squeezing, in addition to stress fracturing patterns showed clear signs of both stress directions being relatively high.

Figure 3 is a complicated view of the area showing local mining, geology, structure, and rockburst damage. The local structural features are important with respect to the observed damage, but the main structure features related to the cause of the bursts are the waste meta-sediment lens included in the ore. Simser[6] reported previous bursting on this type of structure, and several other bursts have been observed along similar inclusions of the country rock. The meta-sedimentary rock sequences tend to be highly laminated, almost 'shale-like' rock. Their behaviour is similar to a gouge filled fault zone. Observations at the mine have shown that where the inclusions are relatively wide (metres) they tend to deform and squeeze, where they are relatively narrow (centimetres) they tend to lock up, and cause bursting in the surrounding sulphides. Local structure such as the near vertical east joint depicted in the wall bursting area, played an important role in the observed damage, making the overall source mechanism difficult to interpret based on observations only.

The dominant structural feature on the 13th appeared to be the south-west wasteband, labelled as '1' in Figure 3. This band plunges at about 65° to the south-east. Based on

Table I

Sequence of large events in the burst region from October 13th to 17th. Note the M_L scale is M_L = 0.58 log E + 0.256 log M –4.9, which is scaled to both the Geological Survey of Canada and the mine's historic database

Date	Time	log M	log E	M_L
13-Oct.-00	19:33:35	11.5	6.1	1.6
13-Oct.-00	23:55:07	11.2	5.6	1.2
13-Oct.-00	23:57:05	12.4	7.2	2.5
13-Oct.-00	23:57:55	11.2	5.6	1.2
13-Oct.-00	23:57:56	10.9	5.9	1.3
13-Oct.-00	23:58:04	12.0	7.3	2.4
14-Oct.-00	01:02:24	11.4	5.8	1.4
17-Oct.-00	01:15:02	12.5	7.6	2.7

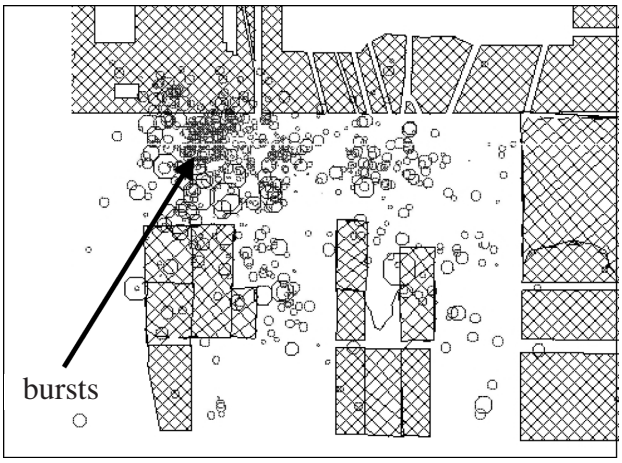

Figure 2—Long section looking west, seismic events from October 13th to 17th , 2000. 668 events in area shown, 250 m vertical by 300 m north/south. Events plotted as circles scaled to magnitude. The burst area was influenced by mining-induced stresses due to cut-and-fill mining above and pillarless sequence below

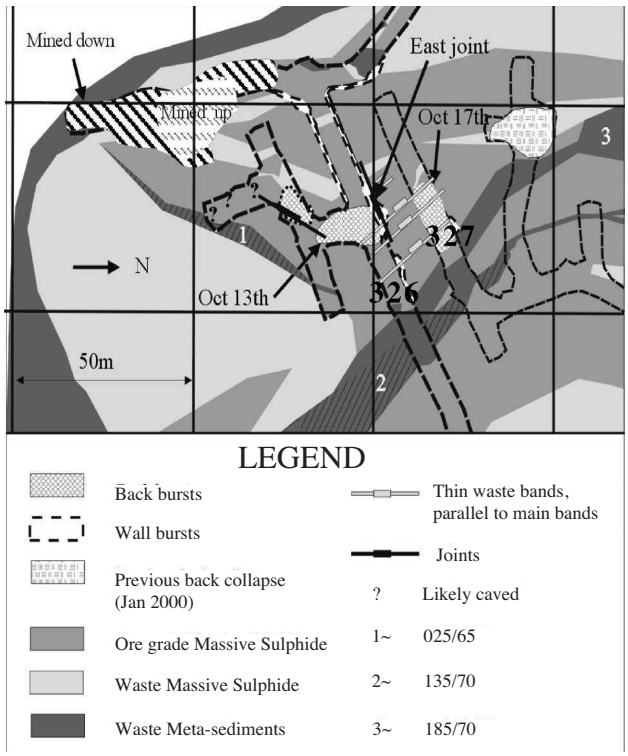

Figure 3—Damage/Geology/Structure of the Burst Areas. Grid spacing is 50 m, drifts are 5.5 m wide, plan view with north to the right

