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ROCKBURSTS

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ROCKBURSTS

by

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ABSTRACT

Rockbursts are the sudden and violent failure of rock structures. They first occurred in the 1930's, in the gold mines at Kirkland Lake and the nickel mines in Sudbury. Since that time they have continued in mines across Ontario with varying levels of activity. The 1980's has been a particularly active period and the 14 mines at Red Lake, Elliot Lake, Sudbury and Kirkland Lake have experienced bursts.

Three types of rockbursts can be identified. Strain energy bursts occur in development drifts including shafts. They are caused by high stress concentrations locally exceeding the compressive strength of the rock. Pillar bursts occur mainly in thin tabular deposits such as those at Elliot Lake, Red Lake and Kirkland Lake. Sometimes the failure of one pillar overloads the adjacent pillars and a chain-reaction ensues. Fault-slip bursts occur when the shear stress along a fault exceeds the frictional clamping stress. It is the same mechanism as an earthquake.

There are two approaches to the alleviation of rockbursts, which can be termed 'strategic' and 'tactical'. The strategic approach is to diminish the possibility of encountering rockburst-prone ground or to reduce their severity. Techniques include sequencing of extraction to minimize large energy releases, or the use of backfill to limit closure and to absorb energy otherwise liberated as seismic energy. The benefits of these techniques are only realized in the long-term.

The tactical approach is to accept that some rockbursting is inevitable, but seeks to limit the extent of the damage. Techniques include:

Key word: Rockburst

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altering the shape of an opening to eliminate high stress concentrations; design of support systems that yield with vibrations rather than snap; and destress blasting to soften the rock and control the timing of energy releases. The benefits of these techniques are realized in the short term.

There are two aspects to rockburst prediction: location and time. In some cases it is possible to identify rockburst-prone areas of a mine based on microseismic activity or computer models. Prediction of time is much more elusive.

ROCKBURSTS

by

D.G.F. Hedley*

BACKGROUND

A rockburst is defined as the sudden and violent failure of rock. During the failure process,excess energy is liberated as kinetic (i.e. seismic) energy, which causes the surrounding rock mass to vibrate. It is these vibrations which are felt by persons underground and on surface. The magnitude of a rockburst is proportional to the amplitude of the vibrations and is measured in the same way as an earthquake, using a modified Richter Scale.

Rockbursts are a 20th century phenomena. They are a direct result of improved mining technology especially in drilling, blasting, pumping, hoisting and ventilation, which allowed the mines to go deeper into an ever increasing stress environment.

Rockbursts were first reported, at the turn of the century, in the gold mines on the Witwatersrand in South Africa and on the Kolar Gold Field in India.

In Canada the first recorded rockbursts were in the late 1920's in Ontario, at the gold mines in Kirkland Lake and some of the nickel mines in Sudbury. By 1940, rockburst incidents had increased so dramatically at these two mining camps, that the Ontario Mining Association appointed R.G.K. Morrison (later of McGill University) to investigate and report on the problem. Morrison's report in 1942, in many respects, formed the basis for implementing rockburst control strategies at Ontario mines for the next 40 years. His concepts and strategies are discussed later.

In the 1960's, the gold mines at Red Lake experienced rockbursts, and in the early 1980's so did the uranium mines at Elliot lake. Interestingly, the mines in the Timmins area, although of the same age and depth as those in Kirkland Lake, are not rockburst-prone.

During the 1980's there has been a large increase in the number of rockbursts in mines across Ontario. Table 1 lists the number of rockbursts by mining district and individual mines for the years 1984 to 1987. In this case, a rockburst is defined as a seismic event of sufficient magnitude to be recorded by the Eastern Canada Seismic Network. Their level of detection is a magnitude of 2.0 or greater for the four mining districts.

During this period, 15 mines in Ontario have experienced 361 rockbursts. Quirke Mine at Elliot Lake dominates the statistics and accounts for almost 50% of all rockbursts. The Campbell Mine at Red Lake, the Strathcona, Creighton and Copper Cliff North mines in Sudbury and the Macassa Mine at Kirkland Lake have also experienced major rockburst activity.

A variety of ore deposits and mining methods are used in these mines. At Red Lake and Kirkland Lake, narrow steeply-dipping vein deposits are mined by shrinkage and cut-and-fill methods. Gently-dipping reef deposits at Elliot Lake are mined by room-and-pillar methods. At Sudbury, massive sulphide deposits are mined by cut-and-fill and blasthole methods.

In response to this growing rockburst problem the Canada/Ontario/ Industry Rockburst Project was initiated in 1985. Management and funding of the project, over an initial 5 year period, is on a tripartite footing. The Government of Canada through CANMET provides the staff to operate the project. The Government of Ontario, through the Ministry of Labour and the Ministry of Northern Development and Mines, provides funds for equipment and services. The Ontario mining industry through Campbell Red Lake Mines Ltd, Denison Mines Ltd, Falconbridge Ltd, INCO Ltd, Lac Minerals Ltd and Rio Algom Ltd contribute

Table 1 - Rockbursts in Ontario Mines, 1984-1987
Recorded by the Eastern Canada Seismic Network.

Mining District	1984	1985	1986	1987*
Red Lake	26	5	10	0
Elliot Lake	59	88	22	9
Sudbury	16	31	56	22
Kirkland Lake	5	3	4	5
Totals	105	127	92	36

* to September 30, 1987

Red Lake	Number	Largest Magnitude
Campbell Mine	32	3.3
Dickenson Mine	9	2.1
Elliot Lake		
Quirke Mine	172	3.4
Denison Mine	6	2.6
Sudbury		
Falconbridge Mine	9	3.5
Lockerby Mine	3	2.6
Strathcona Mine	48	3.1
Fraser Mine	1	1.9
Creighton Mine	44	4.0
Copper Cliff North Mine	14	2.9
Stobie Mine	1	2.4
Garson Mine	3	1.9
Levack Mine	2	3.0
Kirkland Lake		
Macassa Mine	16	3.1
Kerr Addison Mine	1	3.3
TOTAL	361	

their existing monitoring systems, provide field sites, assist in installation of new equipment and provide data on rockbursts at their mines.

The rationale and objectives of the project are to first investigate the causes and mechanisms of rockbursts using existing and new seismic monitoring equipment, and then to develop techniques to alleviate or control the damage from rockbursts.

