A Five-Year Review of the Canada-Ontario Industry Rockburst Project

D.G.F. Hedley
Mining Research Laboratories

CANMET Special Report SP90-4E

Available in Canada through

Associated Bookstores
and other booksellers

or by mail from

Canada Communication Group — Publishing
Ottawa, Canada K1A 0S9

Catalogue No. M38-15/90-4E
ISBN 0-660-13927-8

Foreword

The Canada-Ontario-Industry Rockburst Project was initiated in 1984 because of the re-emergence of a serious rockbursting problem in some of Ontario's mines. The project was probably the first major mining research effort to be undertaken on a tripartite basis in Canada. Involving cooperation between the mining industry of a province and two levels of government, it has been held up as a model for collaborative work. CANMET's Mining Research Laboratories is proud of the role it has played in this project.

In this CANMET Special Report, Dr. David Hedley, the rockburst project leader, reviews the accomplishments that were realized during the first five years of the project, from 1984 to 1989. These have been substantial:

- The mining industry has increased the number of microseismic monitoring systems installed for local mine monitoring from three in 1984 to sixteen in 1989. Such systems are now installed at all Ontario mines where they are needed.

- Seismograph stations to complement the existing stations of the eastern Canada grid of the Geological Survey of Canada have been installed in Red Lake, Elliot Lake, Sudbury and Kirkland Lake. As a result, both the response time and the accuracy of determining the location of an event have improved.

- Macroseismic systems, intermediary to the above, have been developed and installed at Rio Algom's Quirke Mine, Falconbridge's Strathcona Mine, Lac Minerals' Macassa Mine, Placer Dome's Campbell Red Lake Mine and Inco's Creighton Mine. These systems, which record waveforms, provide data that can be used to determine source mechanisms and focal parameters.

- Trials of destress blasting techniques and the use of stiff mine backfill to alleviate and control rockbursting have been conducted. Support systems to contain rockburst damage have been evaluated, and numerical models have been used to assess the stabilities of local systems of faults.

In 1990, there is a much improved awareness of both the causes and effects of rockbursts. The process of mine design has become much more sophisticated and now routinely involves the incorporation of geomechanical concepts.

During the first phase of the project, very high priority was placed on improving the monitoring capabilities of Ontario mines and the accuracy with which the location of seismic events could be determined. During the second phase, efforts to study the fundamental causes of rockbursts and to develop methods by which these may be alleviated and the damage limited will be continued.

CANMET's Mining Research Laboratories looks forward to its continued involvement in this key project.

John E. Udd
Director
Mining Research Laboratories
CANMET

Contents

Tables

Figures

Photographs

Background

Rockbursts first started to occur in Ontario hardrock mines in the early 1930s, mainly in the gold mines in Kirkland Lake and some of the nickel mines in Sudbury. The rockbursts that were reported to the Ontario Ministry of Labour and the associated fatalities are shown in Figure 1.

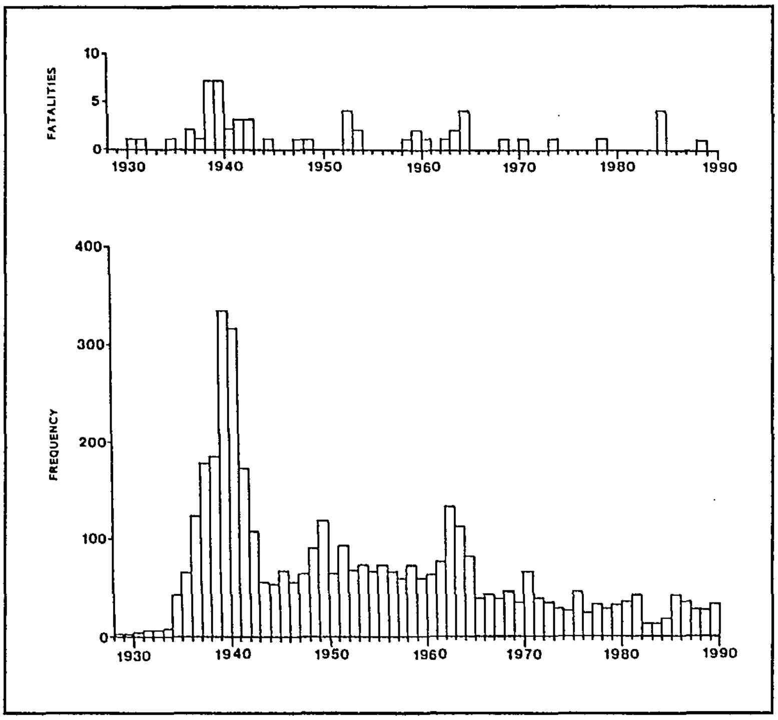


Figure 1 - Reported rockbursts and associated fatalities in Ontario mines, 1928 to 1989

By the late 1930s, however, rockburst incidents and fatalities began to increase at an alarming rate. This led to an extensive research effort within the mining industry to develop methods to alleviate the problem. In 1940, the Ontario Mining Association appointed the Morrison Inquiry to investigate the problem. The inquiry's recommendations--based on observation, experience and trial-and-error methods--included the avoidance of remnant pillars, systematic sequencing of extraction, and procedures for mining around dykes and faults. These methods, when subsequently employed, proved to be partially successful, and the frequency of rockbursting declined.

Until the 1980s, the level of rockburst activity in Ontario mines was relatively low. A noticeable exception was in 1964 when a series of major rockbursts caused the closure of the Wright-Hargreaves Mine in Kirkland Lake.

During the 1980s, however, rockburst activity in Ontario mines increased significantly. Fourteen mines in Red Lake, Elliot Lake, Sudbury and Kirkland Lake were affected. A peculiar feature of this activity was the multiple nature of the occurrences. Previously, rockbursts had occurred mainly as isolated events followed by some microseismic activity.

Multiple rockburst sequences started at Rio Algom's Quirke Mine in Elliot Lake in 1982, and followed at Placer Dome's Campbell Mine in Red Lake in 1983. The following year, 1984, was a particularly active year. First, a series of rockbursts at Falconbridge's No. 5 shaft resulted in four fatalities and the closure of the mine. A few weeks later, a rockburst of magnitude 4.0 occurred at Inco's Creighton Mine and was felt throughout the city of Sudbury. Finally, Quirke Mine became active again, and over an eight-month period, 120 rockbursts of magnitudes up to 3.5 were recorded on the regional seismic network.

This level of rockburst activity, in a short time span and at four separate mines across the province, attracted considerable attention from the public, the media, the mining industry, unions and government agencies. The Ontario Ministry of Labour appointed an inquiry into ground control and emergency preparedness in Ontario mines.

In response to this increased rockburst activity, the Canada-Ontario-Industry Rockburst Project was initiated in 1985. The Government of Canada, through the Canada Centre for Mineral and Energy Technology (CANMET), provided staff to operate the project. The Government of Ontario, through the Ministry of Northern Development and Mines and the Ministry of Labour, provided funds for equipment and services. The Ontario mining industry, through Denison Mines Limited, Falconbridge Limited, Inco Limited, Lac Minerals Ltd., Placer Dome Inc. and Rio Algom Limited, contributed its existing microseismic monitoring systems, assisted in the installation and operation of new equipment, provided data on rockbursts and conducted *in situ* trials on various aspects of rockburst alleviation or control.

The rationale and objectives of this rockburst project were first to develop new seismic monitoring systems capable of capturing complete waveforms, and then to investigate the causes and mechanisms of rockbursts by using improved source location techniques, first motion studies, peak particle velocity, liberated seismic energy and spectral frequency analysis. These techniques would then be used in conjunction with field trials to evaluate methods of alleviating rockbursts or to control their damaging effects or to control the timing of a rockburst.

During the five-year project, seismograph stations have been installed in Red Lake, Elliot Lake, Sudbury and Kirkland Lake to record the larger rockbursts and to determine their magnitude. Macroseismic systems have been installed at Rio Algom's Quirke Mine, Falconbridge's Strathcona Mine, Lac Minerals' Macassa Mine, Placer Dome's Campbell Mine and Inco's Creighton Mine. These systems record seismic waveforms and are used to determine rockburst mechanisms and focal parameters. The mining industry in Ontario has increased the number of microseismic monitoring systems in its mines from 3 to 16, to determine the location of seismic events.

Destress blasting trials on crown/sill pillars have been done at the Campbell and Macassa mines. At the Creighton Mine, a destress slot trial was done in a large crown pillar between levels. Falconbridge has investigated the stability of fault systems using numerical modelling techniques. The use of stiff backfill to limit the damage from rockbursts has been implemented at the Macassa Mine and backfill has been used at Denison

Mine to control violent pillar failure. Inco, Falconbridge and Placer Dome have all tested yielding types of support systems to contain rockburst damage.

Seismicity in Ontario Mines

Since 1984, mining-induced seismic events, including rockbursts, have been classified by their magnitude. A rockburst is defined as a seismic event that causes injury or damage to equipment or the displacement of more than five tonnes of rock. In most years, there are more recorded seismic events than reported rockbursts.

Magnitude values are determined from the Eastern Canada Seismic Network, operated by the Geophysics Division of the Geological Survey of Canada. The Nuttli magnitude scale is used. This scale is specific to eastern North America, but is similar, in many respects, to the Richter magnitude scale used elsewhere. For most mining camps in northern Ontario, the level of detection is an event of magnitude 2.0 or greater. Starting in 1985, the Seismological Service of the Geological Survey of Canada began to publish a quarterly report on *Mining-Related Seismic Activity in Canada*, which lists all the events recorded on its seismograph stations.

Table 1 lists the distribution of mining-induced seismic events of magnitude 2.0 and greater by mining camp for the years 1984 to 1989. Table 2 lists the number of events that have occurred in each mine and the largest magnitude recorded. During this six-year period, mines in Elliot Lake and Sudbury dominated the statistics, accounting for 40% and 46%, respectively, of the 367 seismic events recorded. Most of the seismic activity in Elliot Lake was concentrated in 1984 and 1985; since then, activity has rapidly declined. At Sudbury mines, seismic activity tended to be more constant, except for 1989, when there was a relatively low level of seismic activity across the province.

Table 1 - Distribution of seismic events of magnitude 2.0 and greater by mining camp, 1984 to 1989

Mining Camp	1984	1985	1986	1987	1988	1989	Total
Red Lake	18	3	6	0	0	0	27
Elliot Lake	46	74	13	8	1	4	146
Sudbury	15	20	35	56	36	10	172
Kirkland Lake	5	2	3	3	5	2	20
Timmins	0	0	0	0	0	3	3
Total	84	99	57	67	42	19	368

Table 2 - Distribution of seismic events by individual mines, 1984 to 1989

Location	Number	Largest Magnitude	Location	Number	Largest Magnitude
SUDBURY			RED LAKE		
Falconbridge	7	3.5	Campbell	23	3.3
Fraser	2	2.5	Dickenson	4	2.1
Lockerby	5	2.8	ELLIOT LAKE		
Strathcona	46	3.2	Denison	11	2.8
Copper Cliff North	23	3.3	Quirke	135	3.5
Creighton	60	4.0	KIRKLAND LAKE		
Frood-Stobie	2	2.9	Kerr Addison	3	3.3
Levack	5	2.6	Macassa	14	3.1
Stobie	1	2.4			

The Quirke Mine in Elliot Lake has been the most seismically active, followed by the Creighton and Strathcona mines in Sudbury. Other mines with more than 10 events of magnitude 2.0 and greater are the Copper Cliff North Mine in Sudbury, the Campbell Mine in Red Lake, the Denison Mine in Elliot Lake and the Macassa Mine in Kirkland Lake.

The frequency distribution of the seismic events by magnitude are shown in Figure 2. As expected, there are many more smaller magnitude events than larger events. The distribution can be divided into three broad groups:

- magnitudes between 2.0 and 2.4 account for 65% of the total, and the damage associated with these events is usually minor, involving a few tonnes of displaced rock;
- events of magnitude 2.5 to 2.9 account for 30%, and more damage would be expected, involving about 10 tonnes of displaced rock;
- events of magnitude greater than 3.0 account for only 5% of the total, but the damage is more severe, typically involving hundreds and up to thousands of tonnes of displaced rock.

Over the six-year period, these large events (having a magnitude greater than 3.0) have averaged 3.5 per year in Ontario mines.

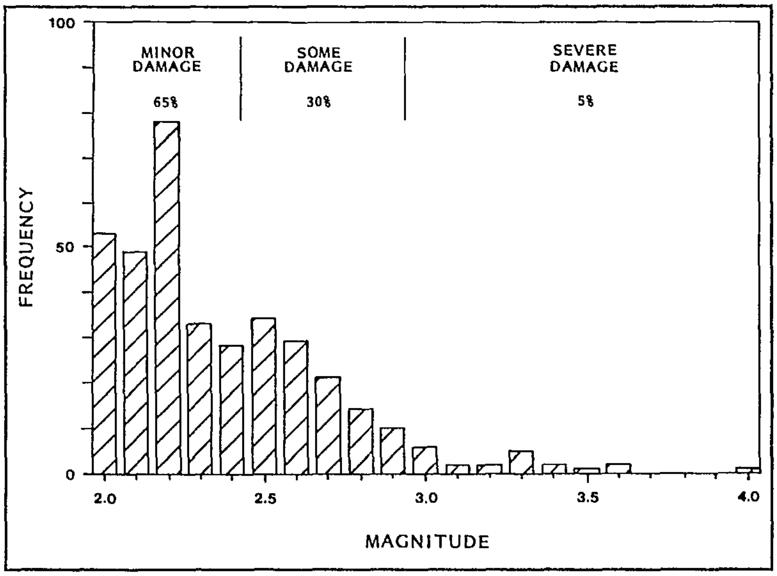


Figure 2 - Distribution of seismic events by magnitude in Ontario mines, 1984 to 1989

During the five-year project, certain trends and characteristics on seismic activity have emerged from the different mining camps. At the mines in Red Lake, Elliot Lake and Kirkland Lake, most of the seismic activity is concentrated in pillars within the orebody. The cause and mechanism appears to be overloading of the pillars, followed by their violent failure. At the mines in Sudbury, most of the large events occur outside the orebody on geological structures. The mechanism appears to be fault slip, similar to earthquakes.