damage observed it is possible that this band had reverse dip slip. The damage noted in the immediate footwall drifts was consistent with a vertical loading component, the upper corners of the drifts punching into the back. The activity on the 17th had migrated to the north to the main south trending waste stringer zone. This waste band has been very seismically active for several years (Simser[6]) and is likely the source of the M_L 2.7 event (labelled '2' in Figure 3). This event's location was not accurately determinable, possibly due to near field effects and other complexities in the waveforms. The damage in the second major rockburst was consistent with a largely strike slip component along the wasteband labelled '2' in Figure 3. The damage in the drift also had lesser reverse dip slip components and was heavily influenced by at least three small (cm thick) parallel waste band structures (shown in Figure 3).

Moment tensor analysis of source mechanisms

Moment tensor analyses were carried out on all seismic events recorded between the 13th and 17th of October in the South Bulk zone. Few solutions could be obtained for seismic events smaller than M_L –1 and solutions for large seismic events (M_L> 1.0) were difficult to obtain as the P-wave—S wave separation was too short. It was necessary to ignore the S-wave, in these cases, in order to obtain a solution. The quality of the moment tensor solution is largely influenced by the configuration of seismic sensors. Uniaxial sensors are ignored in the calculation and the remaining triaxial sensors, from which waveforms were recorded, frequently did not form a satisfactory three-dimensional array. In many cases there were not enough waveforms from triaxial sensors to calculate a moment tensor solution.

Moment tensor solutions, of reasonable quality, were obtained for 40 of the seismic events that recorded during this seismic episode. Two possible fault plane solutions are determined for each seismic event. All fault plane solutions were analysed collectively using the program DIPS. Figure 5 shows the results of this analysis.

In Figure 5 three distinct clusters of poles can be observed. Three fault plane sets were then determined with the following orientations:

The strike of set 1 is similar to that of the waste meta-sediment inclusions and that of orebody towards the north (see Figure 4). However the mapped dip is normally in the 70 to 75° range. Set 2 follows the trend of the south-west waste bands, with a reasonable dip correlation (54° instead of 65°). Set 3 has a good trend correlation with the waste meta-sediment inclusions towards the south and a series of small shears that traverse the mine. Again the dip is normally 70 to 75°. The small shears are typically in the order of a few tens of metres in extent, exhibit well striated surfaces, and the strike may fluctuate 180° . They are also a relatively common source of seismicity at Brunswick (Simser and Andrieux[3]) In sets 1 and 3, the average dip of the fault plane solutions did not correlate well with the dip of the waste meta-sediment inclusions, which could be due to the configuration of sensors from which waveforms were recorded.

It should be noted that several of the fault plane solutions that occur in one set have conjugate pairs that fall in other set (Table III). However 37 of the 40 seismic events, for which moment tensor solutions were obtained, had fault plane solutions which fell into at least one of the three sets.

During the flurry on the 13th of October most of the events located near the south-west waste bands. For these seismic events, the dominant fault plane set was set 2. Nine of the overall 12 seismic events with fault plane solutions in

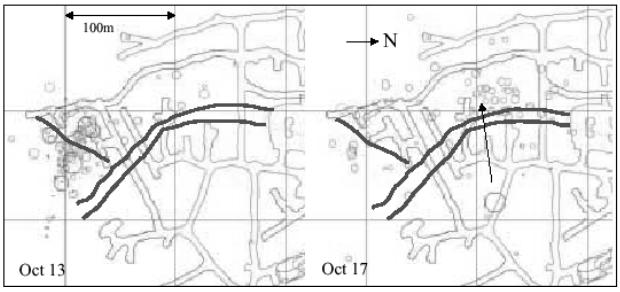

Figure 4—Seismicity 50 m above and below the plan elevation on October 13th , 2000 and then on October 17th, 2000. Symbol size is scaled to magnitude. The M_L 2.7 event that occurred on the 17th had very complex waveforms and could not be located well. The arrow indicates the 'likely' epicentre of the event based on observed damage and knowledge of local structure

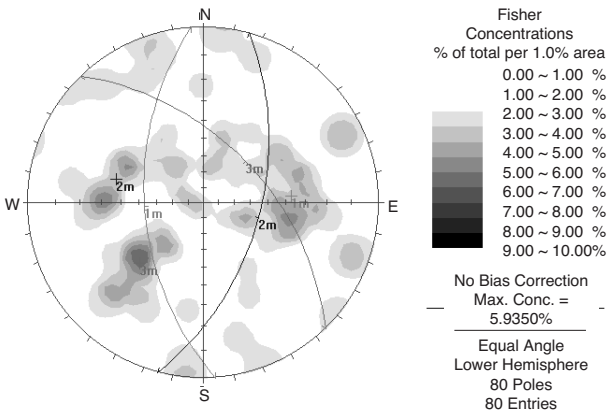

Figure 5—Fault plane sets determined from stereographic projection of poles

Table II

Orientations of fault plane sets for seismic events from both flurries. The strike is measured with structure dipping to the right