Mines in other parts of Canada have also experienced rockbursts, but to a lesser extent than those in Ontario. So called mining induced earthquakes have occurred above the potash mines in Saskatchewan over the last ten years. Rockbursts have been reported at some of the gold mines in the Val d'Or area of Quebec. The lead-zinc mines in New Brunswick are rockburst-prone. In 1958 a rockburst (called a bump) at the Springhill Colliery in Nova Scotia resulted in 75 fatalities. Finally, in Newfoundland a fluorspar mine experienced rockbursts at a depth of only 150 m. Also rockbursts have recently been recorded at the Buchans Mine a few years after it was closed.

In general it is the deep hardrock mines that experience rockburst problems. However, depth and hardness are not the sole criteria as evident from the preceding examples.

ENERGY BALANCE

Since rockbursts are the result of a violent release of energy it is natural that an analysis of energy is used to explain them. When an underground excavation is enlarged, either due to mining or rock failure, the surrounding rock mass moves towards the excavation resulting in a change in potential energy (Wt). The rock removed during enlargement also contained stored strain energy (Um). These two components (Wt + Um) represent the energy entering the mining operation as the result of the enlargement. This energy has to be dissipated somehow.

Stresses acting on the rock which was removed are transferred to the surrounding rock mass, increasing its stored strain energy (Uc). If the excavations are internally supported (e.g. backfill, cribs, posts) then some energy is absorbed in deforming the support (Ws). Any excess energy is normally referred to as released energy (Wr). From the law of conservation of energy:

$$Wt + Um = Uc + Ws + Wr \qquad \text{Eq 1}$$

There are a number of ways in which energy can be released. The stored strain energy in the removed rock is obviously released. If this rock had failed rather than being mined then this energy component would have been consumed in the fracturing process.

If the rock had been removed or failed instantaneously there would be oscillations in the rock mass. Equilibrium would be attained through damping and seismic energy (Wk) would be dissipated in the process. There are no further alternatives, hence:

$$Wr = Um + Wk \qquad \text{Eq 2}$$

It is the seismic energy (Wk) which is recorded by mine microseismic systems, and it is this energy component which is responsible for the damage caused by a rockburst. From Equations 1 and 2:

$$Wk = Wt - (Uc + Ws) \qquad \text{Eq 3}$$

This equation indicates that to reduce the seismic energy the change in potential energy (Wt) has to be reduced or the energy absorbed by the support system (Ws) increased (there is no control over Uc). The former can be achieved by reducing the convergence of the rock mass and the latter by increasing the stiffness of the support (e.g. backfill).

TYPES OF ROCKBURSTS

To initiate a rockburst, part of the rock mass must be at the point of instable equilibrium because either:

a) changing stresses are driving a volume of rock to sudden failure;

b) a system of pillars is approaching a state of imminent collapse:

c) geological weakness planes are on the point of slipping.

These three categories can be conveniently labelled: strain, pillar and fault-slip bursts, which are familiar terminology in mining.

Other conditions are that a change in stress is required to trigger a rockburst. This can be either an increase or decrease in stress depending on the type of rockburst. To initiate stress waves an appreciable stress change must accompany the rockburst. Finally, there must be a substantial amount of energy available to provide the source of the seismic energy. This reservoir can either be the stored strain energy in the surrounding rock mass or a sudden change in potential energy.

STRAIN BURSTS

Strain bursts are caused by high stress concentrations, at the edge of mine openings, which exceeds the strength of the rock. Events can range from small slivers of rock being ejected from the walls to collapse of a complete wall as it tries to achieve a more stable shape. These types of rockbursts are normally associated with development drifts including shafts.

Energy can be released from a number of sources. If the rock goes from a triaxial to biaxial or uniaxial stress condition, some of the stored strain energy is released as seismic energy. Instantaneous failure of this rock will enlarge the opening and seismic energy will be released due to the elastic reactions of the rock mass. Finally, if brittle and soft rocks are present, then minor slippage could occur along the contact.

PILLAR BURSTS

Severe rockbursts, involving thousands of tonnes, have been caused by the complete collapse of support pillars. In some cases, the collapse of one pillar can overstress adjacent pillars and a chain-type reaction ensues. In recent times, the most significant chain reaction occurred in an old stope-and-pillar area of Quirke Mine in Elliot Lake. Figure 1 shows the location and sequence of 22 major rockbursts that occurred in September 1984. All of these rockbursts occurred at the edge of the zone of previous pillar failure and represents a significant expansion of this zone. The 6th sill level was destroyed during this activity. Subsequently, the 5th sill level was lost in February 1985 followed by the 9th sill level in August 1985. The end result of this seismic activity and pillar failures was that the hanging wall could no longer span the affected area, and fracturing progressed to surface (over 500m) with a significant increase in water flow into the mine.

Significant pillar bursts have also occurred in steeply-dipping vein-type orebodies at Red Lake and Kirkland Lake. These normally occur when sill/crown pillars of shrinkage or cut-and-fill stopes reach a critical size.

To understand the mechanics of pillar bursting it is necessary to understand the concept of pillar stiffness and loading stiffness. Figure 2a shows the simple example of a single pillar between two stopes. Figure 2c shows the stress-displacement history of the pillar. As the stress increases the curve has a positive slope up to peak strength. After peak strength, displacement continues but the load decreases and the slope is negative. The shape of this unloading curve depends on the type of rock: brittle rocks have much steeper unloading curves than soft rocks.

Loading stiffness can best be explained by replacing the pillar with a hydraulic jack which exerts the same load as the original pillar as shown in