Seismic events in the Elliot Lake mines and most of the events in the Red Lake mines occur in old mined-out areas of the mines and are related to past mining practices. Events at the Sudbury and Kirkland Lake mines tend to occur near active mine workings and are related to present mining practices.

A number of triggering mechanisms have been identified, including nearby blasting, rehabilitation involving scaling and bolting, the pulling of broken ore from a stope, inflows of water from surface or drainage water from backfill, and variations of temperature and/or air pressure.

Seismic Monitoring Systems

When the rockburst project was started in 1985, three microseismic systems were in operation in Ontario mines along with one seismograph unit in Sudbury. By the end of the first five years of the project, 16 microseismic systems were in operation along with five macroseismic systems, and an additional five seismograph stations were installed in Ontario's mining camps. This level of coverage is comparable to that of the gold mining districts on the Witwatersrand in South Africa.

As previously mentioned, the Geophysics Division of the Geological Survey of Canada operates the Eastern Canada Seismic Network. This system is used to calculate the magnitude of the events and, for the very large events, their focal parameters. The location of the seismograph stations in and around Ontario are shown in Figure 3. This network has been augmented by additional seismograph stations in Sudbury, Elliot Lake, Red Lake and Kirkland Lake. Of these, the network in Sudbury is the most sophisticated, involving three stations located around the rim of the basin, as illustrated in Figure 4. Signals from each station are continuously transmitted over dedicated phone lines to a computer and display facility at Science North, a public science centre in Sudbury. From there, the three signals are continuously transmitted to the Geophysics Division in Ottawa. CANMET employs a person at the facility in Ottawa to look after the Sudbury network and to discriminate between blasting and mining-induced seismic events. Typically, 200 events are recorded each month, of which 60% are blasts and 12% are mining-induced events within the Sudbury mines. The remaining 28% are events emanating from outside the Sudbury Basin, either as naturally occurring earthquakes or as mining-induced events, including blasts.

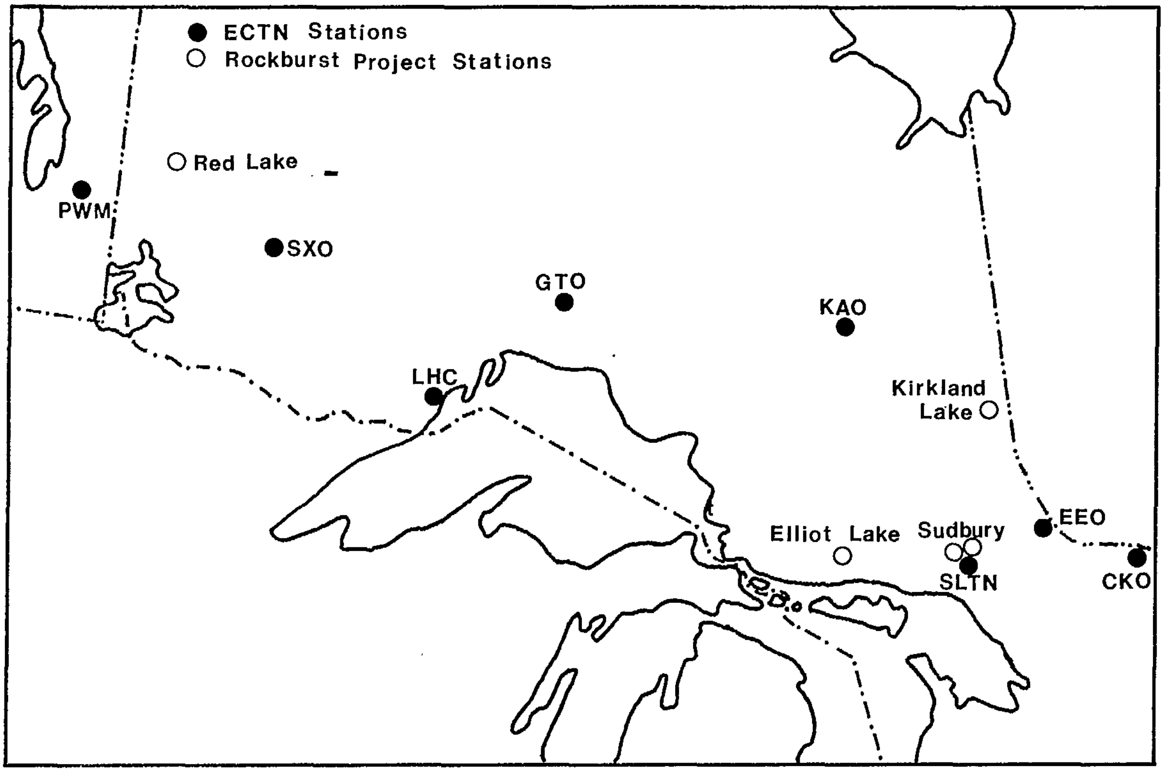


Figure 3 - Location of seismograph stations in northern Ontario

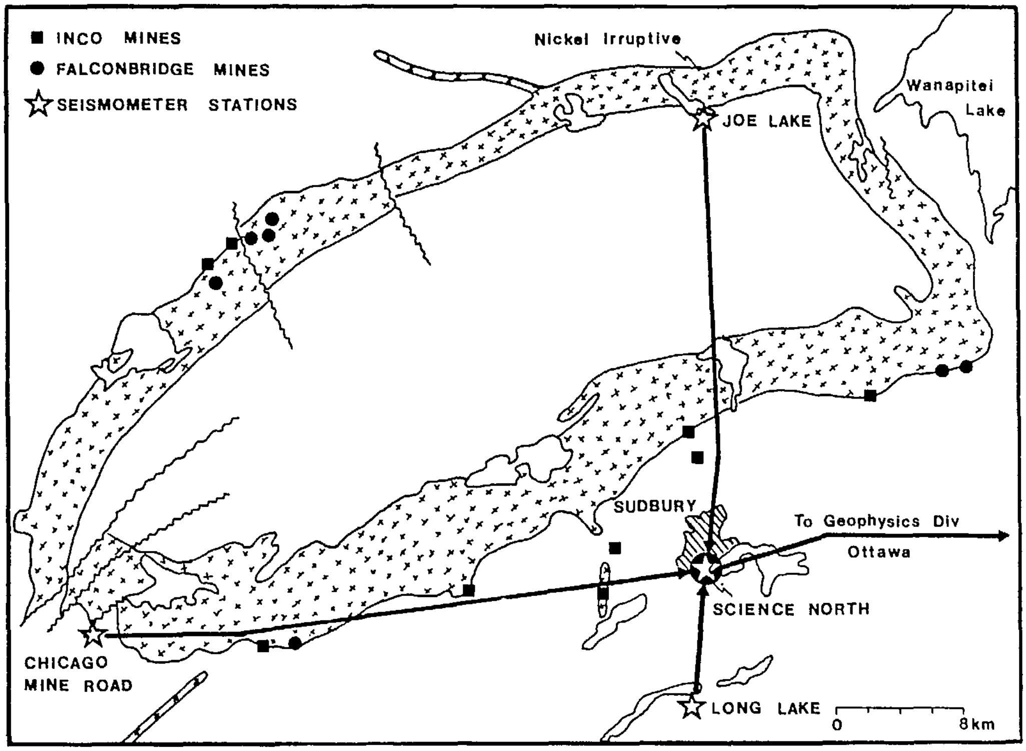


Figure 4 - Location of the seismograph network around the Sudbury Basin

The first macroseismic system, designed under contract by Noranda Inc., was installed at the Quirke Mine in 1987, followed by other installations at the Strathcona, Macassa, Campbell and Creighton mines. Each system consists of five triaxial sensors installed in boreholes on surface or underground, or in both places. To prevent saturation of the sensors, they are usually installed 0.5 to 1.0 km from the active mine workings. Accelerometers are used in the Strathcona system, whereas velocity gauges are used in the other four systems. Typically, the macroseismic systems record seismic signals in the 10 to 300 Hz frequency range and are capable of detecting seismic events of magnitude 0.5 and greater.

These macroseismic systems record the complete waveforms (generally two seconds long) of seismic events. An example of a velocity signal is shown in Figure 5a. In the time domain, the arrival of the P and S waves can usually be distinguished. The time difference is related to the distance from the event to the sensor; using the five sensor array, the location of the event can be calculated. The arrival of the P wave also shows a first motion either towards or away from the sensor, which provides information on the mechanism of the seismic event. The peak particle velocity (PPV) is used to assess the damage potential of a rockburst. Integration of the squared velocity signal gives the seismic energy liberated.

Analysis of the same seismic data in the frequency domain is shown in Figure 5b. The spectral density exhibits a plateau at low frequencies and a steep decay at higher frequencies. The plateau is related to the seismic moment, which is an alternative measure of the magnitude of a rockburst. The intersection of the plateau and the decay slope is the corner frequency, which is related to the areal extent over which slippage is occurring.

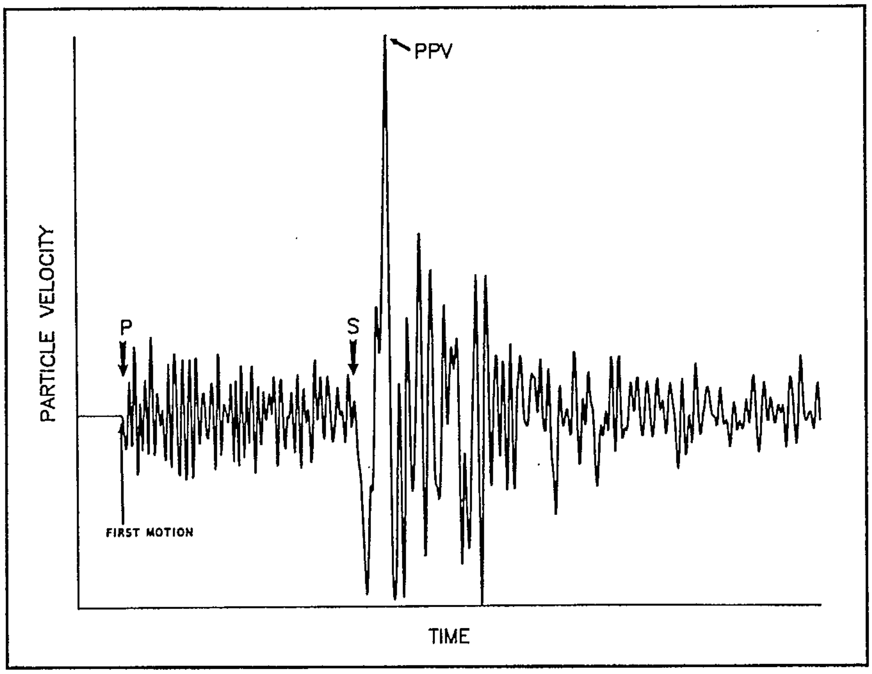


Figure 5a - Typical seismic waveform recorded on a macroseismic system

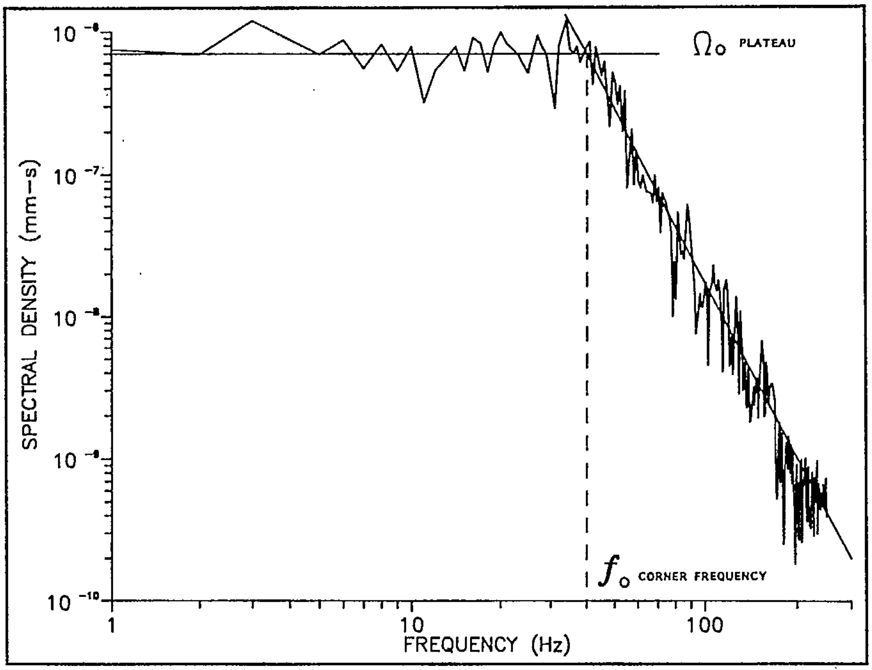


Figure 5b - Analysis of a seismic signal in the frequency domain

Two types of microseismic systems are now being used in Ontario mines: the Electrolab MP-250 system, and a system developed at the Geological Sciences Department of Queen's University. The Electrolab system employs up to 64 sensors installed around the underground working and records the arrival times at different sensors when the seismic signal exceeds a threshold value. From these arrival times, the location of the seismic event can be calculated. A single sensor also acts as an energy channel, and the signal from this sensor is integrated to provide a comparative seismic energy value. In the Queen's system, the complete seismic waveforms are recorded, which allows the P wave arrival to be accurately determined rather than a threshold value. Like the macroseismic systems, the Queen's system can be used for seismic analysis of the waveforms, but only for small-sized events because the sensors are extremely sensitive and are saturated by the larger events.