Set	Orientation (strike/dipR)	Number of fault plane solutions
1	176/53	24
2	15/54	12
3	316/53	16

Table III

Combinations of conjugate pairs falling into two sets

Combination	1–2	2–3	3–1
Quality	6	2	7

set 2 occurred during this flurry and located near this structure. The average strike of the set changes to 25º, which is closer to the strike of the south-west waste band. Most of the largest seismic events recorded during this flurry, including the largest (M_L 2.5), had fault plane solutions in set 2. This confirms that the south-west waste band was the dominant structure during the flurry on the 13th. Other seismic events had fault plane solutions in sets two and three, indicating that the waste meta-sediment inclusions were probably active during this flurry.

Fewer seismic events were recorded during the flurry on the 17th of October and the orientation of the fault plane solutions was less consistent. However, sets 1 and 3 could be identified, with set 1 being more prominent. This is consistent with the orientation of the waste meta-sediment inclusions and the locations of the seismic events.

Description of the damage observed

Seismic damage in the 326 crosscut

The main failure on the 13th of October prompted proactive withdrawal of labour from the work zone. This particular burst was 'hit' again on the 17th of October, where a portion of the wall in front of the intersection that caved, blew out. A very thin band of waste meta-sediments, conformable to the local strike and dip was in the centre of the wall burst. An important consequence of this failure was the behaviour of 'rockburst' support, which had been installed between the cave and the wall blowout. Seven hundred metres of drift had been identified prior to the October failures for rockburst support, based on the proximity of known wasteband structures. A small portion of this support (described in asubsequent section) was installed in the damage area.

The conventional drift support in this portion of the mine consisted of: 7 m twin cablebolts in the back; 2.3 m resined rebar on a 1.5 by 1.5 m pattern; 10 cm aperture weld mesh

Figure 6—East brow of 326 crosscut backburst, where massive sulphide material was finely fragmented. The intersection was supported with two passes of twin 25 tonne capacity cables each pass on a 2 m by 2 m pattern, the cables were 7 m long and the depth of the failure was 6 m vertically. The ejected material was heavily stress fractured consistent with high horizontal stresses

Figure 7—The same intersection after the October 17th seismicity viewed from further east. The wall on the north side of the drift (right side of photo) blew out and increased rockmass bulking occurred before the caved intersection. The right-hand side between the wall blowout and cave had rockburst support in the upper corner. The left side where the bulking is greatest had only chainlink mesh and rockbolts

Figure 8—Same failure looking south into the intersection after it had been mucked out on tele-remote. The back failure in the centre of the photo is consistent with high east/west horizontal stress. Drift width is 5.5 m. The brow on the right-hand portion of the photo is intensely horizontally stress fractured, consistent with high horizontal stress

Figure 9—North wall of intersection and west brow after cave was mucked out. The north wall is an east striking, steeply dipping joint plane. The west brow fracturing is consistent with high horizontal north/south stress. The extent of the fracturing is 6 m above the original back position

screen with 3.7 mm diameter wire in the back; regular shotcrete over the mesh; and steel fibre reinforced shotcrete in the walls (no weldmesh screen in walls). This system typically works well in high stress areas, effectively controlling rockmass bulking and falls of ground. However the system is too 'stiff' for the dynamic loading experienced.

The tele-remote mucking was completed to the 'dotted' failure area indicated in Figure 3. The area labeled with '?' marks is the location of an automated drill. It is presumed that this area has also caved given its proximity to a major wasteband and the recorded seismicity. The burst could be described as very violent shake down of intensely stress fractured material. The stress fracturing was abnormally intense due to the presence of both high horizontal east/west and north/south stress. The depth below surface is 892 metres, with a virgin principal stress gradient of approximately 0.052 MPa/m. The sub-level is located 30 m below previous cut-and-fill mining (sill pillar) and above a pillarless pyramid sequence (Figure 2), both of which have greatly influenced the local stress conditions. Local mining in the hangingwall lens as shown in Figure 3 also contributed to the local mining induced stresses. The easterly striking joint on the north wall is a pre-existing weakness that provided a slip plane for the back failure to propagate along (Figure 9).

Seismic damage in the 327 crosscut

The second major rockburst occurred in the crosscut immediately to the north on October 17th . This crosscut was damaged on the 13th, with observed floor heave, upper corner wall blowouts, and tensile cracks in the back. The upper corner wall blowouts were measured to be in line with three small waste band structures as illustrated in Figure 3. After October 17th, presumably as a result of the local Richter Magnitude 2.7 event, the back of the drift came down for a length of 20 m. The height of the failure was approximately 5 m.