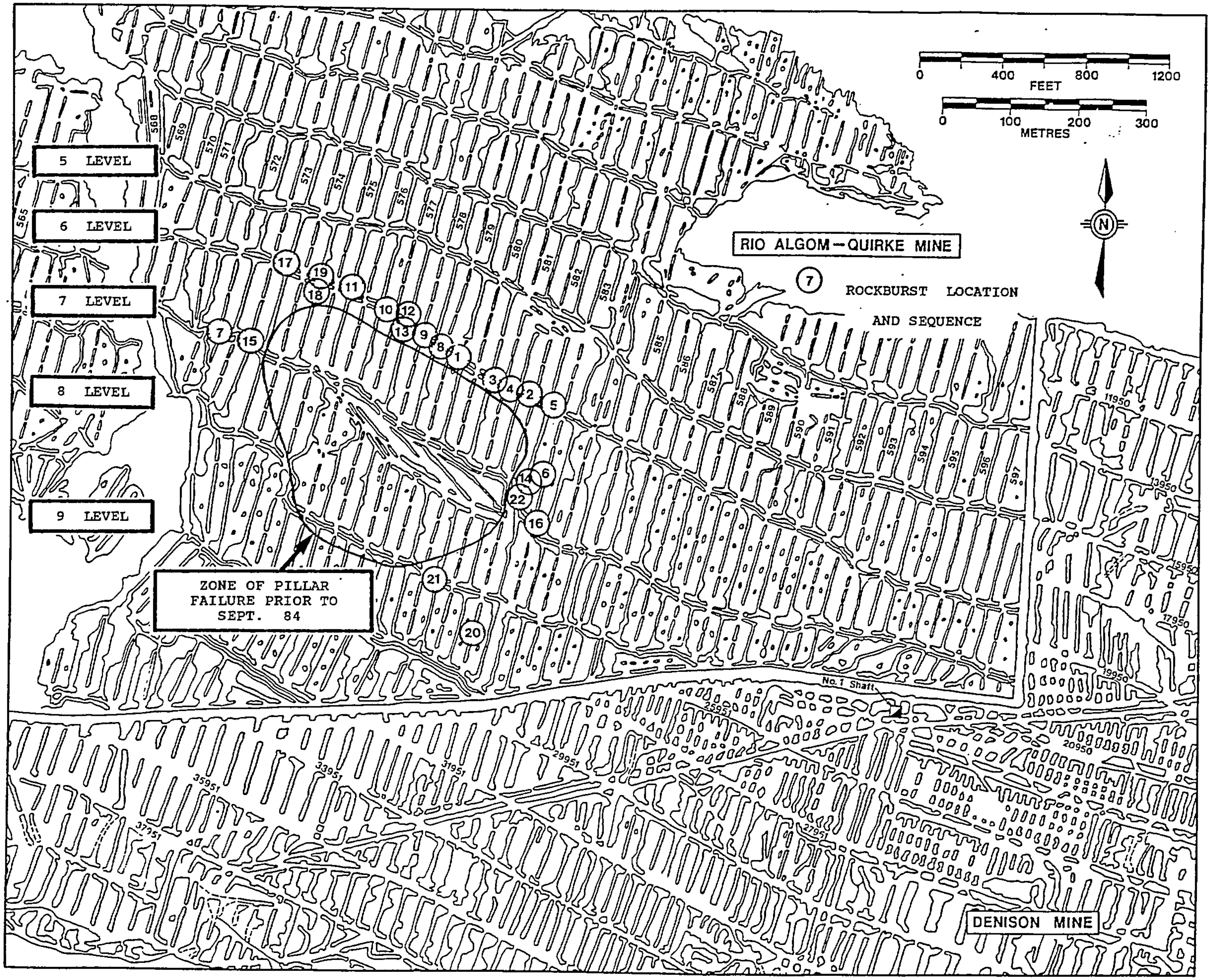
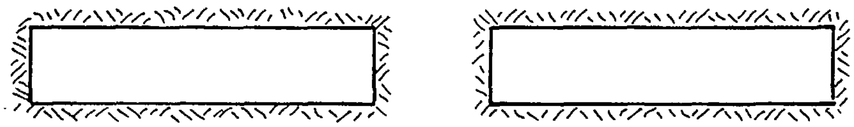
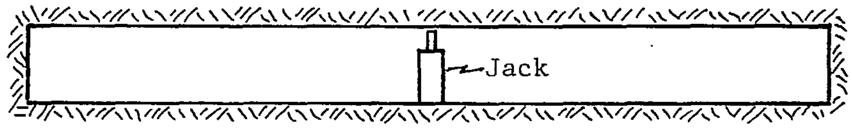


Fig. 1 - Location and sequence of rockbursts at Quirke Mine in September 1984.



a) Pillar between two stopes



b) Loading equivalent

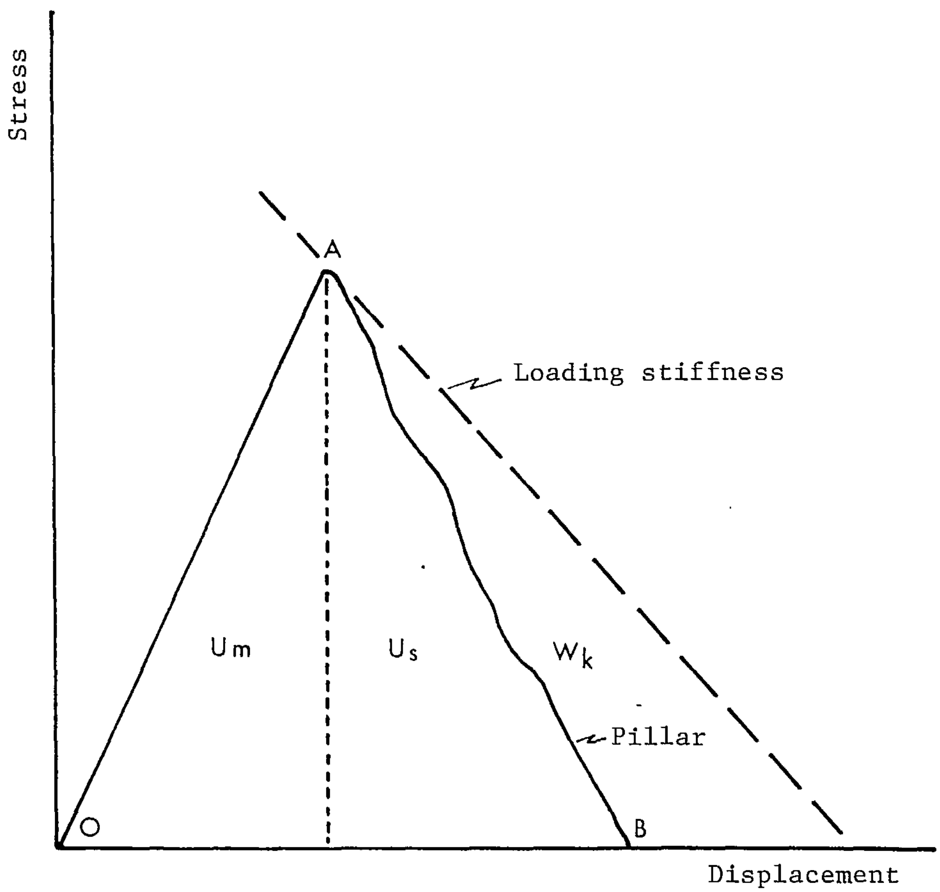


Fig. 2c - Stress - displacement characteristics of a pillar and loading system.

Figure 2b. The loading stiffness, at that location, would be the unloading curve for the jack as the hydraulic pressure is released.

The violence of pillar failure depends on the difference between these unloading characteristics. If the post-failure pillar unloading curve is steeper than the loading stiffness curve (ie. soft loading), as illustrated in Figure 2c, then there is a surplus of energy and failure will be sudden and violent. However, if the loading stiffness curve is steeper than the post-failure pillar curve, then failure will be gradual and non-violent.