Most mining companies have digitized their mine plans and can automatically plot the location of microseismic activity on plans and sections. An example is illustrated in Figure 6, which shows the seismic activity following a rockburst of magnitude 3.6 at the Creighton Mine in October 1987.

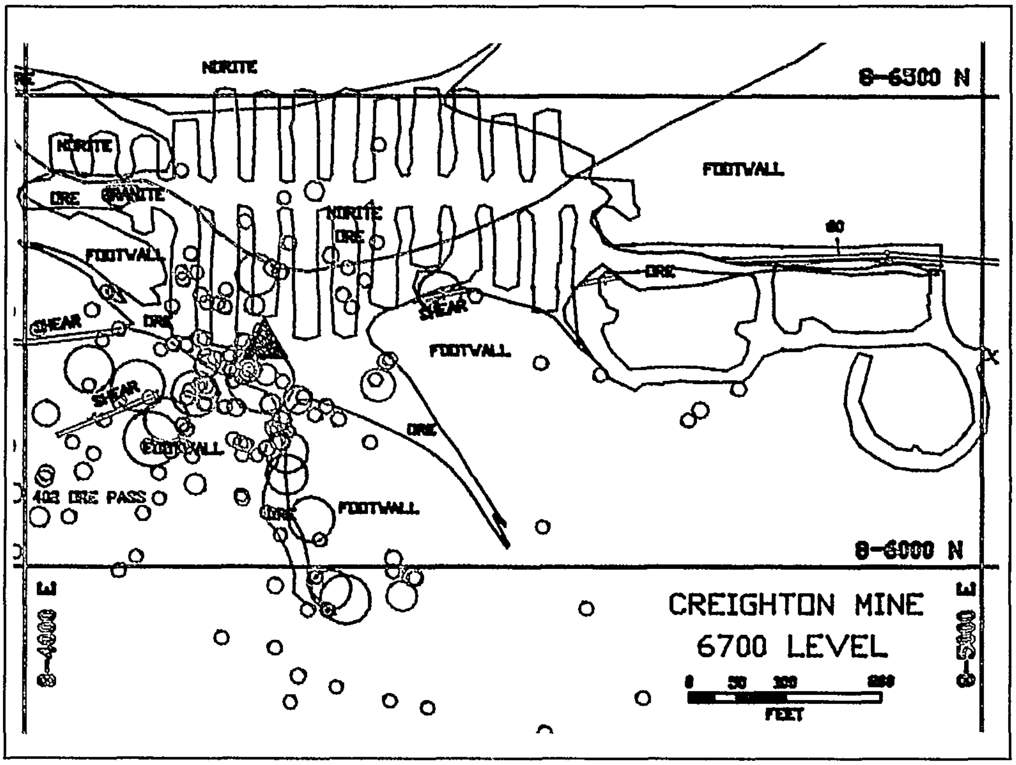


Figure 6 - Plot of seismic activity following a rockburst of magnitude 3.6 at the Creighton Mine

Scaling Relationships

At the beginning of the rockburst project, very little information existed on the inter-relationship between magnitude, seismic moment, seismic energy, peak particle velocity and acceleration for mines in northern Ontario. Relationships developed in earthquake seismology or for gold mines in South Africa had to be used.

By 1990, sufficient data had been recorded on the macroseismic systems as well as on a portable seismograph unit to begin defining relationships specific to northern Ontario.

Figure 7 shows the relationship between seismic energy (E_s) and magnitude (Mn). There is a clear trend to the results in the form:

$$\log E_s = 1.3 \text{ Mn} - 1.75 \text{ in MJ}$$

It was found, however, that 22% of the total seismic energy is typically contained in the P wave, compared with less than 10% in the South African gold mines.

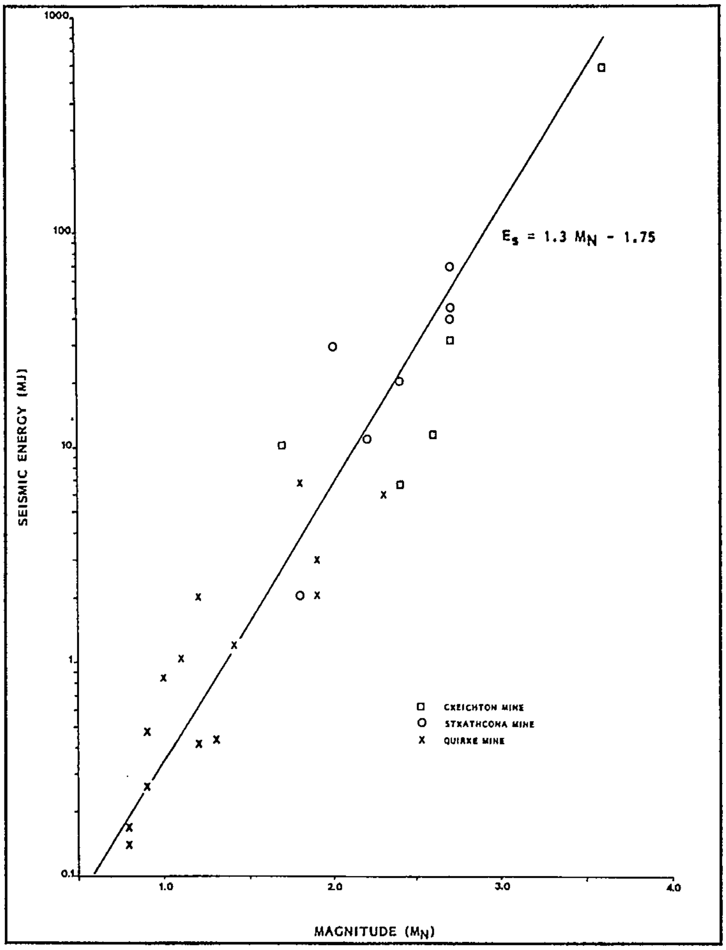


Figure 7 - Relationship between seismic energy and magnitude for Ontario mines

Besides magnitude (Mn), the seismic moment (Mo) is preferred in seismology as a measure of the size of an earthquake since the latter provides information on fault dimensions and slippage. The relationship between seismic moment and magnitude for Ontario mines is shown in Figure 8. A 1983 study by Hasegawa for naturally occurring earthquakes in the Canadian Shield produced the following relationship:

$$\log \text{Mo} = 0.94 \text{ Mn} + 1.32 \text{ in GNm}$$

The results from the mines tend to follow this same relationship.

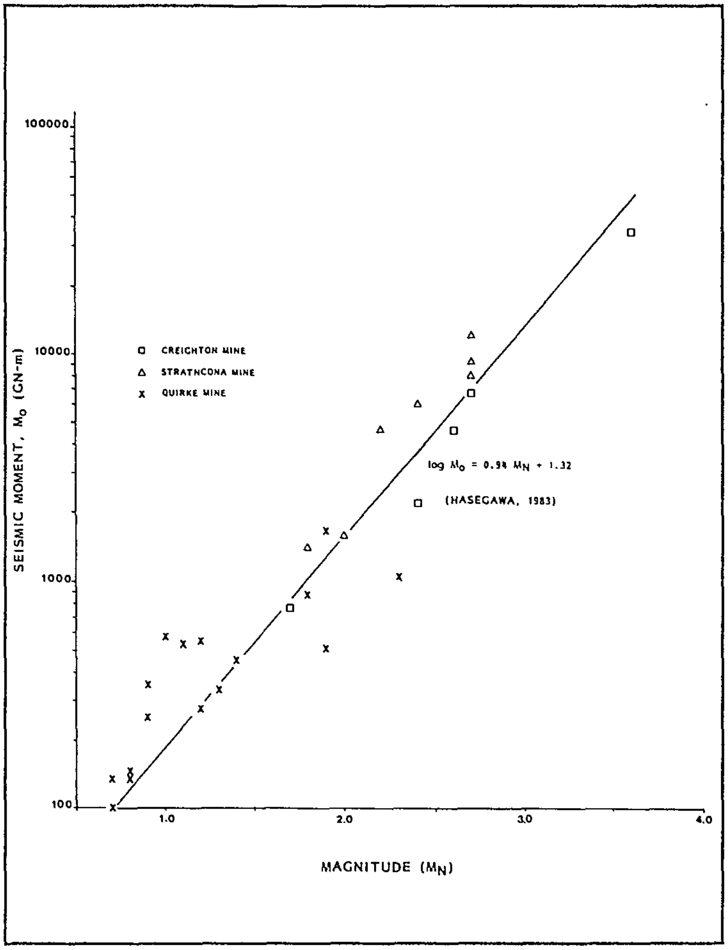


Figure 8 - Relationship between seismic moment and magnitude for Ontario mines

Peak particle velocity and, to a lesser extent, peak acceleration are used to evaluate potential damage from rockbursts. Both of these parameters are controlled by the magnitude of the rockburst and distance from source. A cube root scaling factor used in blasting studies was used to evaluate the measurements. The relationships for peak particle velocity and acceleration are shown in figures 9 and 10, respectively.

For peak particle velocity $\hat{v}$

$$\hat{v} = 4000 \left(\frac{R}{10^{M/3}}\right)^{-1.6} \text{ in mm/s}$$

and for peak particle acceleration $\hat{a}$

$$\hat{a} = 30 \left(\frac{R}{10^{M/3}}\right)^{-1.33} \text{ in g}$$

The attenuation of the seismic signals with distance (i.e., $R^{-1.6}$ and $R^{-1.33}$) are similar to those found in blasting studies and represent near-field effects. At greater distance, the attenuation factor should be R^{-1}.

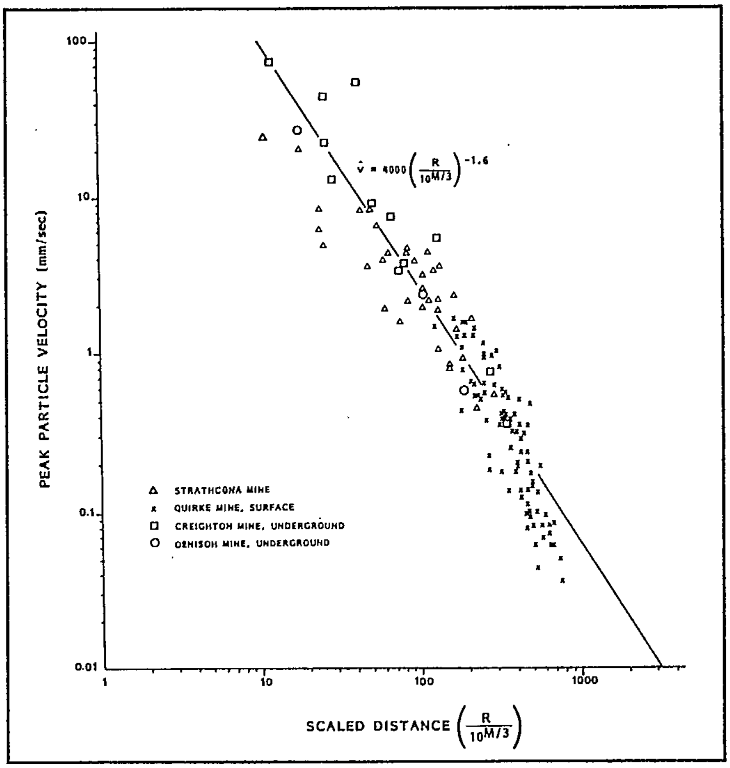


Figure 9 - Peak particle velocity as a function of a scaled distance for Ontario mines

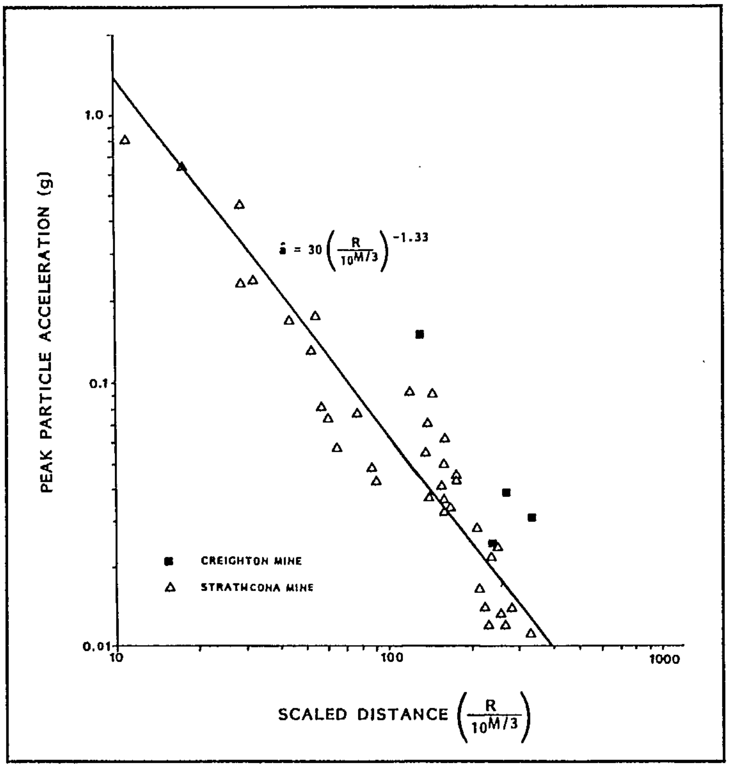


Figure 10 - Peak particle acceleration as a function of a scaled distance for Ontario mines

In contrast to natural earthquakes and rockbursts in South Africa, it is quite common in Ontario mines for the peak acceleration to occur in the P wave and the peak velocity in the S wave. This and the higher percentage of seismic energy in the P wave may suggest a different type of mechanism than a fault-slip rockburst.

