60 YEARS OF ROCKBURSTING IN THE COEUR D'ALENE DISTRICT OF NORTHERN IDAHO, USA: LESSONS LEARNED AND REMAINING ISSUES

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ABSTRACT

Sixty years of rockbursting in the Coeur d'Alene district has taught painful lessons and led to a number of practical advances in controlling rockburst hazards. This paper summarizes those lessons, concentrating on practical measures that have been successfully adopted to reduce hazards. These lessons are explained in the context of district mining history and current understanding of rockburst phenomena. Overall, the paper provides the practicing mine engineer with an appreciation of rockburst hazards and an overview of practical measures that can be used to control these hazards in the context of Coeur d'Alene district experience.

INTRODUCTION

The phenomena of rockbursts in the Coeur d'Alene district were first reported as "air blasts" in the early 1900's. The first fatality to be described as an air blast in the press occurred in the 1600-level stope of the Greenhill-Cleveland Mine in 1914. Rockbursts did not become a severe operational problem until the 1940's, as mining followed veins into deeper and more quartzitic rock. In the past 60 years, the district has suffered 22 rockburst fatalities in five different mines.

Rockburst research in the district began in earnest during the 1940's with the work of Dr. Leonard Obert and Dr. Phil Shenon, among others. Considerable progress in controlling rockburst hazards has been made in the intervening 60 years, thanks to a variety of efforts undertaken by mining companies, universities, and government agencies. Unfortunately, guidance on practical measures that reduce rockburst hazards are often difficult to find in a literature that tends to focus on seismology.

This paper is an attempt to gather and organize the best of this practical knowledge for the use of practicing engineers in rockbursting and potentially rockbursting mines. It begins with a short introduction to the Coeur d'Alene district followed by three main sections that present practical measures for controlling rockburst hazards. The first section addresses the relationship between seismicity and rockbursting. The second reviews tactical measures for controlling rockburst hazards that can be instituted locally on short notice. These measures include ground support, destressing, and changes in mining rate. The final section presents strategic methods for controlling rockburst hazards, including design of mining methods and sequences that minimize hazards.

This paper was written as part of an effort to reduce rockburst hazards that has been undertaken by the Office for Mine Safety and Health Research of the National Institute for Occupational Safety and Health (NIOSH). These efforts include a longstanding cooperative research program in the Coeur d'Alene district, as well as work with other rockbursting, and potentially rockbursting, mines.

Selection, explanation, and evaluation of rockburst safety measures that have been used in the Coeur d'Alene district required considerable judgment on the part of the authors. Given the complexity of the rockburst safety issue, there will likely be differences of opinion and experience. Where such differences occur, the authors invite criticism and discussion. Honest debate of these issues can only improve our methods for controlling rockburst hazards.

ROCKBURSTS AND MINING-INDUCED SEISMICITY

The term "rockburst" has been defined in an impressive variety of ways. From a practical standpoint, the regulatory definition (30 CFR 57.3000) is most relevant to U.S. mines. This definition is

> A sudden and violent failure of overstressed rock resulting in the instantaneous release of large amounts of accumulated energy.

This definition is somewhat vague as to whether a failure must result in actual damage to a mine or even a real hazard to miners in order to be classified as a rockburst. The definition of an MSHA-reportable rockburst is more explicit (30 CFR 57.3461). A rockburst must be reported to MSHA if it

1. Causes persons to be withdrawn,
2. Impairs ventilation,
3. Impedes passage, or
4. Disrupts mining activity for more than 1 hour.

In other words, there must be damage to the mine, sufficient injury to a person for that person to be withdrawn from a work area, or sufficient concern over the safety of miners to either withdraw miners or disrupt mining activity for more than 1 hour.

The MSHA definition requires a sudden or violent failure, implying that a seismic event is produced. Indeed, there has been a regrettable tendency to equate seismic events to rockbursts and to use the latter term for all mining-induced seismic events. Seismic events are created by unstable deformation processes—including fracturing of brittle rock and stick-slip sliding on discontinuities of all scales—that release a pulse of seismic energy. Most seismic events pose no hazard to miners, and only a small minority have the potential for harm or damage to mine openings.

Kaiser et al. (1998) explicitly considered the relationship between seismic events and rockbursts in their similar but simpler and more expansive definition for a rockburst. Their definition simply states that a rockburst is a seismic event that is associated with damage to a mine opening. This definition encompasses two key aspects of rockburst damage. First, damage may be caused by creation of a seismic event and/or by seismic shaking of a mine opening. Second, the deformation mechanism responsible for a seismic event must, directly or indirectly, overcome the structural capacity of an underground opening in order for a rockburst to be said to occur. Thus, the difference between a rockbursting and nonrockbursting mine is as much a characteristic of the mining system as it is of the mining environment.