The observations before the back collapse shown in Figure 10 were consistent with oblique slip on steeply dipping structures. The floor below the cave had heaved, and some wall damage was noted. Reverse dip slip caused by high horizontal stresses acting perpendicular to steeply dipping waste meta-sediment bands has been observed several times at the Brunswick Mine (Simser[6]). Although this formed a component of the 327 crosscut burst, it is more likely that the normally high horizontal east/west stress caused strike slip on the south-east trending portion of the main waste band ('2' in Figure 3). Strike slip on a steeply dipping structure is a possible mechanism for back failures. The thin, parallel bands offer much greater resistance than the highly laminated main waste stringer, thus the violent nature of the failure.

Performance of support package

Design of the rockburst support package at Brunswick has been on-going since 1996. At that time violent ejection failures were not common, but caving of large spans throughout the mine showed extensive evidence of well-developed stress fracturing. It was postulated that a yielding support system would be a big improvement for withstanding the large dilations associated with the fracturing. The increase in violent ejection failures in 1999/2000 led to the urgent development of a complete yielding support system. The package at the time of the bursts consisted of very heavy chain link mesh of 4.9 mm diameter wire forming 50 mm apertures, 300 mm wide straps of 7.7 mm by 100 mm aperture weld mesh; and a 1 by 1 m pattern of 2.3 m long modified conebolts. The conebolts were modified to accommodate resin-grouting applications along with other significant changes from the original conebolt design. The intent was to proceed with full-instrumented field trials, but the urgency of the matter dictated that underground installation should be concurrent with further testing. The bolts were tested/developed in a 1 tonne dynamic drop facility at the Noranda Technology Centre.

Detailed observations of the rockburst support showed bending of plates, large open cracks in the shotcrete behind

Figure 10—327 crosscut backburst, failure occurred on October 17th , 2000. The picture is looking west, the brow at the far end of the drift is formed by the plane of a steeply dipping, thin waste band. The foreground of the photo exposed the main waste band labeled '2' in Figure 3

Figure 11—Close-up view of the rockburst support from the 326 crosscut bursts. The left side of the photo has chainlink mesh temporarily suspended with 0.9 m end anchored rockbolts. The right-hand side has the full rockburst support package of chainlink, mesh straps, and modified conebolts installed. The support installation had not been fully completed at the time of the bursts

the chainlink, mesh and several centimetres displacement on some of the bolts. The fact that the wall blew out to the east of the installed support, and the intersection to the west of the support caved completely while the cone bolt supported area was vitually undamaged indicated that the system performed well. It is, however, important to note that 2.3 m long cone bolts could not be expected to support the 6 m high intersection failure.

The 7 m long cablebolts proved to be not only inadequate for the support of the wide back of the 326 crosscut intersection but also for the normal width 327 crosscut.

A careful scrutiny of the photograph of Figure 12 of the north side of 327 crosscut, showed the following detail of damage to the support. The shotcreted screen was torn away from the tendon plates in 15 instances, 14 resined bars were broken and 7 cables were broken. It is virtually certain that if the plates had not torn free then those tendons also would have failed.

The absolute requirement that rock support tendons should possess a degree of yieldability in order to survive a rockburst, is emphatically illustrated by these examples.

Remedial measures for safe mining in the zone

Mining in this zone was suspended following the bursts until a detailed action plan could be implemented. The main strategic goal is to cut off the driving stresses on the waste band structures. Detailed planning, numerical modelling, and blast designs were being completed at the time of writing. The first part of the mining strategy will focus on rapidly extracting the lower grade, smaller tonnage hangingwall lens. This conceptually will remove the high horizontal east/west driving stresses from the main part of the bulk zone, which has the waste meta-sediment traversing it.

Rockburst support is being installed in all accesses within the known influence of the wastebands. Detailed geotechnical monitoring of intersections, stresses, and movement along the structures is on-going. Seismic monitoring is the primary short-term safety tool for the mine, and will continue to be used for proactive closures of seismically active areas regardless of rockburst support.

Figure 12—Close up view of failed support on north side of 327 crosscut

Conclusions

Relatively high stresses and the presence of weak geological structures caused the bursts. Much can be learned from more detailed analysis of the observations and seismic monitoring data but it is clear that a yielding support system offers superior protection to underground workers in bursting rock. Numerical modelling data should help improve the overall understanding of the failures, but based on underground observations it was clear that they were stress driven and structurally controlled. The mine's recognition of the seriousness of the first burst, and the subsequent closure of the zone was validated by the second major collapse a few days later. The current strategy to stress shadow the area by rapidly mining the hangingwall lens seems to be the best overall approach for continuation in the zone.

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