A sufficient number of rockbursts have occurred in the Quirke, Creighton and Strathcona mines to examine the release of seismic energy over a period of time as shown in Figure 11. Most of the seismic energy releases at the Quirke Mine occurred continuously over a six-month period. The Creighton Mine is characterized by a few large events (3.3 to 4.0 Mn) spread over 12 to 28 months. At the Strathcona Mine, seismic energy was released at a more gradual pace.

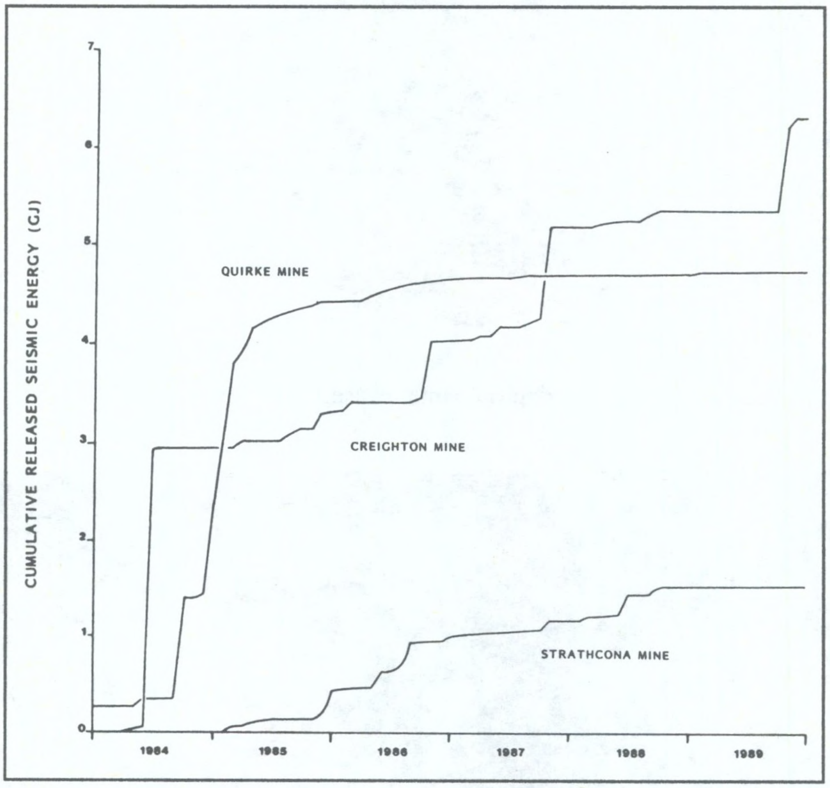
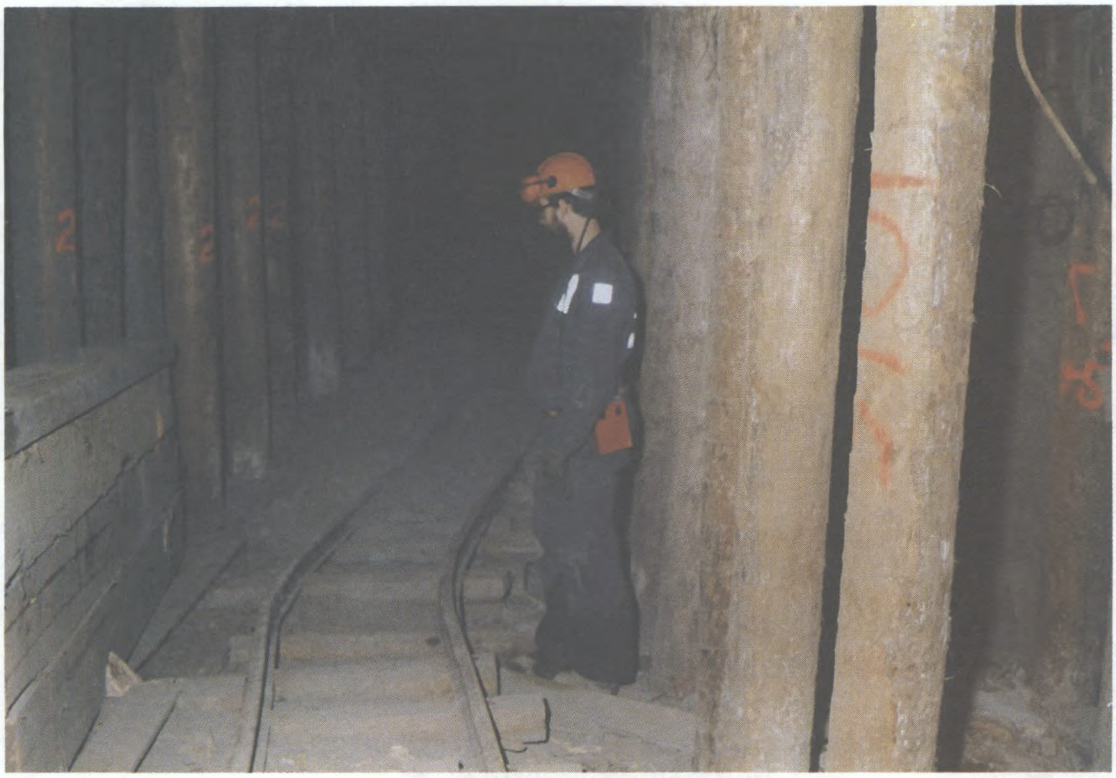


Figure 11 - Temporal release of seismic energy at the Quirke, Creighton and Strathcona mines

Photographic Review of Rockbursts in Ontario Mines

Damage to a drift on the 6600 level of Creighton Mine, caused by a 3.6 Mn rockburst about 25 m away.

Crown pillar at the Campbell Red Lake Mine, which was destressed then mined using longhole methods.



Displacement of the track caused by fault slippage at Falconbridge's No. 5 shaft.

Rockburst damage to a drift supported by timber posts and beams at the Macassa Mine.

More than 800 tonnes of rock displaced because of two small (2.0 Mn) rockbursts in an isolated haulage drift at Strathcona Mine.

Spalling of a rib pillar in the rockburst area on the east side of Denison Mine.

Lacing installed at the Strathcona Mine.
This type of support survived, without damage, a rockburst of magnitude 3.0 that occurred 40 m away.

Damage caused by a 3.1 Mn rockburst at the Macassa Mine.
Bolts and chain-link mesh prevented completed closure of the drift.

Damage to a sill drift at the Quirke Mine.

Backfill being poured around a failed pillar at the Denison Mine.

Elliot Lake Mines

Rio Algom Limited

The rockburst incidents at Quirke Mine are a classic example of a chain reaction of pillar failures. Over a five-year period, more than 160 seismic events, up to magnitude 3.5, were recorded by the Eastern Canada Seismic Network. An area over 70 ha was affected underground.

A plan of the eastern part of the main reef at Quirke Mine showing the locations of the rockbursts is illustrated in Figure 12. The rockburst problem began in 1982, next to a trial trackless area. There was a major increase in activity and expansion of the rockburst area in late 1984 and early 1985. Two patterns of activity were observed. First, violent failure of the pillars occurred at the edge of the affected area, which allowed the area to expand. Second, a number of events occurred in the centre of the affected area, accompanied by a sudden increase in water flow of 1000 L/min into the mine and a drop of 4 m in the water level in a small lake directly above the area. The latter events probably occurred in the hanging wall and were caused by slippage along near-vertical faults or along bedding contacts. Since the hanging wall fractured through to surface, the level of microseismic activity has decreased substantially, as has the number and magnitude of the larger events. The affected area has stopped expanding and has essentially stabilized.

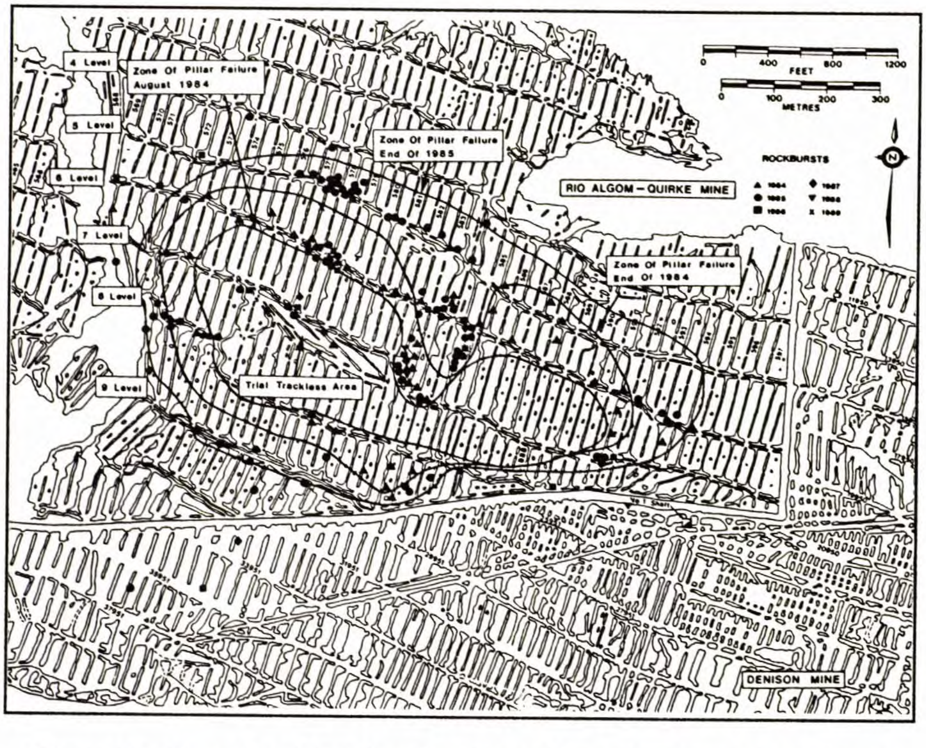


Figure 12 - Plan of Quirke Mine showing rockburst locations, 1984 to 1989

As part of the rockburst project, two diamond drill holes were put down from surface to investigate the degree of fracturing in the hanging wall above the affected area. The first hole utilized an old exploration borehole.

Continuous loss of drilling water down the borehole occurred throughout the drilling operations. Also, it was found that the old borehole had been laterally displaced, due to slip along bedding contacts, at several locations. Eventually, the borehole had to be abandoned at a depth of 265 m, about 240 m above the orebody.

A new diamond drill hole, directly over the centre of the rockburst area, was drilled from surface in 1988. Drilling progressed to a depth of 317 m, about 170 m above the orebody, before the hole was abandoned because of water loss problems. Two types of open fractures were encountered. Down to a depth of 150 m, water circulation was lost at eight locations, which was attributed mainly to minor open fractures on bedding contacts. At a depth of 155 m, a 100 mm wide gap was encountered and air was being sucked down the borehole into the mine. Similar open gaps of 100 mm and 150 mm were encountered at depths of 234 m and 255 m. Figure 13 illustrates the problems that were encountered during the drilling of the two holes.

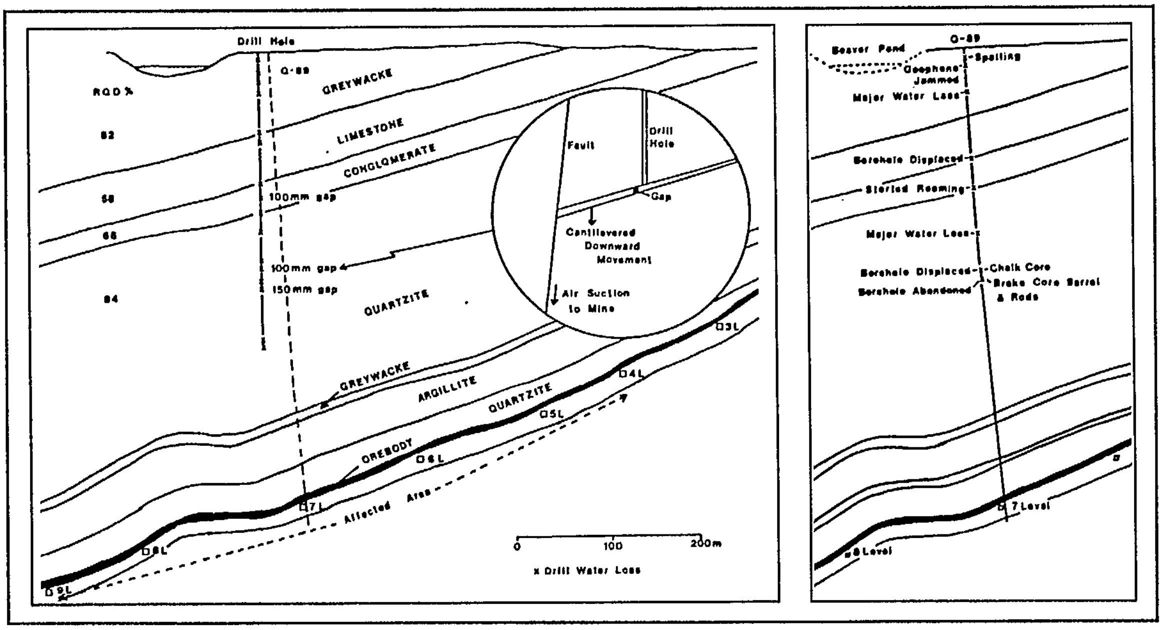


Figure 13 - Problems encountered during drilling of two boreholes above the rockburst area at Quirke Mine

For water and air to flow down the borehole into the mine, vertical fractures must be present. It is postulated that caving is confined to the first few metres of the hanging wall. For the next 350 m, extremely large blocks or slabs have moved down along vertical faults in a cantilever fashion. The top 150 m has subsided without major vertical fractures.