Likewise, the difference between a mine experiencing falls of ground and a mine experiencing rockbursts lies in whether seismic events are produced, since seismic events are indicative of the "instantaneous release of large amounts of accumulated energy" required by the MSHA definition. In the absence of eyewitness accounts, it is often difficult to tell if a fall of ground has been accompanied by a seismic event—i.e., whether it is a rockburst as well. Seismic monitoring systems are often useful for determining whether falls of ground are indeed rockbursts, and small portable systems are readily available. While these systems cannot differentiate damaging seismic events from harmless seismicity, they do provide event time and location reports that can be cross-checked with underground damage reports.

<u>Coeur d'Alene District Seismicity</u>

Mining in the Coeur d'Alene district typically produces considerable levels of seismic activity. Much of this seismicity is a harmless part of the rock mass adjusting to mining. Long-term plots of seismic energy versus tons mined are usually linear within similar geologic regimes. However, large contrasts in the level of seismicity produced per ton mined are generally observed between geologic formations, generally related to the "sandiness" or proportion of quartz in the rock. Seismicity also varies with in situ stress, which has been shown to vary between geologic formations and structures (Whyatt, 2000) as well as with depth.

Microseismic monitoring with sensitive listening equipment was developed by the U.S. Bureau of Mines (USBM) in the late 1930's and tested at the Sunshine Mine in 1941 after a double fatality. While this experiment did detect microseismic activity, systematic seismic monitoring was not attempted until the 1960's, when the USBM initiated seismic monitoring at the Star and Galena mines. These early seismic arrays were often focused on individual sill pillars, since sill pillar bursting was the first type of rockburst to be recognized and was, for a time, thought to be the only type.

Monitoring of mine seismicity showed that seismicity reflects both local geologic structures and changing stress conditions, some of which were associated with rockbursts. However, efforts to predict specific rockbursts based on patterns of seismic activity have largely failed. Seismic systems have also provided invaluable, real-time information on the location of major seismic events or rockbursts. Mine staff use this information to check on crews most likely to be affected and can often begin rescue operations within minutes of a major rockburst.

Further development of seismic systems in the 1980's (Girard et al., 1995) led to the capture of digital seismic waveform records. These records can be used to discern the mechanism, including the direction of slip, that caused a particular seismic event.

<u>Coeur d'Alene District Rockbursts</u>

Coeur d'Alene rockbursts can be divided into three major types—strain bursts, pillar bursts, and slip bursts—primarily by how they relate to mining activities. That is, strain bursts depend on geology of the immediate perimeter of the opening, pillar bursts depend on pillar design and geology, and slip bursts depend on regional changes in the state of stress on faults. These types also differ in the type and distribution of resulting damage and the level of seismic energy accompanying a damaging rockburst. All three types are dangerous, but to different degrees in different mines (table 1). Overall, pillar and strain bursts have proven to be the most hazardous, while slip bursts have the largest seismic magnitudes.

Table 1—Fatalities at Coeur d'Alene district mines by type of rockburst.

Mine	Strain	Pillar	Slip
Sunshine	3	2	
Star/Morning	3	1	
Galena	2	6	
Lucky Friday		2	2
Coeur	1		
TOTAL	9	11	2

Strain burst. Tannant et al. (1996) defines strain bursts as "rapid bulking of a rock mass due to unstable (dynamic) fracturing in the vicinity of an opening." Mining depths typical of the Coeur d'Alene district result in stresses in rock around the perimeter of deep openings that exceed strength. This rock fractures, shifting stresses to better-confined rock deeper in the rock mass. The resulting fracture zones have been mapped in South Africa and, more recently, in the Coeur d'Alène district (figure 1).

Eye-witness accounts of strain bursts in the Coeur d'Alène district usually include a number of the following observations (Whyatt and White 1998).

• Sudden, intense fracturing of intact rock into coffee-cup-size or smaller rubble.

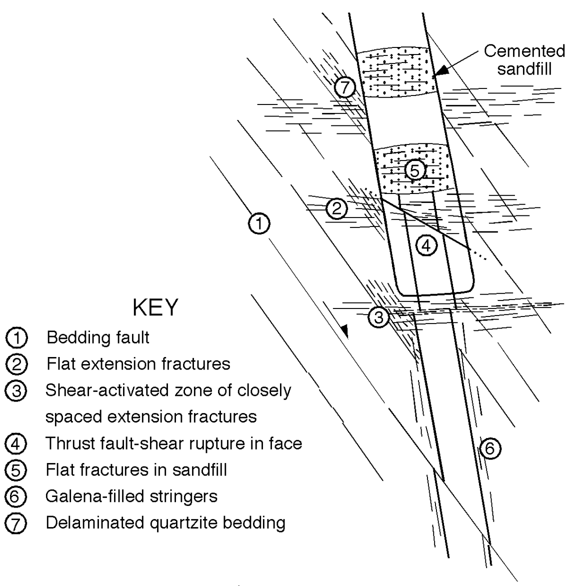

Figure 1.—Fracture zone typically encountered around deep excavations in the Coeur d'Alene diatrict (after White and Whyatt, 1999).

• A loud, instantaneous report. The report is described as resembling an exploding charge or a sonic boom. For nearby observers, the sound seems to originate at the immediate site of the burst.