It is of interest to note the areas under the various curves since these represent the energy components. The area under the pillar curve(i.e. OAB) represents the energy consumed in the fracturing process. It is made up of two components: the stored strain energy at peak strength (Um) and part of the energy stored in the surrounding rock (Us) (i.e. the loading system). The area between the two unloading curves represents the seismic energy (Wk) that is liberated. It is important to note that the violence of pillar rockbursts does not come from the energy stored in the pillar but from the energy in the loading system.

FAULT SLIP BURSTS

Slippage along a fault has long been recognized as the mechanism of an earthquake. Only recently has the same mechanism been recognized as the cause of some rockbursts in Canadian hardrock mines, especially those in Sudbury.

Shear stresses act parallel to a fault or dyke. Slippage is prevented so long as the clamping forces exceed the shear stress. Clamping forces are controlled by the stress acting perpendicular to the fault and the coefficient of friction on the fault. Slippage can be initiated by either an increase in the shear stress or a decrease in the perpendicular stress or coefficient of friction. Once slippage occurs the lower dynamic coefficient of friction comes into effect resulting in a drop in stress along the fault. Theoretical models indicate that only minor slippage and stress drops are required to initiate significant rockbursts. For instance, a rockburst of magnitude 3.0 would result from a stress drop of 3.5 MPa with an average slippage of 12mm over a radius of 100m.

In most cases the damage caused by fault-slip rockbursts is minimal. There is one example of a 2.2 magnitude rockburst at the Falconbridge Mine near Sudbury where no damage was found, although 10 to 20 mm of slippage could be observed on the fault. Normally, what damage is observed is away from the fault where the radiated seismic energy has triggered a critically loaded structure. In one case a magnitude 3.4 rockburst caused a backfill mat to collapse in an undercut-and-fill stope some 20 m away.

ALLEVIATION AND CONTROL OF ROCKBURSTS

There are two approaches to the alleviation of rockbursts, which can be termed "strategic" and "tactical". The strategic approach is to diminish the possibility of encountering rockburst-prone ground or to diminish the severity of the rockbursts. Techniques include sequencing of extraction to minimize large energy releases or the use of backfill to both limit closure and to absorb energy otherwise liberated as seismic energy. The benefits of these techniques are only realized in the long-term.

The tactical approach is to accept that some rockbursting is inevitable, but to seek to limit the extent of the damage. Techniques include design of support systems that yield with the vibrations rather than snap, and destress blasting to soften the rock and control the timing of the change in potential energy. The benefits of these techniques are realized in the short-term.

STRATEGIC METHODS

The cause of rockbursting is usually known. Generally it is the result of mine planning decisions made a number of years previously, and in one case 40 years before the intiation of rockbursts.

A common problem occurs with pillars left to protect shafts where they pass through or are near the orebody. The initial rationale is that mining these pillars would cause the shaft to move with possible damage. Initially these pillars perform this protection function. However, towards the end of the mine's life they become heavily loaded and produce high stress concentrations around the shaft with possible damage. The largest rockburst ever recorded in Canada, of estimated magnitude 5.0 occurred in the shaft pillar at the Wright Hargreaves Mine in Kirkland Lake in 1964. This burst resulted in several fatalities and immediate closure of the mine.

Another common problem is with shrinkage stoping. Once the muck is pulled from a stope it becomes an open stope and pillar method. If the pillars are under-designed, rockbursts can result. Similarly, in room-and-pillar mining under-designed pillars can result in a chain reaction of rockbursts (e.g. Quirke Mine). In both cases, problems are usually not encountered during initial mining but some years later when a more extensive area has been mined out.

Morrison's 1942 report dealt with strategic methods for rockburst control. Rockbursts were attributed to the formation of "domes" which are the fractured zones surrounding individual stopes as illustrated in Figure 3. As stopes approach each other the intervening pillars become increasingly stressed. If these pillars suddenly fail, the volume of the dome also suddenly increases. The rupture of the large volume of rock between two or more initial domes, and the release of its accumulated energy, resulted in a

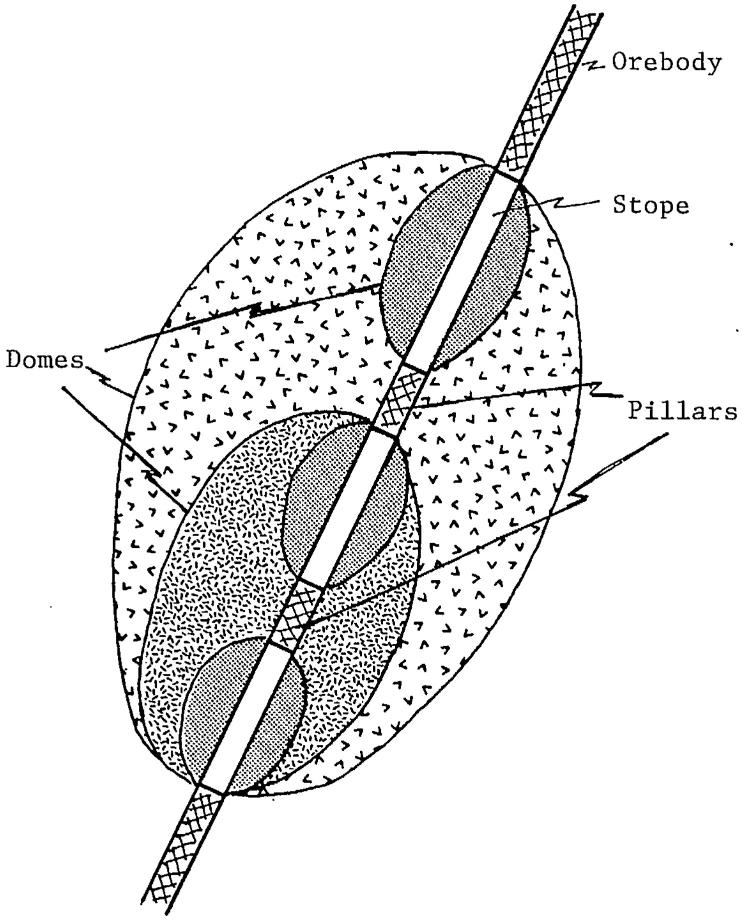


Fig. 3 - Doming theory of rockbursts
(after Morrison, 1942).

rockburst. The magnitude of the rockburst depended on the final size of the dome and the energy stored within it. This in turn was controlled by the areal extent of stoping, depth and the physical properties of the wall rocks.