Denison Mines Limited

Two areas of Denison Mine are seismically active: one directly down dip from the main rockburst area at Quirke Mine and another isolated area about 2 km to the east. In both areas, deslimed tailings and cementitious slag, in a ratio of 30:1, are being poured to stabilize the pillars. Previous laboratory tests conducted by CANMET on rock specimens surrounded by cemented fill indicated that backfill had no effect on the peak strength of the pillars, but did affect the post-failure behaviour. With increasing cement content, the stress on the pillar after peak strength gradually reduces and stabilizes at a significant residual strength (i.e., 60% to 75% of peak strength). Consequently, failure is nonviolent and the seismic energy released is minimal.

A plan of the boundary pillar area of Denison Mine, showing the stopes backfilled and the location of seismic events during 1989 is illustrated in Figure 14. Most of the seismic events occurred at the edge of the backfilled area in pillars not surrounded by backfill. The main exceptions were where pillars were being recovered between backfilled stopes. In this case, it appears that the backfill controlled the violent failure of the pillars and the seismic energy emitted from the backfilled areas was minimal.

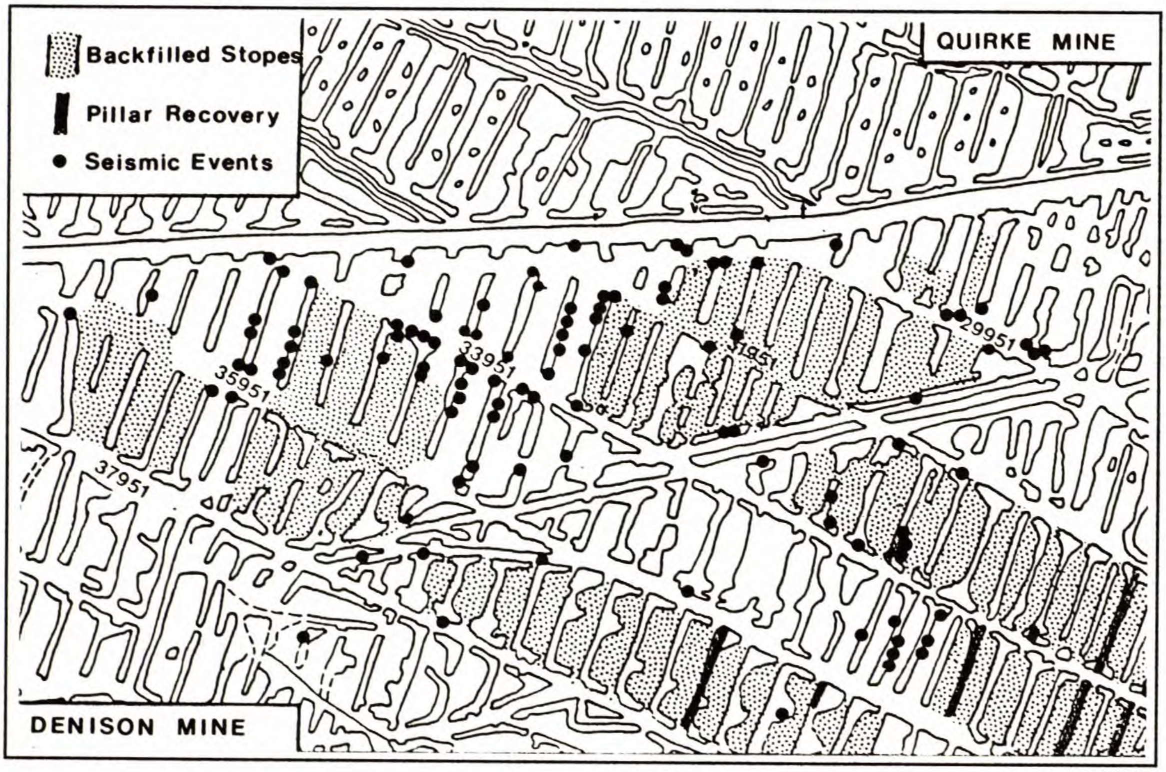


Figure 14 - Plan of Denison Mine showing the location of seismic events in the boundary pillar area during 1989

Figure 15 shows the backfilled stopes and location of seismic activity, between 1987 and 1989, in the eastern area of Denison Mine. A number of large events of magnitudes up to 2.8 have occurred in a narrow band extending northeast to southwest across the area. Microseismic activity is more widespread, extending 800 m on strike by 500 m on dip, although, again, there is a concentration around the larger magnitude events. In this case, there is considerable microseismic activity in some pillars surrounded by backfill. This activity occurred mainly during the pour and is thought to be caused by the water reducing the rock strength on the edge of the pillars. However, once the pillars were encased in backfill, seismic activity in them essentially ceased. This type of behaviour was not observed in the boundary pillar area since the pillars there were larger and less stressed.

Figure 15 - Plan of the eastern part of Denison Mine showing extent of seismic activity, 1987 to 1989

To contain the affected area shown in Figure 15, Denison Mine has begun to pour a 120 m wide backfill barrier in the stopes along the northwest boundary of the area.

Kirkland Lake Mines

Lac Minerals Ltd.

The gold mines at Kirkland Lake have a history of rockbursts dating back to the early 1930s. Of the original seven mines, Macassa Mine is the only one left in production. The steeply dipping narrow-vein orebodies extend to a depth of more than 2200 m, and are mined using cut-and-fill techniques. More than 400 rockbursts have been reported at the Macassa Mine during 55 years of continuous operation. These rockbursts have ranged from strain bursts in development drifts to pillar bursts during mining of the crown pillars. Most of these bursts occurred shortly after central blasting. About 10% of the rockbursts are classified as heavy, having displaced more than 50 tonnes of rock each. Destress blasting and stiff backfill are being used at the Macassa Mine to reduce the hazard and severity of, and damage from, rockbursts.

Levels were driven at 45 m vertical intervals and mining proceeded by overhand cut-and-fill techniques, originally using unconsolidated waste development rock as backfill. Rockburst problems normally occurred in the crown pillars when their nominal thickness was reduced to 15 m with an extraction ratio of about 67%. Computer models indicate perpendicular stresses of about 150 MPa on these pillars. A fairly common procedure is to destress the pillars at this point.

As part of the rockburst project, a destress blast in a crown pillar below the 5725 level was monitored using a microseismic array and convergence meters between the hanging wall and footwall. Before the blast, three rockbursts had occurred in the pillar: two in the raises at each end of the pillar, and one in the stope back. The blast was designed with 14 holes in the orebody spaced at 3 m centres with a powder factor of 0.15 kg/m^3. Boreholes adjacent to the two raises could not be loaded properly because of squeezing ground.

Considerable microseismic activity, as shown in Figure 16, followed the blast and was clustered mainly around the crown pillar. However, some parts of the pillar were free of seismic activity, especially the pillar next to the first borehole by the east raise, which was not fully loaded. Significant convergence of about 25 mm also occurred in the stope except for only 6 mm next to the east raise. Subsequent mining of the crown pillar triggered a small rockburst at this raise causing damage to the timber stalls; the convergence in this area also increased to 33 mm. It was concluded that the initial convergence and microseismic activity was indicative of only partial destressing of the crown pillar.

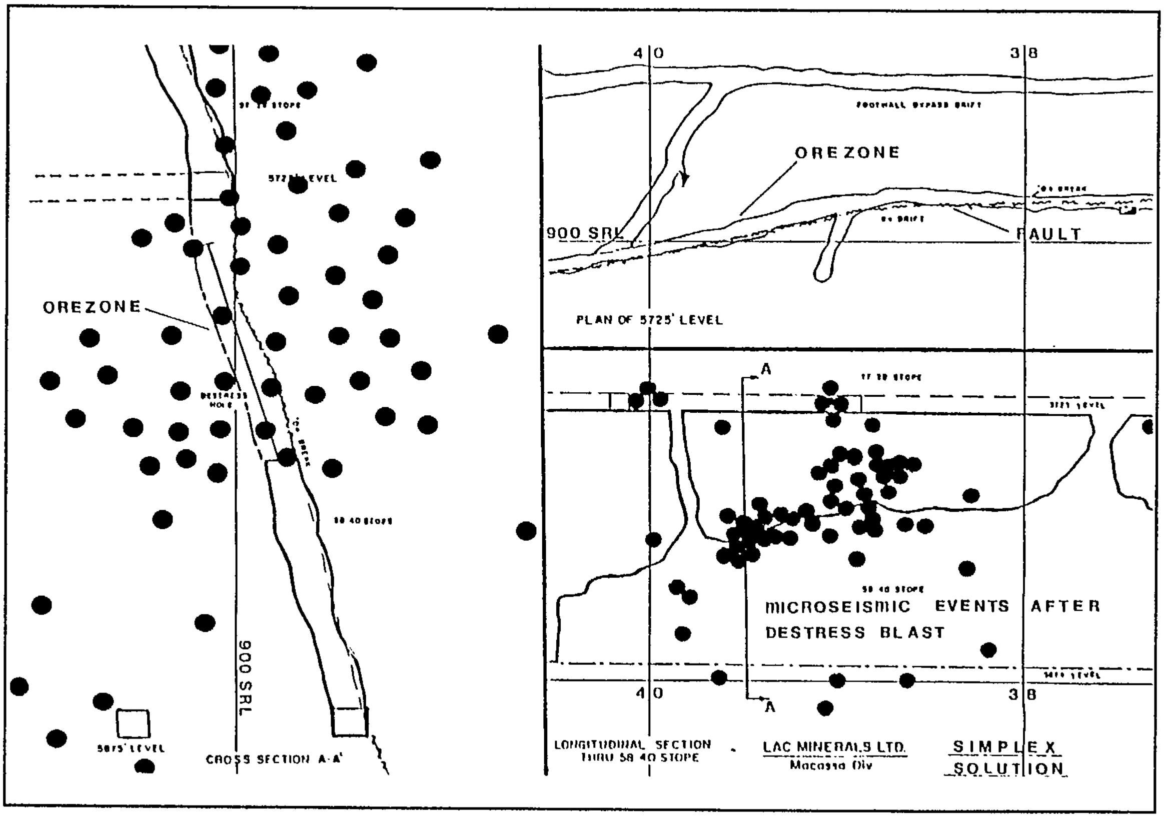


Figure 16 - Location of microseismic activity following a crown pillar destress blast at the Macassa Mine

About one year later, a series of rockbursts occurred after blasting in the crown pillar immediately above the destressed pillar. About 1000 tonnes of rock was displaced, and the drift adjacent to the destressed crown pillar also sustained damage. This drift was above a waste pillar that had not been destressed. In the final analysis, destressing of the crown pillar improved the recovery of the pillar itself but may have contributed to rockburst problems in the surrounding pillars.

Before 1986, Macassa Mine used unconsolidated development rock as a backfill material. When large rockbursts occurred, this rockfill tended to run into the drifts, making rehabilitation costly and time consuming. With the sinking of the new No. 3 shaft to a depth of 2202 m, the backfilling systems were reviewed. Initially, concrete was placed in undercut-and-fill stopes. Although this method limited the wall convergence, it was found to be too costly. Trials were then conducted on pouring a cement slurry over the development rockfill with a 5% cement content. The purpose of the cemented rockfill was twofold: to reduce the closure of the wall rocks and hence reduce the change in potential energy, and to absorb energy otherwise released as seismic energy.

It is possible to compare the reaction of both unconsolidated and cemented rockfill to major rockbursts. In 1982, a rockburst of magnitude 3.1 occurred in a stope with unconsolidated rockfill after an extraction of only 15%. It resulted in more than 1000 tonnes of displaced rock including closure of complete drifts, which took five months to rehabilitate. A second rockburst, of the same magnitude, occurred in the stope above in 1989. Cemented rockfill had been placed in this stope with extraction at 40%. In this case, only 130 tonnes of rock was displaced, which took one month to rehabilitate.

The improved ground conditions with cemented rockfill have made destress blasting obsolete and has allowed improved methods for recovery of crown pillars. Figure 17 illustrates one method being used for crown pillar recovery, and another rill stoping technique for mining at depth without crown pillars. In both cases, maximum reduction in potential energy and absorption is being utilized.

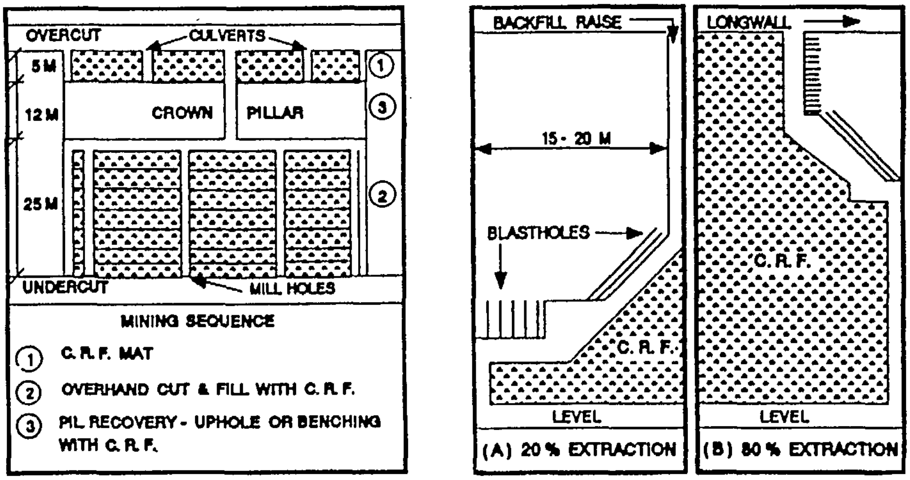


Figure 17 - New mining layouts being used with cemented backfill at the Macassa Mine
(after W. Quesnel, *et al.*, 1989)

Red Lake Mines

Placer Dome Inc.