• Violent expulsion of rock rubble into mine openings before miners can react. Initial expulsion of rubble is followed by a brief period in which debris continues to be distributed about the burst site. Miners involved in these bursts are not generally knocked down by the ejected rock, but are engulfed by a fluid-like flow of rock debris. Miners have been partially or completely buried while standing erect, their legs extensively bruised but not broken. The greatest risk of fatal injury is suffocation, primarily from pressure on the chest.

• A dense cloud of dust that immediately fills the air. A major strain burst may create dust so dense that miners have the impression that their lamps have gone out.

• An air pressure shock wave or "air blast" that travels through the mine. The initial air blast may be followed by a sustained closure-induced wind if there is a significant change in excavation volume.

• A concave cavity that narrows with depth into the rib. A planar fracture, fault or bedding plane often forms the back of the cavity. Cavities 30 to 200 cm deep are commonly reported for 3- by 3-m drifts.

Some excavation-induced fractures are created during blasting, followed by further fracture development that usually decays with time after blasting. However, fracturing may become unstable at any time, creating a seismic event and, if damage is induced, a strain burst. The energy required for unstable fracturing can be supplied by a number of mechanisms, including shattering of brittle rock, buckling of rock plates, and/or sliding along discontinuities. Buckling of rock layers or plates that are defined by geology and/or stress-induced fracturing is often evident in the Coeur d'Alene district. Fairhurst and Cook (1966) have shown how buckling of a plate in the rib of an opening releases both strain energy stored in and around the plate and gravitational potential energy (through subsidence of rock above the opening). Roof subsidence, and hence available gravitational potential energy, can be increased further by the presence of discontinuities (figure 2).

Locations that support strain bursts make up only a small portion of the district rock mass at current mining depths. For instance, a recent study of strain bursting during development of a deep ramp system found that less than 10% of the system was affected by strain bursting (Whyatt and White, 1998). However, strain bursts that did occur pulverized as much as 100 tons of rock in ramp ribs. Relative to damage, strain bursts are generally associated with much smaller seismic events than other rockburst types. Locations prone to strain bursts are often marked by structural weaknesses that define plates parallel to the opening perimeter, strong brittle rock, and/or unusually high stress levels.

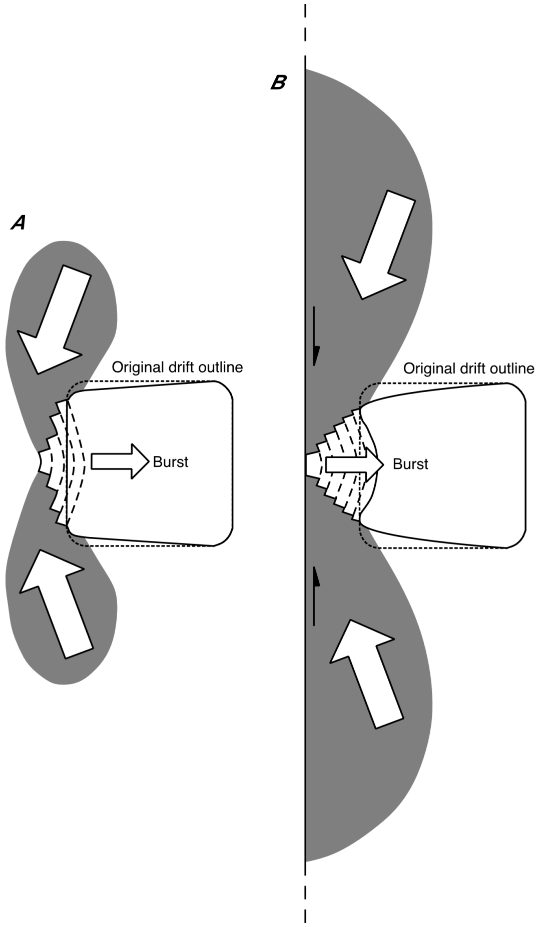

Figure 2.—Buckling of rock plates is driven by release of gravitational and elastic potential energy (A). A weak discontinuity can dramatically increase the amount of energy released, resulting in a more hazardous rockburst (B).

Pillar burst. A pillar burst is an unstable pillar failure that, like a strain burst, is caused by unstable movement resulting from some combination of fracturing, sliding, and buckling. This movement will generally extend deeper into the rock mass than is the case with strain bursts and often involves the core or foundation of a pillar. As such, there is often a loss of pillar load-carrying capacity that can liberate a considerable amount of energy. Despite their similarity to other types of bursts, pillar bursts are considered separately because of their direct dependence on mine layout, mine sequence, and mining method.

In the Coeur d'Alene district, pillars are most commonly created by mining a vein from multiple levels simultaneously in such a way that mining progresses toward previously mined areas. The vein between an advancing stope and previously mined ground is called a "sill" pillar. Typically, mining will create an array of sill pillars that are gradually reduced in size and eventually removed.

Board and Fairhurst (1983) reported that rockbursting in district overhand stopes typically began as the sill pillar was reduced to 18-20 m (and peaked at 12-15 m). Pillar bursts are particularly likely to be triggered if a sill pillar with these dimensions is cut into two smaller pillars by excavation of an "I-drift" (drift cut on the vein) or is intersected by a crosscut or ramp.