Subsequently, the "doming theory" was discredited when it was shown thoretically that the size of the domes decreases with depth. However, many of the characteristics associated with domes are still relevant to rockburst-control strategies. Stope span, depth and elastic properties of the wall rocks also control convergence and the change in potential energy of the surrounding rock mass. This is now recognized as being the driving force behind all rockbursts.

Morrison's main rockburst-control strategy was the use of mining layouts which eliminated small remanent pillars and allowed domes to gradually expand. In practice this meant some form of longwall configuration.

The effect of weakness planes, such as faults or dykes was explained in terms of their effect on the formation of domes and stress concentrations. The concept of slippage along these structures was not recognized. It was recommended to mine away from major weakness planes, or to mine through them at a perpendicular rather than an acute angle. The importance of support, such as backfill, for controlling the number and severity of rockbursts was recognized, although again in terms of its effect on the size of domes.

It is now known that the change in potential energy of the rock mass is the driving force behind a rockburst. Potential energy is basically the pre-mining stress multiplied by the volumetric closure of a stope. We have no control over the stress, but some limited control over closure.

Systematic stabilizing pillars would limit stope span and reduce the closure. However, in practice this means writing off about 20% of an orebody. It is resorted to when the rockburst problem seems insoluble (e.g. South African gold mines).

Backfill and especially stiff backfill will reduce the closure in a stope, and as indicated in Equation 3 absorb energy which otherwise is released as seismic energy. Most benefit from backfill is obtained in thin tabular deposits.

Finally we can try to control the rate at which energy is released. Many mines can extract about 80% of the ore reserves without undue rockburst problems. It is the last 20% that causes all the problems. The reasons for this are illustrated in Figure 4. The last 20% are in the form of pillars which are holding back the regional closure. As these pillars are mined, large changes in potential energy occur. If longwall methods are used, from the beginning of mining, then the rate of energy release is more uniform throughout the life of the mine.

TACTICAL METHODS

At some mines, below a depth of about 1000m, the mere fact of making a mine opening produces high stress concentrations and minor rockbursts. These problems increase in the stoping area. Although strategic methods are still important to reduce the severity of rockbursts, they will not eliminate the problem.

At this point tactical methods can be used to protect the workforce. When a rockburst occurs, a stress wave radiates out from the source. When this stress impulse hits a rigid support system (e.g. mechanical bolts) it can cause it to fail violently and the loose rock is thrown into the mine opening. This characteristic of mechanical bolts has been observed in many mines in Ontario. Grouted rebar is also a rigid support system, but being stronger than a mechanical bolt it takes a large stress wave to fail it. Experience in some mines indicates friction type support (e.g. split sets and Swellex) in conjunction with wire mesh, can withstand rockbursts up to about 2.5

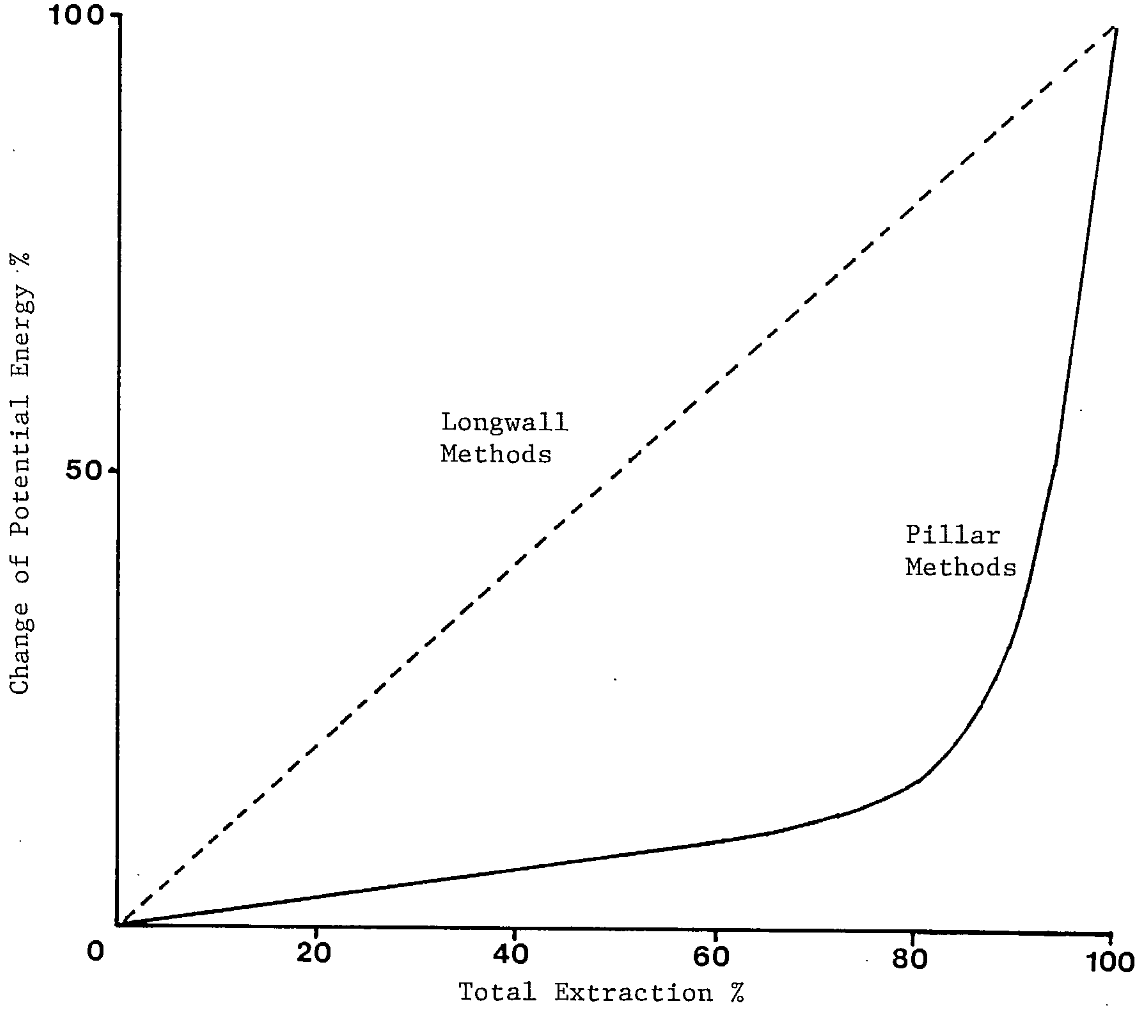


Fig. 4 - Rate of energy release for different mining methods.