The Campbell Mine of Placer Dome has experienced rockbursts since the early 1960s. These bursts have occurred mainly in the crown pillars of both shrinkage and cut-and-fill stopes. In many respects, the narrow steeply dipping orebodies, the mining methods and the rockburst problems in Red Lake are similar to those in Kirkland Lake.

An exception is the rockbursts in the F zone shrinkage stopes at the Campbell Mine. This orebody, about 2 m wide, extends 450 m on strike and has been mined to a depth of 700 m. Boxhole pillars and 6 m wide sill pillars were left with an extraction of about 80%. When the broken ore is removed from a shrinkage stope, the mining layout becomes an open stope and pillar layout that is prone to a chain reaction of pillar failures similar to the occurrence at Quirke Mine in Elliot Lake. This happened at the end of 1983 when 22 major rockbursts of a magnitude up to 3.3 occurred, accompanied by intense microseismic activity over a 28-hour period. The end result was the closure of seven levels over a vertical distance of 280 m, and since then, no mining has taken place in this orebody.

As part of the rockburst project, a back analysis of crown pillar failures in both shrinkage and cut-and-fill stopes was undertaken. Displacement discontinuity numerical models with elastic and post-failure behaviour were used. The graph in Figure 18 shows the average stress on crown pillars as mining progresses upwards. Pillar strength is derived from an empirical equation relating rock mass strength to pillar width and height. In the examples shown, pillar failure occurs at a width of 6.5 m on the 16 level, and 8.5 m on the 18 level. However, ground conditions will deteriorate before this because of the higher stress concentrations on the stope back. This type of analysis indicates when destress blasting is required or when a change in mining methods from horizontal slices to vertical longhole techniques is needed.

Since 1982, four destress blasts have been done in pillars at the Campbell Mine, with varying degrees of success. The main purpose of destressing is to reduce the potential energy of the rock mass. This is achieved by fracturing the pillar and allowing the hanging wall and footwall to converge.

Two destress blasts were done in the crown pillars of cut-and-fill stopes. In one case, a rockburst occurred within seconds of the blast, and the pillar was subsequently recovered without any stress problems. In the second case, a rockburst occurred three days after the blast at a location where very little closure was measured following the blast.

Destress blasting in boxhole pillars of shrinkage stopes triggered rockbursts on other levels. This indicated that destressing in a shrinkage stope layout (or on open stope and pillar layout) is not recommended.

As part of the rockburst project, a destress blast in the crown pillar of a cut-and-fill stope on the 15 level was investigated. In this case, the blast was made in an offshoot vein in the footwall and was aimed at providing a low-stress shadow when mining the main vein. Numerical models were used to estimate the stresses and displacements before and after blasting. The microseismic system was augmented with a recorder to capture the complete seismic waveforms.

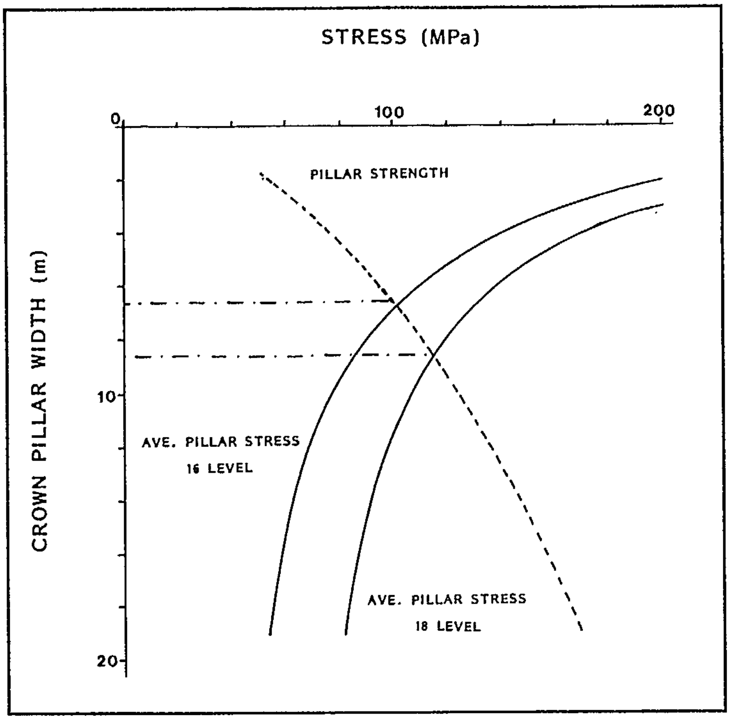


Figure 18 - Analysis of stress and strength of crown pillars at the Campbell Mine

After blasting, convergence and stress instruments indicated a reduction in rock modulus of about 50%, as determined by the numerical models. However, only eight microseismic events were recorded opposite the crown pillar, which perhaps indicated that the pillar was not heavily stressed. Subsequently, the pillar was recovered without any stress problems.

Also as part of the rockburst project, trials were undertaken on the reaction of various support systems to dynamic loading. Eight types of supports, 2 m long, were installed in a small section of a drift, and explosive charges were set off at fixed distances from the supports. Geophones were attached to the ends of the supports, as well as to the rock face, to measure the peak particle velocity. Typical results for selected supports (i.e., tensioned mechanical bolts, grouted rebar and friction-type supports) are shown in Figure 19. It was observed that the peak particle velocities on these supports were consistently less than at the rock face and that there were consistent differences between supports. Probably at greater distances the peak particle velocities on the rock and support converged to a common value. When the peak force pulse on the supports is calculated, the reaction of the three different support systems is very similar, as shown in Figure 19. The peak force takes into account the difference in the cross-sectional area of the steel supports. These results suggest that a constant force model rather than a constant peak particle velocity or stress pulse is applicable for the design of support systems subject to rockbursts. Much further research is required in this area.

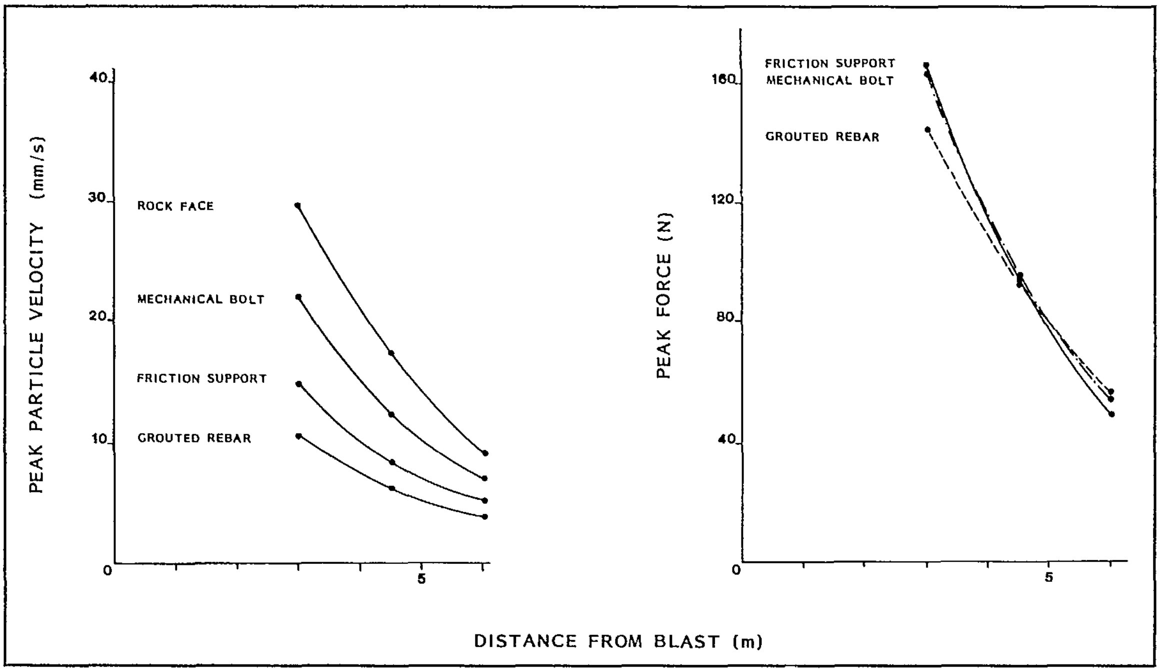


Figure 19 - Peak particle velocity and force on different types of support systems subjected to blasts

Sudbury Mines

Falconbridge Limited

Falconbridge operates six mines in the Sudbury Basin, all of which have experienced rockbursts to varying degrees. However, most rockburst activity has been confined to the Falconbridge No. 5 shaft and the Strathcona Mine. Falconbridge has undertaken studies with the Itasca Consulting Group on fault-slip mechanisms. It has also worked with the Geological Sciences Department of Queen's University on tomography studies and back analysis of microseismic data. Trials on a lacing support system were first conducted at the Strathcona Mine.

The rockburst incidents at the No. 5 shaft in 1984 unfortunately resulted in four fatalities and closure of the mine. These incidents created further impetus for the formation of the Canada-Ontario-Industry Rockburst Project.

These rockbursts provided the first clear evidence of a fault-slip mechanism in Ontario mines. An analysis of the microseismic aftershock patterns following two major rockbursts indicated that all the seismic activity was confined to the footwall in a quadrant configuration. Activity was spread over a radius of 180 to 200 m, centred on the locations of the bursts, which agreed reasonably well with theoretical models.

At the Strathcona Mine, an irregular tabular orebody extended about 800 m on strike and dipped at about 45°. A horizontal sill pillar was left between the 2000 and 2400 levels, with the stopes above and below having been mined out and backfilled with cemented tailings. Mining of the sill pillar using blasthole methods began in 1983, and since 1985, more than 40 rockbursts, up to magnitude 3.2, have occurred in the sill pillar. Figure 20 depicts a longitudinal section of the sill pillar showing the location of the rockbursts and the mining activity. Although the rockbursts are mining induced, the mechanism appears to be slippage along geological structures. These structures are sub-parallel or branch systems associated with the main dyke, which passes through the centre of the sill pillar. There has been no major rockburst on the main dyke itself, only microseismic activity. In many cases, the rockbursts occurred within 24 hours after production blasts. These are usually scheduled for the last shift on Friday night, which leaves two days for the mine to quieten down.

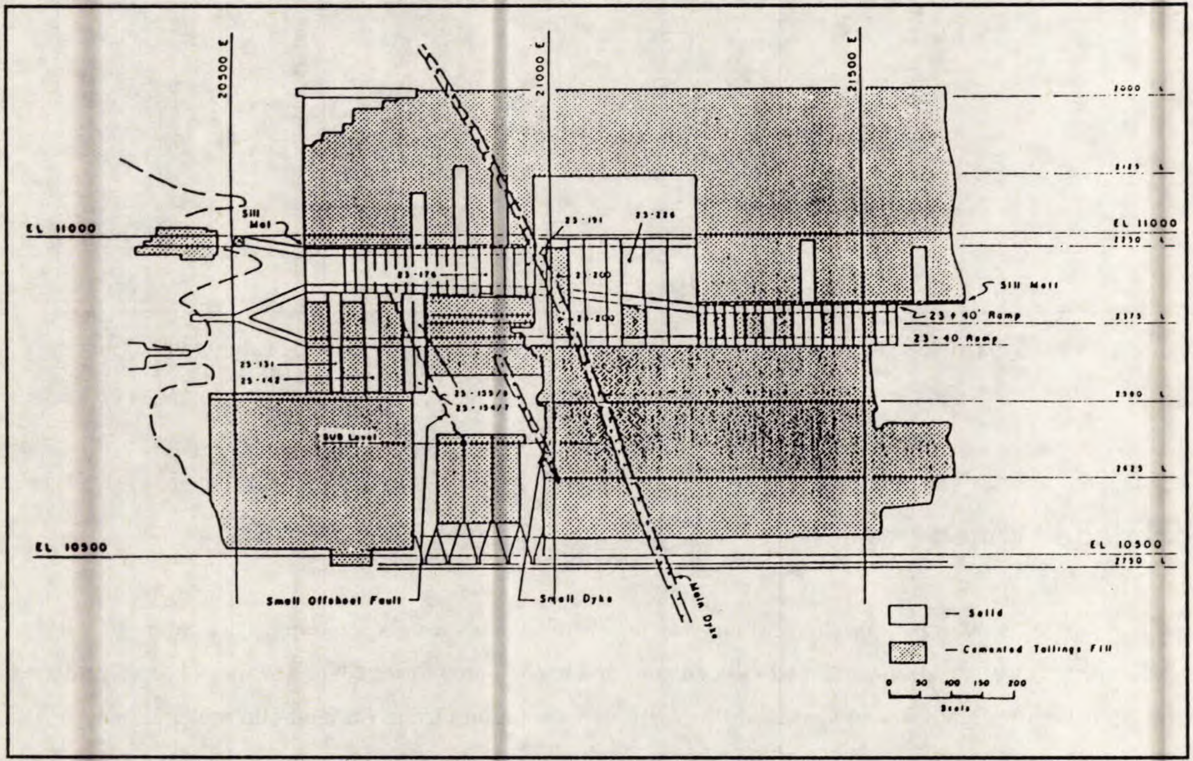


Figure 20 - Longitudinal elevation view of the Strathcona Mine showing the major structural features, the backfilled regions and the remaining panels to be removed (after Davidge, 1987)

The mechanisms of slippage on structures around the 23 to 200 stope were investigated by the company and Itasca Consulting Group using a distinct element block model. Figure 21 shows the stress trajectories and slippage the on structure during the stages of mining in the 23 to 200 stope. During the initial stages of mining (see (a) and (b) in Figure 21), slippage was confined to structures on the south east side of the stope. Further mining (see (c) and (d) in Figure 21) produced a change in slippage to structures on the west side of the stope. The pattern of microseismic activity was consistent with this analysis.