Pillar bursts typically cause damage and closure in adjacent excavations, particularly the associated stope and nearby haulage drifts. The seismic event is the result, rather than the cause, of damage to the load-carrying capacity of the pillar and to immediately adjacent openings. However, shaking of surrounding openings can also cause damage, particularly where ground is weak, poorly supported, and/or loaded close to capacity

The potential for pillar bursting is best managed through mine planning, particularly mining method, pillar geometry, pillar load, backfilling practices, mining rate, and preconditioning. For instance, pillar bursts can be eliminated with a longwall mining method which does not create pillars. However, other types of rockbursts may still occur.

Slip burst. Slip bursts are defined both by mechanism (stick-slip shear movement on a discontinuity) and the regional nature of driving forces. These bursts are less likely to be triggered by a particular blast and are more likely to occur during a shift. Stick-slip sliding can also occur as part of a burst in a pillar or the immediate skin of an opening in more direct response to mining. However, these bursts are best considered as pillar or strain bursts, respectively, since they respond similarly to burst control measures.

Slip occurs when the ratio of shear to normal (effective) stress along the fault plane reaches a critical value, the coefficient of friction (tangent of the friction angle). In most cases, mining activity causes slip by removing normal stress, although some local intensification of shear stress may also occur. Changes in stress along a fault are often linked to mine activities by time-dependent deformation processes. These time-dependent processes can act over long periods of time, regardless of continued mining. For instance, a number of sizable seismic events (almost certainly caused by slip) occurred over a period of several months after mining was halted at the district's Galena Mine. The largest of these, a 3.0-magnitude event, occurred nearly 300 days after mining had ceased (Kranz and Estey, 1996).

The stick-slip mechanism can produce seismic events with significant seismic energy and has been linked to the largest seismic events in the district. For instance, Whyatt et al. (1997) studied large seismic events (2.5 to 4.2 M_l) at the Lucky Friday Mine over a recent 6-year period and showed that all were slip events. Moreover, these events were caused by repeated movement along five separate structures (figure 3). Generally, intense damage was often observed where slip planes crossed excavations. Shaking damage was found near the event and in areas where rock was poorly supported, well fractured, and/or unusually weak.

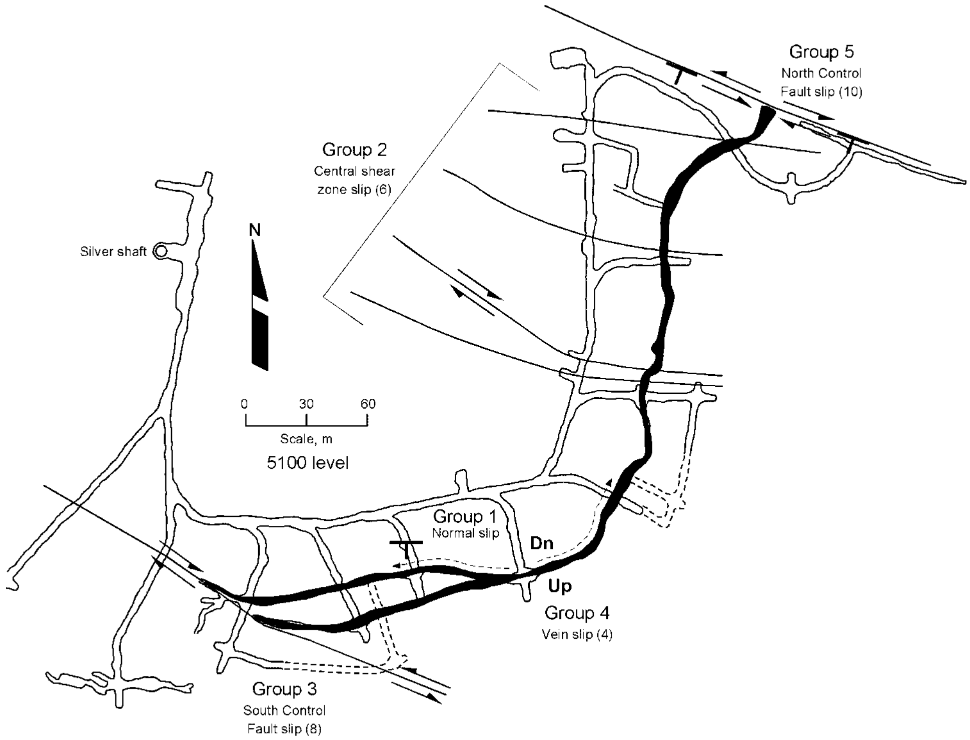

Figure 3.—Plan view of 5100 level, Lucky Friday Mine, showing typical slip movements that produced large-magnitude slip bursts (after Whyatt et al. 1997).

Summary

Summarizing, several lessons have been learned about seismicity and rockbursting in the Coeur d'Alene district.