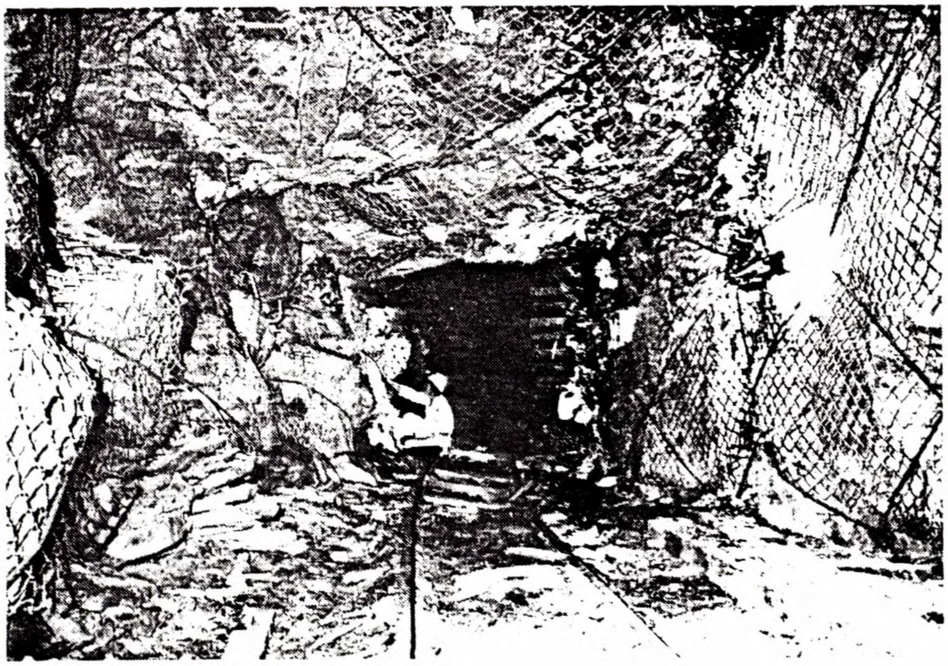
magnitude. The mesh contains the broken rock. For extreme conditions the South African gold mines use a lacing support system. This consists of smooth. mild steel rebar grouted in boreholes with a "shepherd's crook" at the collar. Wire mesh is placed against the rock and then steel cable is threaded through the "shepherd's crook" in a diamond pattern. This type of support system has withstood a rockburst of magnitude 4.0, however, it is very expensive. Figure 5 shows the profile of a haulage drift and the damage after the 4.0 rockburst.

Destress blasting is used in many mines in North America, either in development drifts or in crown pillars of cut-and-fill stopes. The purpose is to change the potential energy of the surrounding rock mass. This is achieved by fracturing the rock to soften it, which allows the walls to converge. However, there are potential problems with this method. One of the basic laws of rock mechanics is that stress can not be got rid of, only transferred. Consequently, destress blasting transfers stress to adjacent structures which could then burst.

At some mines rockbursts occur within minutes or hours of a production or destress blast. These mines invariably have central blasting at fixed times, with no one underground. Hence, it may be possible to choose the time of a rockburst. Mines using blasthole stoping methods tend to set off their large production blasts after the last shift on Friday, leaving the mine two days to settle down.

ROCKBURST PREDICTION

There are two aspects to rockburst prediction: location and time. In some cases it is possible to identify rockburst-prone areas of a mine based on microseismic activity or computer models which give stress distributions. Prediction of time is much more elusive. Earthquakes have been taking place



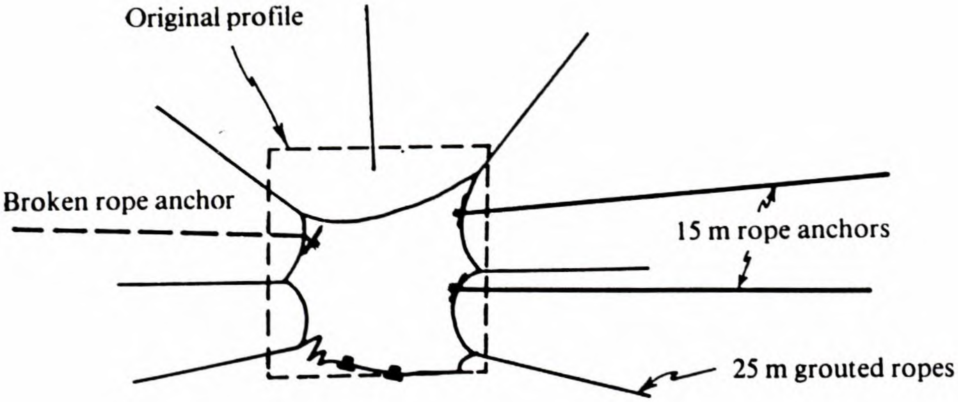


Fig. 5 - Damage to a haulage drift after a rockburst of 4.0 magnitude (after Ortlepp, 1983).

over a much longer time period than rockbursts, and there is still no adequate method of predicting earthquakes.

In some cases there is a build-up in microseismic activity preceding pillar bursts. However, it very much depends on the time scale examined. Figure 6 shows the microseismic activity just prior to the major rockbursts at Quirke Mine in September 1984. If the time scales of minutes or hours before bursts are examined there is no trend or indication of imminent bursts. However, the microseismic record over the preceeding eight months indicates a gradual buildup in microseismic activity.

ROCKBURST MONITORING

Three types of seismic monitoring systems are being deployed to monitor a large range of seismic events.

The Eastern Canada Seismic Network is operated by the Geophysics Division of the Geological Survey of Canada. Seismometers are located across Ontario, Quebec and the Maritime Provinces to monitor naturally occurring earthquakes. These sensors also record the larger rockbursts and magnitude values can be calculated.

In Ontario, the existing seismic network has been augmented by additional seismograph stations at Sudbury, Elliot Lake, Red Lake and Kirkland Lake, as shown in Figure 7. The main purpose of these stations is to provide magnitude values for rockbursts, down to possibly 1.0. A secondary purpose is to have permanent records of the larger seismic events.