In response to this rockburst problem, the company initiated a program of lacing support system in the access drift to the sill pillar. The multicomponent system consisted of 14 mm diameter mild steel eyebolts, fully grouted into 1.8 to 2.4 m holes, spaced at 1.8 m centres. Galvanized chain-link mesh with 100 mm apertures was held

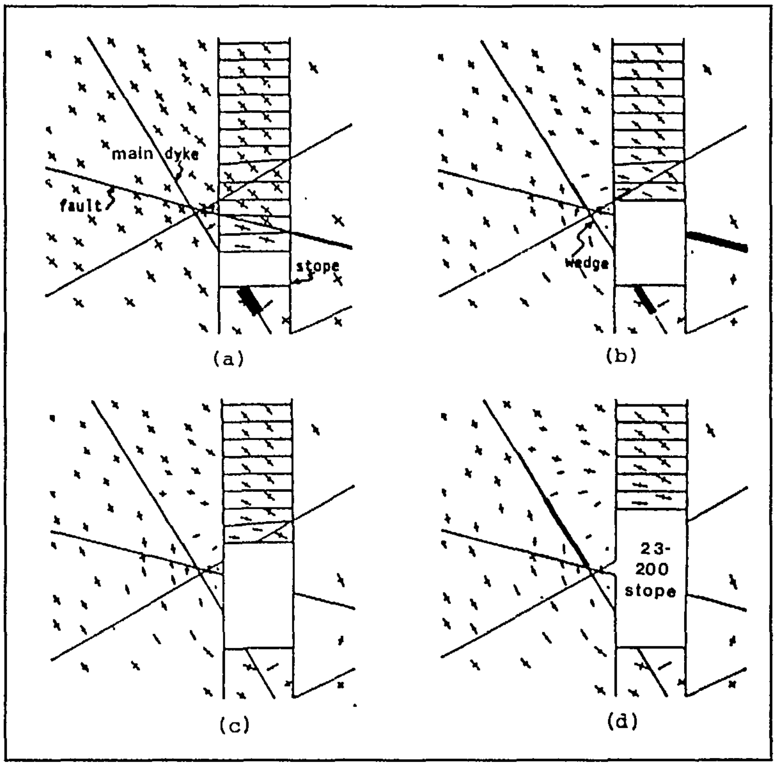


Figure 21 - Calculated shear displacement associated with stope extraction at the Strathcona Mine (after Brady, 1988)

against the rock face with plates on the eyebolts. Wire cable 12.5 mm in diameter was threaded through the eyebolts in a diamond configuration and tensioned to about 2.5 tonnes.

After the drift had been supported with lacing, a rockburst of magnitude 3.0 occurred in the area. This burst severely damaged the conventionally supported stope overcut (grouted rebar and wire mesh), which was about 25 m away. The nearest lacing was about 40 m from where the burst had occurred. This area suffered no damage, although some bagging of the screen and loading of the flexible cables was observed. Another rockburst incident of magnitude 2.7 resulted in one broken wire cable and some bagging and loading of the screen and cables.

The rockburst project has funded studies by the Geological Sciences Department of Queen's University for back analysis of microseismic data at the Strathcona Mine. The accuracy of source location techniques and the relationship between the pattern of microseismic activity and mining sequence has also been examined.

A comparison was made between the P wave time arrival peaks from the Electrolab MP-250 microseismic system and the whole waveforms recorded by Queen's microseismic system. It was found that the MP-250 system sometimes triggers on a noise spike or the S wave arrival time, which produces erroneous source locations. In addition, the MP-250 records nonseismic events, including blasts, drilling, mucking, vibrations from equipment and retriggers of long-duration events. On re-evaluation, it was found that only about 30% of the total number of events recorded were true seismic events. Because of the source location algorithm being used (i.e., least squares), the nonseismic events tended to line along linear trends, which could be interpreted as indicating activity along geological structures.

Inco Limited

Inco currently operates nine mines in the Sudbury Basin. Since the early 1930s, some of these mines have experienced rockbursts. Initially, the Frood Mine was the most seismically active, but in recent years, the Creighton and Copper Cliff North mines have experienced the most seismic activity. To date, five microseismic systems have been installed in these mines.

Over the years, Inco has developed techniques and strategies to deal with the rockburst problem. These have included destress blasting in shafts, drifts and stope pillars; sequencing of extraction to minimize the hazard; and, more recently, identification of which geological structures are seismically active.

Inco has classified its rockbursts into three categories:

- events that occur in development drifts because of high stress concentrations, which can be dealt with by tactical solutions such as altering opening shape, destress blasting, or enhanced support systems;
- events that occur in the stoping operations, including pillar bursts and fault-slip, which can be dealt with by strategic approaches such as designing yielding pillars and sequencing extraction to even out energy release; and
- events that occur in the wall rock away from the orebody, which are inevitably caused by fault-slip and are related to regional mining activity. Little can be done about these bursts except for enhancing support systems.

Creighton Mine has experienced rockbursts since 1934. Mining has now been extended to a depth of 2200 m under very high stress conditions. On the 6600 level, for example, field stresses are about 95 MPa parallel to the orebody, 70 MPa across the orebody and 60 MPa vertically. Under such conditions, destress blasting is routinely undertaken in drifts and pillars. The layout of the destress holes in a drift and in pillars in cut-and-fill operations is shown in figures 22(a) and 22(b), respectively.

In drifts, holes are drilled out ahead of the face and angled out into the corners at the roof line. Sometimes holes are also angled out into the floor corners. Only the bottom part of the holes are loaded with explosives. The destress holes are detonated first, followed by the main blast. The purpose is to create a fractured zone for the next advance of the drift. The walls and back are supported with bolts and wire mesh.

Below 2000 m depth, rockbursts were occurring in the pillars during silling out in mechanized cut-and-fill stopes. The pillars usually had a width-height ratio of one and had not yielded at this stage. The destress pattern shown in Figure 22(b) included both destressing the pillars and the face of the stopes. Although this did not stop rockbursts, it reduced their intensity, and most of the rockbursts occurred shortly after the blast.

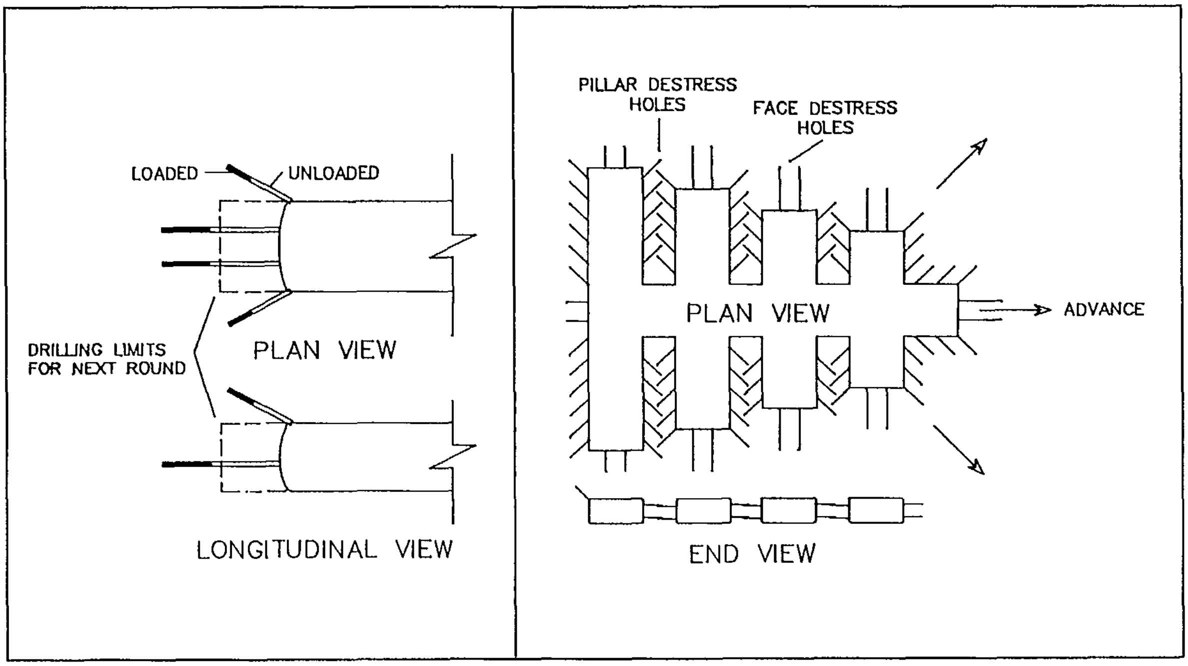


Figure 22 - Layout of destress boreholes in drifts and pillars at the Creighton Mine

Crown pillars in cut-and-fill stopes were determined to be a major source of rockbursts in deep mining operations. Techniques were then developed to advance the stoping sequence in an inverted V formation. This limited rockburst problems to the lead stope. With the conversion from cut-and-fill to vertical retreat mining below 6600 level, it was decided that a destress slot should be created across the orebody in the crown pillar. The aim was to redistribute the stresses in the crown pillar and change the potential energy in the rock mass at the beginning of the mining cycle rather than at the end. Figure 23 shows a perspective view of stopes above and below the crown pillar on the 6600 level. The destress slot was blasted in stages and backfilled after each stage. Thousands of microseismic events were recorded during mining of the slot, usually within two hours of blasting. Mining, using vertical retreat methods, has since progressed in the crown pillar without any high-stress problems.

Most of the large seismic events (of magnitude greater than 3.0) at the Creighton Mine occur in the wall rocks away from the mining zones. This discovery led to a systematic evaluation of geological structures at depth. Figure 24 shows the location of prominent shear zones on the 6600 level. All the shear zones are seismically active, some with only microseismic activity, and others with major seismic events.

As part of the rockburst project, the Geomechanics Centre of Laurentian University is investigating the properties of the shear zone materials.

The orebody at the Copper Cliff North Mine is 8 to 24 m wide, steeply dipping and tabular. Mining is done with vertical retreat methods in alternating 12 m wide stopes and 24 m wide pillars. At present, mining is concentrated between the 3600 and 3935 levels, and the layout is shown in Figure 25.

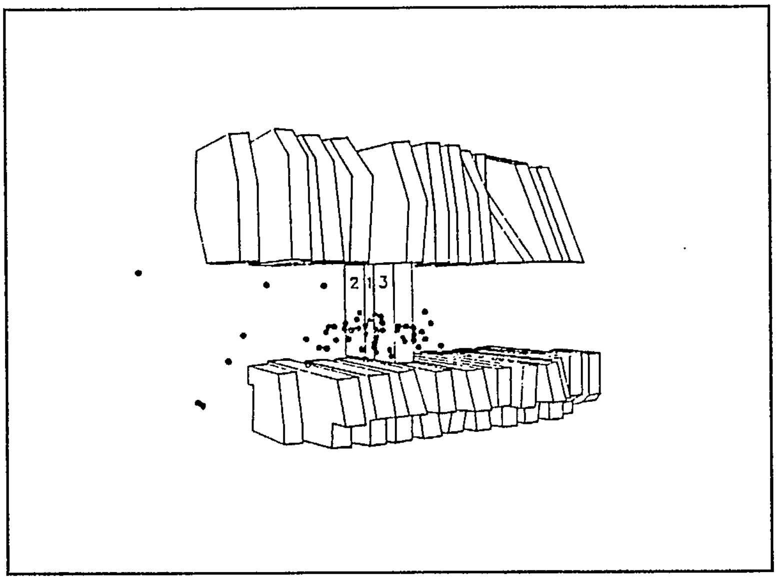


Figure 23 - Destress slot in crown pillar below the 6600 level at Creighton Mine and the location of seismic activity

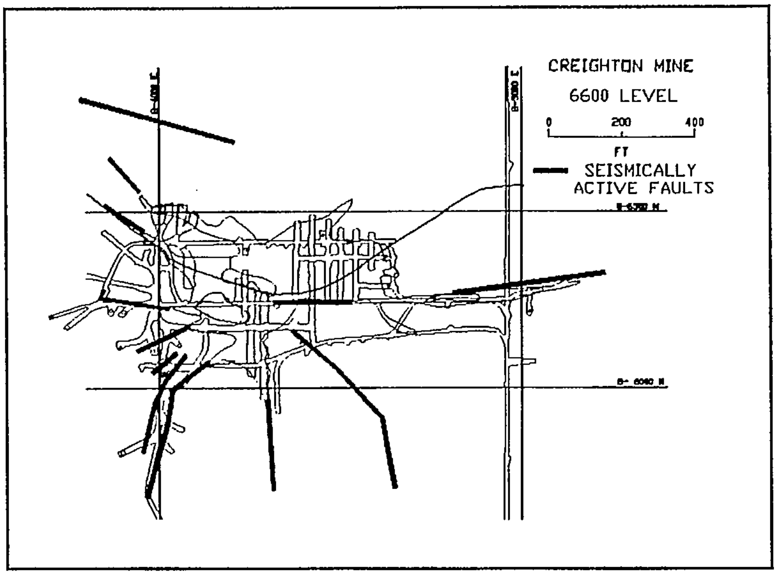


Figure 24 - Location of seismically active fault zones at the Creighton Mine

There were no ground control problems before 1986, when mining was done at almost all of the primary stopes. However, there were operational problems with the backfill system and several stopes were unfilled. Seismicity and rockbursts began to occur during the mining of the 113 stope at the extreme southern end of the orebody.