! Most seismicity is a normal, safe, and desired rock mass response to mining. Only a small minority of seismic events constitute a rockburst hazard. The size of this minority depends on local rock mass conditions and mine practices.

! Individual rockbursts (and seismic events) cannot be predicted. However, changes in mining-induced seismicity can provide insight into changes in rock mass conditions and geologic structures, which can affect the likelihood of a rockburst.

! Three types of rockbursts are active in the district—strain, pillar, and slip. Each type presents a unique hazard and must be considered separately in both evaluating the level of rockburst hazard and designing protective measures.

TACTICAL MEASURES

Measures that can be taken locally and at short notice in response to a heightened level of rockburst hazard can be described as tactical measures. By contrast, strategic measures are those that must be integrated into mine design and long-term planning. Tactical measures that have proven successful in the Coeur d'Alene district include ground control systems, destress blasting, and manipulation of the rate of mining.

Ground Support

Ground support measures in rockbursting ground are designed to suppress damage where possible. Where damage is unavoidable, ground support should serve to contain damage, which preserves access and prevents burial of miners. Conventional rock bolts and timber sets respond best to static loads and are poorly suited for this task. They often fail under the dynamic loads exerted by a rockburst. The addition of energy-absorbing, yielding supports and a flexible surface covering improves prevention and containment of rockburst damage, particularly damage from seismic shaking. These measures confine and knit together fragments of rock within the fracture zones. A well-knit fracture zone will deform without failure of supporting elements or a fall of ground while exerting confining pressure on the rock deeper in the excavation wall.

A typical support configuration in rockbursting ground consists of a combination of Split-Set and resin-grouted Dywidag bolts along with chain link mesh (figure 4). Vulnerable points such as intersections can be reinforced with cable lacing. Steel-fiber-reinforced shotcrete is often used in highly stressed areas where small strain bursts occur during drilling for bolting and blasting. Shotcrete is also useful in suppressing damage from seismic shaking. These measures are described in detail by Blake and Cuvelier (1990, 1992).

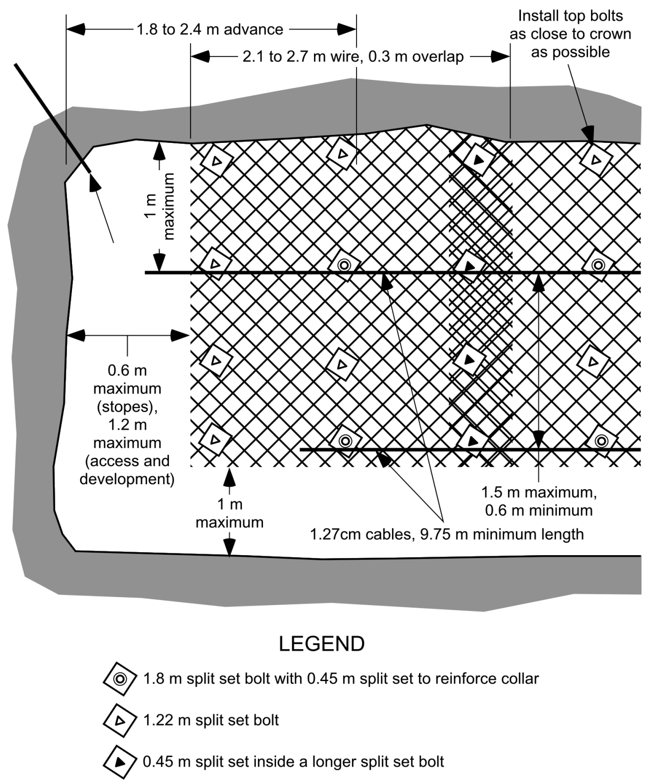

Figure 4.—Typical support scheme employed in rockbursting ground.

<u>Blasting</u>

Control of rockburst hazards with blasting practices started with the recognition that roughly 75% of district rockbursts occur with, or in the hour following, a blast.[1] Thus, blasts are often restricted to the end of a shift, particularly in areas where multiple headings are being worked simultaneously. Blast timing is sometimes used to accentuate, rather than limit, seismic shocks from rounds in an attempt to trigger rockbursts that might otherwise occur during a shift. In some cases, such a blast will sufficiently soften the fractured rock adjacent the opening to prevent a rockburst. In others, the rockburst will occur, but occur with the blast instead of during the shift.

Destressing is an extension of this procedure designed to fracture a highly stressed portion of the rock mass. It is an extension in the sense that additional holes are drilled into ground that is to be fractured by blasting, but not pulled. The objective is to induce a crushing, rather than a bursting, failure mode in the rock. Deformation occurring as part of this crushing failure will cause a shift in stresses from the destressed rock to other areas that can carry it more safely. Destressing can be pursued on a range of scales, from a portion of a future rib to an entire pillar.

When the rock at the face of a stope or heading is "popping" or "bumping" during drilling, face destressing is normally carried out to eliminate this hazard. Two or more holes are drilled ahead of the face and/or are fanned out in the walls. The bottom half of each hole is loaded with explosives and shot early in the round, so that the holes will not "pull" muck. This type of destress blasting fractures the ground around the new face, thereby preventing the ground from "working" at the face. The addition of destress holes to development and stope rounds has proven quite useful in reducing strain bursts.