The most sophisticated new network is the one in the Sudbury Basin as shown in Figure 8. Three seismograph stations are located on the north, south and west rim of the Basin. This allows triangulation, for locating hitherto unlocatable rockbursts. The signals for each seismometer are digitized at the sensor and are continuously transmitted over dedicated phone lines to Science

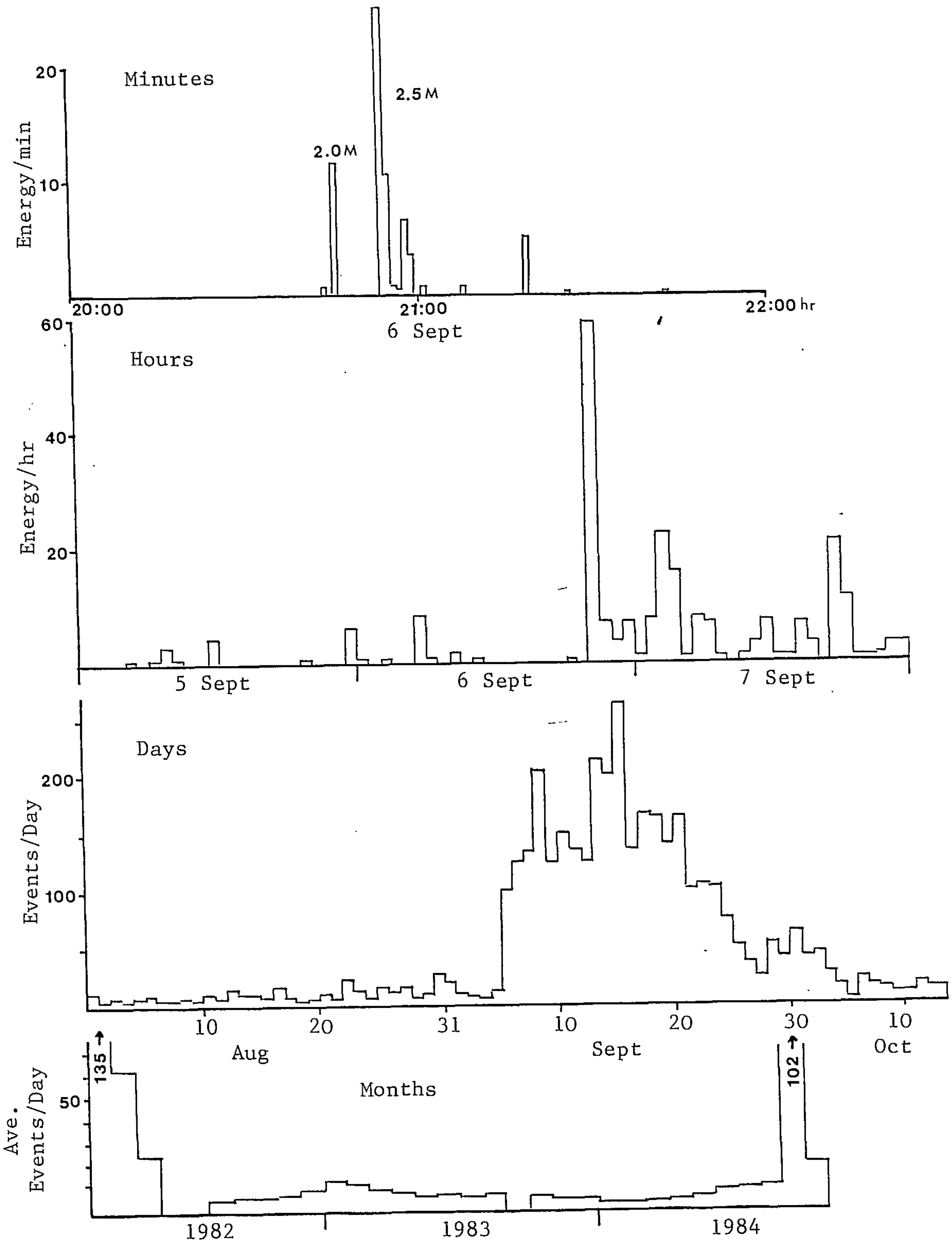


Fig. 6 - Microseismic activity prior to major rockburst activity over different time periods.