After a crown pillar blast, which itself registered at a magnitude of 3.1, four rockbursts of magnitude 2.2 to 2.9 occurred within a one-hour period. These damaged the sill access on the 3835 level. Further mining in the 113 stope caused additional damage to this access as well as to access on the 3600 and 3935 levels. On the basis of the location of the rockbursts and seismic events, it was concluded that the adjacent 114 pillar had violently failed. Mining of the pillar produced further rockbursts and caves of ground. A total of 23 events of magnitude 2.0 and greater have been located in and around these levels. In contrast with the Creighton Mine, these events are not controlled by structural features.

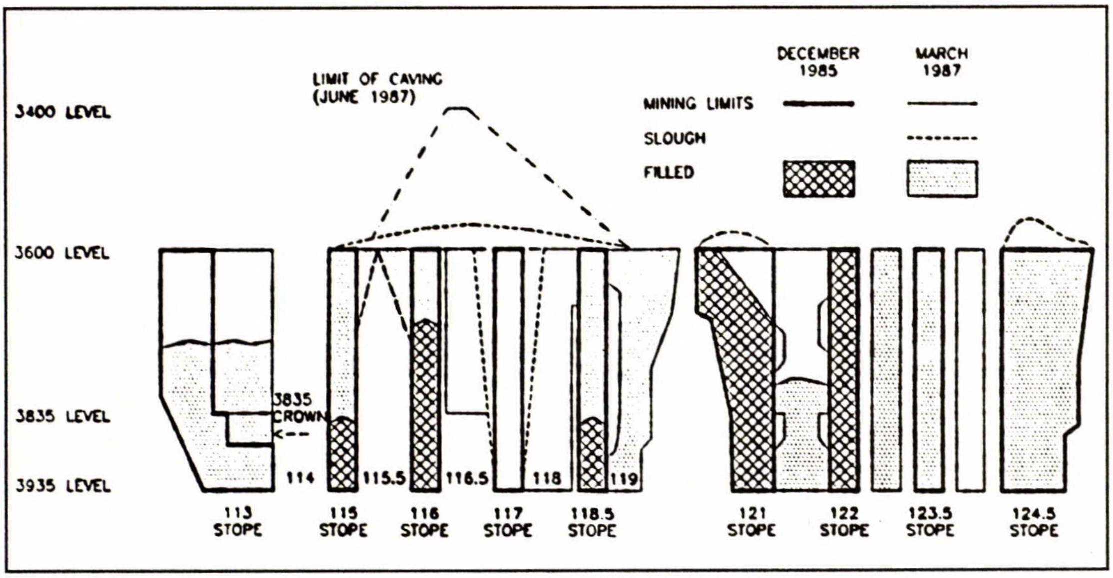


Figure 25 - Longitudinal section of Copper Cliff North Mine showing stopes mined and filled (after Morrison, 1990)

Publications

Udd, J.E.; A proposal for a major research project on rockbursts; Division Report MRP/MRL 84-84(TR); CANMET, Energy, Mines and Resources Canada; 1984.

Brehaut, C.H. and Hedley, D.G.F.; 1985-1986 Annual report of the Canada-Ontario-Industry rockburst project; CANMET Special Report SP 86-3E; CANMET, Energy, Mines and Resources Canada; 1986.

Makuch, A.; Design of a new macroseismic monitoring system; CANMET Special Report SP 84-14E; CANMET, Energy, Mines and Resources Canada; 1986.

Niewiadomski, J.; Source location techniques using P-wave arrivals; CANMET, Special Report SP 86-15E; CANMET, Energy, Mines and Resources Canada; 1986.

Hedley, D.G.F.; Condition of the hanging wall above the rockburst area at Quirke Mine; Division Report M&ET/MRL 86-155(TR); CANMET, Energy, Mines and Resources Canada; 1986.

Udd, J.E. and Hedley, D.G.F.; Rockburst research in Canada - 1987; Division Report MRL 87-1(TR); CANMET, Energy, Mines and Resources Canada; 1987.

Arjang, B. and Nemcsok, G.; Review of rockburst incidents at the Macassa Mine, Kirkland Lake; Division Report MRL 87-21(TR); CANMET, Energy, Mines and Resources Canada; 1987.

Hanson, D.S.G.; Calibration of the NFOLD displacement discontinuity model of the 'A' zone at Campbell Red Lake Mine; Division Report MRL 87-36(TR); CANMET, Energy, Mines and Resources Canada; 1987.

Hedley, D.G.F.; Rockbursts in Ontario mines during 1985; CANMET Special Report SP 87-2E; CANMET, Energy, Mines and Resources Canada; 1987.

Hedley, D.G.F.; Catalogue of rockburst literature; Division Report MRL 87-50(LS); CANMET, Energy, Mines and Resources Canada; 1987.

Hedley, D.G.F.; Rockburst mechanics; Division Report MRL 87-118(TR); CANMET, Energy, Mines and Resources Canada; 1987.

Makuch, A., Neumann, M., Hedley, D.G.F. and Blake, W.; Destress blasting at Campbell Red Lake Mine; Part 1: Rock mechanics concept of destressing pillars; Part 2: Practical applications of pillar destressing at Campbell Mine; Part 3: An instrumented destress blast of the 1604E crown pillar; CANMET Special Report SP 87-8E; CANMET, Energy, Mines and Resources Canada; 1987.

Hanson, D.S.G., Quesnel, W. and Hong, R.; Destressing a rockburst-prone crown pillar at Macassa Mine; Division Report MRL 87-82(TR); CANMET, Energy, Mines and Resources Canada; 1987.

Newmann, M., Makuch, A., Hedley, D.G.F. and Blake, W.; Practical applications of pillar destressing at Campbell Red Lake Mine; 8th CIM Underground Operator's Conference, Elliot Lake, Ontario, February 1987.

Le Bell, G.R., Quesnel, W.T.F. and Glover, W.; An analysis of rockburst events during sinking of Macassa No. 3 shaft; CIM Annual General Meeting, Toronto, May 1987.

Morrison, D.M.; Rockburst research at Falconbridge Limited; CIM Annual General Meeting, Toronto, May 1987.

Brehaut, C.H. and Hedley, D.G.F.; 1986-1987 Annual report of the Canada-Ontario-Industry rockburst project; CANMET Special Report SP 87-7E; CANMET, Energy, Mines and Resources Canada; 1987.

Davidge, G.R.; Rockburst research at Falconbridge Limited; Mining Induced Seismicity Workshop, Montréal, August 1987.

Hanson, D.S.G., Rochon, P. and Semadeni, T.J.; Seismic monitoring systems being used in the Canada-Ontario-Industry rockburst project; Mining Induced Seismicity Workshop, Montréal, August 1987.

Hedley, D.G.F. and Udd, J.E.; The Canada-Ontario-Industry rockburst project; Mining Induced Seismicity Workshop, Montréal, August 1987.

Hedley, D.G.F.; Rockbursts; Proc. Seminar CANMET, Partner with the Quebec Mining Industry, Val d'Or, Quebec, pp. 94-117, February 1988. Division Report MRL 87-160(OP)E; CANMET, Energy, Mines and Resources Canada; 1987.

MacDonald, P. and Cochrane, L.B.; Research related to mining induced seismicity at Inco Limited; Mining Induced Seismicity Workshop, Montréal, August 1987.

Makuch, T.; Rock mechanics at Campbell Red Lake Mine; Mining Induced Seismicity Workshop, Montréal, August 1987.

Niewiadomski, J.; Source location techniques for seismic activity in mines; Mining Induced Seismicity Workshop, Montréal, August 1987.

Oliver, P., Wiles, T., MacDonald, P. and O'Donnell, D.; Rockburst control measures at Inco's Creighton Mine; Proc. 6th Conf. on Ground Control in Mining, West Virginia, 1987.

Quesnel, W.J.F. and Hong, R.; Mining induced seismicity: monitoring and interpretation, Lac Minerals Ltd., Macassa Division; Mining Induced Seismicity Workshop, Montréal, August 1987.

Rochon, P. and Hedley, D.G.F.; Magnitude scaling of seismic events at Elliot Lake; Division Report MRL 87-157(TR); CANMET, Energy, Mines and Resources Canada; 1987.

Udd, J.E. and Hedley, D.G.F.; Rockburst research in Canada - 1987; Proc. 6th Int. Rock Mech. Congr., Vol. 2, pp. 1283-1288, Montréal, September 1987.

Bharti, S.; Safe and productive mining at depth - a strategic approach developed by Falconbridge; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Cochrane, L.B.; Control of structural geology on rock mass failures; Seminar Rock Mass Failure in Hardrock Mining, Laurentian University, Sudbury, Ontario, June 1988.

Davidge, G.R., Martin, T.A. and Steed, C.M.; Lacing support trial at Falconbridge Ltd., Strathcona Mine; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Hedley, D.G.F.; Historical review of rockbursts in Ontario mines; Division Report MRL 88-28(TR); CANMET, Energy, Mines and Resources Canada; 1988.

Hedley, D.G.F.; Peak particle velocity for rockbursts in some Ontario mines; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

MacDonald, P., Wiles, T. and Villeneuve, T.; Rock mechanics aspects of vertical retreat mining at 2000 m depth at Creighton Mine; CARE, University of Newcastle-upon-Tyne, published by IMM, London, 1988.

Makuch, T. and Blake, W.; Practical application of rock mechanics and mine planning for rockburst control at Campbell Red Lake Mine; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Morrison, D.M.; Instabilities induced by fault slip mechanisms; Seminar Rock Mass Failure in Hardrock Mining, Laurentian University, Sudbury, Ontario, June 1988.

Morrison, D.M. and MacDonald, P.; Causes of rockbursts in Inco mines; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Plouffe, M., Cajka, M.G., Wetmiller, R.J. and Andrew, M.D.; The Sudbury local telemetered seismograph network; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Semadeni, T.J., Rochon, P. and Niewiadomski, J.; Waveform analysis of mine-induced seismic events recorded at Rio Algom's Quirke Mine; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Wetmiller, R.J., Plouffe, M., Cajka, M.G. and Hasegawa, H.S.; Investigation of natural and mining-related seismic activity in Northern Ontario; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Wiles, T. and MacDonald, P.; Correlation of modelling results with visual and microseismic monitoring at Creighton Mine; Computers and Geotechnics, Vol. 5, No. 2, pp. 105-122; 1988.

Labuc, V. and Momoh, O.A.; The CANMET-Noranda seismic monitoring system using fibre optic signal transmission; Mining Induced Seismicity Workshop, Montréal, August 1987.

Labuc, V., Bawden, W. and Kitzinger, F.; Seismic monitoring using fibre optic signal transmission; Proc. 6th Int. Rock Mech. Congr., Vol. 2, pp. 1051- 1056, Montréal, September 1987.

Semadeni, T.J. and Calder, P.N.; High frequency microseismic monitoring applied to the determination of stress levels in hard rock mines; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Tabebi, S. and Young, R.P.; Characterizing microseismicity associated with stope development; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Young, R.P., Hutchins, D.A. and McGaughey, W.J.; Seismic imaging ahead of mining in rockburst prone ground; Proc. 2nd Int. Symp. Rockbursts and Seismicity in Mines, Minneapolis, June 1988.

Hedley, D.G.F.; A rockburst primer; The Northern Miner Magazine, Vol. 3, No. 7, pp. 32-37, July 1988.

Hedley D.G.F.; Evaluation of support systems subject to rockbursts; Division Report M&ET/MRL 88-108(TR); CANMET, Energy, Mines and Resources Canada; 1988.

Brehaut, C.H. and Hedley, D.G.F.; 1987-1988 Annual report of the Canada-Ontario-Industry rockburst project; CANMET Special Report SP 88-22E, CANMET, Energy, Mines and Resources Canada; 1989.

Udd, J.E. and Hedley, D.G.F.; A proposal for the continuation of the Canada-Ontario-Industry rockburst project; Division Report MRL 89-15(TR); CANMET, Energy, Mines and Resources Canada; 1989.

Quesnel, W.J.F., de Ruiter, H. and Pervik, A.; The assessment of cemented rockfill for regional and local support in a rockburst environment; Lac Minerals Ltd., Macassa Division, 1989. Conference Mining with Backfill - Innovation in Mining Backfill Technology, Montréal, October 1989.

Morrison, D.M. and Galbraith, J.E.; A case history of Inco's Copper Cliff North Mine; Proc. 31st U.S. Symp. Rock Mech., Colorado, June 1990.

Rockburst Project Management Committee

C.H. Brehaut, Placer Dome Inc., Chairman
C. Barsotti, Inco Limited
M. Musson, Falconbridge Limited
P.V. Kivisto, Ontario Ministry of Labour
J.B. Gammon, Ontario Ministry of Northern Development and Mines
M.D. Everell, CANMET, Energy, Mines and Resources Canada
J.E. Udd, CANMET, Energy, Mines and Resources Canada

Rockburst Project Technical Committee

D.G.F. Hedley, CANMET, Energy, Mines and Resources Canada, Chairman
P. Rochon, CANMET, Energy, Mines and Resources Canada, Secretary
D. Ames, Ontario Ministry of Labour
W. Bromell, Falconbridge Limited
C. Graham, Ontario Mining Research Directorate
A. Makuch, Placer Dome Inc.
D.M. Morrison, Inco Limited
S.N. Muppalaneni, Rio Algom Limited
W.J.K. Quesnel, Lac Minerals Ltd.
P. Townsend, Denison Mines Limited

Other Personnel Involved in the Project

Technical Committee

S. Bharti
P. Campbell
P. Kaiser
M. Kat
W. Logan
P. MacDonald
M. Neumann
A. Sheikh
G. Swan

CANMET

B. Arjang
Z. Chen
D. Hanson
S. Lapointe
W. McNeil
J. Niewiadomski
M. Plouffe
T. Semadeni