Volley-fired backstope rounds are sometimes combined with destress holes. A portion of such a round does pull, allowing for continued production. The shock provided by the volley-fired round, coupled with firing of destress holes, is meant to control the rockburst hazard by triggering incipient rockbursts while the destress holes also serve to prevent further bursting in the immediate back of the stope. When this approach does trigger a rockburst, the damage is rarely "controlled" and is often very extensive, although it is safe as miners are evacuated at blasting time. However, sill pillars will retain a solid core susceptible to bursting until blastholes can be drilled through the entire intact core of the pillar.

Sill pillar destressing by drilling and blasting a single row of holes along the vein was first attempted by a joint USBM-ASARCO research project at the Galena Mine in the late 1960's. Sill pillar destressing quickly became the principal strategy to control pillar bursting and has been routinely carried out at the Galena, Star, and Lucky Friday mines in sill pillars mined to less than 15 m in height. The most effective destress blasts used large-diameter holes (greater than 100 mm) and a hole spacing of 3 m or less. They are loaded with high explosive to within about 4 m of the collar.

However, there are some disadvantages to pillar destress blasts. First, guidelines for design of a destress blast are scarce, so considerable experimentation can be required. Second, there is the operational problem. The length of time and effort to drill destress holes results in a significant loss of production with no guarantee of success. Hence, there is a tendency is to delay sill pillar destressing until the pillar is relatively small and thus very highly stressed. This can result in "bumping" and bursting during the drilling of destress holes, which in one case caused a fatality. Finally, it is difficult to assess whether a mass destress blast has completely eliminated the prospect of bursting in a sill pillar. Injuries, including fatal injuries, have occurred as a result of rockbursts in supposedly destressed sill pillars. Moreover, a failed destress blast may actually increase the level of hazard.

[1]Bill McLaughlin's study of Galena, Star, and Lucky Friday bursting versus blasting and hazard time from 1973-1978 showed that, at the Galena Mine, 79% of bursts occurred with blasting or between shifts. Similar results were obtained for the Star (68%) and Lucky Friday mines (74%) during this period. McLaughlin also found a similar level (68%) at the Lucky Friday Mine from 1982-1985.

Overall, destress blasting has proven to be an effective method for reducing hazards from strain bursting, but it is often problematic when applied to pillar bursts.

Mining Rate

One of the oldest techniques for controlling rockburst hazard is changing the rate of advance. Faces will often be shut down when unusual seismic activity is observed and then restarted after seismic activity quiets down. Miners on a second shift have frequently been kept out of their stopes until the heightened seismic activity from a first-shift blast decays to the “background” rate for that stope. Slowing down the mining rate increases the time available for the rock to deform inelastically (“work”), which transfers stress away from the perimeter of the excavation. Generally, a faster mining rate will produce more seismicity per ton mined than a slower rate.

The importance of time is also evident in the distribution of seismic activity (figure 5) and fatal accidents during the work week (table 2). Generally, activity increases early in the week, reaches a plateau mid-week, and then falls over the weekend. Time effects on seismicity and rockbursting are not well understood, and reasons for the predominance of fatalities on Wednesday (and to a lesser degree, Friday) are not apparent.

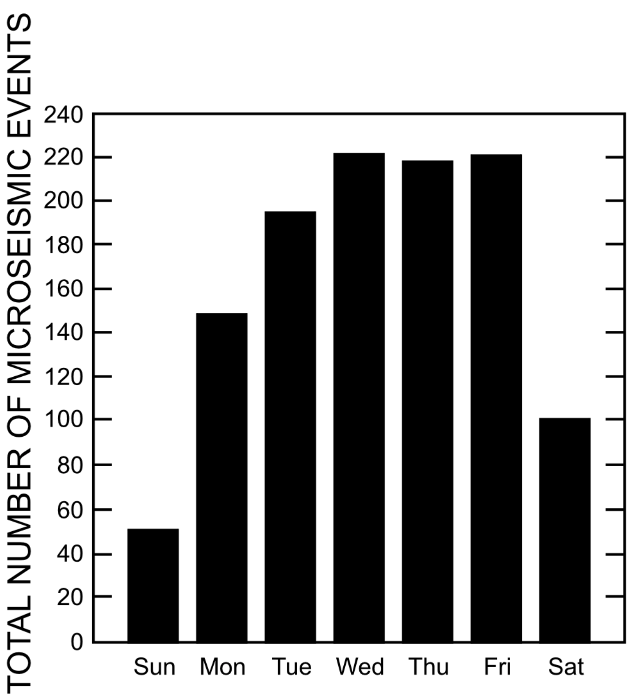

Figure 5.—Typical plot of number of microseismic events occurring by day of the week in a mine working a 5-day week.

Table 2.—Fatal rockburst accidents by mine and day of week.