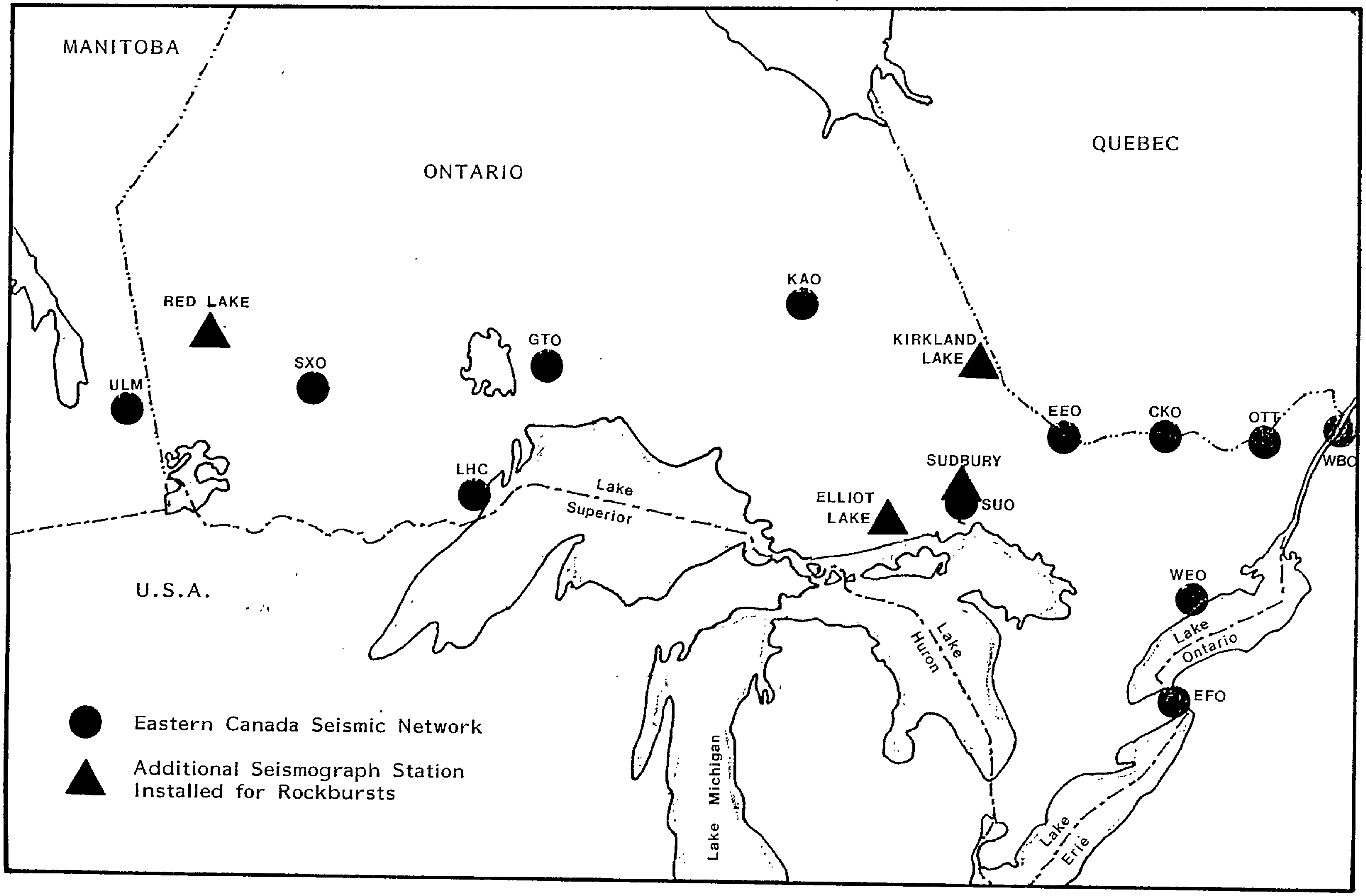


Fig. 7 - Layout of Seismograph Stations in the Eastern Canada Seismic Network and Additional Stations for Rockburst Detection.

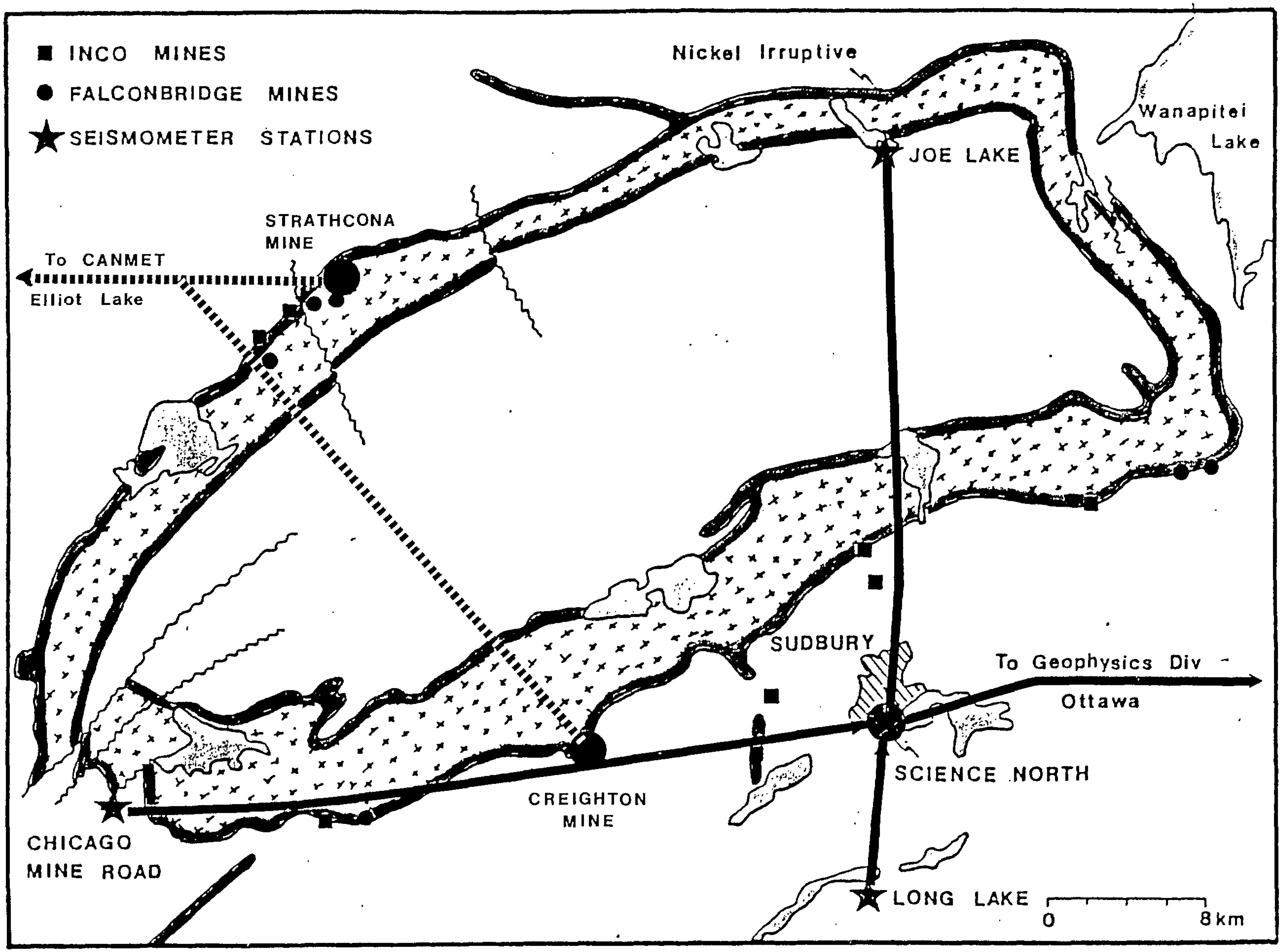


Fig. 8 - Location of Seismograph Station and Mines in the Sudbury Basin.

North. Here the signals are recorded on drum recorders, which are on public display. Also the signals are continuously transmitted over a data line to the Geophysics Division in Ottawa, who do the analysis and calculated magnitude values.

Macroseismic monitoring systems are designed to capture the complete waveforms of the larger seismic events. Strong-motion triaxial geophones are installed 500 to 1000 m away from active mining so as not to saturate the sensors. There are five geophones per system installed on surface, underground or both.

Analysis of wave forms should provide additional information on the mechanism of rockbursts. The direction of first motion should indicate the type of rockburst. For instance pillar bursts are implosions and the first motion is inwards, whereas a blast is an explosion and the motion is outwards. For fault-slip bursts opposite sides of the fault move in opposite directions.

Peak particle velocity is a measure of the damage caused by a rockburst similar to that in blasting. It is used to design support systems so that they can withstand certain levels of rockbursting.

Integration of the waveforms gives the seismic energy liberated in a burst which is fundamental in understanding the energy balance.

Analysis of the signal frequencies has been used in seismology to define the main rockburst parameters (i.e. radius, slippage, stress drop).

Five macroseismic systems will be installed. The first two are already in operation: on surface above Quirke Mine at Elliot Lake and around Falconbridge's Strathcona Mine at Sudbury. Other systems will be installed at INCO's Creighton Mine, Campbell Red Lake Mine and Lac Mineral's Macassa Mine.

Microseismic monitoring systems are owned and operated by the mining companies. At present there are 14 systems, all made by Electrolab, installed in Ontario mines. Additional systems are located in a potash mine in