Mine	Sun	Mon	Tue	Wed	Thu	Fri
Sunshine				3	1	1
Star/ Morning				4		
Galena			2	1	1	4
Lucky Friday			1	3		
Coeur						1
TOTAL			3	11	2	6

Summary

In summary, a number of tactical measures have been used successfully to reduce rockburst hazards. Tactical lessons that have been learned include—

! Support systems that absorb energy and deform without breaking provide the best support in rockburst-prone ground. Even where these systems suffer damage, they are often able to limit falls of ground and permit access where other systems fail completely.

! Destress blasting of rock, particularly highly stressed brittle rock, immediately surrounding an excavation can reduce rockburst hazards. Destress holes can be efficiently integrated into conventional rounds. Destress blasting of entire sill pillars is more problematic, but can improve conditions.

! Slowing the rate of extraction will often reduce the amount of seismicity in relation to tonnage mined and may actually prevent bursting under some conditions.

STRATEGIC METHODS

Measures that must be planned in advance, must be applied to large portions of a mine, and/or are relatively inflexible over time are described as strategic methods for rockburst hazards control. By contrast, tactical measures are those that can be taken locally, and at short notice, in response to a heightened level of rockburst hazard. Strategic measures are inevitably based on judgments about the relative level of rockburst risk inherent in alternative mine designs.

These judgments are based primarily on experience, some of which has been codified in criteria like the energy release rate and excess shear stress. These methods have progressed significantly over the past 60 years, but continue to have important limitations. Where these methods have been applied in the district, they have largely served to confirm and explain old rules that have proven to be of value. These rules can be found in various internal mining company documents dating from the 1950’s, and some can be traced back South African literature of the 1920’s. These rules are listed at the end of this section.

Generally, these old rules seek to avoid creation of large voids and small pillars, particularly in the vicinity of burst-prone geologic features. Where burst-prone geologic features are encountered, these locations should be mined and filled first while the extraction ratio—and the level of mining-induced stress—is low. Similar reasoning applies in the case of multiple veins where the vein is a burst-prone structure. For instance, mining the hanging wall vein first in an overhand stope removes this structure and the accompanying stress from the hanging wall of following stopes. Application of these rules to the Coeur d'Alene district requires changes in mining method and learning to recognize geologic features that contribute to rockburst risk.

Mining Methods

Backfilling of stopes was the first fully implemented adaptation of Couer d'Alene mining methods to rockbursting conditions, with a variety of open stoping methods giving way to overhand cut-and-fill mining by 1940. Backfill improved conditions in a number of ways, including limiting the amount of open ground and hence the severity of air blasts produced by rockbursts.

Work on stope sequencing began with the observation that a pillar burst was more likely to affect multiple adjacent stopes (on strike) when sill pillars of equal size were maintained. This observation was confirmed and explained by one of the first applications of numerical modeling (on an analog computer) and the energy release rate (Board and Crouch, 1997). As a result, single, flat-backed, cut-and-fill mining fronts at both the Star and Lucky Friday mines were changed to a center lead stope geometry. The Galena Mine adopted a stair-stepped (east end leading) sequence for its largest vein.

By the mid-1980's, sill pillar bursting at the Lucky Friday had become severe, with three fatalities in 3 years. As a result, the Lucky Friday converted to an underhand cut-and-fill mining method that did not create pillars. Underhand mining also provided for an engineered back consisting of reinforced cemented fill. The fill back has proven to hold up well under both gradual stope closure and dynamic loads from nearby seismic events. While continuing to be the most seismically active mine in the district, the Lucky Friday has had an outstanding safety record since switching to underhand longwall mining.

Geologic Features

Recognition of geologic features that contribute to rockburst hazards is a key part of formulating strategic measures for minimizing these hazards. Experience in the Coeur d'Alene district indicates that particular rock types and various kinds of discontinuities exert a strong influence on rockburst hazards.

The geologic structure of the district is complex. At least five major periods of tectonic deformation have taken place, resulting in the Belt strata being highly folded and faulted. The high tectonic stresses responsible for the complex structure have also left most district mines with unusually high horizontal stress fields. Veins are generally located in linear bands along fractures and fault zones and consist of highly variable proportions of sphalerite, galena, and argentiferous tetrahedrite in a gangue dominated by either quartz or siderite. White (1998) provides a more comprehensive treatment of district geology.

Coeur d'Alene district veins lie within a regional sequence of Precambrian metasediments referred to as the Belt Supergroup. Belt strata are characterized by thick, uniform sequences of slightly metamorphosed and predominantly fine-grained sediments with varying proportions of quartz and argillite. Veins of the mining district dip steeply, typically cut through strata, and are most economic in quartzitic strata, which is also the host rock for most of the significant rockbursts that have occurred.

In situ stress, as well as rockburst hazards, have been found to vary with geology in the Coeur d'Alene district. Whyatt (2000) has shown that in situ stress levels in quartzitic strata tend to be higher than in softer rocks at similar depths. Moreover, the most intense stress conditions are found in quartzitic strata that lie within the zone of silicification around quartz veins. These intense stresses and the brittle nature of silicified rocks contribute to increases in rockburst hazards. In fact, the degree of rockburst hazard experienced during mining of adjacent quartz and siderite veins has been found to vary significantly (Whyatt et al., 2000).

The connection between rockbursting and geology was made following the first reported rockburst, which occurred at the Sunshine Mine in April 1939 on the 2500 level. This burst was associated with the mining front leaving the relatively soft St. Regis Formation and entering the harder, more massive quartzites of the upper member of the Revett Formation. In April 1956, the first rockburst was reported at the Galena Mine on the 2400 level, also in the upper member of the Revett Formation, as initial mining on the newly discovered Silver vein created small pillars.

In the case of the Lucky Friday, the vein became economic—and burst-prone—as it entered the upper Revett below the 2000 level. This bursting continued with depth until about the 3250 level, when the vein entered the softer middle Revett Formation. A renewal of serious bursting began again in 1983 as the vein entered the harder lower Revett at about the 4450 level. At the Star Mine, thin-bedded sections of lower Revett were not burst prone, but thicker quartzite beds were.

Strain bursts often occur when mine openings intersect a dike or a more massive section of quartzite beds, usually during development. Strain bursts are particularly sensitive to the orientation of discontinuities around the perimeter of an opening, since these discontinuities define plates that can buckle into the opening. Sets of discontinuities (bedding planes, joint sets) should be intersected at as high an angle as possible.

The largest seismic events at both the Star and the Lucky Friday have all occurred out in the walls on faults, primarily in the hanging wall. These large events appear to be associated with the overall geometry of mine excavation rather than day-to-day mining. Individual faults should also be cut at high angles, for several reasons. First, as faults increase in scale, the scale of the associated gouge zone also increases. High-angle intersections minimize the amount of the gouge zone that must be supported. Second, gouge can define strain-burst-prone plates where an opening enters and leaves a fault zone. Third, slip bursts have been shown to cause the greatest damage at the intersections between a fault and mine opening (Whyatt et al., 1997). Some of the most devastating bursts in the Coeur d'Alene district have occurred when the vein becomes a seismically active fault. Thus, high-angle intersections limit exposure to slip-burst damage.

Summary

In summary, a number of strategic guidelines have been used successfully to reduce rockburst hazards in the Coeur d'Alene district. These guidelines include a number of old rules.

! A properly planned sequence of stoping for the whole ore body should be adopted and followed as closely as possible.
! The merging of large excavations at depth should be avoided.
! Pillars should be eliminated or reduced to a minimum.
! Parallel veins should be stoped singly, the hanging wall vein first (footwall vein first if underhand mining).
! Where veins branch, stoping should begin at the intersection and then progress away from the intersection one branch at a time.
! Where possible, stoping should proceed away from a fault or other plane of weakness.
! Mined-out areas should be filled, and filling should proceed concurrently with extraction and be kept as close to the face as possible.

A few additional guidelines can be gleaned from Coeur d'Alene district experience.

! Underhand longwall mining is a practical, economical mining method that can reduce rockburst hazards.
! Openings in rockburst-prone ground should cut weak discontinuities and slip-prone faults at high angles.
! Rockburst hazards vary greatly with geology and are greatest in hard quartzitic strata, particularly in rock altered by silicification around quartz veins.

DISCUSSION

A great deal has been learned about rockburst phenomena during the 60 years of mining in the Coeur d'Alene district. It is now recognized that there are different types of rockbursts with different causal mechanisms and that these mechanisms are affected by mining decisions in different ways. The hard and brittle quartzites of the Revett Formation have been identified as the host rock for almost all rockbursts, and silicified rock within the Revett Formation has been shown to be particularly hazardous. District experience has also shown that many general rules for reducing rockburst hazards proposed early in the twentieth century are valid and worthy of continued application. Indeed, some of the significant advances in district mining have occurred as cost-effective methods for applying these rules have been developed.

District experience has suggested a number of additional rules that the authors have attempted to describe. These descriptions are a first attempt and should be improved by continued discussion and debate within the mining community, which we invite. The rules are offered as an attempt to summarize district experience with rockbursting as a guide for ongoing mine operations within the district and to apply these hard-won lessons to other mining districts.

While a great deal has been learned about rockbursts and developing rockburst control methods and procedures, it is clear that many mysteries remain. Our understanding of the causative mechanisms of rockbursts needs to be improved, taking into account that each burst is both mine and site specific. The element of time in these mechanisms is poorly understood, despite the fact that many mines have long used mining rate to control rockburst hazards. Our knowledge of rockburst damage mechanisms is limited and needs to be improved so that we can design more effective ground support. Finally, we need to improve our ability to anticipate rockburst problems likely to arise from various combinations of geologic setting, mining plans, and various tactical measures.

This paper is an attempt to summarize progress gained from the experience and efforts of a community of miners and mining professionals. The scope of this attempt almost guarantees that important facets of district experience and practice have been neglected or misrepresented. Clarifications, corrections, and extensions of this work are most welcome, for these lessons have been too hard-won—in suffering and in lives lost—to get wrong, ignore, or forget.

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